



Electrophysiological measures of attention during speech perception predict metalinguistic skills in children



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ABSTRACT

Event-related potential (ERP) evidence demonstrates that preschool-aged children selectively attend to informative moments such as word onsets during speech perception. Although this observation indicates a role for attention in language processing, it is unclear whether this type of attention is part of basic speech perception mechanisms, higher-level language skills, or general cognitive abilities. The current study examined these possibilities by measuring ERPs from 5-year-old children listening to a narrative containing attention probes presented before, during, and after word onsets as well as at random control times. Children also completed behavioral tests assessing verbal and nonverbal skills. Probes presented after word onsets elicited a more negative ERP response beginning around 100 ms after probe onset than control probes, indicating increased attention to word-initial segments. Crucially, the magnitude of this difference was correlated with performance on verbal tasks, but showed no relationship to nonverbal measures. More specifically, ERP attention effects were most strongly correlated with performance on a complex metalinguistic task involving grammaticality judgments. These results demonstrate that effective allocation of attention during speech perception supports higher-level, controlled language processing in children by allowing them to focus on relevant information at individual word and complex sentence levels.

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1. Introduction

Selective attention and language processing are two skills that are critical for a child's academic success. These skills interact, as seen in a noisy classroom when children must attend to the teacher's instructions while ignoring irrelevant distracting information. This juvenile version of the "cocktail party effect" (Cherry, 1953) demonstrates the need to use selective attention in order to process language

efficiently. However, the mechanism by which language development interacts with various forms of attention remains largely unexplored.

The role of attention in language processing changes throughout development, partly in response to the different challenges presented in various stages of language proficiency. In the first year of life, infants establish language-specific phonemic categories. Jusczyk's (1997) model of the development of speech perception proposes that infants and toddlers automatically learn to attend to relevant information in the speech signal, allowing for rapid identification of speech categories, and subsequent speech segmentation and word learning. In the second year, infants' vocabulary begins to expand dramatically, and this rapid word learning depends heavily on attention shared between infants and caregivers. There is ample evidence that the amount of time dyads spend in joint

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attentional episodes is positively correlated with vocabulary size in children between the ages of 12 and 18 months (Mundy et al., 2003; Tomasello and Farrar, 1986; Tomasello and Todd, 1983). During these episodes, mothers and children engage in conversations in which mothers' speech is tuned to children's level of comprehension, allowing children to attend to the relevant word forms. For example, in a study by Tomasello and Farrar (1986) maternal references to objects within the child's focus of attention were positively correlated with vocabulary at 21 months. The same study included a more direct experimental manipulation in which an adult taught novel words to 17-month-old children. Words referring to objects within the child's focus of attention were better remembered than words spoken in an attempt to redirect attention. Taken together, these results indicate that joint attention episodes promote novel word learning during early language development.

As basic vocabulary becomes the scaffolding for more complex language skills, attentional control continues to support verbal development in a variety of areas. Continuous performance tasks (CPT) that measure sustained attention by requiring children to respond to target stimuli amongst a continuous stream of distracters have been related to language abilities. For example, in a large sample of children with a wide range of behavioral and language skills, errors of omission in the auditory CPT were negatively correlated with receptive and expressive performance on the Clinical Evaluation of Language Fundamental (CELF-III) (Gomes et al., 2007). Thus, the ability to maintain focused attention in the face of distracting information is related to both receptive and expressive language skills.

Attention also contributes to children's metalinguistic awareness, or their ability to consciously analyze and reflect on the nature of language (Scribner and Cole, 1981). Bialystok and Ryan (1985) described two components of metalinguistic awareness: the analysis of linguistic knowledge and attentional control that allows for processing of specific linguistic information. For example, in a grammaticality judgment task in which children are instructed to determine only if the sentence is grammatical or not and ignore its meaning, analysis skills allow children to recognize a grammatical violation (e.g., *Apples grew on trees*), while attentional control is necessary to ignore semantically anomalous information in a sentence and focus on its correct grammatical structure (e.g., *Apples grow on noses*). Children between the ages of 5- and 9-years old find it difficult to make grammaticality judgments for the semantically anomalous sentences and respond that the sentences are grammatically incorrect, even though the grammar is intact. The difficulty in ignoring irrelevant anomalous meaning reflects the extended developmental trajectory of attentional control mechanisms (Craik and Bialystok, 2006). This protracted development of attentional control is likely due to the fact that frontal control regions are among the last cortical areas to develop in children (Giedd et al., 1999). Importantly, bilingual children, whose management of competing language systems confers attentional control benefits outside the domain of language (Bialystok, 2001) perform better in the semantically anomalous condition than their monolingual peers (Bialystok, 1986), reflecting superior attentional control

within the domain of language as well. These results indicate that linguistic experience can significantly shape the interaction of attention and language in the developing brain.

As children enter noisy classrooms and other distracting environments, spatially selective auditory attention becomes critical for language processing and academic success. The neural basis of spatial attention has been characterized extensively using the event-related potential (ERP) technique. In classic studies of auditory attention employing a dichotic listening paradigm, participants are instructed to attend to a narrative at one location and ignore another narrative at a different location. Task-irrelevant tone pips presented at each location serve as attention probes. Among adults, probes presented to the same ear as the attended narrative elicit a larger negativity than probes presented in the unattended ear beginning around 100 ms after probe onset (N1) (Hink and Hillyard, 1976). In addition to a larger N1, attended stimuli elicit a sustained negativity, termed the processing negativity or negative difference (Nd), that may reflect further selection of attended sounds (Hansen and Hillyard, 1980; Näätänen and Michie, 1979; Näätänen, 1982; Woldorff et al., 1987). Although the control of selective attention continues to develop throughout adolescence (Berman and Friedman, 1995; Kannass et al., 2006), children as young as three years of age can selectively attend to speech at a particular location during a dichotic listening paradigm when provided with sufficient attentional cues. In ERP studies of auditory processing in children, the morphology of auditory evoked potentials does not fully develop into the typical adult P1-N1-P2 response until early adulthood; instead children show a broad positivity in response to abrupt acoustic onsets (Ponton et al., 2002). Among children between the ages of 3- and 8-years old, probes presented at the same location as the attended story elicit a larger positivity beginning around 100 ms after onset compared to probes from the same location as the unattended story (Coch et al., 2005; Sanders et al., 2006). This larger positivity is more prolonged in 3–5-year-old children, while 6–8-year-old children show a more focal positivity followed by a later negativity in response to attended probes. Although the polarity of this early positive attention effect is different from the negative attention effects observed in adults, the latency and scalp distribution are remarkably similar. These similarities indicate that spatially selective attention modulates speech processing at an early perceptual stage in both children and adults.

