Neural Processes of Stutterers Processing Ambiguous Chinese Phrases: Postprint

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Abstract

Prosodic boundaries constitute an integral component of spoken language prosodic features and play a significant role in language comprehension. Stuttering, as a rhythmic speech disorder, is primarily characterized by frequent repetitions, prolongations, or pauses of syllables. The present study employed ERP to investigate the cognitive processes underlying the processing of prosodic boundaries within ambiguous phrases (VO/AN ambiguous structures) in individuals who stutter when performing lexical decision and structural decision tasks. The results revealed no significant differences between individuals who stutter and fluent speakers in the CPS (closure positive shift), an electrophysiological component reflecting prosodic phrasing, elicited during the processing of Chinese ambiguous phrases. In the 0–300 ms time window, at both midline and lateral sites, the scalp distribution of the positive effect elicited by prosodic boundaries in VO phrases was smaller than that in AN phrases for both individuals who stutter and fluent speakers. In the 300–600 ms time window, at midline sites, prosodic boundaries of both phrase types stably elicited a positive effect for both individuals who stutter and fluent speakers across both tasks; at lateral sites, prosodic boundaries of both phrase types elicited a positive effect in the structural decision task, whereas only AN phrases stably elicited this effect in the lexical decision task. In summary, individuals who stutter, like fluent speakers, are sensitive to spoken language prosodic boundaries, and the electrophysiological effects elicited during their processing of prosodic boundaries within ambiguous phrases are influenced by both experimental task and phrase structure type.

Neural Processing of Ambiguous Chinese Phrases in Stutterers

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Abstract

Prosodic boundaries constitute an integral component of spoken language prosody and play a crucial role in language comprehension. Stuttering, as a rhythmic speech disorder, is primarily characterized by frequent repetitions, prolongations, or pauses at the syllable level. The present study employed ERPs to investigate the cognitive processes underlying the processing of prosodic boundaries within ambiguous phrases (verb-object/attributive ambiguous structures) in stutterers performing lexical judgment and structural judgment tasks. The results revealed no significant differences between stutterers and fluent speakers in the CPS (closure positive shift), an ERP component reflecting prosodic segmentation, during the processing of Chinese ambiguous phrases. In the 0–300 ms time window, the scalp distribution of the positive effect elicited by prosodic boundaries in verb-object phrases was smaller than that in attributive phrases for both stutterers and fluent speakers, across both midline and lateral sites. In the 300–600 ms time window, both groups exhibited stable positive effects for prosodic boundaries of both phrase types at midline sites across both tasks; however, at lateral sites, while both phrase types elicited positive effects in the structural judgment task, only attributive phrases consistently elicited this effect in the lexical judgment task. In summary, stutterers, like fluent speakers, are sensitive to prosodic boundaries in speech, and the ERP effects elicited during the processing of prosodic boundaries within ambiguous phrases are influenced by both experimental task and phrase structure type.

Keywords: stuttering; prosodic boundary; ambiguous phrase; CPS

Introduction

Language organization follows certain syntactic and grammatical structures that provide speakers with fundamental principles for segmenting words and sentences. Correspondingly, prosodic information in language also exhibits hierarchical structure, which arises not only from communicative demands but also from physiological constraints on articulation (Shattuck-Hufnagel & Turk, 1996). In written language, readers can rely on punctuation and paragraph markers to segment sentences or passages, facilitating comprehension. In spoken communication, however, listeners lack such cues and must depend on prosodic information (such as prosodic boundaries) to segment continuous speech streams. Indeed, speakers employ prosodic features to bind certain syllables more closely together according to grammatical, semantic, and pragmatic requirements, while listeners utilize this information to comprehend utterances (Li & Yang, 2007). The use of prosodic features promotes effective communication between speakers and listeners.

Stuttering, a common fluency disorder, is characterized by frequent, involuntary repetitions, prolongations of speech sounds, and silent blocks or hesitations that disrupt speech rhythm (World Health Organization, 2010). Stuttering, or developmental stuttering, typically emerges during the preschool years (ages 2–5), affecting approximately 5% of children, though many recover spontaneously, with only about 1% of the population continuing to stutter into adulthood. Unlike acquired stuttering (caused by medication, psychological trauma, or brain injury), developmental stuttering is thought to result from multiple factors including genetics, heredity, and environment, and has attracted attention from psychology, genetics, and cognitive neuroscience (Smith & Weber, 2017; Yairi & Ambrose, 2013). Given that speech production deficits constitute the primary symptom of stuttering, most research has focused on whether stutterers exhibit impairments during speech production and abnormal activity in motor cortical areas (Etchell, Civier, Ballard, & Sowman, 2017). However, speech perception and production are intimately linked, and numerous studies have found abnormal organization in the auditory cortex of stutterers (Chang, Kenney, Loucks, & Ludlow, 2009; Giraud et al., 2008). Moreover, stutterers exhibit temporary alleviation of stuttering symptoms under certain conditions, such as choral reading (Fox et al., 1996) and altered auditory feedback (AAF) (Lincoln, Packman, & Onslow, 2006), which has motivated research into the auditory and neural systems responsible for language processing and demonstrated that language processing in stutterers indeed differs from that of fluent speakers. The present study investigates the cognitive processes and influencing factors involved in stutterers' processing of prosodic boundary information.

