Sentence processing in 30-month-old children: an event-related potential study

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In a previous event-related brain potential study, we provided evidence that preschoolers display different brain electrical patterns to semantic content and syntactic structure processing. In the present study, we aimed to determine the time-course of these event-related potential effects in 30-month-old children, using the same syntactically anomalous, semantically anomalous and control sentences that we used in our previous study. The results show that semantic violations elicit a frontal negativity peaking around 600 ms, whereas the morphosyntactic violations elicit a slow positive shift peaking around 800 ms with a frontocentral distribution. Our findings replicate the event-related potential patterns previously observed in young children and indicate that the neural signatures of sentence processing can be observed at an early point in development. *NeuroReport* 16:645–648 © 2005 Lippincott Williams & Wilkins.

Key words: Child development; Developmental psychophysiology; Event-related potentials; Psychophysiology of language

INTRODUCTION

Behavioral studies on language development demonstrate that children at 18 months of age experience a 'vocabulary burst'; that is, they learn new words very rapidly and start combining words. From 24 to 30 months, they show a 'grammar burst' in which they begin to use functional words, and multiword utterances appear at 28–30 months [1,2]. However, to date very little is known about how a young child's brain processes semantic and grammatical information in sentences. In a recent developmental language event-related potential (ERP) study, Hahne and colleagues [3] showed that children between 6 and 13 years of age listening to syntactically incorrect passive sentences displayed a late positivity similar to the P600 recorded in adult ERP studies. The effect was smaller than those in adults, with latency decreasing with age. Six-year-olds, in contrast to the older age groups, did not show an early left anterior negativity (ELAN) effect. According to Hahne and colleagues [3], ELAN seems to reflect highly automatic structure-building processes. These processes appear not to be established at age 7, but gradually develop toward adult-like processing during late childhood [4].

Our studies show that preschool children (36 and 48-month-olds) also display a late positive wave in response to morphosyntactic violations in sentences, with largest amplitudes over anterior regions of the scalp for 48-month-olds between 500 and 1500 ms [5]. Thirty-six-month-old children show this ERP effect in response to syntactic phrase structure violations in real and jabberwocky sentences (unpublished work). Jabberwocky sentences are sentences in which content (open-class) words are replaced by pseudowords while function (closed-class) words are retained. The study showed that syntactically anomalous jabberwocky sentences elicited a broadly distributed positive ERP effect, whereas syntactically anomalous real sentences elicited a frontocentral-distributed positive effect.

In a major cross-sectional study, Holcomb *et al.* [6] recorded ERPs from participants aged 5–26 years while they were listening to or reading sentences that were well-formed or ended in a semantically unexpected word. Their results showed that the latency and amplitude of the N400 decreased with age. Similar evidence has been provided by Hahne *et al.* [3] in a developmental study with children from 7 to 13 years of age.

In the preschool years, it has been shown that certain ERP (N200 and N350) components are related to semantic aspects of language processing such as word comprehension [7]; however, in these studies, word comprehension is not studied within a semantic context. When processing semantic information in sentences, 48 and 36-month-old children displayed a larger negativity for semantically anomalous sentences than for nonanomalous sentences but they displayed the largest negative effect over anterior regions [5], in contrast to Hahne *et al.*'s [3] youngest population, whose largest negative effect was displayed over posterior regions. This effect in children was most prominent between 600 and 800 ms. In a recent study, Friedrich and Friderici [8] investigated the ERP responses of 19-month-olds on slowly spoken words that do or do not refer to ongoing pictured objects. Children displayed a negative component over frontal areas, which was more prominent when there was a word-picture mismatch at almost the same time as those recorded in adults.

In the present study, we addressed the question of whether even younger children display the same type of ERP patterns we observed in 36 and 48-month-old children. The specific goal of the study was to investigate the distinctiveness and the relative time course of the ERPs elicited by syntactically and semantically anomalous sentences in 30-month-old children.

MATERIALS AND METHODS

Study participants: Children were recruited from the Infant Studies Subject Pool at the University of Washington and had no known hearing deficits. Nineteen 30-month-old children (10 girls; mean age=30.03; range=29.65–30.66) participated in this study. All children included in the analysis had no family history of left-handedness and were exposed to only the English language. Children were healthy at the time of testing. Parents initially signed University of Washington ethics committee approved consent forms and were informed of the procedures. All children had heard at least 95% of the words from the experimental sentences to be considered in the analysis. The mothers received $25 for their participation and the children received a small toy.

