Specific aspects of cognitive and language proficiency account for variability in neural indices of semantic and syntactic processing in children

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\textbf{ABSTRACT}

The neural activity mediating language processing in young children is characterized by large individual variability that is likely related in part to individual strengths and weaknesses across various cognitive abilities. The current study addresses the following question: How does proficiency in specific cognitive and language functions impact neural indices mediating language processing in children? Thirty typically developing seven- and eight-year-olds were divided into high-normal and low-normal proficiency groups based on performance on nonverbal IQ, auditory word recall, and grammatical morphology tests. Event-related brain potentials (ERPs) were elicited by semantic anomalies and phrase structure violations in naturally spoken sentences. The proficiency for each of the specific cognitive and language tasks uniquely contributed to specific aspects (e.g., timing and/or resource allocation) of neural indices underlying semantic (N400) and syntactic (P600) processing. These results suggest that distinct aptitudes within broader domains of cognition and language, even within the normal range, influence the neural signatures of semantic and syntactic processing. Furthermore, the current findings have important implications for the design and interpretation of developmental studies of ERPs indexing language processing, and they highlight the need to take into account cognitive abilities both within and outside the classic language domain.

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1. Introduction

Evidence from research on language acquisition and development in typically developing children suggests that the emergence of language capitalizes on knowledge and cognitive abilities that develop during infancy, including auditory and visual perception, joint attention, symbolic representation, imitation, and memory (e.g., Bates and Dick, 2002; Bates et al., 2003; Tomasello, 2003). Further, domain-general models of cognitive development propose that language comprehension engages distributed neural networks that may not be specific to language functions, but are shared among cognitive processes, such as working memory and attention (Aydelott et al., 2005). To date, the understanding of relationships between cognitive and language domains in development has been primarily based on observations of, and correlations between, individual abilities, such as memory, categorization skills, vocabulary size, and grammar abilities (e.g., Bates et al., 1995, 2003; Marchman and Thal., 2005; Piaget and Inhelder, 1969; Tomasello, 2003).

Neural activity mediating language processing in adults, indexed by event-related brain potentials (ERPs), is known to reflect individual differences across a variety of cognitive
and linguistic capacities, including working memory (e.g., Friederici et al., 1998; Gunter et al., 2003; Nakano et al., 2010; Vos et al., 2001), language experience (e.g., Midgley et al., 2009; Rossi et al., 2006; Pakulak and Neville, 2011), and language proficiency (e.g., Pakulak and Neville, 2010; Weber-Fox et al., 2003). In children, it has been found that early language proficiency (e.g., Mills et al., 1993), language impairments (Neville et al., 1993), and socioeconomic status (SES; Stevens et al., 2009) impact the ERPs elicited by language and attention processing tasks. To date, little is known about how differences in key cognitive domains may impact language processing during typical development in young school-age children. The current study is an investigation of how cognitive and linguistic factors related to language processing, specifically nonverbal IQ, working memory skills, and grammatical proficiency, are reflected in, and contribute to, the variability of individual profiles in the underlying neural functions that mediate language abilities. This line of research is important for a better understanding of the correlates, and potentially causes, of developmental changes in both typical and atypical populations.

In the current study, we utilize converging hypotheses from traditional and more recent domain general models of language learning (e.g., Piaget and Inhelder, 1969; Rice and Kemper, 1984; Tomasello, 2003). Our adapted framework (illustrated in Fig. 1) provides a basis for examining possible relationships between specific factors within cognitive and linguistic domains and neural indices of language processing. The first domain, called “analytical computations,” includes the mental manipulation of actions, such as mentally reversing steps already completed, and the ability to focus on multiple aspects of an object simultaneously, such as focusing on the height and width of a container at the same time (Piaget and Inhelder, 1969; Rice and Kemper, 1984). A second domain, “processing resources,” includes inductive and deductive reasoning, attention, organization, and memory skills. Both analytical computations and processing resources are involved in “rule-based knowledge” and learning, including the categorization of information, recognition of visual and auditory patterns, and the abilities necessary for the acquisition of linguistic grammar (Tomasello, 2003). While many measures can reflect proficiency in each of these domains that encompass a broad set of operations, the current project focuses on one key aspect from each domain. In Fig. 1, the italicized tasks within the larger domains represent examples of one task related to each domain. Analytical computations can be evaluated by measurements of nonverbal IQ. Processing resources, specifically memory skills, can be assessed using verbal working memory tasks, and rule-based knowledge can be examined by analyzing grammatical morphology skills.

1.1. Event-related brain potentials

ERPs provide a functional measure of brain activity with high temporal resolution (Coles and Rugg, 1995; Nunez, 1995). The current study focuses on the neural components indexing semantic and syntactic processing. The N400 has been referred to as an index of the ease of lexical integration or lexical access (Holcomb and Neville, 1990; Holcomb, 1993; Kutas and Hillyard, 1980), or the emergent process of computing the meaning of a stimulus for the initial conceptual representation of meaning (Kutas and Federmeier, 2011). Smaller N400 amplitudes, indicating greater ease of processing, have been observed in older, compared to younger, children (Holcomb et al., 1992) and children and adults with stronger language abilities (Neville et al., 1993; Weber-Fox et al., 2003). N400 peak latencies have been found to be earlier in older, compared to younger, children (Hahne et al., 2004; Holcomb et al., 1992) and adults with greater language proficiency exhibit earlier N400 peak latencies than lower language proficiency peers, indicating greater efficiency in semantic processing (Weber-Fox et al., 2003). The N400 is often followed by a late positive component (LPC), thought to index processing related to integrating a semantic violation into the context of the preceding words or a reanalysis of the sentence containing a violation (Juottonen et al., 1996; Van Petten and Lukács, 2012).

Violations of syntactic rules, such as phrase structure violations or verb agreement violations in language paradigms, typically elicit a biphasic response consisting of an anterior negativity and a P600. The anterior negativity (AN) is thought to index earlier, more automatic syntactic processes, such as assignment of grammatical relationships (for review, see Friederici, 2011). The P600 is thought to index syntactic repair or reanalysis (Friederici et al., 1996; Yamada and Neville, 2007) or difficulty of syntactic integration (Kaan et al., 2000). However, the P600 is not language-specific (e.g., Patel et al., 1998; Schmidt-Kassow and Kotz, 2009) and may reflect a more generalized reprocessing of information when a rule-based expectancy is violated (Schmidt-Kassow and Kotz, 2009). Studies utilizing phrase structure violations observed that increasing age (Hahne et al., 2004) and greater language proficiency (Pakulak and Neville, 2010) are associated with larger P600 amplitudes. Earlier P600 peak latencies in older, compared to younger, children (Hahne et al., 2004) suggest greater efficiency in reprocessing or repair of syntactic violations.

The current study explores the relationships between performance on standardized measures of nonverbal IQ, auditory word recall, and receptive grammatical morphology and the ERP components elicited by semantic anomalies and phrase structure violations in typically-developing (i.e., performance in the normal range on all measures) seven- and eight-year-old children. We tested three hypotheses. (1) As nonverbal IQ can be used as a measure of world knowledge, reasoning, and analytical abilities, and the N400 has been shown to be sensitive to world knowledge (for review, see Kutas and Federmeier, 2011), we hypothesize that processes of lexical access/integration are more efficient in children with higher nonverbal IQ performance and, accordingly, differences in nonverbal IQ will distinguish the N400 responses elicited by semantic anomalies. (2) Greater auditory word recall abilities may indicate stronger word association skills (Delis et al., 1988), thus facilitating lexical access or meaning computation, which will be reflected in greater ease of lexical access/integration. Differences in word association skills will be indexed by smaller N400 amplitudes (suggesting more efficient processing) in the children with
higher word recall skills. Furthermore, previous studies have demonstrated that longer reading span is related to more efficient syntactic processing (e.g., Gunter et al., 2003; Nakano et al., 2010; Friederici et al., 1998; Vos et al., 2001). These findings suggest that word recall abilities will distinguish the P600 component elicited by phrase structure violations between the higher and lower word recall groups. (3) Higher performance on the grammatical morphology task are likely to reflect in part more advanced knowledge of, and greater aptitude for, linguistic rules and structure. Better knowledge of a rule-based system such as grammar, may facilitate repair and/or reanalysis of phrase structure violations. Therefore, we hypothesize that grammatical morphology abilities are selectively associated with syntactic processing, and differences in grammatical proficiency will be reflected in the P600 responses elicited by phrase structure violations.

2. Materials and methods

2.1. Participants

Participants were thirty typically developing children between the ages of 7;5 and 9;1 years;months (13 males; 17 females). The participants were right-handed, as per parent report, and confirmed by an abbreviated handedness assessment (Edinburg Handedness Inventory; Oldfield, 1971). All participants were native, monolingual English speakers with no history of reading, language, hearing, or neurological impairment. All children passed a hearing screening at 20 dB HL at 500, 1000, 2000, and 4000 Hz in both the right and left ears. A parent or guardian for each participant completed a history form, including maternal education to determine socioeconomic status (Hollingshead, 1975).