Like many other measures of attention, ERP indices of spatially selective attention during dichotic listening tasks are related to language skills in preschool children and index normal language development. For example, unlike typically developing children, those with specific language impairment (SLI) fail to show an increased positivity in response to probes in attended stories (Stevens et al., 2006). Similarly, when typically developing children are instructed to attend to a video and ignore concurrently presented speech, global field potential analysis indicates that they continue to attend to task-irrelevant speech, suggesting that they automatically process language, whereas children with SLI do not (Shafer et al., 2007). Taken

together, these data indicate that children with SLI do not effectively allocate attention to speech. Importantly, computerized training interventions designed to improve rapid auditory processing and therefore language skills also improve ERP indices of selective attention in children with SLI (Stevens et al., 2008), demonstrating the potential plasticity of the attentional system in these children.

More recent evidence suggests that another form of selective attention may also play a critical role in speech perception. Temporally selective attention directs processing resources to specific moments in time, improving perception of stimuli presented at those moments (Correa et al., 2006; Nobre et al., 2007). Because sounds unfold over time, temporally selective attention is reasoned to be particularly important in the auditory domain. Like spatially selective attention, temporal attention modulates early perceptual processing, as indexed by a larger N1 response for sounds presented at attended times in adult participants (Lange et al., 2003; Sanders and Astheimer, 2008).

During speech perception, listeners use temporal attention to select for critical moments in the speech stream such as word onsets. Behavioral evidence demonstrates that word onsets are particularly important for spoken word recognition (Connine et al., 1993; Marslen-Wilson and Zwitserlood, 1989); because of their relatively low transitional probabilities, they are highly informative (Aslin et al., 1999). ERP evidence shows that among adult listeners, auditory attention probes presented within the first 100 ms of word onset in a continuous narrative elicit a larger N1 response than probes presented before word onsets or at random control times (Astheimer and Sanders, 2009). This negativity extends into later processing windows such as the P2, thus resembling the adult Nd typical of spatially selective auditory attention (Hansen and Hillyard, 1980). In 3–5-year-old children, probes presented within the first 100 ms of a word also elicit a negative early ERP response (Astheimer and Sanders, 2012). While the polarity of this effect differs from the larger positivity seen during dichotic listening spatially selective attention tasks in young children (Coch et al., 2005; Sanders et al., 2006), the latency and scalp distribution are quite similar. This pattern indicates that preschool children use temporal attention to select for critical moments in the speech stream.

Although many attentional processes may support speech perception, temporal attention to a single speech stream allows listeners to focus on relevant information in a wide variety of language tasks, and may therefore provide a direct link between attention and language. However, it is unclear whether this particular form of attention is related to any higher-level language skills or other cognitive skills. In other words, is there a relation between control over attention to continuous speech and the emergence of complex linguistic ability or nonverbal attentional control in children? One possibility is that attending to word onsets is a necessary consequence of listening to the metrical rhythm of stress-timed English speech (Cutler and Norris, 1988), in which case it would not be related to language or cognitive abilities. Alternatively, temporal attention in speech may reflect domain-general attentional skills, and therefore would be related to general nonverbal cognitive capabilities. Finally, if temporal attention

during speech perception specifically supports language processing, then the ability to select for critical moments in speech may be related to higher-level language skills, in particular, metalinguistic skills that are based on effortful attentional strategies. To discriminate among these possibilities, we measured attentional allocation during speech perception using the ERP attention probe described previously (Astheimer and Sanders, 2012) in a large sample of 5-year-old children. In addition, we measured children's receptive vocabulary, nonverbal intelligence, verbal and nonverbal working memory, and metalinguistic skill. Based on a growing body of evidence that selective attention skills support language development (for a review see Stevens and Bavelier, 2012), we hypothesized that temporally selective attention skills would be specifically related language processing. This hypothesized relationship could work in at least two potential directions. First, attention to critical moments in speech may serve as the foundation for higher-level language skills. Second, because selecting for word onsets requires listeners to use language-specific knowledge to predict when informative moments will occur, stronger linguistic skills may enhance attention to critical moments in speech. Either way, we predicted that the magnitude of the ERP attention effect observed would correlate with higher-level verbal skills.

2. Methods

2.1. Participants

Fifty seven children (26 females) between the ages of 4- and 6-years old ($M=5$ years 6 months, $SD=6$ months) provided behavioral and EEG data for the final analysis. All children were monolingual English speakers recruited from a large urban area, and had no history of auditory, language, or other neurological disorders. Their mean socioeconomic status, assessed on a five point scale of maternal education (1 = no high school diploma, 5 = graduate or professional degree) was 3.43 ($SD=1.0$), corresponding to some college education. An additional fifteen children participated in the study but were excluded from the final analysis because they later reported being bilingual ($n=5$), did not complete the EEG recording ($n=2$), or did not provide a sufficient number of artifact-free EEG trials ($n=8$). A parent or guardian of each child provided written informed consent, and all children were compensated for their participation with a small toy, as well as snacks throughout the testing session.

2.2. Behavioral tasks

All tasks were administered individually in quiet testing rooms. The order in which they were administered was counterbalanced across participants.

2.2.1. PPVT

The Peabody Picture Vocabulary Test (PPVT-III; (Dunn and Dunn, 1997) was administered as a test of receptive vocabulary. In the test, the child chooses which of four visually presented pictures best represents a word spoken by the experimenter. The items are graduated for difficulty;

children begin at an age-determined baseline and continue until they make at least six errors in eight consecutive responses.