Stimuli: Words were taken from the MacArthur Communicative Development Inventories lexical database [9] for 36-month-old children. Thirty-four verbs were used to build 53 correct control sentences (e.g. *My uncle will watch the movie.*). On the basis of these sentences, 53 syntactically anomalous sentences were created by adding the inflexion *ing* to the verb (verb tense violations) (e.g. *My uncle will watching the movie.*). Fifty-three semantically anomalous sentences were created by changing the last word and creating incongruence with the meaning of the verb (e.g. *My uncle will blow the movie.*). Fifty additional sentences were included as filler sentences. In order to keep the proportions of anomalous sentences constant across the experiment, filler sentences with and without syntactic and semantic violations were inserted. Filler sentences were longer (1802.82 ms) and with a higher variance (452.27 ms) than our experimental and control sentences. The time from the onset of the sentence to the onset of the word after the critical word for the syntactically anomalous sentences (mean=1121.94, SD=114.42) was similar with respect to the control sentences at the same point of the sentence (mean=1269.84, SD=126.72). Mean time duration for the whole semantically anomalous sentences was 1798.36 ms (SD=177.05 ms), for the syntactically anomalous sentences, 1620.94 ms, (SD=145.21 ms) and the nonanomalous sentences, 1820.26 ms (SD=167.69 ms).

All sentences were spoken by a female native English speaker. The sentences were recorded on a digital audio system, sampled at 44 kHz with a 16-bit resolution in stereo. The speaker rehearsed all the sentences prior to recording to ensure that they were produced fluently. Each spoken sentence was presented from loudspeakers placed in front the child. The average sound pressure level ranged from 63 to 67 dB SPL. In order to ensure that the time locking of the ERP to each individual sentence was precise, the onset of each word was marked by careful inspection of the auditory and visual signal.

Procedure: Each child was fitted with a 20-channel electrode cap and seated in a comfortable chair close to his/her parent and approximately 1 m in front of a puppet theater. Participants listened passively to the stimuli while watching a puppet show. The puppet show served to decrease eye movement artifacts. Each spoken sentence was presented via loudspeakers that were placed on the puppet theater. The entire session, including fitting the cap, lasted from 45 min to 1 h. Sentences were presented in a randomized order. Each participant received the following number of sentences per condition: 73 in the correct condition, 73 in the semantic violation condition and 73 in the syntactic violation condition. The interstimulus interval was 1500 ms.

Event-related potential recording: The electroencephalogram (EEG) was recorded from 20 tin electrodes secured in an elastic cap (Electrocap International) at the following locations (according to the International 10–20 System): Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, T6, Fz, Cz and Pz. The vertical electrooculogram (VEOG) was recorded from an electrode placed below the left eye. The recordings were referenced against the left mastoid. The activity over the right mastoid was also recorded and did not reveal any condition-specific variations. Electrode impedances were kept below 15 kΩ. The EEG signal was amplified by an Isolated Bioelectric Amplifier System Model SC-32/72BA (SA Instrumentation, San Diego California, USA) with a bandpass of 0.1–100 Hz and was continuously sampled at 250 Hz by an analog-to-digital converter.

Data analysis: ERPs were computed offline from 2048 ms epochs for each participant in each experimental condition. Epochs were composed of the 100 ms preceding and 1948 ms following the presentation of individual critical words within the sentences. Automatic rejection of segments was carried out (electrical activity $\pm 150\,\mu V$ and amplifier blocking for 200 ms at any electrode site were considered artifact and the whole segment was rejected). EEG segments from each participant were also visually inspected and those segments in which eye artifact was detected in the EOG were rejected. Electrical activity from F7 minus F8 (used as the EOG criterion) that exceeded $+50\,\mu V$ was considered artifact. Participants with fewer than 18 artifact-free trials for each condition were excluded from the average. Further bandpass filtering was set from 0.5 to 30 Hz. Baseline correction was performed in relation to the 100-ms prestimulus time mentioned above.

Statistical analyses were performed on mean amplitude values from three windows for the comparisons between well formed and syntactically anomalous sentences: 300–600, 600–1000 and 1000–1400 ms. Three different windows were used for the comparisons between well formed and semantically anomalous sentences: 300–500, 500–800 and 800–1200 ms. Time windows for syntactically and semantically anomalous sentences were determined according to previous adult studies [10,11] and from the inspection of grand average waveforms and individual average waveforms.

