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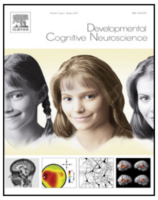

The role of pause as a prosodic boundary marker: Language ERP studies in German 3- and 6-year-olds

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ABSTRACT

Spoken language is hierarchically structured into prosodic units divided by prosodic breaks. The largest prosodic breaks in an utterance are intonational phrase boundaries (IPBs), which are defined by three acoustic cues, namely, pitch change, preboundary lengthening, and pausing. Previous studies have revealed that the electrophysiological marker of IPB perception, the Closure Positive Shift (CPS), is established between 2 and 3 years of age. Here, we examined the neural activity underlying IPB perception in children by targeting their reliance on pausing; hypothesized to be a key boundary cue in German. To evaluate the role of pausing, we tested IPB perception without the boundary pause, but with pitch change and preboundary lengthening. We tested children at the age of 3 years, when the CPS in response to IPBs has just emerged, and at 6 years, when language abilities are further developed. Results revealed that 6-year-olds, but not 3-year-olds, show the CPS in response to IPBs without full prosodic marking. These results indicate developmental differences with respect to the role of pausing as a prosodic boundary cue in German. The correlation of children's IPB perception and their syntactic abilities further corroborates the close prosody–syntax interaction in children's advancing ability to process phrase structure.

1. Introduction

Processing of sentence-level prosody is fundamental to successful language comprehension because prosodic phrasing and pitch accents in sentences can signal syntactic constituents and influence syntactic parsing preferences (e.g., Bögels et al., 2011; Marslen-Wilson et al., 1992; Schafer et al., 2000; Warren et al., 1995; Weber et al., 2006). Regarding prosodic phrasing, utterances are hierarchically structured into prosodic constituents, ranging from prosodic words, to phonological phrases, to intonational phrases (Nespor and Vogel, 1986; Selkirk, 1984). Although there is no one-to-one structure correspondence between prosody and syntax, listeners can reliably derive syntactic information from intonation contours and prosodic boundary cues. For example, intonational phrase boundaries (IPBs)—defined by the acoustic cues of preboundary lengthening, pitch change, and pausing—mostly coincide with syntactic clause boundaries and, thus, mark syntactic structure (Nespor and Vogel, 1986; Selkirk, 1984). Accordingly, the prosodic features of IPBs have been demonstrated to be instrumental in conjointly resolving syntactic ambiguities that arise, temporarily in some cases, as sentences unfold (e.g., Price et al., 1991; Speer et al., 2011). Similarly, smaller prosodic boundaries, framing phonological phrases, have been shown to constrain syntactic analysis, with the more modulated prosodic cues being of more benefit to resolving syntactic ambiguities than less modulated ones (Millotte et al., 2008).

In addition to behavioral evidence of adult listeners' sensitivity to the prosodic cues signaling syntactic boundaries, several event-related brain potential (ERP) studies

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have described the neurophysiological underpinnings of the prosody–syntax mapping (Steinhauer et al., 1999; Kerkhofs et al., 2008; Bögels et al., 2010). In this context, the seminal study by Steinhauer et al. (1999) reported three findings. First, it revealed a particular brain signature associated with the occurrence of IPBs in sentences, expressed in a positive shift in the ERP relative to each IPB (Steinhauer et al., 1999). This so-called *Closure Positive Shift* (CPS) has subsequently been replicated for different languages (Dutch: Bögels et al., 2010; Kerkhofs et al., 2007; 2008; English: Pauker et al., 2011; Chinese: Liu et al., 2009; and Japanese: Wolff et al., 2008), and was specifically associated with the processing of phrasal prosody (Pannekamp et al., 2005). Second, the original study demonstrated a clear prosody–syntax interaction with incorrect prosodic phrasing leading to syntactic misparsing. Thus, the CPS can be viewed as reflecting the structuring of auditory input, based on an entity consisting of boundary markers that simultaneously define prosodic and syntactic units (for a review, see Bögels et al., 2011). Third, this study showed that German adults perceive IPBs independently of the presence of the pause as a boundary cue. For sentences in which only pitch change and preboundary lengthening marked the IPBs, adults still showed the CPS relative to the boundaries (Steinhauer et al., 1999; see also Männel and Friederici, 2009). This suggests that, for German-speaking adults, pausing is less important as a boundary cue (in the presence of the other cues) or, more generally, less acoustic marking is sufficient for boundary perception.

