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Research report

An ERP study of continuous speech processing I. Segmentation, semantics, and syntax in native speakers

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Abstract

Speech segmentation, breaking continuous streams of sound into units that can be recognized, is a necessary step in auditory language processing. To date, most studies of speech segmentation have been limited to behavioral measures that may not index online segmentation as it occurs when listening to natural speech. In the present study, we measured event-related potentials (ERPs) evoked by word-initial and word-medial syllables equated for loudness, length, and phonemic content. This comparison provided an online measure of natural speech segmentation. Word-initial sounds elicited a larger early sensory component (N100). In addition, we measured the effects of semantic and syntactic information on speech segmentation by comparing ERPs to word-initial and word-medial syllables in sentences with varying amounts of semantic and syntactic content. The results indicated that neither semantic nor syntactic information is necessary for the word-onset segmentation effect to be observed. We also identified additional ERP components that index more general semantic and syntactic aspects of natural speech processing.

Theme: Neural basis of behaviour

Topic: Cognition

Keywords: Speech segmentation; Temporal parsing; Speech perception; Auditory; Language; Lexical

1. Introduction

The lack of obvious cues that indicate where one word ends and the next begins in speech is easily demonstrated by listening to an unfamiliar language. There are no pauses between spoken words, as there are spaces between written words, to indicate where continuous streams of speech should be segmented. In contrast, the ease with which one understands one's native language demonstrates the lack of conscious effort or strategies needed to segment familiar speech; the words seem to pop out of the continuous stream as if each were in fact spoken in isolation.

Many behavioral studies have investigated types of information listeners can use to segment speech. Statistical learning, phonotactic constraints, allophonic variation, stress pattern, other rhythmic cues, syntactic structure, semantic content, and lexical recognition have all been shown to be useful for speech segmentation [11,13,14,24,27,38,44,45]. These studies have used a variety of well-designed tasks including juncture misperception, phoneme monitoring, segment monitoring, shadowing, gating, and tests of word learning; however, each of these tasks is limited in its ability to provide direct information about speech segmentation. For example, many studies using gating and segment monitoring tasks have employed word lists rather than continuous speech as stimuli. Juncture misperception and word learning tasks are dependent not only on perception, but also on memory. In addition, many of the behavioral tasks typically used in speech segmentation studies could be influenced by linguistic processing that occurs well after segmentation, and most of the tasks involve presentation of stimuli for which only one kind of segmentation cue is available. As a result, behavioral studies typically show that listeners *can* use a

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specific type of segmentation cue, but fail to address if or how a specific cue is *actually* used in speech perception.

To fully characterize which segmentation cues are used in natural speech processing, where speech streams are segmented, and to begin to explore differences in the ways in which different groups of listeners (including young infants and bilingual speakers) segment speech, another measure of speech segmentation is called for. Specifically, a technique that provides fine temporal resolution, that does not require an overt response, and that can index unconscious, automatic processes is required. Event-related potentials (ERPs) are just such a measure.

The results of early ERP studies of continuous speech indicated that words in natural speech do not elicit the sensory components normally evoked by words presented in isolation [9,35]. The authors of these studies attributed the absence of an N100–P200 complex to reflect the lack of a pause before words in connected speech. In other studies of semantic and syntactic processing of natural speech (not specifically measuring early sensory components), a similar absence of an N100 is apparent in published figures [8,15,18]. The results of these studies somewhat disappointingly suggest that the nature of continuous speech might preclude the existence of ERP components sensitive to word onsets.

Fortunately, visual inspection of published ERP waveforms from other studies of continuous speech indicate that word onsets do indeed evoke an N100 [19,20,23]. Since none of these studies were specifically designed to measure word-onset effects, it is impossible to determine if the presence of early sensory components reflects speech segmentation or simply differences in the physical attributes of the stimuli. However, the results clearly raise the hypothesis that an early ERP index of word onset in continuous speech may exist. This is consistent with a recent study showing that ERPs can index parsing of the speech stream [48]. In this study, a positive shift was found at phrase boundaries—whether or not physical pauses actually occurred at the boundaries.

In order to investigate the hypothesis that ERPs could index word onset effects, particularly if a study were specifically designed to investigate such effects, we conducted an ERP study of speech segmentation. In the present study, ERPs elicited by word onsets were compared to those elicited by word-medial syllable onsets with equivalent acoustic properties. The word-initial and word-medial sounds were matched on phonemic content, loudness, length, and fundamental frequency. The words in which the word-initial and word-medial sounds occurred were matched on length, frequency, position in sentence, and cloze probability. With this carefully balanced design, we attempted to isolate an ERP effect for word onsets and identify an ERP index of speech segmentation.

Additionally, we explored the impact of two types of segmentation cues, lexico-semantic and syntactic information, on word-onset effects. Previous behavioral studies have suggested that both these types of information can influence speech segmentation [7,14,42,45,49]. However, the measures taken in each of these studies may have been influenced by post-segmentation processing and may have required meta-linguistic skills. While it is particularly difficult to design behavioral tasks that differentially provide semantic and syntactic cues and index online segmentation processing, the design of the present ERP study easily allowed for this additional manipulation.

To index the effects of lexico-semantic and syntactic information on speech segmentation, we presented sentences with various amounts of lexical and syntactic content. Normal English sentences (*semantic* sentences) were used to measure segmentation when complete lexical, semantic, and syntactic information was available. Sentences in which all of the open-class words of the *semantic* sentences had been replaced with pronounceable nonwords (*syntactic* sentences) were used to measure segmentation when normal syntactic and acoustic, but less lexico-semantic, information was available. Sentences in which all the open- and closed-class words and morphemes were replaced with nonwords (*acoustic* sentences), were used to index segmentation when the availability of both lexico-semantic and syntactic information was reduced. We reasoned that if lexico-semantic information is used as a cue in online speech segmentation, word-onset effects should be larger for *semantic* than *syntactic* sentences. Similarly, if syntactic information is used as a cue for segmentation, word-onset effects should be larger for *syntactic* than *acoustic* sentences. Alternatively, if lexico-semantic and syntactic information only interacts with post-segmentation processing, word-onset effects should be similar across sentence types.

While the primary focus of the present study was on speech segmentation, measuring ERPs to the three types of sentences also made it possible to index semantic and syntactic processing in general. We employed two contrasts to index semantic processing (1) the difference in response to words and pronounceable nonwords, and (2) the difference in response to *semantic* and *syntactic* sentences.