1.1 Processing of Prosodic Boundaries

Prosodic units in sentences are segmented by boundaries, whose acoustic correlates include inserted pauses/silent intervals, pre-boundary syllable lengthening, and pitch movement around boundaries (Yang, Shen, Li, & Yang, 2014; Steinhauer, Alter, & Friederici, 1999). Prosodic boundaries play a vital role in language acquisition, production, and comprehension. They represent one of the earliest cues used by infants to segment spoken sentences and isolate phonemes during language learning (Ramus, Hauser, Miller, Morris, & Mehler, 2000). Both adults and infants use prosodic boundaries in real time to constrain lexical access (Christophe, Peperkamp, Pallier, Block, & Mehler, 2004; Salverda, Dahan, & McQueen, 2003). Critically, because both syntactic and prosodic boundaries serve to segment language, they are closely related. Early research on prosodic boundaries primarily focused on their role in resolving ambiguity in discourse (Kjelgaard & Speer, 1999; Schepman & Rodway, 2000). For example, the Chinese-specific ambiguous phrase V+NP1+Aux (的)+NP2 (e.g., "understand the hospital' s call") can be disambiguated as a verb-object phrase (understand/ the hospital' s call) when the prosodic boundary appears after the verb ("understand"), or as an attributive phrase (understanding the hospital' s/ call) when the boundary appears after the auxiliary particle ("的"). However, some studies have found that readers tend to interpret such phrases as attributive structures (Wei, Dong, Bland, & Yuan, 2016; Zhang, Zhang, & Shu, 2000).

The discovery of CPS (closure positive shift), the first ERP component specific to prosodic processing, has further advanced research on prosodic boundaries. The discoverers of CPS proposed that this ERP component primarily reflects the closure of intonational phrases (Steinhauer et al., 1999). Subsequent research on prosodic boundaries at different hierarchical levels in spoken sentences and discourse has shown that, in addition to intonational phrase boundaries, prosodic phrase boundaries can also elicit CPS, with latencies and amplitudes showing dynamic patterns over time (Li & Yang, 2009, 2010). Although CPS can be elicited by purely prosodic information alone (Pannekamp, Toepel, Alter, Hahne, & Friederici, 2005), prosodic and syntactic boundaries interact in real time (Kerkhofs, Vonk, Schriefers, & Chwilla, 2007; Bogels, Schriefers, Vonk, Chwilla, & Kerkhofs, 2010), with inconsistent boundaries eliciting larger CPS amplitudes than consistent ones.

Some studies have also found that commas in written language (Steinhauer & Friederici, 2001; Liu, Wang, & Jin, 2010), prosodic boundaries within seven-character quatrains (Li & Yang, 2010; Li & Yang, 2010), and boundaries in music (Knösche et al., 2005; Nan, Knosche, & Friederici, 2006; Zhang, Jiang, Zhou, & Yang, 2016) can elicit this ERP effect, as they implicitly or explicitly trigger prosodic segmentation similar to prosodic boundaries in speech. Furthermore, researchers have found that CPS is consistently elicited across different experimental tasks (semantic comprehension, rhythm judgment, passive listening, etc.) (Li & Yang, 2009; Peter, Mcarthur, & Crain, 2014; Pannekamp et al., 2005), suggesting that this component' s elicitation is independent of the experimental task. Recently, a study using conjunctions to connect three names (e.g., Mona or Lena and Lola) found that CPS was elicited at later boundaries (e.g., after Lena) but not at earlier boundaries (e.g., after Mona), leading researchers to propose that prosodic boundary processing depends on the preceding prosodic context (Holzgrefe et al., 2013).

1.2 Speech Information Processing in Stutterers

Since the 1930s, researchers have investigated whether the brains of stutterers differ from those of non-stutterers. With the maturation of fMRI, MEG, and ERP technologies, an increasing number of studies have demonstrated structural and functional abnormalities in the brains of stutterers compared to normal individuals (Chang, Horwitz, Ostuni, Reynolds, & Ludlow, 2011; Cykowski, Fox, Ingham, Ingham, & Robin, 2010). Early researchers focused on brainstem function in stutterers, comparing the intensity of auditory reflexes and the ability to process low signal-to-noise ratio sounds. However, these studies yielded inconsistent results: some found differences between stutterers and normal controls (e.g., Hall & Jerger, 1978), while others did not (e.g., Hannley & Dorman, 1982). Hannley and Dorman (1982) suggested that this inconsistency might be due to the heterogeneity of stuttering disorders and the small sample sizes in these studies (fewer than 10 participants per group). Additionally, using dichotic listening techniques while controlling for handedness, studies of auditory system processing in stutterers have shown that stutterers exhibit rightward or bilateral cerebral representation of speech sounds, whereas non-stutterers show leftward representation (Dorman & Porter, 1975; Foundas, Corey, Hurley, & Heilman, 2004).

Some researchers have used ERP technology to examine the cognitive and neural processes of semantic, syntactic, and phonological processing in stutterers. Weber-Fox (2001) investigated whether semantic processing differs in stutterers compared to fluent adults. Participants were presented with sentences word-by-word and asked to classify each word as closed- or open-class while also judging whether each sentence was semantically anomalous, with ERP responses recorded simultaneously. The results showed that compared to fluent speakers, stutterers exhibited reduced ERP effects for different word classes and semantic violations within the 200–400 ms time window. Cuadrado and Weber-Fox (2003) examined syntactic processing in stutterers by presenting adult stutterers and normal controls with simple and complex control sentences as well as verb agreement violation sentences. The study found that under no time pressure (i.e., without requiring rapid grammatical judgments), stutterers' accuracy did not differ from that of normal adults; however, under time pressure, stutterers' accuracy was significantly lower than that of fluent speakers, particularly for verb agreement violations in longer and syntactically complex sentences. Moreover, while normal controls showed a typical P600 effect during verb agreement violation processing, stutterers exhibited a P600 with reduced amplitude and altered scalp distribution. Weber-Fox and Hampton presented participants with spoken sentences containing syntactic and semantic constraints and found that non-stutterers showed typical N400 and P600 effects for semantic and verb agreement violations, whereas stutterers elicited a biphasic N400-P600 pattern under both conditions (Weber-Fox & Hampton, 2008). Weber-Fox et al. (2004) examined phonological processing abilities in stutterers by asking them to make rhythm judgments on visually presented word pairs. Although stutterers had longer reaction times, both groups elicited similar ERP effects, with no significant differences in accuracy. Corbera, Corral, Escera, and Idiazábal (2005) used the MMN ERP component to investigate whether auditory speech processing deficits exist in stutterers. They found that stutterers' neural representations of simple acoustic features (such as frequency and duration) in the auditory cortex were normal, while neural representations of speech sounds were abnormal (Corbera, Corral, Escera, & Idiazábal, 2005). This finding has been confirmed by other experiments showing that auditory perceptual deficits in stutterers are specific to speech sound processing, whereas perception of non-speech sounds, such as pure tones, remains normal (Howell, Davis, & Williams, 2006).