2.2.2. Ravens

Raven's Standard Progressive Matrices (Raven et al., 1996) were administered as a test of nonverbal intelligence. The test consists of a series of diagrams with a part missing. For each diagram, the child is asked to select the correct part to complete the diagram from eight choices.

2.2.3. Word span

This was a test of verbal short-term and working memory. The experimenter read a list of words at a rate of one per second, and the child was asked to repeat them back in the same order (forward span) or in reverse order (backward span). The test started with two words, with one word added after every second trial, and stopped when the child was unable to reproduce both trials at a particular level. Word span was defined as the longest list length at which the child could reproduce at least one of the trials correctly. Word span score was defined as the number of correctly recalled items on all trials within the span plus one trial beyond.

2.2.4. Corsi block span

This was a test of spatial short-term and working memory. The experimenter tapped a series of blocks arranged on a wooden board at a rate of one per second, and the child was asked to touch the blocks in the same order (forward span) or in reverse order (backward span). The test started with two blocks, with one block added after every second trial, and stopped when the child was unable to reproduce both trials at a particular level. Block span was defined as the longest sequence at which the child could reproduce at least one of the trials correctly. Block span score was defined as the number of correctly recalled items on all trials within the span plus one subsequent trial.

2.2.5. Grammaticality judgment task

Children were asked to judge the syntactic acceptability of sentences irrespective of semantics, as described previously (Bialystok, 1986). Four types of sentences were presented: grammatically correct and semantically plausible (correct: *Apples grow on trees*), grammatically correct and semantically anomalous (anomalous: *Apples grow on noses*), grammatically incorrect and semantically plausible (ungrammatical: *Apples growed on trees*), and grammatically incorrect and semantically anomalous (incorrect: *Apples growed on noses*). Thus, the appropriate response was "right" for the correct and anomalous sentences, and "wrong" for the ungrammatical and incorrect conditions. Sentences were generated from 24 frames, with each frame capable of filling all the conditions. Each child heard 24 sentences, with 6 of each type arranged in random order. Four test sets were administered so that each child heard every sentence frame only once, but all frames and conditions were balanced across the design.

A puppet character with a bandage on his head was introduced. He explained that he bumped his head and although he is feeling better, he sometimes says things

that are silly, and sometimes says things the wrong way. It is okay to say silly things, but he does not want to say things the wrong way, so the child is asked to help him by telling him when he says something the wrong way. Several examples are then given, such as "*I dranked water from the fountain*" (ungrammatical), and "*Why is the cat barking so loudly?*" (anomalous). During practice, children heard examples from each sentence type; on first presentation of each sentence type, the experimenter provided the correct answer, and on the second the child was asked to respond "right" or "wrong." Verbal feedback was provided for each response, and additional examples were given as needed until the child provided at least one correct answer for each sentence type. The puppet then read the 24 test items, and the child was asked to respond "right" or "wrong" for each item.

2.3. ERP task

2.3.1. Stimuli

Children listened to Curious George stories containing attention probes, as described previously (Astheimer and Sanders, 2012). Three stories from *The Complete Adventures of Curious George* (Rey, 1995) were read by a female narrator in child-directed speech. The entire recording was divided at natural sentence boundaries into 85 10–20 s segments and saved in the left channel of stereo WAV files. Linguistic attention probes were created by extracting a 50 ms excerpt of the narrator saying "ba." One hundred and fifty attention probes were inserted to the right channel of WAV files in each of four conditions: concurrent with a word onset, 100 ms before a word onset, 100 ms after a word onset, and at random control times that were not systematically associated with a word onset, for a total of 600 attention probes. Probes were not presented within the first or last 1 s of a sound file, or within 1.5 s of another probe. Word onsets were defined as the earliest indication of a new phoneme, as determined by three independent coders through visual inspection of the waveforms and listening to sentences with a gating procedure. The specific word onsets with which probes were associated were open class words pertinent to the content of the story, and were not preceded by pauses to avoid the influence of abrupt acoustic onsets on the ERP response. In addition, the acoustic properties of the surrounding narrative were matched across all conditions, such that there were no significant differences in average intensity, peak intensity, average pitch, or pitch change in the segments of the narrative 100 ms before or after probe onset ($ps > .20$).

The narrative with attention probes was presented over two Logitech speakers placed directly in front of participants and connected to a Dell computer using E-prime software. The narrative and probes were presented with a peak intensity of 65 dB SPL (A-weighted) measured at the location of the participants. Small illustrations from the *Curious George* stories were presented with a visual angle of 3.0° at the center of a black background on a computer monitor placed above the speakers, 152 cm in front of the participant, with a new image presented at the beginning of each sound file. Breaks were provided as needed throughout the 18 min recording session.