2.1.1. Cognitive and language testing battery: Inclusionary criteria

Standardized behavioral tests were administered to assess ability level in a variety of domains necessary for understanding and using language. Inclusionary criteria consisted of normal performance on a comprehensive testing battery including: The Columbia Mental Maturity Scale to assess nonverbal IQ (Burgemeister et al., 1972), the complete Test for Auditory Comprehension of Language-3 (TACL-3; Carrow-Woolfolk, 1999) to establish language comprehension abilities, and the Clinical Evaluation of Language Fundamentals-4 (CELF-4; Semel et al., 2003) subtests of Recalling Sentences and Formulated Sentences to evaluate expressive language skills. As the goal of the current study is to assess different aspects of receptive language skills and how they relate to brain functions, the TACL-3 was administered, which contains subtests of Vocabulary, Grammatical Morphemes, and Elaborated Phrases and Sentences. All participants scored within the normal range on the standardized measures of nonverbal IQ,
receptive, and expressive language (standard score ≥ 84). All participants performed within the normal range on the Nonword Repetition Task (Dollaghan and Campbell, 1998), indicating normal phonological processing abilities. Performance on the Passage Comprehension subtest of the Woodcock Reading Mastery Tests – Revised (Woodcock, 1998) demonstrated reading abilities within the normal range (standard score ≥ 92) for all participants. In addition, verbal working memory was assessed using the Auditory Number Memory – Forward, Auditory Number Memory – Reverse, and the Auditory Word Memory subtests of the Test of Auditory-Perceptual Skills – Revised (TAPS-R; Gardner, 1996, standard scores ≥ 75).

2.2. Nonverbal IQ, working memory and grammar proficiency group formation

Three specific measures from the complete testing battery that engage distinct domains of cognitive and language abilities were chosen for comparisons with ERPs. The performance scores across these tests were not correlated (r < .23, p > .12). The Columbia Mental Maturity Scale (Nonverbal IQ: Burgemeister et al., 1972) assessed general reasoning, problem-solving, and analytical abilities. The mean (SD) standard score across all participants was 108.57 (13.21). The Auditory Word Memory (Word Recall) subtest of the TAPS-R (Gardner, 1996) measured immediate recall abilities for strings of unrelated words (group mean [SD] standard score: 103.40 [18.22]). The Grammatical Morphemes (Grammar) subtest of the TACL-3 (Carrow-Woolfolk, 1999) assessed abilities in the comprehension of grammatical morphemes, such as prepositions, noun–verb agreement, and derivational suffixes, in the context of simple sentences. Standard scores on the Grammatical Morphemes subtest of the TACL-3 have been converted to z-scores for ease of comparison. The mean (SD) standard score across all participants was 106.67 (10.78). These three subtests were chosen for comparison because they provided distinct and specific measures of different cognitive domains: analytical skills (nonverbal IQ), processing resources (verbal word recall), and rule-based knowledge (grammatical morphology). Importantly, performances across these three subtests were not correlated with each other, suggesting a level of independence from one another and potential dissociation in neural processes.

To evaluate the relationships between these cognitive and language abilities and neural processes for language, participants were divided into groups based on performance on each of the testing measures. Using a median split, a higher normal (High-Normal) and a lower normal (Low-Normal) performing group were formed for the Nonverbal IQ, Word Recall, and Grammar tasks. As can be seen in Table 1, individual task performance was variable across the three tests, with only three participants in the Low-Normal performing group across all three tasks, and five in the High-Normal (bolded) group for all tasks. Specific characteristics of the Low-Normal and High-Normal performance groups for each cognitive task are displayed in Table 2. The Low-Normal and High-Normal groups differed only on the measure that the division was based on; that is, performance on the other two tasks, as well as age and SES based on maternal education, were the same for the two groups (Table 2).

2.3. Stimuli for the ERP sentence processing task

The ERP stimuli consisted of 160 auditory sentences presented via a speaker located 183 cm directly in front of the participant. To ensure word familiarity for young school-age children, the target and filler sentences were constructed with words from the MacArthur Communicative Development Inventory: Words and Sentences (CDI Advisory Board, 1993) and A Spoken Word Count: Children – ages 5, 6, and 7 (Wepman and Hass, 1969) list of words used by five-year-olds. All of the nouns, pronouns, and prepositions serving as target words were monosyllabic to control for length. All target nouns in the semantic conditions and target closed class words in the syntactic conditions were counterbalanced, such that correct targets also served as anomalies in a different sentence for both the semantic and syntactic conditions. For specific examples, see sentence numbers 20, 25, and 28 in Appendix A.

Forty sentences were semantically and syntactically accurate control sentences (e.g., The ponies pull the sleds for these children). Forty sentences retained the same structure as the control sentences but contained semantic anomalies (e.g., The ponies pull the sauce for these children). Forty additional sentences, also with the same structure as the control sentences, contained phrase structure violations (e.g., The ponies pull the sleds for those these children). The phrase structure violations in the current experiment were created by inserting an extra closed-class word, either a demonstrative (e.g., that, those) or a pronoun (e.g., his, her), in the sentence–final prepositional phrase. This type of syntactic violation was utilized to allow comparisons of words from the same word class for syntactic control and violation sentences. Insertion phrase structure violations such as these have been used successfully in previous studies of syntactic processing in adults and children (e.g., Pakulak and Neville, 2010, 2011; Pakulak et al., 2005; Yamada and Neville, 2007).

The final forty sentences had a different sentence structure than the target sentences and served as filler sentences. The filler sentences included thirty correct sentences (e.g., Jodie could make the pizza with her hands) and ten sentences with the same sentence structure containing phrase structure violations (e.g., Jodie could the make pizza with her hands). A phrase structure violation was used for the filler sentences so as not to overtax the participants by requiring the children to monitor an additional error type. A complete list of the sentence stimuli is included in Appendix A.

The naturally spoken sentences with child-directed prosody were recorded in a sound-attenuating booth by a male and female speaker. Recordings were made using the PRAAT program at a sampling rate of 48,000 Hz and a mouth-to-microphone distance of 46 cm. Participants heard each sentence one time, with fifty percent of the sentences spoken by the male and fifty percent spoken by the female, balanced both within and between presentation blocks. PRAAT was used to create separate wave files, with each individual file containing only one word extracted.
Table 1
Characteristics of individual participants including: age and performance on measures (in standard score) of Nonverbal IQ (Columbia Mental Maturity Scale), Word Recall (Test of Auditory-Perceptual Skills – Revised; TAPS-R), and Grammatical Morphemes (Test for Auditory Comprehension of Language-3; TACL-3). Bolded scores indicate High-Normal performance on a given subtest.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Age</th>
<th>Nonverbal IQ (Columbia)</th>
<th>Word Recall (TAPS-R)</th>
<th>Grammatical Morphemes (TACL-3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.8</td>
<td>129</td>
<td>113</td>
<td>110</td>
</tr>
<tr>
<td>2</td>
<td>8.6</td>
<td>106</td>
<td>87</td>
<td>105</td>
</tr>
<tr>
<td>3</td>
<td>7.11</td>
<td>93</td>
<td>99</td>
<td>120</td>
</tr>
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<td>4</td>
<td>7.10</td>
<td>120</td>
<td>89</td>
<td>125</td>
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<td>5</td>
<td>9.1</td>
<td>106</td>
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<td>115</td>
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<td>130</td>
<td>96</td>
<td>90</td>
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<tr>
<td>9</td>
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<td>122</td>
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<td>105</td>
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<td>124</td>
<td>105</td>
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<td>11</td>
<td>8.8</td>
<td>94</td>
<td>94</td>
<td>85</td>
</tr>
<tr>
<td>12</td>
<td>8.2</td>
<td>114</td>
<td>122</td>
<td>120</td>
</tr>
<tr>
<td>13</td>
<td>8.2</td>
<td>96</td>
<td>88</td>
<td>90</td>
</tr>
<tr>
<td>14</td>
<td>7.11</td>
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<td>115</td>
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<td>7.10</td>
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<td>137</td>
<td>115</td>
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<td>8.10</td>
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<td>105</td>
<td>110</td>
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<td>29</td>
<td>7.5</td>
<td>103</td>
<td>101</td>
<td>105</td>
</tr>
<tr>
<td>30</td>
<td>8.2</td>
<td>110</td>
<td>136</td>
<td>110</td>
</tr>
</tbody>
</table>

Table 2
Means and standard errors (SE) for age, SES (maternal education), and standard scores for performance measures of Nonverbal IQ, Word Recall, and Grammar for Low-Normal and High-Normal proficiency groups are presented.