1.3 Objectives and Hypotheses of the Present Study

In summary, stuttering is primarily characterized by rhythmic fluency deficits, with some stuttering symptoms (such as syllable prolongations and inappropriate pauses) resembling the acoustic cues of prosodic boundaries in speech. However, no study to date has examined whether stutterers differ from fluent speakers in processing prosodic boundaries. The present study uses Chinese-specific ambiguous phrases (V+NP1+ 的 +NP2) and employs both lexical judgment (implicit prosodic processing) and structural judgment (explicit prosodic processing) tasks to investigate the cognitive processes and neural mechanisms underlying prosodic boundary processing in stutterers and fluent speakers. Previous research has primarily examined prosodic boundary processing at the sentence and discourse levels; studies using phrases have found that boundary processing is influenced by its position (Holzgrefe et al., 2013). Whether boundaries within Chinese ambiguous phrases that can be interpreted as either verb-object or attributive structures can reliably elicit CPS remains to be investigated. Since listeners tend to interpret such phrases as attributive structures (Wei et al., 2016; Zhang et al., 2000), will listeners only elicit this effect when processing such phrases as attributive structures? Additionally, research on language processing in stutterers has found that stutterers exhibit weaker ERP effects than fluent speakers during semantic and syntactic processing (Weber-Fox, 2001; Cuadrado & Weber-Fox, 2003); thus, they may also be inferior to fluent speakers in processing prosodic boundaries. However, other studies have found that stutterers' neural representations of simple acoustic features (such as frequency and duration) are normal (Corbera et al., 2005), and their phonological processing abilities do not differ from those of fluent speakers (Weber-Fox et al., 2004). Since boundary processing primarily relies on acoustic cues such as duration and frequency, stutterers may not differ from normal individuals in boundary processing. Finally, although some studies have found that prosodic boundaries reliably elicit CPS across different experimental tasks (semantic comprehension, rhythm judgment, passive listening, etc.) (Li et al., 2009; Peter et al., 2014; Pannekamp et al., 2005), no study has directly examined whether experimental tasks affect CPS amplitude or scalp distribution.

The present study investigates the cognitive processes of prosodic boundary processing in ambiguous phrases in stutterers and fluent speakers by employing lexical judgment and structural judgment tasks. If stutterers can elicit the same degree of CPS as fluent speakers, this would indicate that their speech production deficits do not manifest in speech perception processes, suggesting to some extent that the cognitive and neural substrates underlying human speech production and comprehension are distinct. If stutterers cannot elicit the same ERP effects as fluent speakers when perceiving prosodic boundaries, this would suggest that their stuttering deficits extend to speech perception processes: stutterers exhibit not only rhythmic fluency deficits in speech production but also problems in rhythm perception (such as prosodic boundary processing). This would indicate that the production and perception of rhythmic information share similar cognitive and neural substrates, potentially suggesting that presenting stutterers with rhythmically well-structured speech or music could have therapeutic effects on their speech production. Furthermore, by employing different experimental tasks, we can investigate whether stutterers are equally influenced by experimental tasks as fluent speakers during prosodic information processing, thereby revealing characteristics of speech processing in stutterers. In summary, this study aims to advance our understanding of the cognitive and neural basis of stuttering through research on stutterers' perception of prosodic information, thereby providing theoretical guidance for helping stutterers alleviate their symptoms.

Methods

Twelve stutterers were recruited from universities as the experimental group, all of whom self-reported stuttering symptoms before age 6 and had received stuttering therapy. Stuttering severity was assessed using the Overall Assessment of the Speaker' s Experience of Stuttering (OASES) (Yaruss & Quesal, 2006). Additionally, twelve fluent speakers were recruited as the control group, matched with the stuttering group in age, gender, and education level (see Table 1). All participants were right-handed, had no history of psychiatric disorders, had normal or corrected-to-normal vision and hearing, and were native Chinese speakers. The study was approved by the Ethics Committee of Liaoning Normal University. Participants signed informed consent forms before the experiment and received compensation afterward.

Table 1 Basic participant information

The experiment employed 168 ambiguous Chinese phrases that could be equally interpreted as verb-object or attributive structures, which had been used in previous research (Li, Yang, & Lu, 2010). Additionally, 84 unambiguous verb-object phrases and 84 unambiguous attributive phrases were created as filler materials. Before the formal experiment, a female professional speaker recorded each ambiguous phrase twice, once in the attributive structure and once in the verb-object structure, with filler materials recorded normally at a sampling rate of 22 kHz.