Repeated measures ANOVAs were performed separately for each group, each time window and each type of sentence comparison. Data acquired at midline and lateral sites were also treated separately to assess the scalp distribution of ERP effects and the significance of differences between left and right hemisphere scalp locations. Two-way repeated measures ANOVAs, with sentence type (nonanomalous and anomalous sentences) and anterior–posterior localization (Fz, Cz and Pz) as factors, were performed. Three-way repeated measures ANOVAs (sentence type × left–right hemisphere × electrode location: Fp1–Fp2, F3–F4, C3–C4, P3–P4, O1–O2, F7–F8, T3–T4, T5–T6) were performed on data from lateral sites. Although multiple ANOVAs were performed in the present study, no corrections were made for multiple analyses. The Newman–Keuls tests for post-hoc pairwise comparisons ($p<0.05$) in the repeated measures analysis were used. The Huynt–Feldt correction was applied to all analyses with more than one degree of freedom in the numerator. The size of each effect (η_p^2) is also provided.

RESULTS

Grand average ERP waves elicited by critical words in the nonanomalous, syntactically anomalous and semantically anomalous sentences are shown in Fig. 1.

Morphosyntactic violations elicited a positive shift starting at 600 ms, peaking at 800 ms and ending at around 1000 ms. Differences between syntactically anomalous and nonanomalous sentences within the 600–1000 ms time window approached significance [$F(1,18)=4$, $p=0.06$, $\eta_p^2=0.18$] at lateral sites. This effect was largest at the midline [$F(1,18)=5.6$, $p=0.03$, $\eta_p^2=0.24$].

The results showed that semantic violations elicit an early frontal negativity peaking around 500 ms and ending at 800 ms. Statistical analysis showed that this negative wave was significantly larger in response to the semantically anomalous sentences in the 300–500 ms window [$F(1,18)=6.9$, $p=0.017$, $\eta_p^2=0.28$] and largest over anterior electrode locations [sentence × electrode site $F(3.14,56.5)=3.42$, $p=0.022$, $\eta_p^2=0.28$; Fp1, Fp2, F3, F4, F7 and F8].

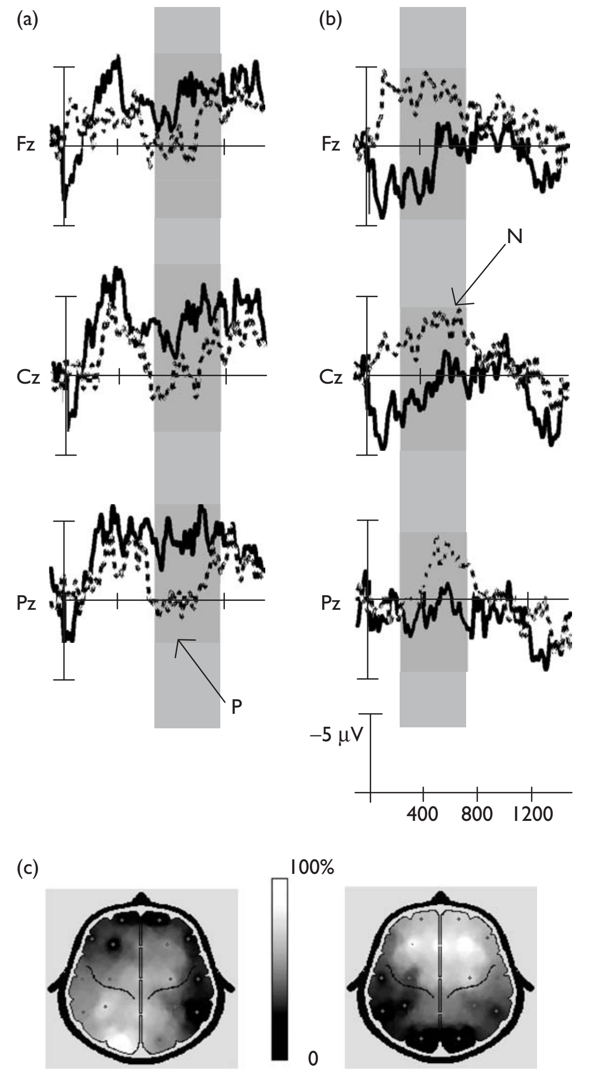

Fig. 1. This figure shows grand average event-related potentials (ERPs) to: (**a**) semantically anomalous (dotted line) and nonanomalous sentences (bold line) at the last word onset; a negative wave response can be observed; (**b**) syntactically anomalous (dotted line) and nonanomalous sentences (bold line) at the verb onset; (**c**) amplitude topographic maps from the difference wave between ERP responses to nonanomalous and anomalous sentences in two time windows (300–600 and 600–1000). Bright areas indicate the maximum positive peak percentage during that time window, dark regions display a lower percentage of the peak amplitude.