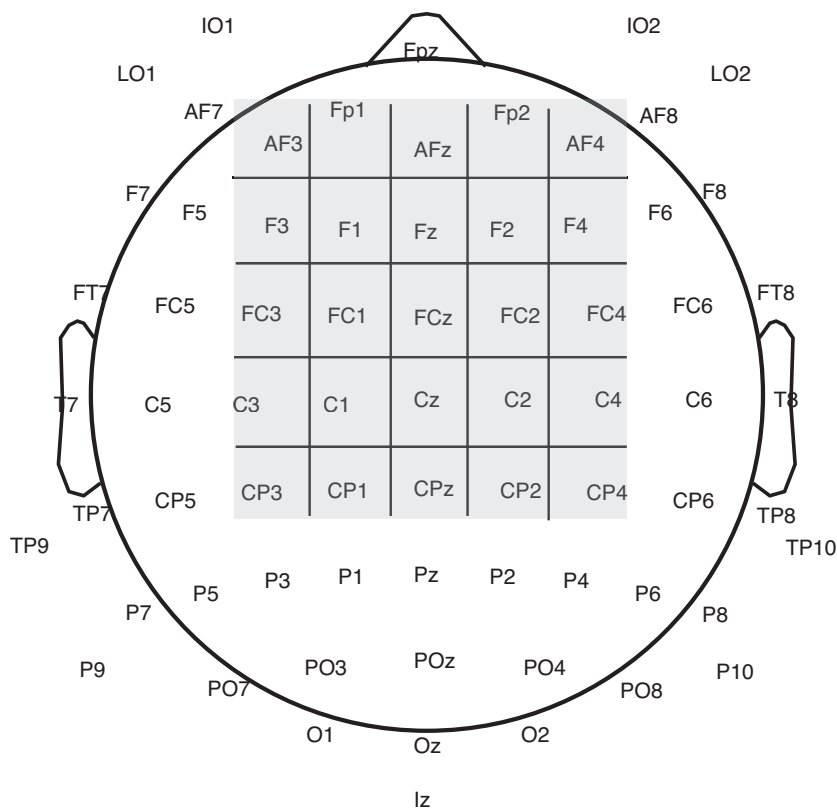


Fig. 1. Approximate scalp locations of 68 recording electrodes. Measurements were taken from 25 electrodes in the shaded gray region, arranged in a 5 (left/right position) by 5 (anterior/posterior position) grid.

Following the story, participants were asked two comprehension questions to ensure their attention throughout the task.

2.3.2. Procedure

Continuous electroencephalogram was recorded from active Ag/AgCl electrodes (Biosemi Active Two system, Amsterdam, Netherlands) located at 64 standard scalp positions (International 10/20 system) as well as the left and right mastoid. All signals were recorded with a Common Mode Sense (CMS) reference, bandpass filtered from .01–80 Hz, and digitized at 512 Hz. Electrode impedances were maintained below 20 k Ω throughout the recording session using an electrolytic gel. To detect eye movements and blinks, electro-oculogram (EOG) was recorded from four additional electrodes placed below and at the outer canthi of each eye.

All analyses were conducted using the ERPLAB Toolbox and EEGLAB toolbox on Matlab software. EEG signals were referenced to the average of the left and right mastoids and segmented into epochs 100 ms before to 500 ms after attention probe onset, baseline corrected to the 100 ms pre-stimulus interval. Eyeblinks and eye movements were modeled with Infomax independent components analysis (ICA) decomposition in EEGLAB and removed from the recording. Additionally, trials with extreme voltage values, as determined by individual maximum amplitude criteria and visual inspection, were excluded from individual

subject averages. Only data from participants with at least 50 artifact-free trials in each condition were included in the final analyses. Individual averages were filtered with a low pass of 30 Hz to improve visualization of components of interest.

2.3.3. Analysis

Mean amplitude was measured in time windows 90–170 ms and 250–400 ms after probe onset, based on visual inspection of the waveforms. Measurements were made at 25 electrode sites distributed across fronto-central electrode sites and arranged in a 5 (left–right, or LR) \times 5 (anterior–posterior, or AP) grid (see Fig. 1) and entered into a 4 (probe time) \times 5 (LR) \times 5 (AP) repeated-measures ANOVA (Greenhouse-Geisser adjusted). Planned comparisons were conducted for all significant ($p < .05$) main effects and interactions.

2.3.4. Brain–behavior correlations

The magnitude of the ERP attention effect was quantified by computing a difference wave between probes presented after word onset compared to random control probes. The mean amplitude of this difference in the 90–170 ms and 250–400 ms time windows was averaged over the central electrode sites where the response was largest. The mean difference in this ROI was then correlated with performance on each of the behavioral measures.

Table 1

Mean scores (and standard deviations) on all behavioral measures and correlations with ERP attention effects.

Behavioral measure	Mean (SD)	Brain–behavior correlations	
		Early attention effect	Late attention effect
Verbal tasks			
PPVT Standard Score	111.4 (12.2)	$r = .02, p > .9$	$r = .00, p > .9$
Word Span Score			
Forward	18.0 (5.3)	$r = .16, p > .2$	$r = .14, p > .3$
Backward	9.2 (3.8)	$r = .00, p > .9$	$r = -.26, p < .1$
Grammaticality judgment (out of 6)			
Correct	5.5 (0.8)	$r = -.11, p > .4$	$r = .09, p > .5$
Ungrammatical	2.6 (1.9)	$r = -.17, p > .2$	$r = .09, p > .5$
Anomalous	2.6 (2.3)	$r = -.43, p < .001^{**}$	$r = .01, p > .9$
Incorrect	4.3 (1.7)	$r = .31, p < .05^{*}$	$r = -.02, p > .8$
Nonverbal tasks			
Ravens Standard Score	100.9 (14.6)	$r = .14, p > .3$	$r = .23, p < .1$
Corsi Block Score			
Forward	17.6 (8.0)	$r = -.01, p > .9$	$r = -.16, p > .2$
Backward	9.3 (6.4)	$r = .16, p > .2$	$r = .13, p > .3$

* correlation significant at the .05 level

** correlation significant at the .001 level

3. Results

3.1. Behavior

Mean scores indicating performance on the behavioral tasks are shown in Table 1. All participants demonstrated age-typical receptive vocabulary (PPVT) and nonverbal intelligence (Ravens) scores. For span tasks, participants performed significantly better on the forward than backward tasks, $F(1,56) = 173.84, p < .001$, with similar performance on both word span and Corsi block spans, $p > .7$.

For the grammaticality judgment task, a one-way repeated measures ANOVA revealed a significant effect of sentence type, $F(3,168) = 35.17, p < .05$; as seen in Table 1, grammaticality judgment was easiest for correct sentences, followed by incorrect sentences while the ungrammatical and anomalous sentences were the most difficult (Bonferroni $ps < .01$), and did not differ from each other ($p > .9$). Performance on the grammaticality judgment task was correlated with language proficiency as indexed by PPVT scores. Specifically, there was a positive correlation between PPVT scores and performance on anomalous sentences, $r = .44, p < .005$, and a negative correlation with performance on incorrect sentences, $r = -.34, p < .01$. PPVT scores were marginally correlated with performance on correct sentences, $r = .23, p < .09$, and there was no correlation between PPVT scores and performance on ungrammatical sentences $r = .12, p > .35$.