Using PRAAT software (http://www.fon.hum.uva.nl/praat/), all ambiguous phrases were segmented into V/NP1+ 的/NP2 components and subjected to acoustic parameter analysis (duration and fundamental frequency). As shown in Figure 1a [Figure 1: see original paper] (using "understand the hospital' s call" as an example), duration analysis revealed that the verb duration in verb-object structures (M = 604, SD = 70) was significantly longer than that of the same verb in attributive structures (M = 411, SD = 46), $t(167) = 36.51$, $p <$

0.001. The duration of NP2 (e.g., "call") in attributive structures (M = 696, SD = 68) was significantly longer than that in verb-object structures (M = 546, SD = 66), t(167) = 27.73, $p < 0.001$. Additionally, verb-object phrases exhibited a pause (#1) after the verb (M = 60, SD = 40), while attributive phrases showed a pause (#2) before NP2 (M = 159, SD = 59). As shown in Figure 1b, pitch analysis was conducted by calculating the starting, ending, maximum, and minimum fundamental frequency values for each of the three segments of the ambiguous phrases. Statistical analysis indicated that the maximum fundamental frequency of the verb in verb-object structures (M = 343, SD = 33) was significantly higher than that in attributive structures (M = 322, SD = 41), t(167) = 6.12, $p < 0.001$. The maximum fundamental frequency of NP2 in attributive structures (M = 319, SD = 47) was significantly higher than that in verb-object structures (M = 297, SD = 39), t(167) = 6.75, $p < 0.001$. These acoustic analyses demonstrate that verb-object phrases feature syllable lengthening and stress on the verb, with a clear silent interval after the verb, whereas attributive phrases feature syllable lengthening and stress on NP2, with a clear silent interval before NP2.

To ensure that participants could accurately identify the recorded ambiguous phrases based on their acoustic characteristics, 20 fluent university students were recruited for a pretest (different from participants in the formal experiment). The pretest consisted of two versions, balanced across participants. Version 1 included ambiguous phrases 1-84 in verb-object structure and phrases 85-168 in attributive structure, plus 84 unambiguous phrases (verb-object phrases 1-42 and attributive phrases 43-84). Version 2 included ambiguous phrases 85-168 in verb-object structure and phrases 1-84 in attributive structure, plus another 84 unambiguous phrases (attributive phrases 1-42 and verb-object phrases 43-84). Participants were asked to judge whether each presented phrase was verb-object or attributive structure. Statistical analysis revealed a mean accuracy rate of 94.8% (SD = 2.66), indicating that the recorded materials met the requirements of the present study and that participants could accurately identify phrase structure types.

2.3 Experimental Design

In the formal experiment, phrases were presented in pairs. The two phrases in each experimental trial had consistent structures; to balance participant responses, filler trials presented phrases with inconsistent structures. All experimental and filler materials were presented in pseudorandom order, with participants completing lexical judgment and structural judgment tasks across two experimental sessions (see Experimental Procedure). To balance differences in acoustic characteristics, experimental materials were divided into four versions, ensuring that each ambiguous phrase appeared as either a verb-object or attributive phrase in the first or second position across different participants. Only ambiguous phrases appearing in the first position were included in statistical analyses.

A 2 (participant type: stutterers, fluent speakers) × 2 (task type: lexical judgment, structural judgment) × 2 (structure type: verb-object phrase, attributive phrase) × 2 (boundary: present, absent) mixed factorial design was employed. Participant type was a between-subjects factor, while task type, structure type, and boundary were within-subjects factors.

2.4 Experimental Procedure

The experiment consisted of six blocks, with three blocks for each task type, each containing 56 trials. Within each block, experimental materials from the same condition were not presented consecutively more than three times. Each block lasted approximately 6 minutes, with participants resting between blocks as needed.

The experiment was conducted in a dimly lit, quiet, and comfortable room. Participants sat 90 cm from a liquid crystal display monitor (23” , 60 Hz refresh rate) with speakers positioned at a distance of 90 cm, at a sound intensity of 75 dB. After practicing to become familiar with the experimental requirements, participants began the formal experiment, completing the lexical judgment task followed by the structural judgment task. In each trial, a fixation cross (“+”) and a cue tone were presented simultaneously for 300 ms, after which the “+” remained on the screen to minimize eye movements. Two phrases were then played sequentially, with a 400 ms interval between them. In the lexical judgment task, after the auditory stimuli were presented, a word appeared at the center of the screen, and participants were asked to judge as quickly and accurately as possible whether the word had appeared in the two previously heard phrases, pressing “F”for yes and “J”for no. In the structural judgment task, participants were asked to judge as quickly and accurately as possible whether the two heard phrases had the same structure, pressing “F” for consistent and “J” for inconsistent.

2.5 Data Acquisition and Analysis

EEG data were recorded using an ANT Neuro system with a 64-channel electrode cap according to the extended international 10-20 system. The sampling rate was 500 Hz, with CPz as the online reference. Electrodes M1 and M2 were placed at the left and right mastoids, respectively. Impedance between electrodes and scalp was maintained below 5 kΩ, with an online filter bandpass of 0.01-100 Hz. Offline analysis involved re-referencing each channel to the average of the two mastoids.

Brain Vision Analyzer 2.0 software was used for data processing, with EEG signals filtered (high-pass 0.01 Hz, low-pass 30 Hz). EEG analysis was time-locked to the offset of the verb (e.g., “understand”) and the auxiliary particle (“的”) of the first ambiguous phrase in each trial, with data segmented from 100 ms before to 800 ms after each critical point and baseline-corrected. ERP effects elicited by boundaries were obtained by comparing verb-object phrases with boundaries to corresponding attributive phrases without boundaries, and attributive phrases with boundaries to verb-object phrases without boundaries. Trials with eye movement artifacts and other artifacts exceeding $±$80 V were excluded, with at least 30 valid trials remaining per condition. Based on the distribution of the elicited ERP effects and previous research (Li & Yang, 2009; Holzgrefe et al., 2013; Kerkhofs et al., 2007), we conducted repeated-measures ANOVA on the mean amplitudes of ERP effects in two time windows (0–300 ms and 300–600 ms) at midline and lateral sites. At midline sites, a repeated-measures ANOVA was performed with participant type (stutterers, fluent speakers) × task type (lexical judgment, structural judgment) × structure type (verb-object, attributive) × boundary (present, absent) × brain region (frontal, central, parietal). Three regions of interest at midline included frontal (Fz, FCz), central (Cz, CPz), and parietal (Pz, POz) areas. For lateral analysis, hemisphere (left, right) was included as an additional variable. Based on hemisphere and region, six regions of interest were defined: left anterior (F1, F3, F5, FC1, FC3, FC5), right anterior (F2, F4, F6, FC2, FC4, FC6), left central (C1, C3, C5, CP1, CP3, CP5), right central (C2, C4, C6, CP2, CP4, CP6), left posterior (P1, P3, P5, PO3, PO5, PO7), and right posterior (P2, P4, P6, PO4, PO6, PO8). Greenhouse-Geisser correction was applied to ANOVA degrees of freedom when sphericity assumptions were violated.