Several studies have investigated the differences in ERPs elicited by words, pronounceable nonwords, and consonant strings. When presented in isolation or in pairs, pronounceable nonwords elicit a larger N400 than words, which in turn elicit a larger N400 than consonant strings or backward speech [6,21,22,53]. The authors of these studies interpreted the N400 as indexing lexical search processes. Since pronounceable nonwords could only be identified as such after a lexical search was complete, they would be expected to elicit a larger N400. However, a different picture emerges for words and nonwords presented in sentences. When presented as the last item in sentences otherwise comprised of words, pronounceable nonwords have been shown to elicit a larger N400, as expected [43]. However, there are no differences in the N400 elicited by words presented at the end of sentences comprised of words and the N400 elicited by nonwords presented at the end of sentences comprised of words and a few nonwords [31]. In fact, when nonwords are presented in blocks of sentences containing other nonwords, nonwords do not elicit an N400 at all [20].

In addition to the word/nonword comparison, we investigated semantic processing by comparing ERPs elicited by the *semantic* and *syntactic* sentences. Few studies have reported ERPs averaged across entire sentences. However, it is known that the N400 typically elicited by open-class words decreases in amplitude across sentence position [50]. Additionally, sentences that create greater processing demands have been shown to elicit a broadly distributed negativity [29]. Other studies have used the same kind of sentences described here (*semantic*/normal and *syntactic*/jabberwocky), but have only reported ERPs elicited by specific words in the sentences [4,5,20,31]. Therefore, it was unclear what to expect from our cross-sentence comparisons.

To index syntactic processing, we compared the responses to the *syntactic* and *acoustic* sentences, as well as the responses to the same nonwords in those two types of sentences. Neither of these comparisons has been made previously in the literature: for the most part, ERP studies of syntactic processing have focused on the effects of violations of syntactic rules. These studies have shown that phrase structure violations first elicit an early negativity approximately 100–200 ms after onset over left anterior regions (e.g., Refs. [2,15,17,33]). In some cases, this early negativity is followed by a later left anterior negativity (300–500 ms) (e.g., Refs. [15,17,26,30,33]). In almost all cases, these early negativities are followed by a later, broadly distributed bilateral positivity referred to as the P600 (e.g., Refs. [16,18,37,39]).

While there have been few ERP studies using sentences similar to the *syntactic* sentences in the present study, researchers have found that syntactic violations in sentences partially composed of nonwords can elicit the ERP components typical of syntactic violations in normal sentences [5,20,31]. However, the studies report disparate findings concerning which syntactic components are preserved for sentences containing nonwords. Nevertheless, the results of all of these studies indicate that syntactic processing can and does occur for *syntactic*-type sentences. Given that the sentences presented in this study did not contain syntactic violations, but rather varied the amount of syntactic information available, it is unclear what effects might be seen in the comparison of nonwords presented in the *syntactic* and *acoustic* sentences. Further, given that no previous study including *syntactic*-type sentences has averaged ERPs across entire sentences, it was equally unclear what sentence-level effects might be seen.

In summary, in the present ERP study of continuous speech processing, we investigated a possible word-onset effect by comparing the ERP responses to word-initial and word-medial syllables matched on a number of characteristics. In addition, we investigated the effects of lexico-semantic and syntactic information as segmentation cues. Finally, we looked at semantic and syntactic processing more generally.

2. Materials and method

2.1. Participants

Eighteen (10 females) right-handed, monolingual English speakers participated. All were students at the University of Oregon between the ages of 18 and 35 ($M=22;5$). Some of the participants ($N=6$) had been in a previous behavioral experiment using the same stimuli.

Since many of the results found for this study had not previously been reported in the literature, it was important to replicate the findings. Therefore, we included another group of 10 adults (five females) in the same experiment. This group also consisted of 18–35-year-old ($M=24;8$), right-handed, monolingual English speakers, who were university students. The data from these participants were collected approximately 2.5 years after those for the first group.

The task was self-paced so subjects took from 3 to 5 h to complete the experiment. They were encouraged to take brief breaks at least every 20 min, and a longer meal break halfway through. All subjects were paid $7 per hour for their time.

2.2. Stimuli

The stimuli used in this study were fully characterized previously [45,47] and will be described briefly here. To index speech segmentation, similar sounds in different word positions were needed. We selected syllables that began with the same consonants and consonant clusters, received the same lexical stress (stressed or unstressed), and occurred in different positions within words. Representative examples of word-initial and word-medial syllables are given in Table 1.

To measure the effects of lexico-semantic and syntactic information on speech segmentation, we used sentences with various amounts of lexico-semantic and syntactic content. The syllables selected for the word-initial/word-medial comparisons were presented in three types of sentences: *semantic*, *syntactic*, and *acoustic*. *Semantic* sentences were simply normal English sentences ($N=240$). All of the open-class words in the *semantic* sentences were replaced with pronounceable nonwords to create sentences with less lexical and semantic content (*syntactic* sentences, $N=240$). Furthermore, all of the closed-class words and morphemes in the *syntactic* sentences were replaced with pronounceable nonwords to create sentences with less syntactic content (*acoustic* sentences, $N=240$). Examples of each sentence type are given in Table 2.

Table 1
Word-initial and word-medial syllables

Word-Initial (N=120)		Word-Medial (N=120)	
banter	ballet	obey	symbol
dangerous	decisive	pedestrians	verdict
ghetto	gourmet	negate	bagels
coffee	compete	stockade	vacant
figment	phonetic	perform	pilfer
massacre	mistake	harmonic	atmosphere
navigate	necessity	tornado	witness
gravity	grammatical	ingredient	fragrances

The underlined portion of each word indicates the syllable ERPs were averaged to. Both stressed and unstressed syllables in word-initial and word-medial positions were selected. The word-medial group included many examples of word-final syllables. These syllable types (word-medial and word-final) were considered together since the onset of the phonemes to which ERPs were time-locked was always word-medial.

Several measurements were taken to ensure that syllables in word-initial and word-medial positions were acoustically similar. These two groups of syllables were matched on phonemic content, loudness, length, and fundamental frequency as is shown in Table 3. Additionally, words that contained the syllables in different positions were matched on length, written and spoken word frequency, cloze probability, and position in the sentences (Table 4). Furthermore, we determined that the physical characteristics were constant across the different sentence types by measuring both speech rate (Table 5) and pitch contours (Fig. 1).

All sentences (N=720) were recorded digitally (22 kH sampling rate, 16 bit) by a native English speaker. Syllable onsets were defined as the earliest point at which evidence of the upcoming phoneme could be heard in the sound file or seen in the waveform. These onsets were determined independently by two native English speakers. Only onsets for which the measurements of the two coders were within 10 ms were included in the final stimulus set.