### Nonverbal IQ

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Low-Normal ( n = 16, 7M 9F )</th>
<th>High-Normal ( n = 14, 6M 8F )</th>
<th>Group statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>8.38 (.10)</td>
<td>8.16 (.11)</td>
<td>( F = 2.24, p = .146 )</td>
</tr>
<tr>
<td>SES</td>
<td>5.94 (.20)</td>
<td>5.86 (.22)</td>
<td>( F &lt; 1 )</td>
</tr>
<tr>
<td>Nonverbal IQ</td>
<td>98.13 (.172)</td>
<td>120.50 (.84)</td>
<td>( F = 79.22, p &lt; .001, \eta^2_p = .739 )</td>
</tr>
<tr>
<td>Word Recall</td>
<td>104.13 (.463)</td>
<td>102.57 (.95)</td>
<td>( F &lt; 1 )</td>
</tr>
<tr>
<td>Grammar</td>
<td>105.31 (.272)</td>
<td>108.21 (.290)</td>
<td>( F &lt; 1 )</td>
</tr>
</tbody>
</table>

### Word Recall

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Low-Normal ( n = 16, 8M 8F )</th>
<th>High-Normal ( n = 14, 5M 9F )</th>
<th>Group statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>8.27 (.10)</td>
<td>8.28 (.11)</td>
<td>( F &lt; 1 )</td>
</tr>
<tr>
<td>SES</td>
<td>5.94 (.20)</td>
<td>5.86 (.22)</td>
<td>( F &lt; 1 )</td>
</tr>
<tr>
<td>Nonverbal IQ</td>
<td>109.13 (.336)</td>
<td>107.93 (.59)</td>
<td>( F = 49.66, p &lt; .001, \eta^2_p = .639 )</td>
</tr>
<tr>
<td>Word Recall</td>
<td>109.00 (.278)</td>
<td>118.71 (.298)</td>
<td>( F &lt; 1 )</td>
</tr>
<tr>
<td>Grammar</td>
<td>105.63 (.273)</td>
<td>107.86 (.291)</td>
<td>( F &lt; 1 )</td>
</tr>
</tbody>
</table>

### Grammar

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Low-Normal ( n = 13, 5M 8F )</th>
<th>High-Normal ( n = 17, 8M 9F )</th>
<th>Group statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>8.35 (.11)</td>
<td>8.23 (.10)</td>
<td>( F &lt; 1 )</td>
</tr>
<tr>
<td>SES</td>
<td>6.15 (.22)</td>
<td>5.71 (.19)</td>
<td>( F = 2.40, p = .132 )</td>
</tr>
<tr>
<td>Nonverbal IQ</td>
<td>105.69 (.366)</td>
<td>110.77 (.20)</td>
<td>( F = 1.09, p = .305 )</td>
</tr>
<tr>
<td>Word Recall</td>
<td>100.08 (.508)</td>
<td>105.94 (.444)</td>
<td>( F &lt; 1 )</td>
</tr>
<tr>
<td>Grammar</td>
<td>96.92 (.181)</td>
<td>114.12 (.58)</td>
<td>( F = 51.30, p &lt; .001, \eta^2_p = .647 )</td>
</tr>
</tbody>
</table>
from the naturally spoken sentence. Using stimulus presentation software, Presentation (Neurobehavioral Systems), 65 ms were inserted between the individual words within each sentence to ensure that sentences sounded natural in child-friendly prosody, and to allow for clear delineation of word onsets for coding ERP stimuli. Sentences were determined to sound natural in pitch and prosody by an independent listener.

Average fundamental frequency (pitch in Hz) was assessed for the naturally spoken sentences by evaluating changes across 100 ms windows for the 500 ms leading up to, and 500 ms following, the critical word in both the semantic and syntactic canonical and violation conditions. For the semantic conditions, there were no differences in fundamental frequency \( F(1, 78) < 2.198, p > .144 \) between the canonical and violation sentences. For the syntactic conditions, fundamental frequencies were similar between canonical and violation conditions from the critical word through 500 ms post-stimulus word onset \( F(1, 78) < 1 \). However, fundamental frequencies of the syntactic violation sentences were higher than fundamental frequencies for the canonical condition for the 400 ms leading up to the critical word \( F(1, 72) > 5.074, p < 0.029 \). This is likely due to the difference in timing of the prosodic boundary \( \text{e.g., Mannel and Friederici, 2011} \) relative to the critical word between the two conditions. For example, the prosodic boundary is just prior to the critical-minus-one word in the canonical condition (The ponies pull the sleds [prosodic boundary] for these children) and just prior to the critical-minus-two words in the syntactic violation condition (The ponies pull the sleds [prosodic boundary] for those these children). To account for the differences in timing of the prosodic boundary, long (1000 ms) baseline periods were used in analysis of the syntactic canonical and violation sentences (described in Section 2.6.2).

The sentences were presented in five blocks, with 32 sentences per block. Different sentence types were pseudo-randomized between and within blocks so that each block contained equal numbers (8) of each target sentence (control, semantic anomaly, phrase structure violation) as well as 8 filler sentences (six control, two phrase structure violation). Sentence topics were also pseudo-randomized between blocks, with no sentence topic repeated within a block. Talker gender was pseudo-randomized between blocks and sentence type, with an equal number of sentences (16) read by the male and female speaker within each block. Block presentation order was consistent across participants.

2.4. Electroencephalographic recordings

Electrical activity from the scalp was recorded using 32 Ag-CI electrodes secured in an elastic cap (Quik-cap, Compumed-Neuroscan). Twenty-eight electrodes were placed over homologous locations as dictated by the International 10–10 system (American Encephalographic Society, 1994). Electrode locations were as follows: lateral sites F7/8, FT7/8, T7/8, TP7/8/FP7/8; medial–lateral sites F3/4, FC3/4 C3/4, CP3/4 P3/4, O1/O2; midline sites FZ, FCZ, CZ, CPZ, PZ, OZ (bottom right corner of Fig. 3). Recordings were referenced online to an electrode placed over the left mastoid and were re-referenced offline to an average of the electrode recordings from the left and right mastoid placements (Luck, 2005). Horizontal eye movements were monitored by electrodes placed over the left and right outer canthi while electrodes over the left inferior and superior orbital ridge monitored vertical eye movements. All electrode impedances were reduced to 5 kΩ or less. Electrical signals were digitized online at a rate of 500 Hz (Neuroscan 4.2) and filtered and amplified within a bandpass of 0.1–100 Hz.

2.5. Procedures

The child was comfortably seated in a sound-attenuating booth positioned 175 cm from a 43 cm monitor and an experimenter sat in the booth with the child throughout the experiment. The procedure is graphically displayed in Fig. 2. Each sentence began with a “READY?” image presented on the computer screen. Once the child was ready, he/she pressed a button on a response pad to begin the sentence. After 750 ms, a small photograph or clip art image depicting the subject (actor) but not the action of the sentence topic appeared on the screen subtending a visual angle of 2.45° vertically and 3.45° horizontally. A different picture was used for each sentence so that no picture was viewed more than once during the experiment. The picture provided a visual focus throughout the sentence, which began after a variable stimulus onset asynchrony (SOA; 800–1200 ms). The picture disappeared at the completion of the sentence. A “YES/NO” image appeared 1200 ms after the completion of the sentence prompting the child to respond by pressing “YES” if the sentence sounded correct or “NO” if they detected an error in the sentence. The response hand for “YES” was counterbalanced across participants. The “YES/NO” prompt appeared 1200 ms after the completion of the sentence to minimize movement associated with the button press and children were instructed to respond after they saw the prompt. Therefore, only response accuracy, and not reaction time, measures were recorded. After the child responded, the process was repeated for the next sentence. Prior to the experiment, a short practice sequence was administered, which all participants completed successfully on the first attempt.

2.6. Data analysis

2.6.1. Sentence judgment accuracy

Sentence judgment accuracy was obtained from signals generated by the response pad. Sentence accuracies were averaged across trials for each participant for each condition. Online sentence judgment accuracies were compared using ANOVAs with repeated measures that included a between-groups factor (group: Low-Normal, High-Normal) and a within-subject factor (sentence type: Control, Semantic Anomaly, Phrase Structure Violation). To explore the relationships between performance on standardized measures of Nonverbal IQ, Word Recall, and Grammar and the level of accuracy on the sentence judgment task, correlations between these standardized
behavioral scores and overall sentence accuracy, as well as accuracy for each condition, were performed.

2.6.2. EEG and ERP signal processing

Independent component analysis (ICA) was performed on each continuous electroencephalogram (EEG) data file and eye artifact components were removed from the data (EEGLAB; Delorme and Makeig, 2004). Using the ERPLAB (Lopez-Calderon and Luck, 2010) toolbox, the EEG was then low-pass filtered offline at 30 Hz with a 12 dB roll-off. The data was averaged by condition for each participant and only trials with correct sentence judgment responses were included. For the semantic condition, averages were triggered 100 ms prior to and 1500 ms after the onset of the target word. ERP data from 100 ms interval prior to the word onset (time 0 ms) served as a measure of baseline activity and each EEG epoch was baseline corrected prior to averaging (ERPLAB; Lopez-Calderon and Luck, 2010). To accommodate for differences in preceding word type (preposition vs. pronoun) and differences in timing of the phrase boundary (e.g., Mannel and Friederici, 2011) relative to the onset of the target words in the phrase structure control and violation sentences, a longer baseline epoch was used. The epochs for the syntactic condition were triggered 1000 ms prior to and 2000 ms after the onset of the target word. Data from 1000 ms prior to the word onset (time 0 ms) served as baseline activity and each EEG epoch was baseline corrected prior to averaging.