The studies on German-speaking adults' boundary processing without the boundary pause indicate listener's flexibility in speech structure perception without full prosodic marking. This flexibility can enhance the course of processing, particularly given inter-speaker variability in the use of prosodic modifications (Cole et al., 2010; Schafer et al., 2000) and differences in the prominence of acoustic marking across different linguistics units (Cooper and Paccia-Cooper, 1980; see also Cutler and Butterfield, 1990). The lack of comparative data in children makes it difficult to determine when during language development this flexibility evolves at the phrasal level. However, behavioral studies in American English attest to general developmental differences; suggesting that infants, as compared to adults, require more boundary cues for successful phrase boundary processing (Aasland and Baum, 2003; Gerken et al., 1994; Seidl, 2007; Streeter, 1978). In the studies with American English-learning infants, pitch was the most relevant cue (Seidl, 2007), while in a study with German-learning infants, pausing was observed as the necessary cue in signaling speech breaks (Männel and Friederici, 2009). Thus, the importance of individual acoustic markers for boundary perception might differ across languages as a function of the respective intonation system (see Hirst and Di Cristo, 1998). Consequently, children learning German might rely on the presence of pausing, as the most prominent durational cue, until they reach an adult-like flexibility in the perception of prosodic phrasing.

Previous ERP studies have demonstrated a developmental shift in prosodic boundary perception between children's second and third years of age. Similarly to adults, children at 3 years showed a CPS in response to IPBs signaled by all prosodic boundary markers (Männel and Friederici, 2011). In contrast, children at the age of 2 years did not yet show a CPS, but instead obligatory auditory ERP components in response to IPBs, which are already observed in infant IPB processing (Männel and Friederici, 2009). The occurrence of obligatory auditory ERP components, relative to the sentence part following the IPB, indicates that children's ERP response is perceptually driven by the recognition of sentence continuation after speech interruption. These findings point to a progression in IPB processing from lower-level detection of speech breaks (i.e., sensory processes marked by obligatory ERP components) to higher-level perception of speech structure (i.e., cognitive processes indicated by the CPS). This change occurs at an age when children also become more advanced in their syntactic processing abilities (see Guasti, 2002). Based on the results of these studies, we assume that at this specific developmental stage, children may have gained a concept of speech structure based on syntactic knowledge that is triggered by the closely linked prosodic cues in the speech input. In light of the described developmental shift, children may also eventually become more flexible in processing speech structure on the basis of less pronounced phrasal prosody. In other words, children's increasing linguistic competence during preschool-age may lead to a decrease in sensitivity to particular prosodic parameters, such that less acoustic information is sufficient to trigger boundary perception. The current study is devoted to investigating whether these developmental changes occur during preschool age.

Based on these considerations of developmental differences and language-specific weighting of boundary markers, we aimed to test the role of pausing in German-speaking children's higher-level boundary perception at an age when the CPS in response to fully marked IPBs is established (Männel and Friederici, 2011). Specifically, we examined IPB processing by means of ERP at two ages: first, at 3 years of age, when the CPS in response to IPBs has just emerged, and second, at 6 years of age, when children have mastered most language acquisition steps in German (Grimm, 2000; Szagun, 2006). In order to evaluate the proposed relation between prosodic and syntactic development, we conducted a standardized syntax comprehension test. We reasoned that an adult-like IPB processing (see Männel and Friederici, 2009; Steinhauer et al., 1999) is driven by syntactic structure knowledge, and, therefore, we expected children's higher-level prosodic processing to be correlated with their syntactic abilities. This relationship can be explained by two tightly linked processes that might also mutually interact during development: Initially, acoustic cues in prosodic information foster the building of syntactic structure representations, because most prosodic phrase boundaries are also syntactic boundaries. Later during development, syntactic knowledge can, in turn, support prosodic phrase processing, because expectations about the occurrence of syntactic boundaries, based on structural regularities, can make up for less pronounced acoustic marking.

2. Materials and methods

2.1. Participants

Children were recruited from the database of the *German Language Development Study* in Berlin, Germany. All children were raised in monolingual German-speaking families and were born full-term after a normal pregnancy and normal birth. None of the children had any known hearing deficits or neurological problems or had experienced delays in their language development. For all children, parental written informed consent was obtained prior to participation. The study was approved by the ethics committee of the University Leipzig and conformed to the guidelines of the Declaration of Helsinki (Williams, 2008).

From the participants initially tested, data from five 3-year-olds and two 6-year-olds were excluded from the final analyses due to insufficient EEG quality, caused by movement and perspiration during data acquisition. Additionally, data from four 3-year-olds and four 6-year-olds were excluded, due to below-normal range performance (i.e., $T < 40$) in the syntax comprehension test, *TROG-D* (Fox, 2008). The final participant samples consisted of 27 3-year-olds (15 female, mean age 159.4 weeks, $SD = 2.5$) and 24 6-year-olds (10 female, mean age 314 weeks, $SD = 3.4$).