2.3. Procedure

All subjects were fitted with a 29-channel cap containing tin electrodes (Electro-Cap International). Scalp electrode locations are shown in Fig. 2. Impedences at all electrode

Table 3
Characteristics of word-initial and word-medial syllables

Position	Amplitude	Length (ms)	F0 (Hz)
Initial:			
Semantic	0.51	126	246
Syntactic	0.55	125	266
Acoustic	0.54	119	241
Medial:			
Semantic	0.61	148	236
Syntactic	0.60	136	220
Acoustic	0.55	146	254

For all measures, the syllable was defined as beginning at the first indication of the consonant or consonants and ending at the last indication of the following vowel. All sentences had been normalized to have a maximum amplitude of 1. The amplitude reported here is the maximum value during the span of the syllable (between 0 and 1). Fundamental frequency (F0) was measured as the average frequency within the span of the syllable.

Table 4
Characteristics of words containing target syllables

Position	Written frequency	Spoken frequency	Cloze probability	Word length (ms)	Position in sentence (ms)
Initial	20.6	2.3	0.044	481	1514
Medial	21.1	2.4	0.021	498	1717

Written word frequency [25] and spoken word frequency [1] were calculated from published corpuses. Cloze Probability was calculated from responses of 40 participants asked to complete the sentences starting from the word of interest.

Table 5
Characteristics of sentences

Sentence type	Speech rate (words/s)	Length (ms)
Semantic	4.29	3416
Syntactic	4.40	3390
Acoustic	4.31	3471

Table 2
Examples of *semantic*, *syntactic*, and *acoustic* sentences

Condition	Example
Word-Initial:	
Semantic	In order to recycle bottles you have to separate them.
Syntactic	In order to lefatal bokkers you have to thagamate them.
Acoustic	Ah ilgen di lefatal bokkerth ha maz di thagamate fon.
Word-Medial:	
Semantic	If the only thing in it were tobacco it wouldn't cause so much harm.
Syntactic	If the ilmy shord in it were dobatty it wouldn't gaff so much hilm.
Acoustic	Os fa ilmy shord el ak hon dobatty ag hapsel gaff sha nes hilm.

Underlined portions indicate the syllables ERPs were averaged to.

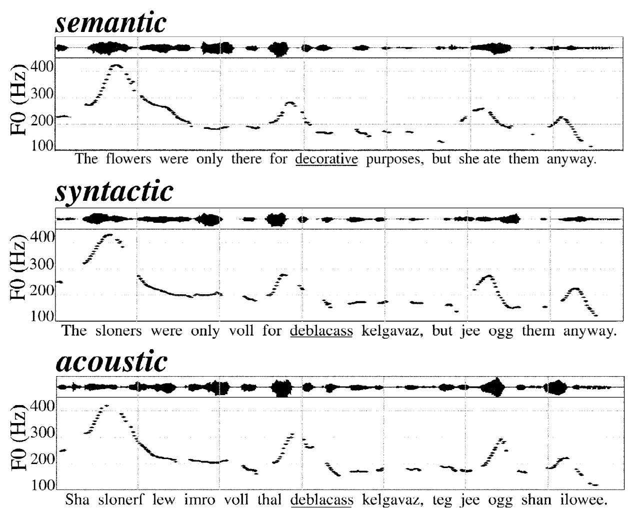

Fig. 1. Waveform and pitch contours for representative *semantic*, *syntactic*, and *acoustic* sentences. The three versions of every sentence were inspected to ensure that contours were similar across sentence types.

sites were maintained below 3 kΩ for the duration of the experiment. Additionally, the electrooculogram was recorded from electrodes above and below, as well as left and right of the eyes. Trials during which blinks or eye movements occurred were rejected before averaging. All electrodes were referenced to a single mastoid (right) online, and later rereferenced to the average mastoid (right and left). The EEG was amplified by Grass 7P511 amplifiers with a bandpass of 0.01–100 Hz and sampled every 4 ms continuously throughout sentence presentation.

Subjects were asked to press a button to initiate the presentation of each sentence. After pressing the button, a fixation point appeared on the monitor (55 inches away) 700 ms before the beginning of a sentence and remained on the screen for 1000 ms after the end of each sentence. Subjects were asked to not blink or move their eyes during the interval in which the fixation point was on the screen. Sentences were presented over headphones at an average of 65 dB above normal hearing threshold.

After a random 10% of the trials subjects were asked to report if a specific word (*semantic* sentences) or nonword (*syntactic* and *acoustic* sentences) had been heard in the previous sentences. An equal number of questions was asked for each sentence type. Half of these items were presented in the previous sentence; the other half were new items not presented in any of the sentences. Questions were asked by the experimenter during brief breaks after random sentences such that subjects would not know which sentences would be followed by a question. Participants responded by stating either 'yes' or 'no', and were then asked to press a button when they were ready to begin the next trial. All subjects responded correctly to at least 95% of both the word and nonword questions.

ERPs were averaged to the beginning of each sentence with a prestimulus baseline of 500 ms, and to selected words and syllables within the sentences with a prestimulus baseline of 300 ms. Peak amplitudes between 20 and 80 ms (P50), between 70 and 130 ms (N100), and between 170 and 230 ms (P200) were measured for selected syllables, words, and for sentence onsets. Additionally, the mean amplitude between 200 and 300 ms was measured across syllables. The mean amplitude between 150 and 600 ms and between 400 and 800 ms was measured across words. The mean amplitude between 400 and 1200 ms and between 1400 and 3000 ms was measured across sentences.

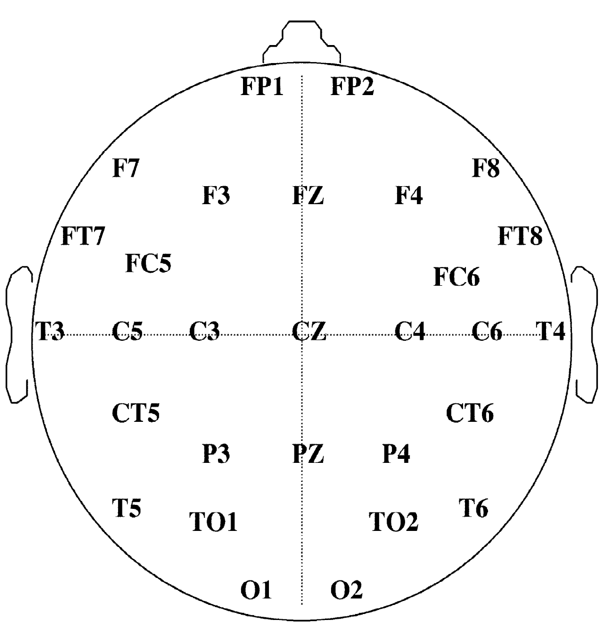

Fig. 2. Approximate location of the 29 scalp electrodes.