The negative correlation between PPVT scores and performance on incorrect sentences may reflect a response bias in which lower proficiency participants were not focusing on grammatical information as instructed, but rather responding “wrong” to any sentence that sounded abnormal, yielding a correct response in this condition. More proficient children understood that anomalous sentences were sometimes correct and so were more deliberate in their judgments of these sentences. To test this possibility of response bias, responses were converted to sensitivity measures as described by Lum and Bavin (2007).

While Lum and Bavin reported nonparametric “A” measures, this calculation is known to sometimes confound bias and ability (Pastore et al., 2003) and so we adopted a more conventional d-prime calculation. Because the grammaticality judgment task involves both syntactic analysis and cognitive control (i.e., ignoring semantic information to focus on grammaticality), two sensitivity measures were computed. An analysis d-prime score was calculated by comparing hits (“yes” responses to correct sentences) to false alarms (“yes” responses to ungrammatical sentences). A control d-prime score was calculated by comparing hits (“yes” responses to anomalous sentences) to false alarms (“yes” responses to incorrect sentences). Overall, analysis d-prime scores ($M = 0.76, SD = 0.86$) were significantly higher than control d-prime scores ($M = 0.33, SD = 0.53$; $t(56) = 4.74, p < .001$), indicating that in general, children show better grammatical representations than attentional control at this age.

3.2. Event-related potentials

As seen in Fig. 2, attention probes in the story elicited an early positivity that peaked around 120 ms and was largest over frontal–central electrodes (LR × AP), $F(16,896) = 52.23, p < .001$. In this early time window (90–170 ms), there was a main effect of time, $F(3,168) = 9.35, p < .001$, such that probes presented 100 ms after word onset elicited a more negative response than probes presented at any other time ($ps < .05$). The largest difference was observed between probes presented after word onset and probes at random control probes ($p < .05$; see difference waves in Fig. 3).

Following the early positivity, a negativity that was more broadly distributed over central electrode sites (LR × AP), $F(16,896) = 4.069, p < .02$, peaked around 300 ms (Fig. 2). In this time window (250–400 ms), there was also a main effect of time, $F(3,168) = 9.908, p < .001$, with probes presented after word onset eliciting a larger negativity than probes before word onset and at random control times ($p < .01$). Probes presented simultaneous with word onsets

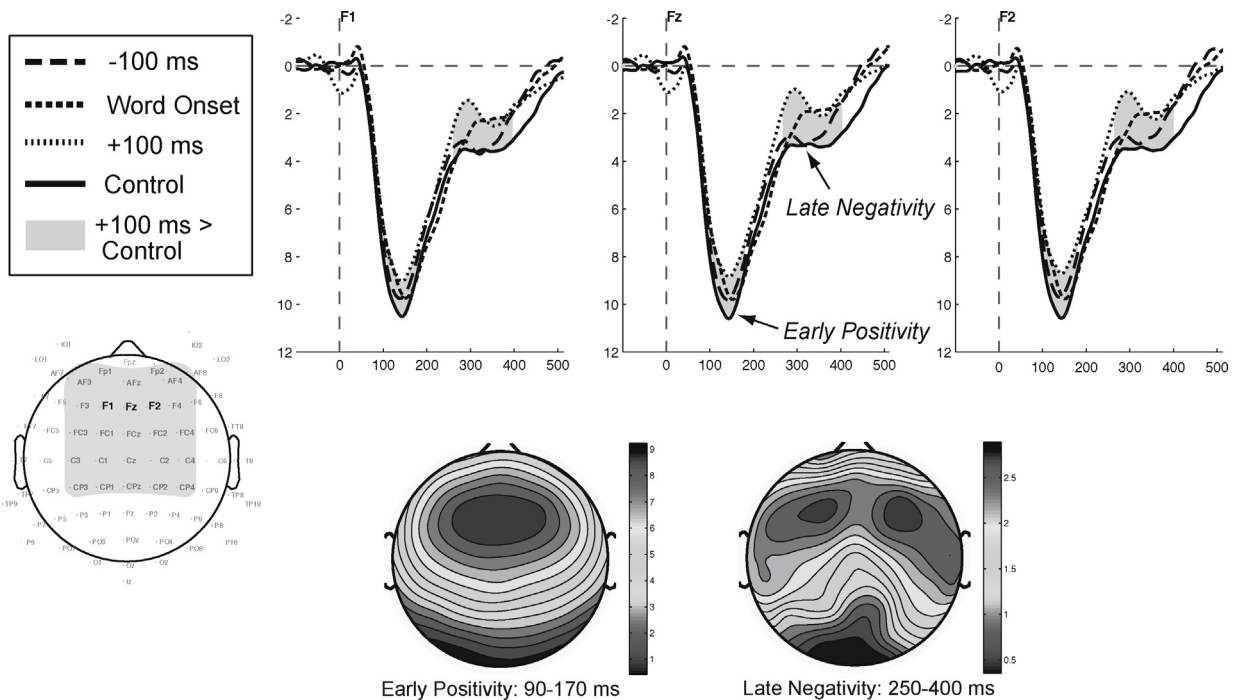


Fig. 2. Auditory evoked potentials elicited by probes presented at four times relative to word onset: 100 ms before (long dashed line), concurrent with word onset (short dashed line), 100 ms after word onset (dotted line), and random control times (solid line). Shaded regions indicate that probes after word onset were more negative than control probes. Data are shown from three representative central/anterior electrodes (F1, Fz, F2). Topographic maps show the average amplitude collapsed across conditions during the early positivity (90–170 ms) and later negativity (250–400 ms).