2.2. Prosodic ERP experiment

2.2.1. Stimuli

Stimuli consisted of 50 sentences with an IPB and 50 sentences without an IPB used in previous infant ERP studies on IPB processing (Männel and Friederici, 2009). All sentences were produced in a sound-proof chamber by a trained female speaker in a child-directed manner. After recording, sentences were digitized (44.1 kHz/16-bit sampling rate, mono) and normalized in amplitude to 70%. To assess the role of the pause in IPB processing, we deleted the boundary pause in sentences with an IPB. Apart from pause removal, the other boundary parameters, i.e., pitch change and preboundary lengthening, remained the same (for more detail, see Männel and Friederici, 2009). Instead of contrasting three sentence types, i.e., sentences with IPB (full prosodic marking), sentences with IPB (without boundary pause), and sentences without IPB, we decided to focus on the latter two conditions. First, this comparison should, in principle, reveal whether children still show the CPS when the IPB is signaled by preboundary lengthening and pitch change, but not the boundary pause; given that previous ERP studies have demonstrated that 3- and 6-year-olds show the CPS in response to fully marked IPBs (Männel and Friederici, 2011). Second, we aimed to avoid intra-experiment effects of repetition or surprise that could have resulted from a direct contrast of sentences with fully marked IPBs versus sentences with IPBs lacking the boundary pause.

The different intonational realization of the sentences, with and without IPB, resulted from their underlying syntactic structures which varied with the syntactic valence of the verb in the infinitive phrase, i.e., the verb at the end of the sentence. Sentences with an IPB contained a verb that requires a noun phrase as a complement. For example: In the sentence *Tommi verspricht, # Papa zu helfen* (Tommi promises # to help papa), the verb *zu helfen* (to help) demands an accompanying noun phrase, e.g., *Papa* (indirect object). As a consequence, an IPB occurred at the first verb, marking a first syntactic phrase *Tommi verspricht* (Tommi promises), followed by a second phrase *Papa zu helfen* (to help papa). In contrast, sentences without an IPB ended with an intransitive verb that does not require a complement, as in *Tommi verspricht Papa zu schlafen* (Tommi promises papa to sleep). Here, the noun phrase *Papa* is the indirect object of the verb in the main clause *verspricht* (promises), and sentences of this type, therefore, did not contain a sentence-internal IPB.

Sentences with and without an IPB were constructed in pairs that only differed in their wording for the last verb, which determined the syntactic sentence structure. The identical word order in German results in a structural ambiguity regarding the syntactic role of the noun phrase (i.e., complementing the infinitive or the main clause). However, this ambiguity can be determined prior to the appearance of the last verb because, from sentence onset, intonation and duration characteristics signal the respective syntactic units, resulting in sentences with and without an IPB. Thus, the stimulus manipulations across sentence types targeted children's prosodic and syntactic processing abilities. In contrast, processing differences related to children's lexico-semantic knowledge (e.g., use of verbs in sentences) could be disregarded, given that these features were identical in the critical sentence parts across conditions (i.e., before and after the IPB).

The successful acoustic realization of the intonation contour of both sentence types were proven in acoustic analyses. Specifically, analyses revealed significant differences between sentences with and without an IPB regarding preboundary syllable lengthening, $t(98) = -22.99$, $p \leq 0.01$, and pitch rise at the boundary position, $t(98) = -36.22$, $p \leq 0.01$, but not with respect to pause length after removal of the boundary pause, $t(98) = -1.03$, $p = 0.31$ (for more detail see Männel and Friederici, 2009; see also Fig. 1).

2.2.2. Experimental procedure

During the EEG recordings, children sat in an armchair or on their parent's lap in an electrically shielded and sound-attenuated testing booth. The sentences were delivered via a speaker controlled by ERTS software (BeriSoft Cooperation). For a total of 8 min, sentences with and without an IPB were presented in a pseudo-random order (i.e., no more than three succeeding sentences of one type), and each sentence was followed by an inter-stimulus interval of 1.5 s. While the children were listening to the sentences, a visual distraction (i.e., silent children's video) was presented to keep them entertained.