3. Results

A six-factor repeated measures ANOVA (Geisser-Greenhouse adjusted) was conducted: Position (word-initial, word-medial) by Stress (stressed, unstressed) by Sentence type (*semantic*, *syntactic*, *acoustic*)×electrode Hemisphere (right, left) by electrode Laterality (lateral, medial)× electrode Anterior/Posterior position (six levels). For all resulting interactions including Position, Stress, or Sentence type, additional ANOVAs were carried out. These ANOVAs were restricted to only one sentence type, or to specific electrode sites as determined by Hemisphere, Laterality, or Anterior/Posterior interactions.

3.1. Speech segmentation

3.1.1. N100: negative peak between 70 and 130 ms

ERPs were averaged to word-initial and word-medial syllables (Fig. 3). Position had no effect on P50 amplitude. However, effects were found for the N100: there was a

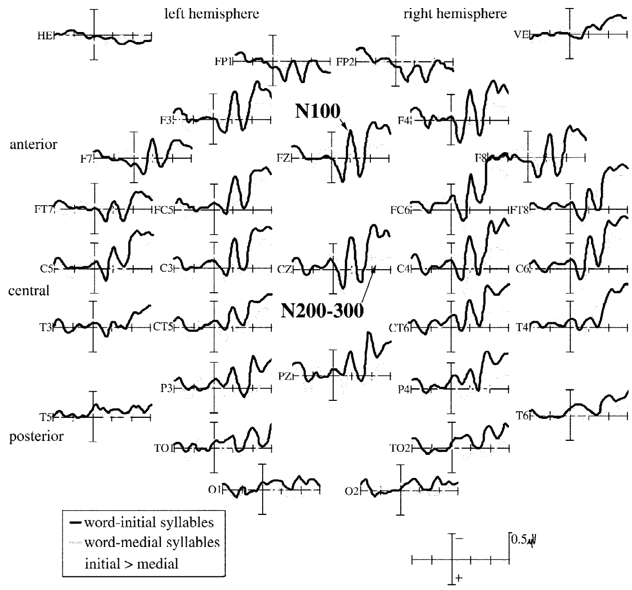

Fig. 3. ERPs to word-initial and word-medial syllables matched on acoustic characteristics. Shading indicates electrodes included in the ANOVA showing a main effect of position. N100: word-initial sounds elicited a larger N100 at medial electrode sites. N200–300: word-initial sounds elicited a larger negativity at midline and medial right hemisphere sites.

Position by Laterality by Anterior/Posterior interaction on N100 amplitude ($F(5,85)=5.21$, $P<0.001$). To further investigate the distribution of position effects, ANOVAs including anterior electrodes, central electrodes, and posterior electrodes alone were conducted. However, no significant position effects were found for these subsets of electrodes. Nor were position effects found for lateral electrodes or medial electrodes alone. However, when midline (Fz, Cz, and Pz) and medial electrodes were included in the same ANOVA, word-initial syllables were shown to elicit a larger N100 than word-medial syllables ($F(1,17)=4.52$, $P<0.05$).

The N100 position effects interacted with sentence type at some electrode sites (Position×Sentence×Laterality interaction: $F(2,34)=5.87$, $P<0.01$). For the *acoustic* sentences alone, word-initial syllables elicited a larger N100 at medial electrode sites (Position×Laterality interaction: $F(1,17)=10.34$, $P<0.01$; Position, medial electrodes only: $F(1,17)=6.83$, $P<0.05$). Similarly, for the *syntactic* sentences alone, word-initial syllables evoked a larger N100 at medial electrode sites (Position×Laterality interaction: $F(1,17)=9.66$, $P<0.01$; Position, medial electrodes only: $F(1,17)=8.74$, $P<0.01$). With this analysis, no significant effects were found for the *semantic* sentences. However, as will be discussed later, open-class words in the *semantic* sentences elicited a large N400. A likely reason for the lack of N100 position effects for the *semantic* sentences is that word-medial syllables were presented during the N400. To account for this, a different measure of ERP components was used. For the *semantic* sentences, we measured the difference in amplitude between the P50 and N100. The peak-to-peak amplitude between 20 and 120 ms was larger for word-initial than word-medial syllables at medial electrode sites (Position× Laterality interaction: $F(1,17)=11.41$, $P<0.01$; Position, medial electrodes only: $F(1,17)=10.30$, $P<0.01$). Thus, the same word-onset effect was found for the *semantic* sentences as well.

The word-onset effect replicated in the second group of subjects (Fig. 4). Word-onsets elicited a larger N100 than word-medial syllable onsets at midline and medial electrode sites (Position×Laterality×Anterior/Posterior interaction: $F(5,45)=5.82$, $P<0.001$; Position, midline and medial electrodes only: $F(1,9)=6.11$, $P<0.05$). The word-onset effect interacted with sentence type (Position× Sentence×Laterality×Anterior/Posterior: $F(10,90)=7.11$, $P<0.001$). For the *semantic* sentences, position did not affect the N100 amplitude. However, the peak-to-peak amplitude between 20 and 120 ms was larger for word-initial than word-medial syllables at medial, anterior electrode sites (Position×Laterality×Anterior/Posterior interaction: $F(5,45)=11.21$, $P<0.001$; Position, medial anterior electrodes only: $F(1,9)=7.24$, $P<0.05$). For the *syntactic* sentences, word-initial syllables evoked a larger N100 over medial electrode sites (Position×Laterality interaction: $F(1,9)=7.74$, $P<0.05$; Position, medial electrodes only: $F(1,9)=8.06$, $P<0.05$). For the *acoustic* sentences, word-initial syllables also evoked a larger N100 over medial and anterior electrode sites (Position× Laterality×Anterior/Posterior interaction: $F(5,45)=5.41$,

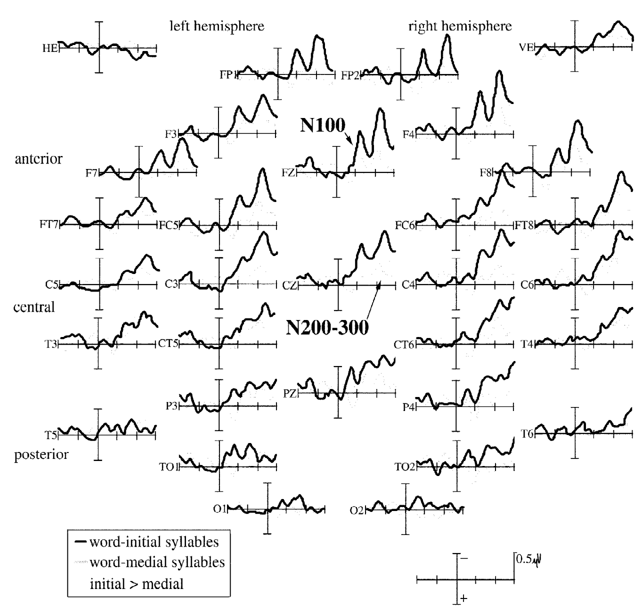

Fig. 4. ERPs recorded from the second group of subjects to word-initial and word-medial syllables. Shading indicates electrodes included in the ANOVA showing a main effect of position. N100: word-initial sounds elicited a larger negativity at medial electrode sites. N200–300: word-initial sounds elicited a larger negativity at midline and medial right hemisphere sites.