Results

3.1 Behavioral Results

Behavioral data indicated that participants' accuracy rates for lexical and structural judgment tasks were 93.8% (fluent speakers: 94.2%, stutterers: 93.4%) and 73.9% (fluent speakers: 73.1%, stutterers: 74.6%), respectively, demonstrating that participants listened carefully to the phrases and performed the experimental tasks conscientiously. The purpose of including two tasks was to direct participants' attention to (structural judgment task) or away from (lexical judgment task) prosodic boundary information, with analysis focusing only on the first phrase in each pair. Moreover, it was difficult to determine from behavioral responses whether participants had "correctly processed" the prosodic boundary of the first phrase in the pair. Therefore, reaction times and accuracy rates were not analyzed further.

3.2 ERP Results

In both lexical judgment (Figure 2 [Figure 2: see original paper]) and structural judgment (Figure 3 [Figure 3: see original paper]) tasks, both stutterers and fluent speakers elicited a positive wave when processing boundaries compared to non-boundaries. This positive wave was distributed across the entire scalp, with larger amplitudes at frontal-central sites. Based on previous research (Steinhauer et al., 1999, 2001), this positive wave can be identified as CPS.

Figure 2. Grand-average ERP waveforms elicited at verb-object phrase bound-

aries (a) and attributive phrase boundaries (b) during lexical judgment task for stutterers and fluent speakers ($n = 12$ each). ERP analysis was time-locked to the offset of the verb (e.g., "understand") for verb-object phrases and the offset of the auxiliary particle ("的") for attributive phrases.

Figure 3. Grand-average ERP waveforms elicited at verb-object phrase boundaries (a) and attributive phrase boundaries (b) during structural judgment task for stutterers and fluent speakers ($n = 12$ each). ERP analysis was time-locked to the offset of the verb (e.g., "understand") for verb-object phrases and the offset of the auxiliary particle ("的") for attributive phrases.

0-300 ms Time Window Statistical analysis revealed a significant main effect of boundary at midline sites, $F(1, 22) = 24.28$, $p < 0.001$, $p^2 = 0.525$, with boundaries ($M = 0.34$, $SE = 0.15$) eliciting larger positive components than non-boundaries ($M = -0.31$, $SE = 0.17$). The interaction between structure and boundary was significant, $F(1, 22) = 5.84$, $p < 0.05$, $p^2 = 0.21$. Simple effects analysis indicated that verb-object structures with boundaries did not elicit a significant positive effect compared to those without boundaries, $F(1, 22) = 2.63$, $p = 0.119$, whereas attributive structures with boundaries elicited a positive effect compared to those without boundaries, $F(1, 22) = 16.44$, $p < 0.005$, $p^2 = 0.43$. The four-way interaction among task, structure, boundary, and brain region was significant, $F(2, 44) = 5.84$, $p < 0.05$, $p^2 = 0.15$. Simple effects analysis revealed that in the lexical judgment task, verb-object structures elicited a positive effect at posterior sites with boundaries compared to without boundaries, $F(1, 22) = 4.42$, $p < 0.05$, $p^2 = 0.17$, while attributive structures elicited positive effects at anterior, central, and posterior sites, $F(1, 22) = 19.34$, $p < 0.001$, $p^2 = 0.47$; $F(1, 22) = 17.45$, $p < 0.001$, $p^2 = 0.44$; $F(1, 22) = 7.74$, $p < 0.05$, $p^2 = 0.26$. In the structural judgment task, verb-object structures elicited a positive effect at anterior sites with boundaries compared to without boundaries, $F(1, 22) = 8.92$, $p < 0.01$, $p^2 = 0.28$, while attributive structures elicited positive effects at anterior, $F(1, 22) = 8.33$, $p < 0.05$, $p^2 = 0.28$, central, $F(1, 22) = 4.89$, $p < 0.05$, $p^2 = 0.18$, and posterior sites, $F(1, 22) = 8.12$, $p < 0.01$, $p^2 = 0.27$. Interactions between participant type and boundary, $F(1, 22) = 0.002$, $p = 0.968$, participant type and task, $F(1, 22) = 2.37$, $p = 0.138$, and participant type and structure, $F(1, 22) = 1.06$, $p = 0.315$, were all non-significant.

At lateral sites, the main effect of boundary was significant, $F(1, 22) = 45.51$, $p < 0.001$, $p^2 = 0.67$, with boundaries ($M = 0.16$, $SE = 0.08$) eliciting larger positive components than non-boundaries ($M = -0.46$, $SE = 0.07$). The interaction between structure and boundary was marginally significant, $F(1, 22) = 4.18$, $p = 0.053$, $p^2 = 0.16$. Simple effects analysis indicated that both verb-object and attributive structures with boundaries elicited positive effects compared to those without boundaries, $F(1, 22) = 10.35$, $p < 0.005$, $p^2 = 0.32$; $F(1, 22) = 29.69$, $p < 0.001$, $p^2 = 0.57$. The six-way interaction among participant type, task, structure, boundary, hemisphere, and brain region was significant,