2.2.3. EEG recordings and analysis

The EEG was continuously recorded from 23 silver silver-chloride electrodes attached to an elastic cap (Easy Cap GmbH, Germany) at the following electrode positions: F7, F3, FZ, F4, F8, FC3, FC4, T7, C3, CZ, C4, T8, CP5, CP6, P7, P3, PZ, P4, P8, O1, O2, M1, and M2 (10-10 system; Chatrian et al., 1988). An electrooculogram (EOG) was recorded from

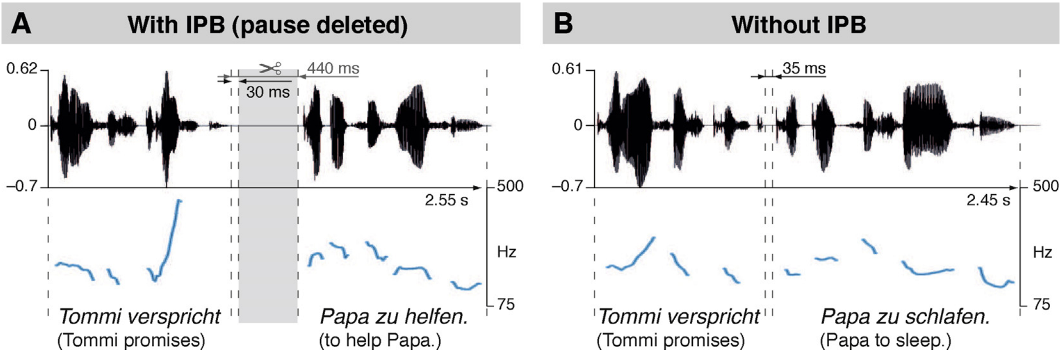

Fig. 1. Stimuli examples. Waveform (normalized values) and pitch track (F0 contour in Hz) for example sentences (with literal translation). (A) Sentence with an intonational phrase boundary (IPB) and (B) sentence without an IPB. For sentences with an IPB, the boundary pause was deleted, while preboundary lengthening and pitch change remained.

single electrodes placed at the outer canthi of both eyes (horizontal EOG) and on the infra- and supraorbital ridges of the right eye (vertical EOG). The EEG recordings were referenced to CZ and an electrode at FP1 served as common ground. Electrode impedances were mostly kept below 10 kΩ (max. 20 kΩ). The EEG signal was amplified with a gain of 20 using a PORT-32/MREFA (Twente Medical Systems), with an input impedance of 1012 Ω. The EEG data were digitized online at a rate of 500 Hz (AD converter with 22 bit, digital filter from DC to 125 Hz) and stored for further analyses. Offline, the EEG data were processed using the EEP 3.3 software package (Max Planck Institute for Human Cognitive and Brain Sciences, Germany). Data were algebraically re-referenced from CZ to the average of both mastoids and band-pass filtered at 0.2–20 Hz (−3 dB cutoff frequencies of 0.25 Hz and 19.91 Hz).

For the ERP analysis, time segments of 2500 ms relative to sentence onset were extracted from the continuous EEG signal and adjusted to a pre-stimulus baseline of 200 ms (see ERP analyses in Steinhauer et al., 1999; Männel and Friederici, 2009, 2011). EEG epochs were individually checked for eye movements and corrected using a computer algorithm (EEP 3.3, Max Planck Institute for Human Cognitive and Brain Sciences, Germany). All other artifacts were detected manually and the affected EEG epochs were excluded. The remaining epochs were averaged for sentences with and without an IPB for each participant. For all children, at least 25 artifact-free EEG epochs (50%) were required per sentence type in order for an individual average to be entered into the final sample. For the 3-year-olds, the mean number of averaged epochs across participants was 39 (*SD* = 6) for sentences with an IPB, and 39 (*SD* = 7) for sentences without IPB. For the 6-year-olds, the mean number of averaged epochs across participants was 36 (*SD* = 6) for sentences with an IPB, and 37 (*SD* = 7) for sentences without an IPB. Thus, the average number of epochs did not differ significantly between sentence types.

Statistical analyses were performed separately for mean amplitudes recorded at midline and lateral electrodes across time windows (TWs) of 500 ms. For midline electrodes (FZ, CZ, PZ), a three-way analysis of variance (ANOVA) was computed with the factors condition (with IPB, without IPB), electrode site (anterior, central, posterior), and TW (0–500 ms, 500–1000 ms, 1000–1500 ms, 1500–2000 ms, 2000–2500 ms). For lateral sites, six regions of interest (ROIs) were created combining hemisphere (left, right) and region information (anterior, central, posterior): left anterior (F7, F3, FC3), right anterior (F8, F4, FC4), left central (T7, C3, CP5), right central (T8, C4, CP6), left posterior (P7, P3, O1), and right posterior (P8, P4, O2). For these ROIs, a four-way ANOVA was computed with the factors condition (with IPB, without IPB), region (anterior, central, posterior), hemisphere (left, right), and TW (0–500 ms, 500–1000 ms, 1000–1500 ms, 1500–2000 ms, 2000–2500 ms). The Greenhouse–Geisser correction was applied when there was more than one degree of freedom (*df*). All significant effects involving condition are reported and significant interactions with the factors condition and TW were further analyzed using one-sample *t*-tests (False Discovery Rate for multiple comparisons correction, Benjamini and Hochberg, 1995).