A second stage of artifact rejection using a moving 200 ms window was employed for any remaining eye or movement artifact exceeding a specified threshold. For most participants, extraneous artifact exceeding 100 μV was rejected, though for two participants, secondary artifact rejection was performed at 125 and 150 μV due to larger amplitude baseline activity. This method was performed for all epochs for each participant (ERPLAB; Lopez-Calderon and Luck, 2010) with an average of 15.63% of correct epochs rejected. The average number of remaining correct trials per condition was 29.35 (range: 26–33 trials per condition).

2.6.3. ERP measures

ERPs elicited by the target words in the control, semantic anomaly, and phrase structure violation sentences were measured within temporal windows determined by visual inspection of the grand average waveforms and that corresponded with the predicted time for course for the anterior negativity, N400, and P600 components previously observed in children (Hahne et al., 2004). The time window in which mean amplitudes were measured: for the anterior negativity was between 250 and 450 ms; for the N400 was between 350 and 750 ms; for the P600 was between 650 and 950 ms; and for the LPC was between 1100 and 1400 ms post-stimulus onset. Additionally, visual inspection of the data revealed an unexpected late negativity elicited by the phrase structure violations. To assess this unexpected late syntactic negativity, mean amplitudes were measured between 1000 and 1400 ms. Mean amplitudes were computed as the mean voltage within the specified time window using ERPLAB (Lopez-Calderon and...
Luck, 2010; Luck, 2005). Temporal changes in the amplitudes of the ERP components were also computed over successive 100 ms windows. Mean amplitudes were computed across the 100 ms windows between 0 and 800 ms for the N400 and 500 and 1000 ms for the P600. This allowed for comparison of the timing of the ERP component activation patterns across conditions and across groups for the broad components elicited by the current paradigm (Luck, 2005).

2.6.3.1. Statistical analyses – omnibus ANOVAs based on median group splits. Statistical analyses of mean amplitudes measured within each broad and 100 ms time window were performed using omnibus ANOVAs, which allow for evaluation of the distribution of components from anterior to posterior electrode sites across both hemispheres (e.g., Hahne et al., 2004; Handy, 2005; Luck, 2005; Oberecker et al., 2005; Pakulak and Neville, 2010). ANOVAs were performed with repeated measures including: the between-group factor of task performance group (G: Low-Normal, High-Normal) and within-group factors of condition (C: Control, Violation), hemisphere (H: Left, Right), anterior/posterior (AP: fronto-temporal, central [anterior sites]; centro-parietal, parietal, occipital [posterior sites]), and laterality (L: lateral, medial–lateral). Based on a priori hypotheses from previous studies and visual inspection, the distribution of the anterior negativity is greatest over frontal regions of the brain; therefore, the omnibus analyses for the AN included more anterior electrode sites (frontal, fronto-temporal [anterior]; central, centro-parietal, parietal [posterior]) rather than fronto-temporal to occipital sites used in the omnibus analyses for the remaining ERP components that have a greater central–parietal distribution (e.g., Pakulak and Neville, 2010). Only significant (p < .05) Group effects or interactions including Group and Condition are reported. For midline electrode sites, analyses were performed with the between-group factor of performance (G: Low-Normal, High-Normal) and within-group factors of condition (C: Control, Violation), and anterior/posterior (AP: fronto-temporal, central [anterior sites]; centro-parietal, parietal, occipital [posterior sites]). Statistics for midline sites are not reported if they reflect findings at lateral and medial–lateral sites. Following omnibus ANOVAs, further analyses using step-down ANOVAs were performed to isolate significant interactions of p < .05, collapsing across factors where no interactions were observed.

2.6.3.2. Statistical analyses – correlational analyses. Correlations between performance on standardized tests of Nonverbal IQ, Word Recall, and Grammar and mean amplitudes of the ERP components elicited by the semantic and
syntactic conditions were performed for comparisons in which group interactions were significant \( (p < .05) \). Composite mean amplitude measures across an aggregate of electrode sites were created separately across left and right hemisphere electrode sites for which the ERP components were most pronounced based on the ERP component distribution results from the omnibus ANOVAs. For the N400, aggregate sites were created across left hemisphere electrode sites C3, CP3, P3 and C4, CP4, P4 in the right hemisphere for both the canonical and violation conditions. For the P600, aggregate sites were created across C3, CP3, P3, and O1 and C4, CP4, P4, and O2 for both the canonical and violation conditions. These aggregate sites were correlated with the standard scores for the IQ, Word Recall, and Grammar tasks. Only significant correlations \( (p < .05) \) are reported.

Significance values were set at \( p < .05 \). For all repeated-measures with greater than one degree of freedom in the numerator, the Huynh–Feldt \((H–F)\) adjusted \( p \)-values were used to determine significance \( (\text{Hays}, 1994) \). Effects sizes, indexed by partial-eta square values \( (\eta^2_p) \), are reported for all significant effects.

3. Results

3.1. Sentence judgment accuracy for ERP stimuli

All participants performed the online sentence judgment task with high accuracy, with an overall mean \( (SE) \) accuracy of 89.2\% \((.70) \). Across all thirty participants, judgment accuracy was highest for phrase structure violations at 95.7\%, with accuracy for semantic violations second at 89.9\%, and the lowest accuracy for the control condition at 81.9\% \((C: F (1, 29) = 24.13, p < .001, \eta^2_p = .454) \). Furthermore, across all participants, sentence judgments were more accurate for detection of phrase structure violations compared to semantic violations or canonical sentences \((F (1, 29) = 27.34, p < .001, \eta^2_p \geq .485) \) and also more accurate for detection of semantic violations compared to canonical sentences \((F (1, 29) = 13.32, p = .001, \eta^2_p = .315) \). When participants were divided into Low-Normal and High-Normal performance groups based on Nonverbal IQ, Word Recall, and Grammar, no group or group by condition interactions were observed for the sentence judgment accuracies \((G \times C: F (1, 28) < 1.79, p > .187) \). Nonverbal IQ and Grammar performance did not correlate with sentence judgment accuracy. However, correlational analyses revealed that children with higher Word Recall performance also completed the sentence judgment task more accurately across all three conditions \((p = .023, r = .366) \).

3.2. Semantic anomalies

The N400 responses elicited by the semantic control target words and semantic violations for all participants are illustrated in Fig. 3. As the comparison words (direct objects) in the control sentences were not highly primed, N400s were elicited by the semantic control target words as well as the semantic violations \((C: F (1, 29) = 2.65, p = .115, \eta^2_p = .084) \). N400 mean amplitudes elicited by both the canonical and violation conditions were larger over centrally distributed medial–lateral electrode sites over the left hemisphere \((H \times AP \times Lat: F (4, 116) = 3.79, p = .027, \eta^2_p = .116) \), as can be seen in Fig. 3. The late positive component, elicited by semantic violations, was significant across all electrode sites \((C: F (1, 29) = 6.58, p = .016, \eta^2_p = .185) \) with the largest amplitude over medial–lateral electrode sites \((\text{Fig. 3; } C \times Lat: F (1, 29) = 4.21, p = .049, \eta^2_p = .127) \). However, the mean amplitude measurements of the LPC did not differ between higher and lower Nonverbal IQ, Word Recall, or Grammar groups \((G \& G \times C: F (1, 28) < 1) \) and, therefore, are not reported in detail below.

3.2.1. Semantic processing associated with nonverbal IQ

Mean amplitude of the N400. N400 responses elicited by the semantic control target words and the semantic violations for the Low-Normal and High-Normal Nonverbal IQ groups can be seen in Fig. 4 (top). Only medial–lateral electrode sites are shown for illustrative purposes. N400 mean amplitudes did not differ between the two groups, with no group or group by condition interactions, \( F (1, 28) < 1 \).

Timecourse of the N400 activation. The High-Normal Nonverbal IQ group displayed an earlier onset for processing the semantic violations compared to the Low-Normal Nonverbal IQ group, evidenced by larger N400 mean amplitudes for the High-Normal group compared to the Low-Normal Nonverbal IQ group in 100–200 ms time window \((G \times C: F (1, 28) = 5.61, p = .025, \eta^2_p = .167) \). This difference in the timecourse of activation of the N400 between the High-Normal and Low-Normal Nonverbal IQ groups, illustrated in Fig. 4 (bottom), indicates that the N400 elicited by semantic violations is present for the children with higher Nonverbal IQ performance at an earlier latency compared to the N400 elicited in the Low-Normal Nonverbal IQ group. No other time windows revealed significant group interactions \((0–100\text{ and }200–800\text{ ms }G \& G \times C: F < 3.25, p > .083) \).