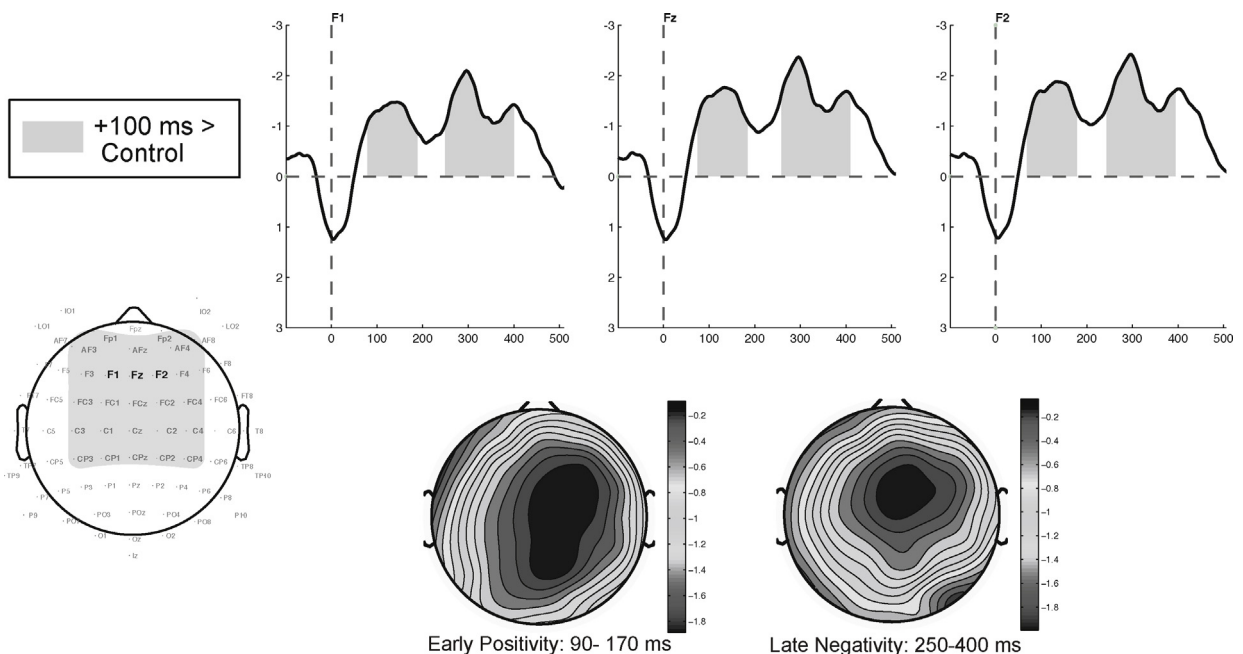


Fig. 3. Difference waves showing the response to probes presented 100 ms after word onset minus control probes. The size of this difference was used to quantify the magnitude of the observed attention effect for subsequent correlational analyses. Data are shown from three representative central/anterior electrodes (F1, Fz, F2). Shaded regions indicate the time windows in which probes after word onset were more negative than control probes. Topographic maps show the distribution of the difference during the early positivity (90–170 ms) and later negativity (250–400 ms).

also elicited a more negative response than probes presented at random control times ($p < .05$), but there was no difference between word onset probes and probes presented before or after word onset.

3.3. Brain–behavior correlations

To examine brain–behavior relationships, the magnitude of the ERP attention effect was quantified as the difference in mean amplitude between probes presented after word onset and random control probes (100 ms after – Control), both during the early positivity (90–170 ms) and the later negativity (250–400 ms). As shown in Fig. 3, a negative difference indicates a larger (more negative) attention response for probes presented after word onset, which is typical in this paradigm (Astheimer and Sanders, 2009, 2012). Because the observed attention effects were widely distributed, the mean difference was averaged over all electrodes for each participant, yielding a single attention measurement for each time window. This measurement was then correlated with performance on each behavioral task to assess the relationship between attention during speech perception and verbal and nonverbal skills. All brain–behavior correlations for the early and late time windows are reported in Table 1.

The attention effect in the early time window was not correlated with performance on the PPVT, Ravens, word span, or Corsi span ($ps > .2$). However, significant correlations did emerge between the early attention effect and performance on the anomalous sentences of the sentence judgment task, $r = -.43$, $p < .001$, such that a larger attention effect was associated with better performance on this condition. This early attention effect was not correlated with performance on the correct or ungrammatical conditions ($ps < .2$), but it was moderately correlated with performance on the incorrect condition, $r = .31$, $p < .05$, indicating that a smaller attention effect was associated with better performance on this condition. Because the incorrect condition contains both semantic and grammatical violations, it is difficult to interpret the correlation because of potential response bias to say “no” to unusual sounding sentences. Therefore, correlations were calculated separately for the relation between the attention effect in the ERP data and the analysis and control d-prime scores representing the two components of performance for the sentence judgment task. As shown in Fig. 4a,¹ there was no relationship between attention effects and analysis abilities, $r = -.16$, $p > .2$, but as shown in Fig. 4b, there was a significant correlation between larger early attention effects and higher control abilities, $r = -.30$, $p < .05$. In the later time window, the attention effect was not correlated with performance on the PPVT, Corsi span, or sentence judgment task ($ps > .1$).

¹ The lack of correlation for analysis d-prime scores and ERP attention effect (Fig. 4a) appears to be influenced by an outlier with a large negative attention effect and a negative d-prime analysis score. Therefore, we removed this participant and recalculated the correlation between attention and analysis d-prime and it still failed to reach significance ($p > .08$). Because the magnitude of the attention effect and grammaticality judgment performance scores for this participant were within normal range, we did not remove this data point from the overall analysis.