2.3. Syntactic comprehension test

To assess children's syntactic comprehension abilities, the *TROG-D: Test zur Überprüfung des Grammatikverständnisses* (test for the evaluation of syntax comprehension; Fox, 2008), was employed. This standardized test takes 10–20 min and was administered before the EEG for half of the children and after the EEG for the other half. The test uses a sentence-picture matching task and assesses children's developmental status in the reception of syntactic categories, and verbal and nominal inflections, as well as different syntactic structures, such as relative clauses. Only children who performed within the normal range (age-normed *T* scores) were included in our study.

2.4. Correlation analysis of ERP data and syntax comprehension test

For evaluation of the relationship between IPB processing and syntactic abilities, Pearson's correlations were performed on ERP mean amplitudes and *T* scores of the language test. Specifically, ERP difference measures (with IPB–without IPB) were created across the TW enclosing the expected condition differences, for the lateral ROI and the midline electrode that exhibited the most pronounced ERP effects. Performance measures of the syntax comprehension test were translated into standardized age-normed *T* scores (Fox, 2008). ERP difference values and *T* scores were then entered into a Pearson's correlation.

3. Results

3.1. IPB processing: ERP data

For the 3-year-old group, visual inspection of the average ERP responses to sentences with and without an IPB revealed no apparent processing difference between the two types of sentence (Fig. 2a). Accordingly, ANOVAs relative to sentence onset across TWs of 500 ms only revealed an interaction of condition × region × TW at lateral ROIs ($F(8,208) = 2.98$, $p \leq 0.05$), for which subsequent one-sample *t*-tests did not deliver significant condition differences in any of the five TWs. Thus, for 3-year-old children, statistical analyses revealed no processing differences between sentences with and without IPBs.

In contrast to the younger age group, visual inspection of the data from 6-year-olds revealed a positive shift (peaking at around 1500 ms) in response to sentences with an IPB compared to sentences without an IPB (Fig. 2b). This observation was supported by ANOVAs with post-sentence onset effects involving the factor condition in the TWs 1000–1500 ms and 1500–2000 ms at lateral ROIs and midline electrode sites (Table 1). Thus, for 6-year-olds, statistical analyses provided evidence of processing differences between sentence types in IPB-relevant TWs, that appear as a centrally distributed positive shift for sentences containing IPBs, starting at around 1300 ms post-sentence onset and lasting up to 2000 ms.

3.2. Relationship between IPB processing and syntax comprehension: correlation of ERP and behavioral data

In 6-year-olds, the correlation of ERP and behavioral measures was performed for the TW 1300–2000 ms (i.e., enclosing the observed ERP effect) at the left central ROI and the electrode site CZ, i.e., the two sites showing the strongest condition differences in the distribution of the ERP effect at lateral ROIs and midline electrode sites, respectively (Fig. 3a). Both Pearson's correlations revealed significant effects (Fig. 3b), i.e., left-central ROI: $r = 0.43$, $p = 0.038$ and CZ: $r = 0.54$, $p = 0.012$ (False Discovery Rate for multiple comparisons correction; Benjamini and Hochberg, 1995). No correlation effect could be observed for the 3-year-olds, who showed no ERP effect in response to IPB processing.

4. Summary of results

In summary, when presented with sentences containing IPBs, in the absence of a boundary pause, 6-year-olds, but not 3-year-olds, showed a positive shift relative to the IPBs, starting at around 1300 ms post-sentence onset (Fig. 2). This suggests that IPB perception, as indicated by the CPS, is a stable process in 6-year-olds, but not in 3-year-olds, when the IPB is not signaled by all available prosodic boundary cues. Moreover, in 6-year-olds, the ERP effect for IPB perception, in the absence of the boundary pause, is correlated with children's performance in a behavioral test of syntax comprehension (*TROG-D*; Fox, 2008; Fig. 3).

5. Discussion

The current ERP results suggest that, similar to adults, at 6 years of age children perceive IPBs independent of the boundary pause, as indicated by the presence of the CPS (Männel and Friederici, 2009; Steinhauer et al., 1999). In contrast, at 3 years of age, when the CPS has just emerged (Männel and Friederici, 2011), IPB perception still seems to require the presence of all available prosodic boundary cues. These findings indicate a developmental progression between the ages of 3 and 6 years regarding the role of pausing as a prosodic boundary marker or, more generally, the necessity of a certain boundary strength for evoking boundary perception as indicated by the CPS.