$F(2, 44) = 7.53$, $p < 0.005$, $p^2 = 0.26$. Simple effects analysis revealed that in the lexical judgment task, stutterers showed a positive effect for verb-object structures only at right hemisphere central sites with boundaries compared to without boundaries, $F(1, 22) = 4.62$, $p < 0.05$, $p^2 = 0.17$, while attributive structures elicited positive effects at left hemisphere anterior and central sites, $F(1, 22) = 5.21$, $p < 0.05$, $p^2 = 0.19$; $F(1, 22) = 8.47$, $p < 0.01$, $p^2 = 0.28$, and right hemisphere anterior and central sites, $F(1, 22) = 15.32$, $p < 0.005$, $p^2 = 0.41$; $F(1, 22) = 19.47$, $p < 0.001$, $p^2 = 0.47$. In the structural judgment task, attributive structures elicited positive effects at right hemisphere anterior and central sites, $F(1, 22) = 6.98$, $p < 0.05$, $p^2 = 0.24$; $F(1, 22) = 9.11$, $p < 0.01$, $p^2 = 0.29$. In the lexical judgment task, fluent speakers showed positive effects for attributive structures at left hemisphere anterior sites, $F(1, 22) = 7.91$, $p < 0.05$, $p^2 = 0.27$, and right hemisphere anterior and central sites, $F(1, 22) = 14.79$, $p < 0.005$, $p^2 = 0.40$; $F(1, 22) = 20.12$, $p < 0.001$, $p^2 = 0.48$. In the structural judgment task, fluent speakers showed positive effects for verb-object structures at left hemisphere anterior and central sites, $F(1, 22) = 8.41$, $p < 0.01$, $p^2 = 0.28$; $F(1, 22) = 6.93$, $p < 0.05$, $p^2 = 0.24$, and right hemisphere anterior and central sites, $F(1, 22) = 9.56$, $p < 0.01$, $p^2 = 0.30$; $F(1, 22) = 14.84$, $p < 0.005$, $p^2 = 0.40$. Attributive structures also elicited positive effects at left hemisphere central sites, $F(1, 22) = 6.18$, $p < 0.05$, $p^2 = 0.22$, and right hemisphere anterior, central, and posterior sites, $F(1, 22) = 5.19$, $p < 0.05$, $p^2 = 0.20$; $F(1, 22) = 6.35$, $p < 0.05$, $p^2 = 0.22$; $F(1, 22) = 4.42$, $p < 0.05$, $p^2 = 0.17$. Interactions between participant type and boundary, $F(1, 22) = 0.17$, $p = 0.681$, participant type and task, $F(1, 22) = 0.13$, $p = 0.726$, and participant type and structure, $F(1, 22) = 2.28$, $p = 0.146$, were all non-significant.

300-600 ms Time Window Statistical analysis revealed a significant main effect of boundary at midline sites, $F(1, 22) = 36.61$, $p < 0.001$, $p^2 = 0.61$, with boundaries ($M = 0.71$, $SE = 0.16$) eliciting larger positive components than non-boundaries ($M = -0.69$, $SE = 0.14$). The interaction between boundary and brain region was significant, $F(2, 44) = 10.07$, $p < 0.005$, $p^2 = 0.31$. Simple effects analysis indicated that boundaries elicited larger positive components than non-boundaries at anterior, $F(1, 22) = 34.11$, $p < 0.001$, $p^2 = 0.61$, central, $F(1, 22) = 43.22$, $p < 0.001$, $p^2 = 0.66$, and posterior sites, $F(1, 22) = 14.52$, $p < 0.005$, $p^2 = 0.40$. Interactions between participant type and boundary, $F(1, 22) = 1.725$, $p = 0.203$, participant type and task, $F(1, 22) = 1.737$, $p = 0.201$, and participant type and structure, $F(1, 22) = 0.097$, $p = 0.758$, were all non-significant.

Lateral analysis revealed a significant main effect of boundary, $F(1, 22) = 36.59$, $p < 0.001$, $p^2 = 0.71$, with boundaries ($M = 0.66$, $SE = 0.16$) eliciting larger positive components than non-boundaries ($M = -0.53$, $SE = 0.11$). The interaction between boundary and brain region was significant, $F(2, 44) = 24.16$, $p < 0.001$, $p^2 = 0.52$. Simple effects analysis indicated that boundaries elicited larger positive components than non-boundaries at anterior, $F(1, 22) = 43.30$, $p < 0.001$, $p^2 = 0.66$, central, $F(1, 22) = 55.91$, $p < 0.001$, $p^2 = 0.72$, and posterior sites, F(1, 22) = 4.74, $p < 0.05$, $p^2 = 0.18$. The three-way interaction among task, boundary, and structure was significant, F(2, 44) = 3.95, $p < 0.05$, $p^2 = 0.15$. Simple effects analysis indicated that in the lexical judgment task, verb-object structures did not elicit a positive effect, F(1, 22) = 2.47, p = 0.13, whereas attributive structures did, F(1, 22) = 23.41, $p < 0.001$, $p^2 = 0.52$. In the structural judgment task, both verb-object and attributive structures elicited positive effects, F(1, 22) = 17.02, $p < 0.001$, $p^2 = 0.44$; F(1, 22) = 11.65, $p < 0.005$, $p^2 = 0.35$ (as shown in Figure 4 [Figure 4: see original paper]). Interactions between participant type and boundary, F(1, 22) = 0.27, p = 0.607, participant type and task, F(1, 22) = 0.38, p = 0.545, and participant type and structure, F(1, 22) = 0.19, p = 0.67, were all non-significant.