There were, however, marginally significant correlations between the magnitude of the late attention effect and Raven's score ($r = .23$, $p < .1$) and backward word span score ($r = -.26$, $p < .1$). No other correlations approached significance.²

4. Discussion

The current study examined the electrophysiological signature of attentional allocation during speech perception in preschool children with a range of language and cognitive abilities to assess whether attention during speech perception is associated with higher-level language skills. Attention probes presented 100 ms after a word onset elicited a more negative early ERP response than probes presented at any other time, indicating that overall, 5-year-old children attend to word-initial segments during speech perception. This pattern of results largely replicates previous findings of a negative attention effect for critical moments in speech (Astheimer and Sanders, 2012). This early negative difference appears within 90 ms after probe onset, at which point a broad positivity dominates the ERP waveform in young children. Despite obvious differences in underlying ERP morphology, the polarity, latency, and scalp distribution of the attention effect found in children in the current study resemble typical N1 or Nd attention effects seen in most adult spatial and temporal auditory paradigms (Alho et al., 1987; Hansen and Hillyard, 1980; Näätänen, 1982). Although previous studies have reported a more negative ERP response for probes presented both simultaneous with word onset and 100 ms after word onset in both 3–5-year-old children (Astheimer and Sanders, 2012) and adults (Astheimer and Sanders, 2009), in the current study, only probes presented 100 ms after onset elicited a more negative response. This suggests that in larger samples of 5-year-old children, attention to word-initial segments rather than the earliest indication of a word onset is the most consistent ERP attention signature. As seen in Fig. 2, there is some indication that the response to probes after word onsets diverges from the other conditions prior to probe onset, which may reflect attentional preparation prior to the presentation of critical word-initial information, but the precise timing of attentional allocation during speech perception still needs further characterization.

In examining individual subject averages, it appeared that a portion of the children tested showed a more negative response within the early time window to word onset probes compared to control probes, as reported by Astheimer and Sanders (2012), while another subset of children showed a less negative response (a larger positivity) to word onset probes compared to control probes, resulting in a null effect overall. These different patterns of results could reflect at least two possibilities: first, to

² Although there was a significant ERP difference between word onset probes and control probes in the later time window, this difference did not correlate with any of our behavioral measures. In order to define the same attentional effect in early and late time windows, we restricted our brain–behavior correlations to the ERP difference between probes presented 100 ms after word onset and control probes.

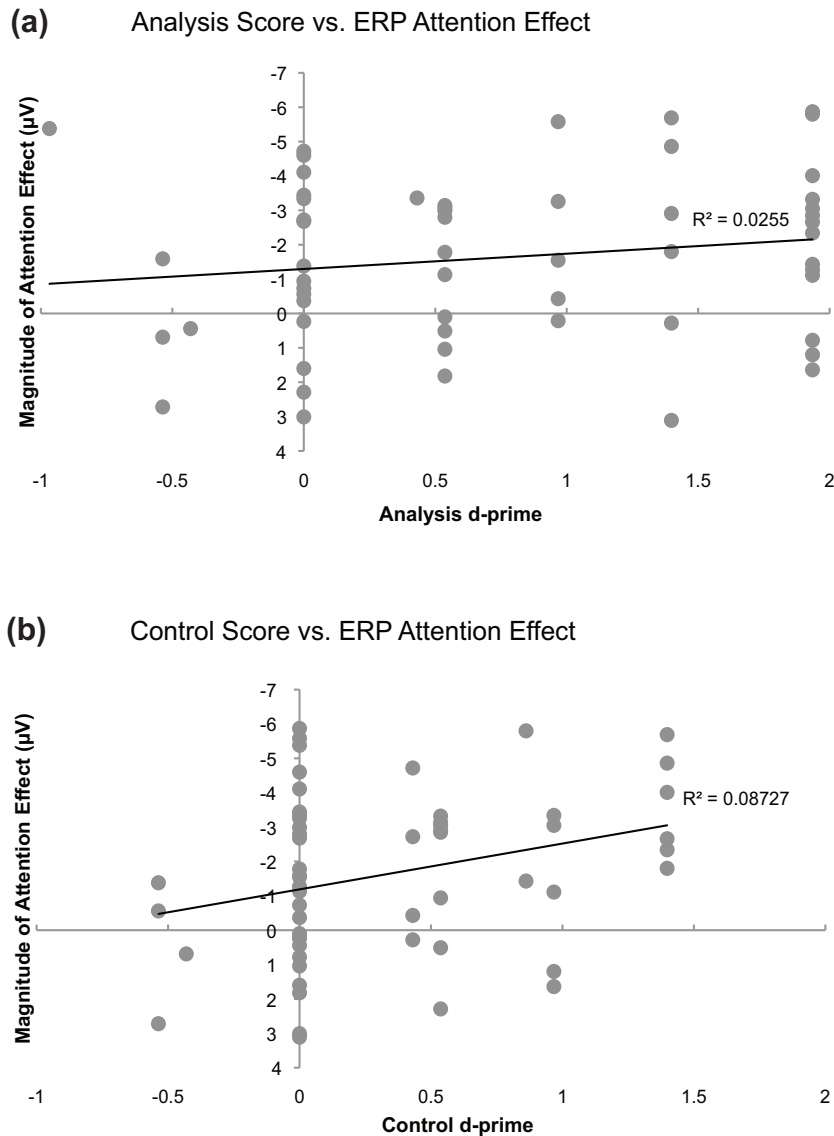


Fig. 4. Scatterplots showing the magnitude of the early ERP attention effect (mean amplitude for probes 100 ms after word onset versus control probes) in the story task versus behavioral performance on the grammaticality judgment task. (A) The magnitude of the early attention was not correlated with analysis d-prime scores, which reflect the ability to recognize simple grammatical violations. (B) A larger early attention effect was associated with higher control d-prime scores, which reflect the ability to focus on task-relevant grammatical information and ignore semantic violations.

the extent that a more negative response indexes greater attention, it is possible that for some children, attention probes at word onsets capture attention early in processing, while other children attend more to probes presented at random control times. Second, given that auditory spatially selective attention studies typically report a larger positivity in response to probes at attended locations, it is possible that for probes at word onset, some children are showing a negative attention effect and others are showing a positive attention effect. This variability may be due to the fact that critical information at word onsets maximizes the demands of developing attentional systems.

Previous research has demonstrated complex interactions between ERP polarity, acoustic density, and attention among 5-year-old children (Astheimer and Sanders, 2012;

Coch et al., 2005; Sanders et al., 2006). Around this age, the morphology of auditory evoked potentials begins to transition from the broad positivity observed in the current study and typical of younger children to a more adult-like N1 response (Ponton et al., 2002). This dynamic period in development may have contributed to individual differences in ERP morphology and attentional patterns in our large sample. Put another way, the children in our study were in different stages of the transition to the more mature pattern. Although the polarity of the attention difference was not correlated with any of our behavioral measures, further investigation could reveal physiological or cognitive explanations for these individual differences. Regardless of the polarity of the difference, most children's ERP patterns differentiate between probes presented at

various times relative to word onset, indicating that most children are modulating temporally selective attention during speech perception.