DISCUSSION

The present study examined ERP responses to syntactically and semantically anomalous spoken sentences in 30-month-old children. Syntactically anomalous sentences elicited a late positive wave effect widely distributed over the head, starting at 600 ms, peaking at 800 ms and ending around 1000 ms, whereas the semantically anomalous sentences elicited a negative wave peaking around 500 ms during sentence processing and mainly distributed over anterior sites.

In the present study, there was no effect before the late positive effect elicited by syntactic violations, but in 36 and 48-month-old children [5], using the same stimuli, a positive wave effect was observed in the same latency range reported for the adult LAN effect [12–17]. Hahne and colleagues [3] have shown that 6-year-olds did not show an ELAN effect; however, we have observed (unpublished study) a right negative wave in 36-month-olds. The discrepancy between these findings may be owing to the fact that LAN reflects highly automatic structure-building processes that are not yet established at age 7 but gradually develop toward adult-like processing during late childhood [3], to the developing cytoarchitecture of Broca's area [18] and lastly, to dramatic changes in neural development (i.e. synaptic pruning, synaptogenesis) that take place during the preschool years [19].

Important developmental effects on both the morphology and the topographical distributions of the ERPs have been noted from childhood to adulthood. Language ERP components that are initially broadly distributed over the scalp become more focal during development [7,20]. This neural specialization can be correlated with the observed syntactic processing ERP component. Even though the previous early effects do not reflect a consistent finding across ages or types of stimuli, the late positive wave seems to be very consistent during syntactic violations processing from very early ages in human beings. The positive wave effect was found to be more broadly distributed in 36-month-old children than in 48-month-old children [5] and in the present study, 30-month-old children also displayed a broad distribution of the late positive effect. Although the ERP pattern displayed at 48 months is not the mature pattern of responding observed in adult studies, it is interesting that from 30 and 36 months of age, the syntactic processing reflected by this ERP component is associated with an increasing anterior–posterior specialization. In other words, the change we observed in this ERP component from 30 (this study) and 36 months of age to 48 months of age [5] moves in the direction that is more typical of responses at later stages in development and may reflect the fact that the specialization of brain mechanisms continues to mature until the mid-teen years [2,19]. This developmental specialization is reflected in the latency measures, which decrease with age for this positive effect [3]. Although the positive ERP effect does not decrease in latency from 30 to 48 months of age, we observed slower latencies in these toddlers and preschoolers than have been observed in 6-year-old children studied previously in the study of Hahne *et al.* [3].

Regarding semantic processing, Holcomb *et al.* [6] have shown that the latency and amplitude of the N400 decrease linearly with age, probably owing to facilitation of lexical access and semantic integration processes. Consistent with this developmental pattern, Hahne *et al.* [3] found that children displayed reduced amplitudes and shorter latencies of the N400 that increased with age. In the present study, children clearly showed a larger negativity in their ERPs, which were anterior-distributed across the scalp, replicating what 36 and 48-month-old children showed when responding to the same stimuli [5]. The peak latency was longer than that reported in studies evaluating adults, and longer latencies suggest that semantic information may be processed at a slower rate in preschoolers than in the mature brain. However, under the more detailed approach, our results show that the electrical brain responses observed in these children were similar in latency of onset to those recorded in adults [21]. Although brain developmental changes do occur during the preschool years, previous child ERP studies using language paradigms have shown no significant effects of age on certain specific brain electrical responses, such as semantic picture–word priming in 19-month-olds [8] and phonological N400 effects [22].

Thirty-month-olds (present study), and 36 and 48-month-olds [5], displayed anteriorly distributed negativities to semantically violated sentences. It is likely that the anterior-specific concept-relevant brain areas that are active during spoken sentence processing appear very early in development and are identifiable as specific brain electrical responses. Friedrich and Friderici [8] have provided evidence that 19-month-olds display an anterior negative wave to semantic incongruities in the temporal range of the adult N400. However, this anterior negativity might reflect image-specific semantic processing, given that a picture–word matching task was used. In this way, the more anterior distribution of the negative effect from these previous studies compared with those from the study of Mill *et al.* [7] might be a result of stimulus differences. Word comprehension is arguably a task of sufficient complexity to draw upon neural systems that display an early clear functional and brain specialization [7]. Sentence processing is a more complex task and may require more time to be reflected in clear brain specialization.