Figure 4. Both stutterers and fluent speakers elicited significant positive waves when processing prosodic boundaries of attributive phrases during the lexical judgment task (left). During the structural judgment task (right), both groups elicited significant positive waves when processing prosodic boundaries of both structure types. *$\mathbf{p < 0.001}$**,** $p < 0.005$

Discussion

The present study presented participants with pairs of ambiguous phrases and employed lexical judgment and structural judgment tasks to investigate the ERP effects of prosodic boundary processing and their influencing factors in stutterers and fluent speakers. The results demonstrated that stutterers and fluent speakers did not differ significantly in the CPS component elicited during the processing of Chinese ambiguous phrases. In the earlier time window (0-300 ms), the scalp distribution of the positive effect elicited by prosodic boundaries in verb-object phrases was smaller than that in attributive phrases for both groups at midline and lateral sites. In the later time window (300-600 ms), both groups elicited CPS when perceiving boundaries within both types of ambiguous phrases at midline sites across both tasks. At lateral sites, although both phrase types reliably elicited CPS in the structural judgment task, only attributive phrases consistently elicited this effect in the lexical judgment task. These findings indicate that stutterers, like fluent speakers, are sensitive to prosodic boundaries in speech, and that their boundary processing is modulated by experimental task and phrase structure. The results are discussed below in relation to previous literature.

4.1 Prosodic Information Processing in Stutterers

Some researchers have proposed that auditory processing deficits contribute to stuttering (Hall & Jerger, 1978). However, Hampton and Weber-Fox (2008) found that most stuttering participants showed normal responses to non-speech sounds, with only a minority exhibiting abnormalities. Earlier ERP studies of language processing in stutterers indicated that even without explicit speech production requirements, their language processing showed subtle differences compared to fluent speakers (Weber-Fox, 2001; Cuadrado & Weber-Fox, 2003;

Weber-Fox et al., 2004). For instance, although stutterers and non-stutterers did not differ in early-latency ERP components primarily reflecting sensory and perceptual processes (N100, N180, P200), stutterers exhibited reduced amplitudes in endogenous, longer-latency ERP effects (such as N400, P600, P300) (Cuadrado & Weber-Fox, 2003; Weber-Fox, 2001; Weber-Fox et al., 2004).

In the present study, both stutterers and fluent speakers reliably elicited similar CPS effects when processing prosodic boundaries within ambiguous phrases, indicating comparable neural processes during boundary processing. These results are consistent with behavioral findings from Bosshardt, Ballmer, and de Nil (2002), who found no differences between stutterers and fluent speakers in response time or accuracy for prosodic information (rhyme) judgments. They also align with Weber-Fox et al.' s (2004) ERP findings that stutterers and fluent speakers did not differ in amplitude or latency of ERP effects during rhyme processing. Despite stutterers exhibiting acoustic characteristics similar to boundaries during speech production, such as syllable prolongations and inappropriate pauses, they did not differ from normal individuals in boundary perception. Combined with previous research, this may suggest that stutterers' prosodic information processing is similar to that of normal individuals. Alternatively, the current results may be related to the mode of stimulus presentation and task requirements. In the present study, participants were not required to produce any speech throughout the experiment; they simply listened carefully to the materials and made button-press responses after listening. Some previous studies presented visual materials, which, although not requiring direct speech production, involved phonological encoding during reading of Chinese characters/letters, potentially including subvocalization, rehearsal, or inner speech processes (Baddeley, 1992). Consequently, stutterers may differ from normal individuals to some extent in processing syntactic, semantic, and phonological information (Weber-Fox, 2001; Cuadrado & Weber-Fox, 2003; Weber-Fox et al., 2008; Corbera et al., 2005). Furthermore, stutterers' speech disfluency is related to lexical retrieval and cognitive monitoring factors, and their language processing abilities are more likely to differ from those of normal controls under conditions of increased cognitive load or syntactic/semantic violations (Cuadrado & Weber-Fox, 2003). Boundary processing primarily involves processing acoustic parameters such as pitch and duration, and the task settings in the present study did not involve increased cognitive load. Therefore, at least under conditions without explicit speech production requirements, the phonological encoding systems of stutterers and fluent speakers appear similar. In this study, stutterers' speech production deficits did not manifest in speech perception processes, suggesting that the cognitive and neural substrates underlying human speech production and comprehension are distinct. Future research examining the processing of implicit prosodic boundaries through visual presentation of commas in stutterers and fluent speakers may reveal differences between the two groups.

4.2 Processing of Internal Boundaries in Ambiguous Phrases and Influencing Factors

The present study used Chinese verb-object/attributive ambiguous phrases as experimental materials and detected the CPS component reflecting prosodic segmentation at internal boundaries. Previous studies have found that prosodic boundaries within Chinese sentences and quatrains reliably elicit this component (Li & Yang, 2009, 2010; Li & Yang, 2010). The present study extends the conditions that elicit CPS to internal boundaries within ambiguous phrases, further demonstrating that CPS is elicited whenever listeners segment continuous speech streams into relatively independent units, regardless of the size of the prosodic unit.

Previous research has also observed CPS in short, non-sentential phrase sequences (e.g., Mona or Lena and Lola), but its elicitation depended on boundary position (Holzgrefe et al., 2013). Specifically, later boundaries (e.g., after Lena) elicited CPS, whereas earlier boundaries (e.g., after Mona) did not. Researchers proposed that prosodic boundary processing depends to some extent on preceding contextual information. In the present study, both stutterers and fluent speakers elicited this effect when processing prosodic boundaries in both types of ambiguous phrases. This may be because the ambiguous phrases used in this study could be clearly distinguished into two significantly different syntactic structures (verb-object/attributive). Additionally, in Holzgrefe et al.' s (2013) study, materials were presented repeatedly and no experimental task was set (participants were only asked to listen carefully and avoid blinking or other movements), which may have resulted in insufficient processing of the syntactic/prosodic structure and consequently reduced attention to and segmentation of the experimental materials. In the present study, all experimental materials were presented without repetition, and participants needed to listen carefully to the pairs of ambiguous phrases to complete the tasks (lexical or structural judgment), which likely encouraged more detailed processing of prosodic boundaries.