$P<0.001$; Position, medial anterior electrodes only: $F(1,9)=5.89$, $P<0.05$).

3.1.2. N200–300: mean amplitude between 200 and 300 ms

There were also position effects on the N200–300 (Fig. 3). In this time range, there was a Position by Hemisphere by Anterior/Posterior interaction ($F(5,85)=6.14$, $P<0.001$). For the anterior three rows of electrodes, the difference was larger over right hemisphere sites (Position×Hemisphere interaction: $F(1,17)=4.48$, $P<0.05$). However, a main effect of position was only found when midline and medial sites over the right hemisphere were included ($F(1,17)=8.96$, $P<0.01$). The electrodes included in this analysis are shaded in Fig. 3. This word-onset effect (N200–300) did not interact with sentence type. All of the effects replicated in the second group of participants (Fig. 4) (Position×Hemisphere×Anterior/Posterior interaction: $F(5,45)=4.99$, $P<0.01$; Position×Hemisphere interaction, anterior sites only: $F(1,9)=8.43$, $P<0.05$; Position, midline and medial sites over right hemisphere only: $F(1,9)=5.92$, $P<0.05$).

3.2. Stress processing

3.2.1. N100: negative peak between 70 and 130 ms

The word-onset effects described above were elicited by syllables matched on loudness and length. However, these physical attributes may also affect ERPs evoked by continuous speech. Therefore, the ERPs elicited by stressed syllables (louder and longer) were compared to those elicited by unstressed syllables (softer and shorter) matched for word position (Fig. 5). A Stress by Anterior/Posterior interaction was found for N100 amplitude ($F(5,85)=5.87$, $P<0.001$). For the three anterior rows of electrodes, stressed syllables elicited a larger N100 than unstressed syllables ($F(1,17)=4.93$, $P<0.05$). This effect was replicated in the second group of subjects.

3.2.2. N200–300: mean amplitude between 200 and 300 ms

Stressed syllables also elicited a larger N200–300 than unstressed syllables ($F(1,17)=6.72$, $P<0.05$) (Fig. 5). This main effect was found across electrode position. However, Stress also interacted with Anterior/Posterior electrode site ($F(5,85)=4.90$, $P<0.01$) such that effects were larger over anterior regions. Additionally, Stress interacted with Sentence type ($F(2,34)=4.51$, $P<0.05$). When each sentence type was analyzed separately, only the *semantic* sentences showed a significant effect of stress ($F(1,17)=9.30$, $P<0.01$). Each of these effects replicated in the second group.

3.3. Semantic processing

3.3.1. N400: mean amplitude between 150 and 600 ms

ERPs elicited by open-class words in the *semantic* sentences and position- and length-matched nonwords in the *syntactic* sentences were compared (Fig. 6). No

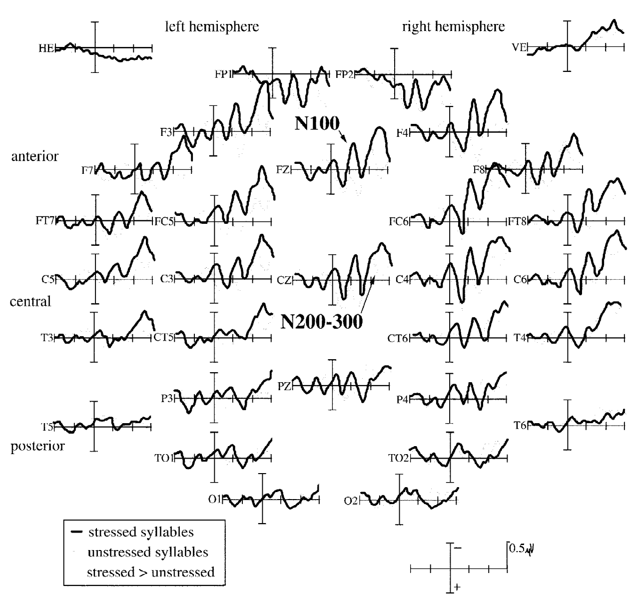

Fig. 5. ERPs averaged to stressed and unstressed syllables. Shading indicates electrodes included in the ANOVA showing a main effect of stress. N100: stressed syllables elicited a larger N100 over anterior electrode sites. N200–300: stressed syllables elicited a larger negativity across electrode sites. The difference was larger over anterior regions.

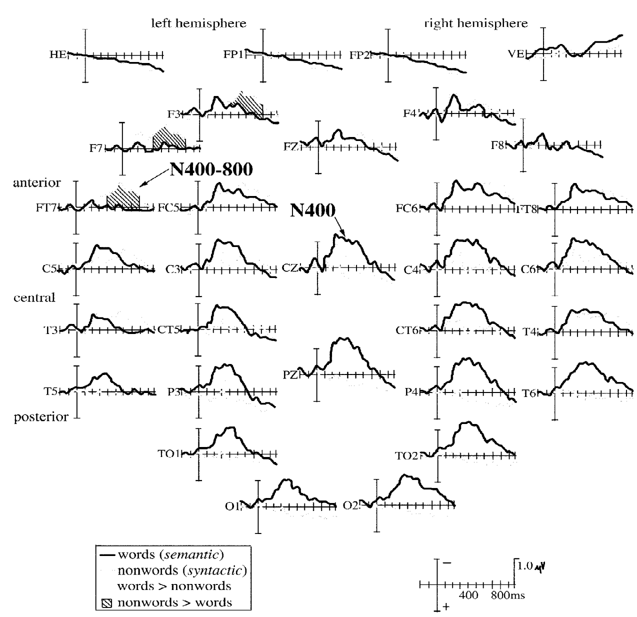

Fig. 6. ERPs elicited by open-class words in *semantic* sentences and their nonword equivalents in the *syntactic* sentences. Shading indicates electrodes included in the ANOVA showing a main effect of word/nonword. N400: words elicited a larger negativity than nonwords over posterior electrodes. This difference was larger at right hemisphere sites for the first, but not the second, group of participants. N400–800: nonwords elicited a larger negativity over F3, F7, and FT7. However, this effect did not replicate in the second group.