With respect to prosodic boundary strength, here defined as the number of prosodic boundary parameters, there is previous evidence for differences between infants and adults from behavioral studies using American English. In adults, either preboundary lengthening or pitch is each sufficient for boundary perception (Aasland and Baum, 2003; Streeter, 1978). In contrast, in infants more boundary markers have to co-occur (Seidl, 2007; Seidl and Cristia, 2008; see also Gerken et al., 1994). Moreover, Seidl and Cristia (2008) described a developmental progression in boundary detection during infancy, such that 4-month-old infants required the presence of all available boundary cues, while at 6 months of age fewer boundary markers were sufficient. The authors interpret these findings as a developmental change in the weighting of speech cues, with a shift from larger, more global cues to smaller, local cues. The current ERP study on higher-level boundary perception indicates that, initially, children's perception is restricted to phrases which are prominently marked by the entire acoustic information, while later during development, less information is sufficient. This developmental change may occur once children have acquired the concept of a boundary as a correlation of several acoustic cues, with the remaining cues standing in when, for example, the pause is absent. In this context, prosodic boundary perception may be viewed as an interactive process where, in the absence of one boundary cue, the other cues become more relevant (see *cue trading*; Beach, 1991).

The second interpretation targets more directly the language-specific role of pausing as a boundary marker and is motivated by the particular characteristics of the German intonation system (Gibbon, 1998). German, in contrast to English, uses a relatively flexible word order, and a relatively high number of inflections and discourse particles that likely take over functions achieved by intonation patterns in other languages (see Schubiger, 1980). Thus, in German the functional demands on pitch modulations for structuring and focalization are lower than in English (see Gibbon, 1998), and durational parameters, especially pauses, gain more importance as a structuring device in German (Butcher, 1981). Consequently, English mostly uses pitch to characterize intonational phrases, whereas

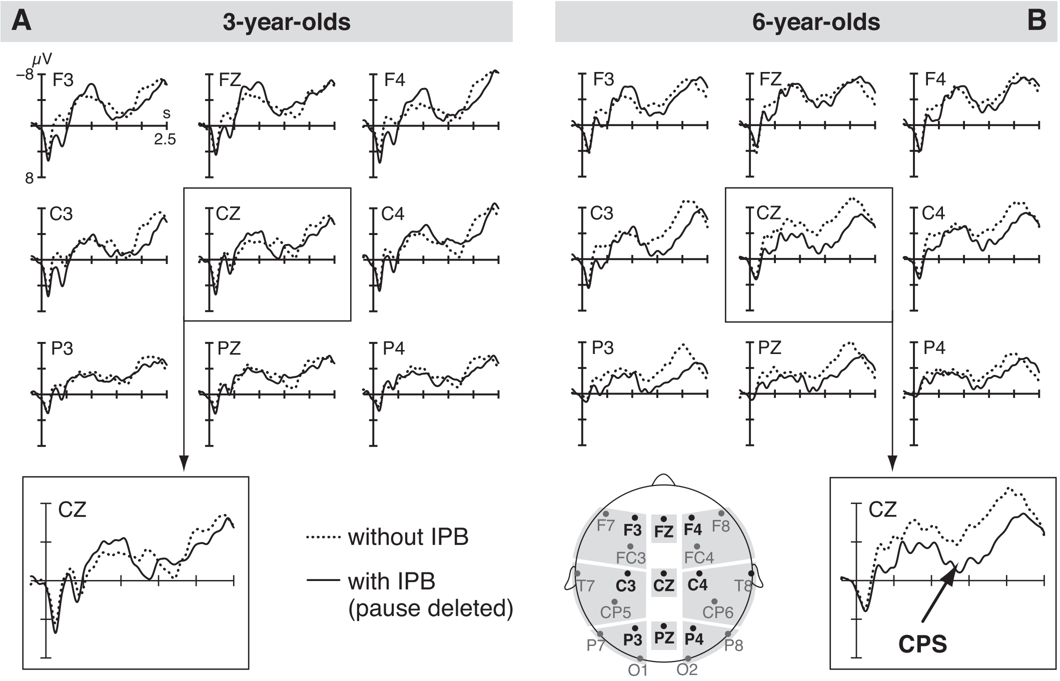

Fig. 2. ERP results. ERPs of (A) 3-year-olds, and (B) 6-year-olds relative to sentence onset for sentences with an IPB (pause deleted; solid line) and without an IPB (dotted line).