Within this early, 100–200 ms time window, N400 mean amplitudes elicited by the canonical condition over the left hemisphere were significantly correlated with IQ performance \((p = .009, r = .426) \). This indicates that children with higher IQ performance displayed smaller N400 mean amplitudes elicited by the semantic canonical condition. There were no significant correlations between Nonverbal IQ performance and N400 mean amplitudes elicited by the semantic violation condition.

3.2.2. Semantic processing based on word recall ability

Mean amplitude of the N400. There were no main effects of group or group by condition, \( F (1, 28) < 1.38, p > .250 \), across medial–lateral and lateral electrode sites. A significant interaction between group, anterior-posterior distribution, and laterality \((F (1, 28) = 3.86, p = .020, \eta^2_p = .121) \) revealed smaller N400 amplitudes for both canonical and violation conditions over central medial–lateral electrode sites and centro-parietal and parietal lateral electrode sites in the High-Normal compared to the Low-Normal Word Recall group. Analyses across midline electrode sites revealed a significant effect of group \((F (1, 28) = 4.59, p = .041, \eta^2_p = .141) \), with smaller overall N400 mean amplitudes for the High-Normal compared to the Low-Normal Word Recall group for both semantic
Fig. 4. Grand average ERPs (top) elicited by the semantically correct target words and the semantic anomalies for the Low-Normal (left) and High-Normal (right) Nonverbal IQ groups are illustrated for medial–lateral electrode sites. N400 mean amplitudes (with standard errors) across 100 ms time windows (bottom) reveal that N400s elicited by the semantic violations had an earlier onset for the higher compared to the lower Nonverbal IQ group. Asterisks (*) indicate significant effects.

canonical and violation conditions. For illustrative purposes, only midline and medial–lateral electrode sites are presented in Fig. 5.

N400 mean amplitudes elicited by the canonical condition over the left hemisphere were correlated with Word Recall performance (p = .024, r = .364), indicating that children with higher Word Recall abilities displayed smaller N400 amplitudes in response to semantically correct words. As with Nonverbal IQ, no significant correlations were observed between Word Recall performance and N400 mean amplitudes elicited by the semantic violations.

Timecourse of the N400 activation. Across medial–lateral and lateral electrode sites, there were no main effects of group or interaction of group by condition, F (1, 28) < 2.10, p > .159, across any of the successive 100 ms time windows. However, consistent with the overall mean amplitude
3.2.3. Semantic processing based on grammar test performance

**Mean amplitude of the N400.** N400 mean amplitudes were similar overall between the Low- and High-Normal Grammar groups, with no main effect of group or group by condition interaction, $F(1, 28) < 1.50, p > .232.$ A significant interaction of group, condition, and anterior–posterior distribution ($F(1, 28) = 4.52, p = .020, \eta^2_g = .139$) revealed smaller N400 amplitudes for the canonical condition over fronto-central and central electrode sites for the High-Normal compared to the Low-Normal Grammar group. This interaction can be seen in Fig. 6 (top). For illustrative purposes, only medial–lateral electrode sites are shown.

**Timecourse of the N400 activation.** Omnibus analyses of N400 mean amplitudes across the 200–300 ms and 300–400 ms time windows revealed smaller N400 mean amplitudes for both semantic canonical and violation conditions for the High-Normal compared to the Low-Normal Grammar group across these early time windows ($G: F(1, 28) = 4.54, p = .042, \eta^2_g = .140$ and $F(1, 28) = 6.53, p = .016, \eta^2_g = .189$, respectively). These differences are illustrated in Fig. 6 (bottom). Additionally, interactions of group, condition, and anterior–posterior distribution across the 200–300 ms, 300–400 ms, 400–500 ms, and 500–600 ms time windows demonstrated smaller N400 mean amplitudes elicited by semantically correct words over fronto-central, central, and centro-parietal electrode sites for the higher compared to the lower Grammar group ($G \times C \times AP: 3.23 < F(4, 112) < 4.84, .045 > p > .016, .103 < \eta^2_g < .147$), consistent with the overall mean amplitude interaction described above (Fig. 6). For the 500–600 ms time window, a significant interaction of group, condition, and laterality was also observed ($F(1, 28) = 5.93, p = .022, \eta^2_g = .175$).

The timecourse analyses revealed smaller N400 mean amplitudes elicited by the semantic canonical and violation conditions across early time windows for the High-Normal compared to the Low-Normal Grammar group. Furthermore, N400 mean amplitudes were more anteriorly distributed across early and mid-latency time windows for the canonical condition in the Low-Normal Grammar group.

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**Fig. 5.** Grand average ERPs elicited by the semantic control and violation target words across medial–lateral and midline electrode sites for the Low-Normal and High-Normal Word Recall group. Overall N400 amplitudes were smaller for the High-Normal Word Recall group across midline electrode sites.
3.3. Phrase structure violations

The anterior negativity, P600, and late syntactic negativity elicited by the syntactic control and phrase structure violation target words for the thirty children are illustrated in Fig. 7. Across all participants, analysis of the anterior negativity revealed a significant condition effect over anterior electrode sites (C × AP: $F(4, 116) = 6.88$, H-F $p = .004$, $\eta^2_p = .192$). Step-down analyses confirmed that the AN was significant over frontal and fronto-temporal electrodes sites and not central to posterior electrode sites (Anterior: $F(1, 29) = 4.84$, $p = .036$, $\eta^2_p = .143$; Posterior: $F(1, 29) < 1$).
The AN did not differ across hemispheres (Anterior C × H: \( F(1, 29) < 1 \)). No group or group by condition interactions for the AN were observed between the higher and lower Nonverbal IQ, Word Recall, or Grammar groups (G × G × C: \( F(1, 28) < 1 \)).

Robust P600 components were elicited by syntactic violations (C: \( F(1, 29) = 11.16, p = .002, \eta^2_p = .278 \)). P600 mean amplitudes were largest over central to parietally distributed medial–lateral electrode sites (C × AP × Lat: \( F(4, 116) = 4.64, p = .005, \eta^2_p = .138 \)), as illustrated in Fig. 7. The late syntactic negativity elicited by the phrase structure violations was largest over right hemisphere fronto-temporal and temporal (lateral) electrode sites (C × AP × Lat: \( F(4, 116) = 5.88, p = .004, \eta^2_p = .169 \)), as can be seen in Fig. 7. No group effects or interactions of group and condition were observed between higher and lower Nonverbal IQ, Word Recall, or Grammar groups (G × G × C: \( F(1, 28) < 2.87, p > .105 \)). Since the mean amplitude measurements of the AN and late syntactic negativity did not differ between higher and lower Nonverbal IQ, Word Recall, or Grammar groups, only results from P600 measures are reported in detail below.

### 3.3.1. Syntactic processing associated with nonverbal IQ

**Mean amplitude of the P600.** Overall P600 mean amplitudes for the Low- and High-Normal Nonverbal IQ groups did not differ (G & G × C: \( F(1, 28) < 2.02, p > .166 \); Fig. 8 (top)). However, interactions of group, condition, hemisphere, and laterality (\( F(1, 28) = 5.48, p = .027, \eta^2_p = .164 \)) revealed that P600 mean amplitudes for the High-Normal Nonverbal IQ were more positive over right hemisphere lateral electrode sites compared to P600 amplitudes elicited in Low-Normal Nonverbal IQ group.

**Timecourse of the P600 activation.** A significant group effect (\( F(1, 28) = 4.25, p = .049 \)) in the 600–700 ms time window indicated that the High-Normal Nonverbal IQ group displayed an earlier onset of the P600 compared to the Low-Normal Nonverbal IQ group (Fig. 8 (bottom)). As can be seen in Fig. 8 (bottom), larger P600 mean amplitudes elicited by the violation condition drive the group differences in this early time window. Earlier and subsequent time windows did not reveal any significant effects of group or group by condition (\( F(1, 28) < 1.98, p > .170 \)). The interaction of group, condition, hemisphere, and laterality (described above for overall mean amplitude) was only significant across the 800–900 ms time window (G × C × H × Lat: \( F(1, 28) = 6.50, p = .017, \eta^2_p = .188 \)), suggesting that the larger P600 amplitudes over right hemisphere lateral electrode sites in the higher nonverbal IQ group were limited to this specific time period for the P600 component (Fig. 8).

Significant correlations between Nonverbal IQ performance and P600 mean amplitudes elicited by the phrase...
structure violations in the 600–700 ms time window indicated that children with higher Nonverbal IQ performance displayed an earlier onset of the P600 elicited by the phrase structure violation over right hemisphere electrode sites ($p = .037, r = .331$) compared to peers with lower Nonverbal IQ performance. Together these findings reveal that, while overall P600 mean amplitudes elicited by syntactic violations are comparable between higher and lower Nonverbal IQ groups, the onset of the P600 is earlier for children with higher Nonverbal IQ performance.