The present study found that CPS was elicited in both lexical and structural judgment tasks. Previous research has shown that CPS can be reliably elicited whether listeners are asked to comprehend stimulus meaning (Steinhauer et al., 1999; Li & Yang, 2009), detect a word (Pannekamp et al., 2005), listen passively (Peter et al., 2014), or perform rhythm-matching tasks (Li & Yang, 2010). The present results are consistent with these findings, showing that CPS was elicited at corresponding prosodic boundaries regardless of whether participants were asked to attend to prosodic information (structural judgment task) or not (lexical judgment task). This indicates that both stutterers and fluent speakers are highly sensitive to prosodic boundary information and process it in a highly automatic manner.

However, examination of the statistical results and ERP effects (Figures 2-4) reveals that although both groups elicited CPS for both phrase types across both time windows and tasks, some specific patterns emerged. In the 0–300 ms time window, the scalp distribution of the positive effect elicited by prosodic boundaries in verb-object phrases was smaller than that in attributive phrases when processing both phrase types, for both stutterers and fluent speakers, at midline and lateral sites. In the 300–600 ms time window, both groups elicited CPS when perceiving boundaries within both types of ambiguous phrases at midline sites across both tasks. At lateral sites, although both phrase types reliably elicited CPS in the structural judgment task, only attributive phrases consistently elicited this effect in the lexical judgment task. These results indicate that people segment speech input prosodically across various conditions, and this process begins before the appearance of important boundary markers (silent intervals), as evidenced by positive effects in the 0–300 ms time window for boundary versus non-boundary conditions. This may be related to the fact that prosodic boundaries within ambiguous phrases are primarily realized through pre-boundary syllable lengthening (as shown in Figure 1). On the other hand, when experimental tasks direct attention to prosodic information, they generally elicit stronger prosodic segmentation and consequently larger positive effects (primarily in the 300–600 ms time window). Furthermore, the results suggest that people are more sensitive to internal boundaries in attributive phrases. Previous research has found that people tend to interpret verb-object/attributive ambiguous phrases as attributive structures (Wei et al., 2016; Zhang et al., 2000). Although the ambiguous phrases used in this study could be equally interpreted as both structures (see Li et al., 2010), verb-object phrases elicited positive effects with smaller scalp distributions in the earlier time window, and failed to elicit positive effects at lateral sites in the lexical judgment task for stutterers and in the structural judgment task for fluent speakers. In the later time window, verb-object phrases did not reliably elicit positive effects at lateral sites, whereas attributive phrases consistently elicited CPS. In conclusion, while experimental task and syntactic structure may not be decisive factors in eliciting CPS, both exert influence on this component.

Finally, although the CPS elicited by prosodic boundaries in this study was distributed across the entire scalp, it was generally larger at frontal-central sites, consistent with previous research (Holzgrefe et al., 2013; Pannekamp et al., 2005; Li & Yang, 2010). A common feature of these studies is that they all used materials with minimal semantic content. Specifically, Li and Yang (2010) used unfamiliar quatrains, Pannekamp et al. (2005) used so-called jabberwocky sentences (i.e., sentences stripped of syntactic and semantic content), and Holzgrefe and colleagues (2013) used six names connected by conjunctions. Consistent with these studies, the ambiguous phrases in the present study may also have been processed in a relatively semantically neutral manner. That is, listeners did not deeply analyze the semantic content of the ambiguous phrases but instead focused on completing the specific experimental tasks. The scalp distribution of CPS is influenced by experimental materials.

Conclusion

Using ERP technology and Chinese ambiguous phrases as experimental materials, the present study investigated the cognitive processes and influencing factors involved in prosodic boundary processing during lexical and structural judgment tasks in stutterers and fluent speakers. The results demonstrated that both groups elicited CPS when processing prosodic boundaries within attributive and verb-object phrases, with no significant differences between them. In the earlier time window (0-300 ms), boundary processing was influenced by phrase structure type, with verb-object phrase boundaries eliciting positive effects with smaller scalp distributions than attributive phrases. In the later time window (300-600 ms), both groups elicited CPS when perceiving boundaries within both types of ambiguous phrases at midline sites across both tasks. At lateral sites, although both phrase types reliably elicited CPS in the structural judgment task, only attributive phrases consistently elicited this effect in the lexical judgment task. In summary, the present study demonstrates that stutterers and fluent speakers show similar sensitivity to prosodic boundaries, and the ERP effects elicited during processing of prosodic boundaries within ambiguous phrases are influenced by both experimental task and phrase structure type.

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Neural Processing of Ambiguous Chinese Phrases in Stutterers

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Abstract

Prosodic boundaries constitute an integral component of spoken language prosody and play a crucial role in language comprehension. Stuttering, as a rhythmic speech disorder, is primarily characterized by frequent repetitions, prolongations, or pauses at the syllable level. The present study employed ERPs to investigate the cognitive processes underlying the processing of prosodic boundaries within ambiguous phrases (verb-object/attributive ambiguous structures) in stutterers performing lexical judgment and structural judgment tasks. The results revealed no significant differences between stutterers and fluent speakers in the CPS (closure positive shift), an ERP component reflecting prosodic segmentation, during the processing of Chinese ambiguous phrases. In the 0-300 ms time window, the scalp distribution of the positive effect elicited by prosodic boundaries in verb-object phrases was smaller than that in attributive phrases for both stutterers and fluent speakers, across both midline and lateral sites. In the 300-600 ms time window, both groups exhibited stable positive effects for prosodic boundaries of both phrase types at midline sites across both tasks; however, at lateral sites, while both phrase types elicited positive effects in the structural judgment task, only attributive phrases consistently elicited this effect in the lexical judgment task. In summary, stutterers, like fluent speakers, are sensitive to prosodic boundaries in speech, and the ERP effects elicited during the processing of prosodic boundaries within ambiguous phrases are influenced by both experimental task and phrase structure type.

Keywords: stuttering; prosodic boundary; ambiguous phrase; CPS