in German, length and loudness are the most important cues (see Gibbon, 1998; Markus, 2006). Accordingly, the comparison of previous studies with English- and German-learning infants' suggests crosslinguistic differences in the role of particular boundary cues in speech break detection, most likely driven by infants' early tuning toward their respective native language. In a study with English-learning 6-month-olds, pitch was the relevant boundary marker, converging with either lengthening or pausing (Seidl, 2007). In a study with German-learning 5-month-olds, however, pausing was observed as the necessary cue in signaling speech breaks (Männel and Friederici, 2009). The notion of crosslinguistic differences in prosodic boundary perception based on the particular intonation characteristic of German, as opposed to English, is corroborated by a study with Dutch-learning infants (Johnson and Seidl, 2008). Similarly to German, Dutch exhibits a narrower pitch range than English (Willems, 1982) and Dutch-learning 6-month-olds were only able to detect clauses when clause boundaries were additionally signaled by pauses. Together, these studies indicate a specific role for pausing as boundary marker in languages like German and Dutch. Future studies on prosodic boundary perception need to specify the role of other acoustic markers in addition to the pause. Given the described features of the German intonation system and the resulting role of durational parameters for structuring and focalization (Butcher, 1981; Gibbon, 1998), different outcomes are expected when eliminating pitch change or preboundary lengthening compared to the pause. For pitch marking, we suggest that 3-year-olds learning German are still able to perceive IPBs, in contrast to what one would expect, for example, in English (see Seidl, 2007). Furthermore, given the prominent duration marking by pauses, syllable duration might not be as relevant for IPB perception in German, contrary to what one would expect, for example, in French (see Di Cristo, 1998).

Our data demonstrate that, over the course of children's development, the postulated specific role of individual acoustic cues declines as language acquisition progresses. For infants, it has been assumed that they initially

Table 1

6-year-olds: significant effects of ANOVAS for mean amplitudes across the latency range of 0–2500 ms relative to sentence onset.

Lateral ROIs			Midline sites		
Effect	*df*	*F*/*t*	Effect	*df*	*F*/*t*
Condition	1,23	7.30*	Condition	1,23	6.63*
Condition × TW	4,92	3.75*	Condition × electrode site	2,46	4.43*
TW 1500–2000 ms	1,23	3.83**	Condition × TW	4,92	2.75*
Condition × region × TW	8,184	3.51*	TW 1000–1500 ms	1,23	2.51*
Central region TW 1500–2000 ms	1,23	4.39*	TW 1500–2000 ms	1,23	4.48**

TW, time window.

* $p \le 0.05$.

** $p \le 0.005$ (False Discovery Rate for multiple comparisons correction; Benjamini and Hochberg, 1995).

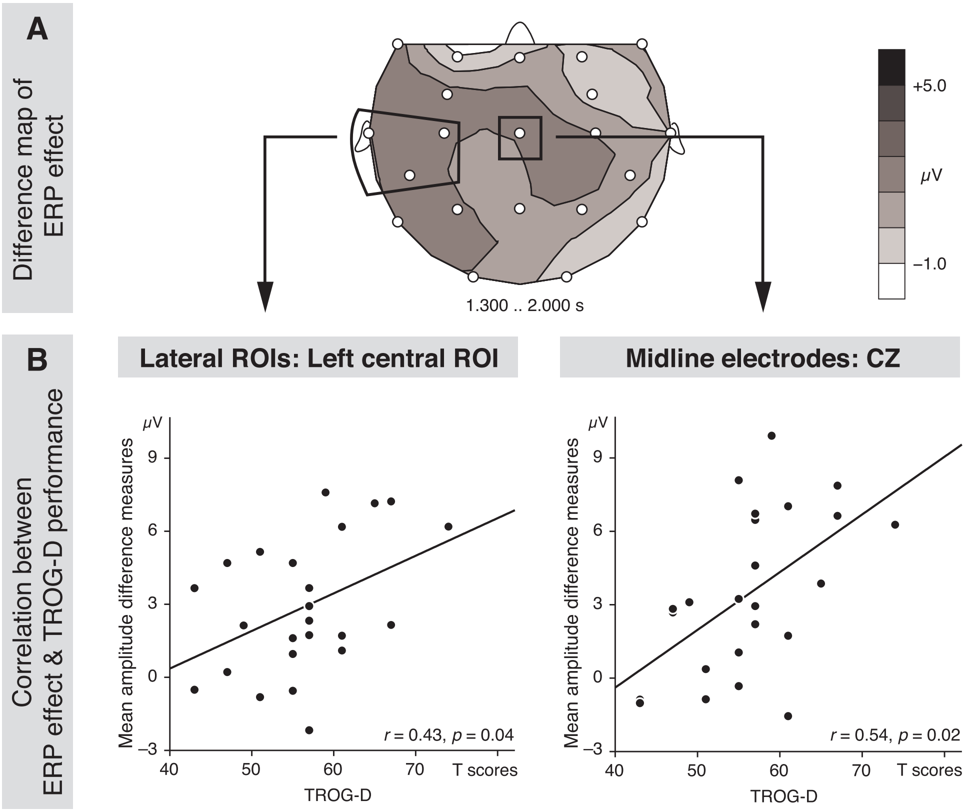

Fig. 3. Correlation results of 6-year-olds. (A) Difference map of the ERP effect (with IPB–without IPB) in the TW 1300–2000 ms relative to sentence onset. (B) Regression function between the ERP effect in the TW 1300–2000 ms at the left-central ROI (left) and CZ (right) and TROG-D performance (*T* scores) indicating syntax comprehension (False Discovery Rate for multiple comparisons correction; Benjamini and Hochberg, 1995).