In addition to the early positivity, attention probes also elicited a later negative component that was also modulated by probe time. In this later window probes presented both *at and after* word onsets elicit a larger negativity than control probes. The amplitude and scalp distribution of this sustained negativity, seen in Fig. 3, resembles the late component of the negative difference (Nd) typical of auditory spatially selective attention studies in adults (Alho et al., 1987; Hansen and Hillyard, 1980; Näätänen, 1982). While the early Nd has been implicated in initial selection, the late Nd is thought to reflect further processing of the attended stimulus. In the current study, the early Nd was only consistently observed for probes after word onset, while the late Nd was elicited by probes *at and after* word onsets. This suggests that while children at this age do not always attend to the earliest indication of a word onset in a manner that affects early selection, they perform more detailed processing of all word-initial information, as reflected by the pattern of the late Nd.

Our results add to a growing body of evidence that attention supports speech perception in young children. To examine brain–behavior relationships, the magnitude of the attention effect was quantified as the difference in mean amplitude between probes presented 100 ms after word onset and random control. Greater attention to word onsets should allow children to preferentially process informative moments in the speech stream (Astheimer and Sanders, 2012). More efficient allocation of attention may also require language-specific knowledge to allow children to predict when critical information like word onsets will be presented. We therefore hypothesized that the magnitude of the attention effect should be correlated specifically with higher-level language skills.

By correlating this attention difference with performance on a variety of cognitive and language assessments, a clear pattern emerged. First, the magnitude of the attention effect was not correlated with any nonverbal measures, indicating that this type of attention does not simply reflect general cognitive processing, but rather a language-specific process. Second, among the verbal tasks, the magnitude of the attention effect was not related to basic vocabulary (PPVT) or simple grammaticality judgment performance, indicating that this type of attention is not related to low-level receptive language skills. Instead, the magnitude of the attention effect was significantly correlated with performance on the anomalous condition of the grammaticality judgment task, in which semantically anomalous information must be ignored in order to focus on the correct grammatical structure. As demonstrated previously (Bialystok and Ryan, 1985; Bialystok, 1986), this was a particularly difficult condition because it requires focused attention and metalinguistic skill, posing a significant challenge to young children who have not developed the ability for controlled language processing.

In order to isolate the role of language analysis versus cognitive control processes in the grammaticality judgment task, we used signal detection analysis to account for response bias and compute sensitivity measures for each of

these processes (Lum and Bavin, 2007). As expected, analysis d-prime scores, or the ability to discriminate between correct versus ungrammatical sentences when semantics remained intact, were not correlated with the magnitude of the attention effect. This suggests that attention to word onsets is not closely related to syntactic processing. However, larger attention effects were associated with higher control d-prime scores. This control measure reflects the ability to focus on task-relevant grammar while ignoring semantic anomalies. Similarly, in the ERP story task, attending to word-initial segments may allow children to identify words more efficiently, thus achieving the primary goal of comprehension. In both cases, children are employing cognitive control mechanisms in order to attend to task-relevant information, a strategy that supports better performance. This relationship substantiates the notion that low-level attention during speech perception supports higher level, controlled language processing. Moreover, it suggests that indexing attention to word onsets in speech may provide an important neural signature for cognitive control of language processes in the developing brain.

While our results demonstrate that attention to speech perception is correlated with controlled language processing, it is unclear what other cognitive processes may also be related to attention during speech perception. Although attention to word onsets is a language-specific process, this type of attention could be related to cognitive control outside the domain of language. Our ERP index of attention during speech was not correlated with any nonverbal measures, but we did not include a nonlinguistic measure of cognitive control. Future investigations could employ a cognitive test battery that focuses on attention and cognitive control within and outside the language domain to determine whether attentional allocation during speech perception reflects language-specific or domain-general cognitive control.

The observed correlations contribute to a growing body of evidence for a relationship between attentional control and language skills in both typically developing and disordered populations (Stevens and Bavelier, 2012). In a similar grammaticality judgment task, Lum and Bavin (2007) reported that children with SLI had lower control scores than their typically developing peers, despite comparable analysis scores. Previous electrophysiological evidence demonstrates that children with SLI show deficiencies in spatially selective attention while attending to one story and ignoring another (Stevens et al., 2006). The attentional deficits observed in children with SLI extend beyond the realm of language into simple attention and rapid processing tasks in both the visual and auditory modalities, suggesting a domain-general attentional deficit (Asbjørnsen and Bryden, 1998; McArthur et al., 2008; Sperling et al., 2005). Similar attention deficits, which are related to phonological encoding abilities, have been reported in children with dyslexia (Facoetti et al., 2010; Hornickel et al., 2012; Lallier et al., 2010). The results of the current study suggest that temporally selective attention during speech perception may represent a direct link between attention and language skills, although to date this type of attention has not been measured in language-disordered populations.

The current study provides the first evidence that temporally selective attention during speech perception is related to metalinguistic skills in preschool aged children. Specifically, children who selectively allocate attention to informative moments in the speech stream such as word onsets also perform better on difficult metalinguistic tasks that require controlled attention to language. There was no such correlation with language judgments that did not require control, supporting the lifelong distinction between processes involved with representation and those involved with control described by Craik and Bialystok (2006). Given previous research demonstrating profound effects of intervention and enrichment-based training on attentional and auditory systems in children (Hornickel et al., 2012; Stevens et al., 2008), the potential plasticity of temporal attention in speech should be explored in future studies. Perhaps, through attention training, children who struggle with language can learn to attend to the speech stream in a manner that enhances early perceptual processing of informative moments. This will allow children who would otherwise be overwhelmed by the abundance of information available in the speech signal to focus on the most relevant information, thus improving higher-level language comprehension.

Conflict of interest

The authors confirm that we have no conflicts of interest to report in this study.

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