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

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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 weakness 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.

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

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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 (Hahne et al., 2004; 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 Luka, 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