differences were found before 150 ms; however, between 150 and 600 ms, a Word/Nonword by Hemisphere by Anterior/Posterior interaction was found ($F(5,85)=11.02$, $P<0.001$). When the posterior four rows of electrodes were included, words elicited a larger negativity than nonwords ($F(1,17)=13.27$, $P<0.01$). Over these posterior electrode sites, the difference between words and nonwords was larger over the right hemisphere (Word/Nonword×Hemisphere interaction: $F(1,17)=5.07$, $P<0.05$). In the second group of subjects, words elicited a larger N400 than nonwords over posterior electrode sites; however, there were no hemisphere effects.

3.3.2. N400–800: mean between 400 and 800 ms

For the N400–800, there was a Word/Nonword by Hemisphere by Anterior/Posterior interaction: $F(5,85)=9.77$, $P<0.01$). There were no Word/Nonword or Word/Nonword by Hemisphere interactions for the two most anterior rows of electrodes. However, at three selected electrode sites (F3, F7, and FT7), nonwords elicited a larger negativity than words ($F(1,17)=4.52$, $P<0.05$). Unlike the N400, this N400–800 effect was not found for the second group of participants.

3.4. Sentence onsets

Sentence onsets clearly elicited typical auditory onset components (Fig. 7): P50, N100, and P200. These effects had much larger amplitudes than those seen for word or syllable onsets within the sentences. There were no differences between the sentence types for these early components.

3.4.1. Sent1400–3000: mean between 1400 and 3000 ms

Between 1400 and 3000 ms, there was a Sentence by Hemisphere by Anterior/Posterior interaction ($F(5,85)=14.12$, $P<0.001$). When the three rows of posterior electrodes were further examined, a Sentence by Hemisphere interaction ($F(2,34)=5.91$, $P<0.01$) was found. When only right hemisphere electrodes from the posterior three rows were included in an ANOVA, a main effect of sentence type was found ($F(1,17)=22.47$, $P<0.001$). At these sites, *semantic* sentences elicited a larger negativity than *syntactic* sentences. For the second group, a larger negativity to *semantic* sentences was elicited over posterior electrodes, but this effect did not interact with hemisphere.

During the same time window at anterior electrode sites, *syntactic* sentences elicited a larger negativity than *semantic* sentences ($F(1,17)=9.36$, $P<0.01$). Unlike the posterior effect, this difference did not interact with hemisphere. This effect over anterior electrode sites was replicated in the second group.

3.5. Syntactic processing

3.5.1. N400–800: mean between 400 and 800 ms

The only difference in ERPs elicited by nonwords in the

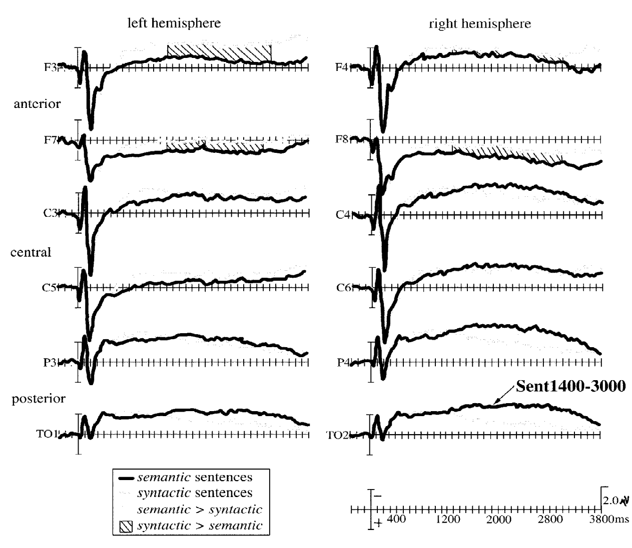

Fig. 7. ERPs averaged to *semantic* and *syntactic* sentences. Shading indicates electrodes included in the ANOVA showing a main effect of sentence type. Posterior: semantic sentences elicited a larger negativity over posterior electrodes of the right hemisphere. For the second group, this effect was found at posterior electrodes, but was not lateralized. Anterior: syntactic sentences elicited a larger negativity than semantic sentences. This effect was limited to anterior electrode sites for both groups.

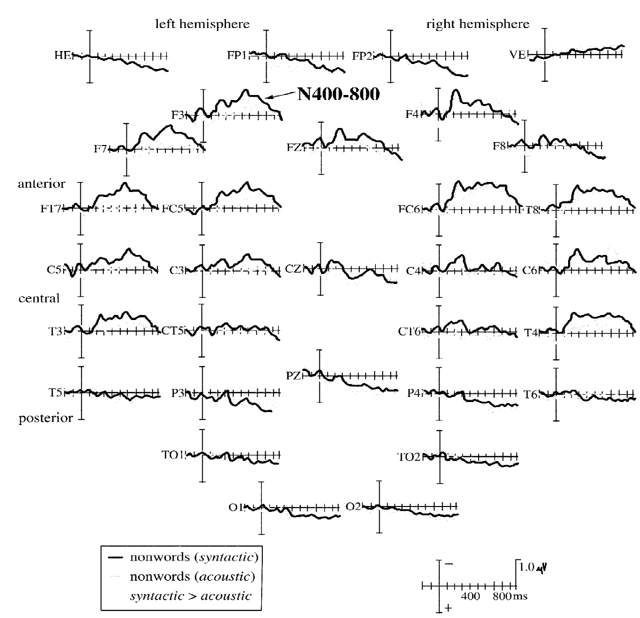

Fig. 8. ERPs elicited by the same nonwords in *syntactic* and *acoustic* sentences. Shading indicates electrodes included in the ANOVA showing a main effect of sentence type. N400–800: nonwords elicited a greater negativity when presented in *syntactic* sentences over anterior electrodes of the left hemisphere. The same effect was found over anterior electrodes for the second group, but was not left lateralized.