CONCLUSION

These results demonstrate that 30-month-old children replicate the ERP patterns observed at 36 and 48 months of age using the same stimuli, wherein semantic and syntactic processing are represented by separate ERP components, probably reflecting different neural pathways for each component of language structure. This finding indicates that the neural signatures of sentence processing can be observed at a very early point in development.

REFERENCES

1. Hirsh-Pasek K, Golinkoff RM (eds). A coalition model of language comprehension. The Origins of Grammar: Evidence From Early Language Comprehension. Cambridge, Massachusetts: The MIT Press; 1996, pp. 150–203.
2. Bates E, Thal D, Janowsky JS. Early language development and its neural correlates. In: Rapin I, Segalowitz S (eds). *Handbook of Neuropsychology. Child Neurology*, Vol. 6. Amsterdam: Elsevier; 1992, pp. 69–110.
3. Hahne A, Eckstein K, Friederici AD. Brain signatures of syntactic and semantic processes during children's language development. *J Cogn Neurosci* 2004; **6**:1302–1318.
4. Friederici A. Children's sensitivity to function words during sentence comprehension. *Linguistics* 1983; **21**:717–739.
5. Silva-PereyraJ, Rivera-GaxiolaM, Kuhl PK. An event-related brain potential study of sentence comprehension in preschoolers: semantic and morphosyntactic processing. *Cogn Brain Res* (in press).
6. Holcomb PJ, Coffey SA, Neville HJ. Visual and auditory sentence processing: developmental analysis using event-related brain potentials. *Dev Neuropsychol* 1992; **8**:203–241.
7. Mills D, Coffey-Corina SA, Neville HJ. Language comprehension and cerebral specialization from 13–20 months. *Dev Neuropsychol* 1997; **13**: 397–445.
8. Friedrich M, Friderici AD. N400-like semantic incongruity effect in 19-month-olds: processing known words in picture contexts. *J Cogn Neurosci* 2004; **16**:1465–1477.
9. Dale PS, Fenson L. Lexical development norms for young children. *Behav Res Methods Instrum* 1996; **28**:125–127.
10. Friederici AD, Steinhauer K, Frisch S. Lexical integration: sequential effects of syntactic and semantic information. *Mem Cogn* 1999; **27**:438–453.
11. Osterhout L. On the brain response to syntactic anomalies: manipulations of word position and word class reveal individual differences. *Brain Lang* 1997; **59**:494–522.
12. Friderici AD. Towards a neural basis of auditory sentence processing. *Trends Cogn Sci* 2002; **6**:78–84.
13. Friderici AD, Kotz SA. The brain basis of syntactic processes: functional imaging and lesion studies. *Neuroimage* 2003; **20(Suppl 1)**:S8–S17.
14. Hagoort P, Brown CM, Osterhout L. The neurocognition of syntactic processing. In: Brown CM, Hagoort P (eds). *The Neurocognition of Language*. Oxford: Oxford University Press; 1999, pp. 273–316.
15. Hagoort P, Wassenaar M, Brown CM. Syntax-related ERP-effects in Dutch. *Brain Res Cogn Brain Res* 2003; **16**:38–50.
16. Friederici A, Hahne A, Mecklinger A. Temporal structure of syntactic parsing: Early and late event-related brain potential effects elicited by syntactic anomalies. *J Exp Psychol Learn Mem Cogn* 1996; **22**:1219–1248.
17. Muente TF, Heinze HJ. ERP negativities during syntactic processing of written words. In: Heinze HJ, Muente TF, Mangun GR (eds). *Cognitive Electrophysiology*. Boston, Massachusetts: Birkhauser; 1994, pp. 211–238.
18. Amunts K, Schleicher A, Ditterich A, Zilles K. Broca's region: cytoarchitectonic asymmetry and developmental changes. *J Comp Neurol* 2003; **465**:72–89.
19. Huttenlocher PR. Basic neuroscience research has important implications for child development. *Nat Neurosci* 2003; **6**:541.
20. Neville HJ. Developmental specificity in neurocognitive development in humans. In: Gazzaniga MS (ed.). *The Cognitive Neurosciences*. Cambridge, Massachusetts: MIT Press; 1995, pp. 219–231.
21. Kutas M, Federmeier K. Electrophysiology reveals semantic memory use in language comprehension. *Trends Cogn Sci* 2000; **4**:463–470.
22. Grossi G, Coch D, Coffey-Corina S, Holcomb PJ, Neville HJ. Phonological processing in visual rhyming: a developmental ERP study. *J Cogn Neurosci* 2001; **13**:610–625.

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