**Fig. 8.** Grand average ERPs (top) elicited by the syntactic correct and violation target words for the Low-Normal (left) and High-Normal (right) Nonverbal IQ groups are illustrated for medial–lateral electrode sites. P600 mean amplitudes (with standard errors) across 100 ms time windows (bottom) reveal that P600s elicited by the syntactic violations had an earlier onset for the higher compared to the lower Nonverbal IQ group. Asterisks (*) indicate significant effects.
performance. Additionally, children with higher nonverbal IQ performance demonstrate a broader, more right lateralized, P600 distribution across the narrow 800–900 ms time window.

3.3.2. Syntactic processing based on word recall ability

Mean amplitude of the P600. Higher Word Recall performance was associated with larger P600 mean amplitudes for the syntactic violations compared to the lower Word Recall group \((G \times C: F (1, 28) = 6.83, p = .014, \eta^2_p = .196)\), plotted across medial–lateral electrode sites in Fig. 9 for illustrative purposes.

Timecourse of the P600 activation. Time window analyses revealed significant interactions of group and condition between 700–800 ms, 800–900 ms, and 900–1000 ms \((4.33 < F (1, 28) < 12.47, \ .047 > p > .001, .134 < \eta^2_p < .308)\). The differences across multiple time windows confirm that the overall mean amplitude differences described above were not due to differences in the timecourse of the onset or offset of the P600 between the High-Normal and Low-Normal Word Recall groups (Fig. 9).

3.3.3. Syntactic processing based on grammar test performance

Mean amplitude of the P600. Overall P600 mean amplitudes did not differ between the lower and higher performance groups for the grammar task, indicated by no main effect of group or group by condition interaction, \(F (1, 28) < 1\). However, a significant interaction of group, condition, hemisphere, and anterior–posterior distribution \((F (4, 112) = 3.12, p = .020, \eta^2_p = .100)\) revealed larger P600 mean amplitudes over left hemisphere posterior electrode sites \((T7, TP7, P7 and CP3, P3, O1)\) for the higher compared to the lower Grammar group. These effects can be seen in Fig. 10 (top).

Timecourse of the P600 activation. A significant interaction of group and condition for the 600–700 ms time window, \(F (1, 28) = 4.39, p = .045, \eta^2_p = .135\), revealed an earlier onset of the P600 component elicited by phrase structure violations for the High-Normal compared to the Low-Normal Grammar group. This interaction was also trending toward significance in the 500–600 ms time window \((F (1, 28) = 4.05, p = .054, \eta^2_p = .126)\). The group differences in timing for processing syntactic violations are illustrated in Fig. 10 (bottom). Additionally, interactions of group, condition, hemisphere, and anterior–posterior distribution, as observed across the broad P600 window for mean amplitude, were only significant for later time windows, 800–900 ms and 900–1000 ms \((G \times C \times H \times AP: F (4, 112) = 3.94, p = .007, \eta^2_p = .123\) and \(F (4, 112) = 3.96, p = .006, \eta^2_p = .124\), respectively). This suggests that P600 activations over left hemisphere posterior electrode sites had a longer duration for the High-Normal compared to the Low-Normal Grammar group (Fig. 10).

Correlations were only significant within the 600–700 ms time window, and indicated that children with higher Grammar performance exhibited larger P600 mean amplitudes elicited by the syntactic violations over the right hemisphere \((p = .036, r = .333)\). Together, these findings reveal that children with higher, compared to lower, Grammar performance display an earlier onset of the P600 elicited by phrase structure violations as well as larger P600 amplitudes over posterior electrode sites.

4. Discussion

The aim of the current study was to examine the relationships between specific aspects of cognitive and language proficiency and the neural functions mediating semantic and syntactic processing. Typically developing seven- and eight-year-olds were divided into High-Normal and Low-Normal performance groups based on measures of nonverbal IQ, auditory word recall, and grammatical morphology abilities. ERPs were elicited by violations of semantic expectation and phrase structure in auditory sentences. The timing of both the N400 and the P600 indicated that children with greater nonverbal IQ differentiated semantic and syntactic violations more rapidly than lower performing peers. In contrast, stronger verbal working memory abilities were associated with greater ease of lexical access, or easier generation of meaning representations, indexed by smaller N400 amplitudes. For syntactic processing, children with better verbal working memory performance demonstrated larger P600 amplitudes, suggesting greater allocation of neural resources for reprocessing of phrase structure violations compared to lower performing peers. Grammatical morphology abilities facilitated both semantic and syntactic processing, as children with better grammatical performance demonstrated more efficient lexical access and/or integration, indexed by smaller N400 amplitudes. Additionally, repair and reanalysis of syntactic violations was initiated more rapidly and processed using more robust allocation of neural resources in children with higher grammatical proficiency, as demonstrated by an earlier onset and broader distribution of the P600 component. In summary, nonverbal IQ performance appears to be associated with speed of processing for semantic and syntactic violations, verbal working memory is related to resource allocation for semantic and syntactic processing, and grammatical morphology proficiency is related to resource allocation for both semantic and syntactic processing, as well as processing speed for syntactic violations. Taken together, these findings indicate that specific cognitive and language abilities differentially contribute to variability in neural indices of semantic and syntactic processing in young school-age children. Furthermore, the current results have strong implications for the interpretation of developmental studies of ERPs for language processing and highlight the need to take into account cognitive abilities both within and outside the classic language domain.

4.1. Sentence judgment accuracy differences between conditions

Across all thirty children participating in the study, sentence judgments were most accurate for phrase structure violations, followed by the semantic anomalies, and least accurate for the canonical condition. The insertion phrase
structure violations, with the addition of an extra pronoun in the final prepositional phrase where a noun is expected, creates a highly salient, easily detectable violation. The semantic anomalies are also frank violations of expectation, leading to high detection rates for this type of error. For the canonical sentences, not all of the semantic target words were highly primed, which likely contributed to lower judgment accuracies than for the semantic violation sentences, consistent with previous findings indicating lower accuracy with less expected semantic content (e.g., Kounious and Holcomb, 1992). Children still performed well above chance, approximately 82% accurate, for judgment of canonical sentences. Importantly, there were no group differences in judgment accuracy between conditions. The significant correlation between Word Recall performance and judgment accuracy is discussed in Section 4.4.

One potential confound of the current stimuli is that the phrase structure violation sentences were ~420 ms longer than canonical sentences, due to the additional word. This could contribute to differences in working memory load requirements between the canonical and violation conditions. Previous studies have shown that higher working memory load leads to reduced performance, though most studies have evaluated sentence complexity, not length (for review, see Caplan and Waters, 1999). Higher sentence judgment accuracy for the phrase structure violations compared to the canonical condition indicates that the longer duration of the syntactic violation sentences did not affect sentence judgment performance. However, we did find relationships between verbal working memory abilities and syntactic processing comparable to previous literature (e.g., Friederici et al., 1998; Pakulak and Neville, 2010; Vos et al., 2001), as discussed in Section 4.4.

4.2. Neural responses to semantic and syntactic conditions

The semantic canonical and violation conditions elicited an N400 response followed by an LPC as expected. As discussed in Results, the semantic target words, which were not highly primed (lower cloze probability), such that the canonical sentences elicited N400 components, which can be seen in Fig. 3. This is consistent with previous studies demonstrating N400 components elicited by correct, but less expected, words (e.g., Kutas and Hillyard, 1984; for reviews, see Kutas and Federmeier, 2000, 2011). The N400 component elicited by the auditory sentences in the current study is largest over left hemisphere central and centro-parietal distributed medial–lateral electrode sites, consistent with previous studies (e.g., Hahne et al.,

Fig. 9. Grand average ERPs for the syntactic control target words and syntactic violations for the Low-Normal (left) and High-Normal (right) Word Recall groups are illustrated for medial–lateral electrode sites. P600 amplitudes elicited by the syntactic violations were larger for the High-Normal Word Recall group.
Fig. 10. Grand average ERPs (top) elicited by the syntactic canonical and violation target words for the Low-Normal (left) and High-Normal (right) Grammar groups are illustrated for medial–lateral electrode sites. P600 mean amplitudes (with standard errors) across 100 ms time windows (bottom) illustrate that P600s elicited by the phrase structure violations had an earlier onset for the higher compared to the lower Grammar group. Asterisks (*) indicate significant effects.

The LPC elicited by the semantic anomalies was largest over medial–lateral electrode sites (Fig. 3). While previous studies of auditory semantic processing in children (Hahne et al., 2004; Holcomb et al., 1992) do not specifically report late positive components, inspection of waveforms in these studies reveals the presence of late positivities following N400 components in 7- and 8-year-old children. Together, these findings indicate that children in this age range are engaging later, controlled neural processes for reanalysis of semantic violations and/or integration of semantic violations into the context of the preceding words (Juottonen et al., 1996; Van Petten and Luka, 2012). Interestingly, this
semantic reanalysis and/or integration process appears to be robust regardless of nonverbal IQ, verbal word recall, or grammatical morphology abilities, as the LPC did not differ in relation to higher or lower performance on these tasks.