allocate their attention to acoustically salient speech cues that signal the location of phrases (see Männel and Friederici, 2009). Continued language experience enables infants to learn about other cues associated with phrase boundaries, so that they eventually acquire the concept of a boundary as a correlation of several cues. This change occurs at an age when children also become more advanced in their syntactic processing abilities and may have gained a concept of speech structure based on syntactic knowledge that is triggered by the closely linked prosodic cues in the determined speech input. As a result, syntactic knowledge reinforces structure perception and children are no longer entirely dependent on prosodic markers in boundary perception (see Männel and Friederici, 2011). At this developmental stage, children are, similar to adults, more flexible with respect to acoustic variations in the speech input, including speaker-dependent variants of prosodic phrasing (see Cole et al., 2010; Schafer et al., 2000) and speech units with less reliable acoustic marking (see Cutler and Butterfield, 1990).

In order to further evaluate the proposed prosody–syntax interplay in children's boundary perception, we correlated electrophysiological measures of IPB perception with behavioral measures of syntax comprehension. The observed significant correlation indicates that children with better knowledge of the structural rules of their native language are less reliant on the prominent boundary pause in prosodic phrase perception. In line with the proposed prosody–syntax interplay, the correlation, in turn, implies that children who are advanced in their interpretation of fragmentary prosodic input have also higher syntactic abilities. We interpret our findings as further evidence for the CPS as an indicator of structure perception, based on the closely linked processing of prosodic and syntactic phrasing. Future research needs to determine the specificity of this relation with respect to syntactic or, more generally, overall language processing skills.

The developmental progression of the interplay between prosodic processing and syntactic knowledge has to be considered in the context of language development, but also in the context of children's general cognitive development. Although, different cognitive functions are known to have separable neurodevelopmental trajectories and, thus, mature at different rates (Munakata et al., 2012), there is converging evidence for a general cognitive processing shift at around age four (Carlson, 2005; Ramscar and Gitcho, 2007), co-occurring with prefrontal cortex maturation (Bunge and Wright, 2007; Gogtay et al., 2004). Children at the age of four are able to recognize relational similarities between representations, instead of applying feature-based matching (Loewenstein and

Gentner, 2005) and master cognitive tasks by switching between several non-competing rules, instead of following only one rule (Zelazo et al., 2003). Furthermore, children show a steady increase in working memory performance with age (Davidson et al., 2006), but this ability is more predictive of problem solving in children above, rather than below, age four (Senn et al., 2004). Importantly, working memory has also been found to be a predictor of sentence comprehension in preschool children (Magimairaj and Montgomery, 2012). One might speculate that for sentences with different prosodic and syntactic phrase structures, successful maintenance and monitoring of the speech input across different phrase lengths become relevant. Also, perception of boundaries with insufficient acoustic marking might be aided by cognitive aspects, relying on abstract conceptual rather than features-based processes.

With respect to continued development of language comprehension during pre-school age, ERP studies have reported changes in syntactic processing between the ages of 3 and 6 years, in particular, for non-canonical sentences (Schipke et al., 2012). Specifically, at 3 years of age, children still show immature ERP patterns in response to object- versus subject-first sentences, while in 6-year-olds responses are adult-like. In order to correctly process object-first sentence constructions, the parsing system has to override initial parsing preferences. Prosody has been shown to support children's comprehension of such non-canonical sentences (e.g., Grünloh et al., 2011). Concerning continued prosody acquisition, behavioral studies with English-speaking children have revealed that between 5 and 10 years of age, children significantly improve their ability for prosodic phrase identification (Wells et al., 2004). Thus, the described advancements in children's higher-level processing of prosodic and syntactic structure goes hand in hand with the advancement of IPB processing without full prosodic marking between 3 and 6 years of age.

6. Conclusions

In conclusion, the current ERP data indicate a developmental change in higher-level boundary perception with respect to the importance of particular boundary cues or, more generally, the strength of prosodic boundary marking: Initially, when the concept of a phrase boundary has just been established, all available prosodic cues are necessary to trigger boundary perception. Later in language development, when phrase structure knowledge has been consolidated, less prosodic information, lacking the pause as a boundary marker, is sufficient.

Conflict of Interest

The authors declare no conflict of interest.

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