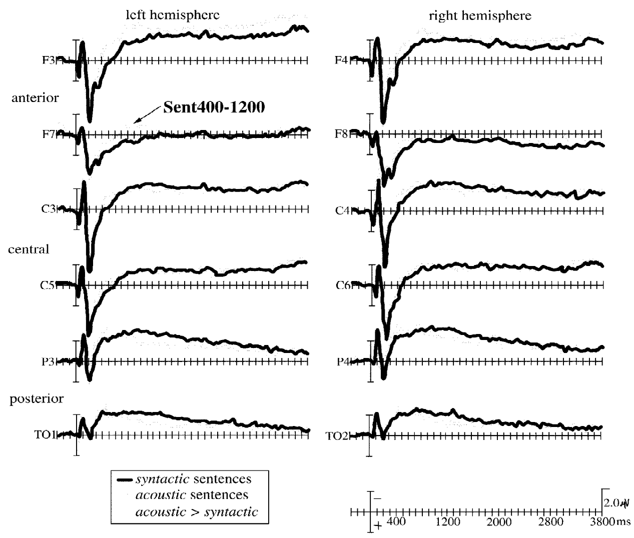

Fig. 9. ERPs averaged to *syntactic* and *acoustic* sentences. Shading indicates electrodes included in the ANOVA showing a main effect of sentence type. Sent400–1200: acoustic sentences elicited a larger negativity than syntactic sentences at anterior electrode sites. This difference was larger over the left hemisphere for the first group, but not for the second.

syntactic and *acoustic* sentences was found between 400 and 800 ms (Nonword-*syntactic*/Nonword-*acoustic*× Hemisphere×Anterior/Posterior interaction: $F(5,85)=3.91$, $P<0.01$) (Fig. 8). When electrodes from three anterior rows were analyzed, a Nonword-*syntactic*/Nonword-*acoustic* by Hemisphere interaction was found ($F(2,34)=3.60$, $P<0.05$). At left anterior electrode sites, nonwords in the *syntactic* sentences elicited a somewhat larger negative shift than the same nonwords in *acoustic* sentences ($F(1,17)=3.86$, $P=0.066$) However, this differences was only marginally significant. A larger N400–800 to nonwords in *syntactic* sentences over anterior electrode sites was also found for the second group of subjects, but was bilaterally distributed.

3.5.2. Sent400–1200: mean between 400 and 1200 ms

There were no differences in the early ERP components (P50, N100, and P200) elicited by the onset of the *syntactic* and *acoustic* sentences (Fig. 9). However, the analyses of these two sentence types revealed a Sentence by Hemisphere by Anterior/Posterior interaction ($F(5,85)=4.27$, $P<0.01$) on the mean amplitude between 400 and 1200 ms. When only anterior electrodes were included, *acoustic* sentences were found to elicit a larger negativity than *syntactic* sentences ($F(1,17)=7.94$, $P<0.05$). Furthermore, this difference was larger over the left hemisphere (Sentence×Hemisphere interaction: $F(1,17)=7.11$, $P<0.05$). This sentence effect was also found for the second group of subjects; however, it was bilaterally distributed.

4. Discussion

Previous ERP research suggested that word onsets may elicit similar auditory onset components when presented in isolation and in continuous speech [19,20,23]. However, the present study is the first to systematically address this issue. Just as the onsets of sentences preceded by silence elicited a P50 and N100, the onsets of syllables in speech elicited a P50 and N100. These components clearly have a much smaller amplitude when elicited by continuous speech; the decrease in amplitude is consistent with findings from studies of auditory refractory periods indicating the sensory response to auditory onsets decreases with increased presentation rate (e.g., Refs. [3,52]). However, the presence of such components in continuous speech suggests that word onsets are processed similarly to auditory onsets.

As outlined in the introduction, some ERP studies of natural speech do not seem to show auditory onset effects to sentence-medial words [8,9,15,18,35]. There are several possible reasons for this. First, these components are high frequency and could easily be filtered out during data processing. Additionally, in continuous speech P50 and N100 components have small amplitudes and may require many trials to be seen in averages. Third, the lack of obvious indications of word onset makes it difficult to know not only where speech is being segmented, but also where ERPs should be averaged. Any imprecision in determining onsets to average ERPs to may cause high frequency, low-amplitude components to be lost while lower-frequency, higher-amplitude components are preserved. Finding auditory onset components in continuous speech likely requires recording, and not filtering, high frequency ERPs (up to 100 Hz in this study), presenting a large number of stimuli, and precisely defining the stimulus onsets.

Since words in continuous speech can elicit auditory onset components, it seemed reasonable that these onset components might also index speech segmentation. In the present study we tested that hypothesis by comparing the response to physically similar word onsets and word-medial syllable onsets. Word onsets elicited a larger N100. Although the magnitude of this difference was small, the effect was reliable in both groups of subjects. The difference in N100 amplitude may be indexing speech segmentation.

Importantly, the differences in ERPs averaged to syllables in different positions were not identical to those found for ERPs averaged to physically different stimuli. The ERPs to word-initial and word-medial syllables matched on physical characteristics differed over midline and medial electrodes. The stress effects had a different distribution, concentrated over anterior electrodes at both lateral and medial sites. Modulation of the N100 ERP component by loudness has been well documented (e.g., Refs. [40,41]), so it is not surprising that stressed syllables elicited a larger N100 than unstressed syllables. However, the fact that word-onset effects and stress effects had different distributions supports the conclusion that word-onset effects were indexing speech segmentation rather than physical differences in the stimuli.

Although the physical characteristics of the specific syllables to which ERPs were averaged were carefully balanced in this study, the acoustic properties of the preceding syllables and phonemes likely differed. This fact leads to two additional interpretations of the N100 word onset effect. First, N100 amplitude could be indexing either late (longer than 100 ms) processing of these preceding physical characteristics or differences in the EEG used as a baseline (the 300 ms before syllable onsets) that reflect these physical characteristics. The length of the baseline, longer than the average word in this study, helps to ensure that it includes the responses to many types of sounds preceding both word-initial and word-medial syllables. Furthermore, the variability in both the timing and type of sounds that preceded the syllable onsets would make it less likely that responses to unidentified preceding features would be time-locked to word onsets. Additionally, a companion study of late bilingual speakers [46] failed to show the N100 word onset effect indicating that it is dependent on linguistic experience and does not reflect purely acoustic processing. However, additional research will be necessary to rule out the possibility that the N100 word-onset effect indexes preceding physical characteristics rather than segmentation. Second, N100 amplitude could be indexing cognitive processes that arise from the prediction of word onsets. For example, if listeners use the lexical, syntactic, and acoustic information available in a sentence to predict word onsets (rather than recognize them after they have occurred), they may allocate additional attention to the word onsets. The additional cognitive processing of word onsets, rather than segmentation of the speech stream, could result in enhanced N100 amplitude. Regardless of whether the N100 word-onset effect indexes preceding physical characteristics that can be used to segment speech, perceived onsets that do not correspond to acoustic onsets, or differential cognitive processes assigned to speech that has already been segmented, it is clear that it is related to the difficult to measure process of speech segmentation.