Syntactic violations elicited the expected biphasic responses consisting of an AN followed by a P600 (Fig. 7). A late syntactic negativity was also elicited by syntactic violations. The AN was largest over bilateral frontal and fronto-centrally distributed electrode sites. A previous study investigating syntactic processing in children found no significant ERP components between 100 and 300 ms, but a significant bilateral anterior negativity between 400 and 600 ms in 7- and 8-year-old children (Hahne et al., 2004). The current results are consistent with the previous findings, demonstrating a significant bilateral AN in a slightly earlier time window, between 250 and 450, in children of the same age. The AN did not differ as a function of Nonverbal IQ, Word Recall, or Grammar proficiency.

Consistent with findings by Hahne et al. (2004), P600 components elicited by syntactic violations were largest over central to parietally distributed electrode sites. Unexpectedly, syntactic violations also elicited late negative components, largest over fronto-temporal and temporal (lateral) electrode sites. Late negativities elicited by syntactic violations have been previously reported in adults by Steinhauser et al. (2010) and Steinhauser and Drury (2012). They report a left-lateralized left anterior negativity and suggest it may be an index of increased working memory demands related to a search of the violated syntactic structure in working memory stores (Steinhauser et al., 2010). However, they did not directly assess relationships between working memory and the late syntactic negativity. The distribution of the late syntactic negativity observed in the current findings differs from that of Steinhauser et al. (2010), which may suggest a less mature, or perhaps a separate, distinct, ERP component. We did not find a relationship between word recall skills and the late syntactic negativity, which may suggest a different ERP component. More work is needed to understand how this late negativity relates to syntactic processing as well as working memory capacity.

4.3 Higher nonverbal IQ is related to greater speed of processing for semantic and syntactic violations

Consistent with our hypothesis, nonverbal IQ was related to semantic processing. However, we also found, unexpectedly, that nonverbal IQ was related to syntactic processing. This was evidenced by earlier initiation of ERPs elicited by both semantic and syntactic violations in children with higher nonverbal IQ. As nonverbal IQ is a measure that relies on interactions between world knowledge, logic, reasoning, and analytical skills (e.g., DeThorne and Schaefer, 2004; McGrew and Flanagan, 1997), it is possible that the stronger cognitive abilities indexed by higher nonverbal IQ facilitated earlier initiation of lexical access or more rapid construction of meaning for unexpected words. Additionally, better logic and analytical skills may facilitate repair or reanalysis of violations of the rule structure of grammar. The present findings suggest that earlier timing of both the N400 and P600 previously associated with increased chronological age (Hahne et al., 2004) may also reflect increased nonverbal reasoning and analytical abilities in older, compared to younger, children.

4.4. Stronger verbal working memory abilities are related to more mature neural indices of semantic and syntactic processing

Word Recall performance was correlated with behavioral accuracy for the online sentence judgment task. While there were no accuracy differences between the higher and lower Word Recall groups, this correlation suggests that children with stronger word association and verbal working memory skills were better able to detect correct sentences as well as sentences containing semantic anomalies and phrase structure violations. Our findings are consistent with previous studies demonstrating higher sentence judgment accuracy for individuals with higher performance on verbal working memory tasks (e.g., Caplan and Waters, 1999; Carpenter et al., 1995).

Stronger verbal working memory abilities, revealed by better performance on the auditory Word Recall task, were associated with greater ease of lexical access/integration, indexed by smaller N400 amplitudes. Better word recall performance has previously been associated with greater reliance on semantic strategies, such as using the semantic relationships or associations between words, and not the serial ordering of words, to improve recollection of word lists (Longenecker et al., 2010). The current findings suggest that stronger word recall abilities, and thus better use of semantic associations, may have facilitated lexical access and/or integration of words, resulting in reduced neural resources allocated toward meaning conceptualization. Furthermore, the current findings suggest that the smaller N400 amplitudes across development previously thought to reflect age-related changes in neural maturation (Holcomb et al., 1992) may also reflect changes in neural functioning associated with improved word association skills in older, compared to younger children.

As hypothesized, stronger verbal working memory abilities were also associated with enhanced P600 amplitudes, which are thought to reflect greater allocation of neural resources toward repair and/or reanalysis of a sentence following the violation of rule-based expectations (Schmidt-Kassow and Kotz, 2009; Pakulak and Neville, 2010). The present findings are consistent with previous reports of larger P600 amplitudes in adults with longer reading spans, indexed by the Daneman and Carpenter Reading Span task, a measure of verbal working memory (Friederici et al., 1998; Pakulak and Neville, 2010; Vos et al., 2001). Larger P600 amplitudes have also been observed with increasing chronological age (Hahne et al., 2004). Thus, the current findings indicate that enhanced P600 amplitudes previously associated with developmental neural maturation in children may also reflect functional changes associated with stronger verbal working memory skills in older, compared to younger, children.
4.5. Advanced grammatical morphology proficiency is associated with increased efficiency in semantic and syntactic processing

As with both nonverbal IQ and verbal working memory, the current results indicate that grammatical morphology skills are also associated with both semantic and syntactic processing. In contrast to our original hypothesis, better performance on a grammatical morphology task was associated with more efficient processes of lexical access and/or integration, as indexed by smaller N400 amplitudes in children with higher grammatical proficiency. Performance on the grammatical morphology task requires strong understanding of relational aspects of words in a sentence (e.g., Lew-Williams and Fernald, 2007; Radford, 1997), and this stronger structural framework (i.e., better association of words within a sentence) may facilitate lexical access and integration. Previous research has found smaller N400 amplitudes with increasing age (Holcomb et al., 1992) and suggests a reduced reliance on sentence context for semantic processing across development. The current findings indicate that strong grammatical morphology abilities may also facilitate reduced reliance on sentence context for lexical access and integration, relying more on sentence structure abilities, and that maturational changes associated with age may in part reflect maturational changes associated with increased grammatical proficiency.

Consistent with our hypothesis, stronger grammatical morphology abilities were associated with earlier initiation, as well as more robust processes, of repair and/or reanalysis of syntactic violations, as indexed by earlier P600 onsets and a broader distribution of the P600 over left hemisphere posterior electrode sites. Children with better performance on the grammatical morphology task are assumed to possess greater knowledge of morphological and syntactic rules. Thus, increased knowledge of grammatical rules may have facilitated more rapid and robust processes of repair or reanalysis of phrase structure violations. Earlier P600 peak latencies have previously been reported with increasing age and have been hypothesized to reflect age-related changes in the brain (Hahne et al., 2004). Additionally, more robust P600 components have been reported in adults with higher language proficiency (Pakulak and Neville, 2010). Together with previous findings, the present results suggest that earlier initiation of and more robust P600 responses previously associated with increased chronological age may, at least in part, reflect increased neural maturational associated with stronger grammatical morphology abilities.

While the current study only assessed rule-based knowledge in the context of grammatical morphology, and elicited the P600 using linguistic stimuli, the P600 has been shown to reflect rule-based knowledge beyond the domain of language (Schmidt-Kassow and Kotz, 2009). Therefore, it is possible that P600 differences observed in the current study suggest a broader relationship between rule-based knowledge and resource allocation for processing violations of rule-based expectancy. Further research is needed to directly assess these relationships outside of the language domain.

4.6. Conclusions and implications

Results from the current study indicate that nonverbal IQ, verbal working memory spans, and grammatical morphology abilities account for some of the variability in timing and resource allocation observed in neural processes mediating semantic and syntactic processing in typically developing children. The relationships between each of the proficiency measures reflecting three broad cognitive domains and the ERPs associated with semantic and syntactic processing are illustrated in Fig. 11. As can be seen in this illustration, increased world knowledge, logical, and analytical skills, indexed by higher nonverbal IQ performance, were associated with timing, or speed of processing, for semantic anomalies and syntactic violations. In contrast, verbal working memory abilities were associated with the allocation of neural resources in that higher verbal working memory skills facilitated lexical access and integration and reprocessing and/or repairing syntactic violations. Grammatical morphology skills, reflecting strong representations of syntactic rule-based knowledge, were related to resource allocation for both semantic and syntactic processing as well as speed of repair or reanalysis of phrase structure violations. Although these three proficiency measures were distinctly associated with specific aspects (i.e., timing or resource allocation) of ERP components, these results do not suggest that the broader domains of analytical computations, processing resources, and rule-based knowledge are independent of one another. Instead, they demonstrate that specific skills within these broader domains have differential relationships, both in nature and degree, with the neural signatures of semantic and syntactic processing. It will be important for future research to investigate how other aspects of cognition and language, such as expressive language, spatial reasoning, nonverbal working memory, and vocabulary, are related to individual variability in ERPs that index language processing.

The current findings suggest that timing and resource allocation for neural processes associated with semantics and syntax may function independently of one another. In other words, faster processing speed does not always correspond with more efficient, or mature, resource allocation. Children with higher nonverbal IQ performance processed semantic and syntactic violations more quickly than lower performing peers, but with comparable neural resources allocated to completing the task. In contrast, children with higher verbal working memory abilities demonstrated more mature resource allocation for processing semantic information and syntactic violations than lower performing peers, but with comparable timing. However, timing and resource allocation are not necessarily distinct either, as children with higher grammatical morphology abilities processed syntactic violations both more rapidly and with greater resource allocation, reflecting more mature processing.

A next step in this line of research is to more precisely identify proficiency measurements of specific, clearly delineated cognitive and language skills. Determining proficiencies based on standardized tests has limitations since these assessment tools often measure composite abilities.
A goal for future studies will be to utilize standardized tests primarily for the inclusion/exclusion criteria of participants, and then additional, more precise tasks could be utilized to measure distinct, well-delineated cognitive abilities. The examination of how very specific operations within the broader cognitive domains influence neural processing of language will provide a more comprehensive understanding about the dynamic interactions of various cognitive operations that support linguistic information processing.

Individual variability and the factors contributing to it have long been of interest to researchers investigating neural indices of language processing. Previous research has identified several elements that contribute to ERP variability across individuals, including handedness (e.g., Kutas and Hillyard, 1982), age (Hahne et al., 2004; Holcomb et al., 1992), socioeconomic status (e.g., Pakulak and Neville, 2010; Stevens et al., 2009), and language proficiency (e.g., Pakulak and Neville, 2010; Weber-Fox et al., 2003). The current study reveals that in earlier studies of neural processing, inclusionary criteria for participants may not be sufficient and some variability may not be accounted for, as performance on specific cognitive and language tasks, even within the normal range, can result in important differences in neural indices of semantic and syntactic processing.

The present findings also have implications for ERP investigations of language processing across development. Developmental changes in language ERPs have often been attributed to maturational changes in the brain (e.g. neuronal density and synaptic connections; Hahne et al., 2004; Holcomb et al., 1992). However, the results of the current study suggest that ERP changes across development may also be attributable, at least in part, to neural changes and maturation associated with growth in cognitive and linguistic abilities. In order to comprehensively characterize neural organization for language, we need to consider and account for individual variability in aspects of cognitive and language proficiency.

Conflict of interest

There is no conflict of interest.

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Appendix A.

Words in *italics* indicate violations. Words with a single *underline* served as comparison words for semantic anomalies. Words with a double *underline* served as comparison words for the phrase structure violation.
Target sentences

1. The alligators fight the snakes at that zoo.
The alligators fight the shoes at that zoo.
The alligators fight the snakes at this that zoo.

2. The animals build the home in this backyard.
The animals build the mouse in this backyard.
The animals build the home in their this backyard.

3. The baby eats the sauce with his fingers.
The baby eats the home with his fingers.
The baby eats the sauce with that his fingers.

4. The boy swings the bat at that ball.
The boy swings the glass at that ball.
The boy swings the bat at his that ball.

5. The bears taste the juice in that bottle.
The bears taste the books in that bottle.
The bears taste the juice in this that bottle.

6. The babysitters sweep the stairs with their broom.
The babysitters sweep the scarves with their broom.
The babysitters sweep the stairs with that their broom.

7. The brothers burn the trash in this can.
The brothers burn the drinks in this can.
The brothers burn the trash in that this can.

8. The butterfly tickles the nose of that tiger.
The butterfly tickles the cake of that tiger.
The butterfly tickles the nose of this that tiger.

9. The cats drink the milk off this plate.
The cats drink the tree off this plate.
The cats drink the milk off their this plate.

10. The chickens watch the snow out their window.
The chickens watch the wood out their window.
The chickens watch the snow out this their window.

11. The child starts the game on that playground.
The child starts the snakes on that playground.
The child starts the game on her this playground.

12. The clowns fit the scarves in their coats.
The clowns fit the cows in their coats.
The clowns fit the scarves in these their coats.

13. The cowboys feed the cows by that bench.
The cowboys feed the doors by that bench.
The cowboys feed the cows by their that bench.

14. The daddy pours the drinks in these cups.
The daddy pours the sleds in these cups.
The daddy pours the drinks in his these cups.

15. The doctor opens the doors to her closet.
The doctor opens the sticks to her closet.
The doctor opens the doors to this her closet.

16. The elephants carry the sticks in their mouths.
The elephants carry the lake in their mouths.
The elephants carry the sticks in those their mouths.

17. The farmers plow the field by this river.
The farmers plow the box by this river.
The farmers plow the field by that this river.

18. The fireman breaks the glass with his hammer.
The fireman breaks the soup with his hammer.
The fireman breaks the glass with this his hammer.

19. The friends shine the shoes at their store.
The friends shine the juice at their store.
The friends shine the shoes at that their store.

20. The girls fill the pool at this park.
The girls fill the rocks at this park.
The girls fill the pool at that this park.

21. The grandma holds the cake at that party.
The grandma holds the field at that party.
The grandma holds the cake at her that party.

22. The grandpa spills the peas on his pants.
The grandpa spills the dog on his pants.
The grandpa spills the peas on that his pants.

23. The kitties climb the tree in their yard.
The kitties climb the bug in their yard.
The kitties climb the tree in that their yard.

24. The lady wakes the dog for his breakfast.
The lady wakes the trash for his breakfast.
The lady wakes the dog for this his breakfast.

25. The mailman drops the box at that church.
The mailman drops the pool at that church.
The mailman drops the box at this his church.

26. The man cuts the meat at his dinner.
The man cuts the cars at his dinner.
The man cuts the meat at this his dinner.

27. The mommy closes the jar by her sink.
The mommy closes the snow by her sink.
The mommy closes the jar by that her sink.

28. The monkeys throw the rocks off this wall.
The monkeys throw the rose off this wall.
The monkeys throw the rocks off that this wall.

29. The nurse hugs the lamb at her house.
The nurse hugs the milk at her house.
The nurse hugs the lamb at that her house.

30. The owls catch the mouse on this porch.
The owls catch the jar on this porch.
The owls catch the mouse on that this porch.

31. The people ride the bus to this circus.
The people ride the dress to this circus.
The people ride the bus to their this circus.

32. The person cooks the soup in this kitchen.
The person cooks the bus in this kitchen.
The person cooks the soup in his this kitchen.

33. The police drive the cars on those streets.
The police drive the bowl on those streets.
The police drive the cars on these those streets.

34. The ponies pull the sleds for these children.
The ponies pull the sauce for these children.
The ponies pull the sleds for those these children.

35. The sister rips the dress on that nail.
The sister rips the peas on that nail.
The sister rips the dress on this that nail.

36. The teachers read the books at their schools.
The teachers read the meat at their schools.
The teachers read the books at these their schools.

37. The turkey dumps the bowl on that grass.
The turkey dumps the lamb on that grass.
The turkey dumps the bowl on this that grass.

38. The turtle hears the bug by that garden.
The turtle hears the cows by that garden.
The turtle hears the bug by this that garden.
39. The uncle swims the lake with his wife.  
   The uncle swims the bar with his wife.  
   The uncle swims the lake with those his wife.  
40. The woman chops the wood on this farm.  
   The woman chops the gum on this farm.  
   The woman chops the wood on her this farm.

**Filler sentences**

41. Abby can knock the lamp off the table.
42. Barbara can touch the ducks at the park.
43. Brian will blow the bubbles at his daddy.
44. Carl would like the ice cream with the strawberries.
45. Celia will paint the pictures in the basement.
46. Dad would buy the tractors with his money.
47. David can bump the high chair with his knee.
48. Emma could stop the tricycle with her feet.
49. Fido will chase the hens in that yard.
50. Fred can jump the sandbox on his bicycle.
51. George will pick the flowers with his grandma.
52. Hannah will dry the dishes in the kitchen.
53. Holly can take the muffins to her friends.
54. Jane could splash the water at the beach.
55. Jimmy can find the pennies in the sofa.
56. Jodie could make the pizza with her hands.
57. Joe could take the popcorn to his bedroom.
58. John will bring the blankets to this picnic.
59. Ken could slide the trucks on the sidewalk.
60. Laura can hide the puppy in this basket.
61. Louis could give the dolls to his sister.
62. Matt will wear the boots in the rain.
63. Sally will draw the pigs with her pencil.
64. Sam will see the giraffes at the zoo.
65. Sarah can show the penguins to her brother.
66. Sarah can show the penguins to her brother.
67. Sharon could wipe the oven in the morning.
68. Spot can shake the sweater off his head.
69. Steve could write the story in the country.
70. Susie can cover the food with her napkin.

**References**


Hollingshead, A., 1975. Four factor index of social status. Yale University, Department of Sociology, New Haven, CT, unpublished manuscript.