The present study was also designed to measure the impact of semantic and syntactic information on speech segmentation. Word-onset effects were found for normal English sentences (*semantic*), sentences with little semantic content (*syntactic*) and sentences with little semantic and syntactic content (*acoustic*). From this finding, it is clear that the normal presence of semantic and syntactic information (i.e., to the same extent it is available in natural speech) is not necessary for segmentation. These results seem to conflict with those of behavioral studies showing semantic and syntactic information is used for segmentation [7,14,42,45,49]. However, it is quite possible that semantic and syntactic information are important for segmenting normal speech, but that word-onset effects are still found without them. This could be the case if listeners rely on other segmentation cues to a greater extent when some sources of segmentation cues are absent [45]. Alternatively, semantic and syntactic cues may be more important for re-segmentation of speech rather than initial parsing. If so, they would be unlikely to affect early ERP components associated with word onsets. Either of these possibilities could account for the finding that word-onset effects were present for each of the three sentence types used in this study.

The later word-onset effect (N200–300) overlapped with the N400. Therefore, it is difficult to determine if it is indexing aspects of segmentation or reflects the beginning of lexical search. The fact that the word-onset N200–300 did not interact with sentence type, whereas the N400 was found only for words in the *semantic* sentences, suggests this component might be independent from the N400. In contrast, the stress N200–300 effects were found only for the *semantic* sentences. There are at least two possible explanations for this finding. First, stressed syllables are more likely to be treated as word onsets than unstressed syllables in English [10–12,28]. Although stress pattern was carefully matched for the words included in this study, lexical search may begin earlier for words that conform to the normal English stress pattern (word-initial stress). If so, the N400 would be expected to have an earlier onset for words with normal English stress which may have been reflected in the N200–300 differences. Second, the N200–300 stress effects may have reflected the use of prosodic information in language processing. Since this effect was only found for *semantic* sentences, it must be indexing something other than the physical differences in loudness and length. However, it could be indexing the actual use of these prosodic cues in speech comprehension.

The finding that words elicited a larger N400 than nonwords in this study was somewhat unexpected. In studies using lexical decision tasks in the visual or auditory modality, pronounceable nonwords have typically elicited a larger N400 than words [6,21,22,53]. However, these findings may be dependent on participants processing nonwords as if they could be words. In the present study, by the time listeners heard the target nonwords in either the *syntactic* or *acoustic* sentences, they were likely expecting more nonwords. In this context, as when sentences containing nonwords were presented in blocks [20], listeners would not be expected to search their lexicons for items they could already assume are not there.

The negativity over posterior electrodes seen in response to *semantic* sentences in comparison to *syntactic* sentences may reflect the N400s in response to open-class words across the *semantic* sentences. However, the greater negativity over anterior regions in response to *syntactic* as compared to *semantic* sentences requires another explanation. There is some evidence of a similar negativity in the response to nonwords in the syntactic sentences and words in the semantic sentences (N400–800). However, this effect was only seen over the left hemisphere in the first group of subjects, and did not replicate in the second group. One possible explanation for the anterior negativity seen across the sentences is found in the task used in the present study. Subjects were occasionally asked (10% of trials) if a specific word or nonword occurred in the previous sentence. This task would clearly be more difficult for nonwords than words. The anterior negativity seen across *syntactic* (and *acoustic*) sentences may be indexing the greater use of phonological working memory for the nonword task.

A comparison of responses to nonwords in the *syntactic* and *acoustic* sentences revealed a larger negativity for nonwords in the *syntactic* sentences over anterior sites. This effect was left lateralized for the first group of subjects only. In contrast, across sentences a larger negativity was seen for the *acoustic* sentences at anterior electrode sites. These two effects were clearly not indexing the same processes. Neither the N400–800 in response to words in *syntactic* sentences nor the N400–1200 in response to *acoustic* sentences is similar to what has been found in studies employing syntactic anomalies in either normal or jabberwocky sentences. However, several possible explanations for these effects emerge from the design of this study.

The nonword/nonword effects for the two sentence types could reflect lexical search. The presence of closed-class words in the *syntactic* sentences could be enough to encourage a lexical search of the nonwords as well. However, the effects seen for the nonwords in *syntactic* sentences had a very different distribution than that of the N400. Interestingly, some of the studies investigating ERP responses to open- and closed-class words found an anterior negativity between 400 and 700 ms (N400–700) for very high frequency closed-class words including determiners [32,34]. Many of the target nonwords in the *syntactic* sentences were immediately preceded by such high frequency closed-class words. Although the ERPs were time-locked to the nonwords, the anterior negativity could reflect processing of the previous word. A third possibility is that the anterior negativity is indexing grammatical processing of the *syntactic* sentences. For example, it could be related to assigning the nonwords a part of speech and role in the sentences. This process would be both more likely for the *syntactic* than *acoustic* sentences, and more difficult for the *syntactic* than *semantic* sentences. More research will be needed to distinguish among these and other hypotheses for the syntactic effects seen here. However, this study does suggest that syntactic sentence processing can be indexed with ERPs without using syntactic violations.

To study natural speech processing using ERPs it is necessary to overcome problematic issues including overlap in responses to individual words, co-articulation effects that make determining words onsets difficult, and the intricacies of manipulating stimuli within the context of continuous speech. However, multiple studies have shown that these issues can be dealt with such that semantic and syntactic processing can be studied using natural speech stimuli [8,15,18,20,23,29,36,48,51]. The present study showed that the same careful techniques that make it possible to study semantic and syntactic processing of natural speech, also make it possible to study an aspect of language processing than can only be addressed with this type of stimuli—speech segmentation.

An ERP index of speech segmentation could provide a greater understanding of speech perception and, more generally, language processing. From the present study, it is not clear whether the observed ERP word-onset effects indexed greater attention to word-initial sounds, initial processing of speech that had already been segmented, or the process of speech segmentation itself. However, the fact that word-initial and word-medial sounds were processed differently indicates that N100 amplitude can be used as an online measure of segmentation. By using many of the manipulations previously employed in behavioral studies, it will be possible to determine what segmentation cues normal adults use to segment speech. Furthermore, the fact that ERP measures do not require an overt response means the exact same measures can be used in monolingual and bilingual adults, listeners processing unfamiliar languages, and young infants who have not yet acquired a language. These approaches could provide invaluable information about the development and plasticity of the language systems.

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