NeuroImage xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg

Preschoolers' brains rely on semantic cues prior to the mastery of syntax during sentence comprehension

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A R T I C L E I N F O

Article history:
Received 27 April 2015
Accepted 15 October 2015
Available online xxxx

Keywords:
fMRI
Syntax
Semantics
Language development
Pars opercularis
Pars triangularis

A B S T R A C T

Sentence comprehension requires the integration of both syntactic and semantic information, the acquisition of which seems to have different trajectories in the developing brain. Using functional magnetic resonance imaging, we examined the neural correlates underlying syntactic and semantic processing during auditory sentence comprehension as well as its development in preschool children by manipulating case marking and animacy hierarchy cues, respectively. A functional segregation was observed within Broca's area in the left inferior frontal gyrus for adults, where the pars opercularis was involved in syntactic processing and the pars triangularis in semantic processing. By contrast, five-year-old children sensitive to animacy hierarchy cues showed diffuse activation for semantic processing in the left inferior frontal and posterior temporal cortices. While no main effect of case marking was found in the left fronto-temporal language network, children with better syntactic skills showed greater neural responses for syntactically complex sentences, most prominently in the posterior superior temporal cortex. The current study provides both behavioral and neural evidence that five-year-old children compared to adults rely more on semantic information than on syntactic cues during sentence comprehension, but with the development of syntactic abilities, their brain activation in the left fronto-temporal network increases for syntactic processing.

Introduction

An essential aspect of sentence comprehension is to understand the relations between words in a string, such as the agent–patient relation which determines who is doing what to whom. Humans make use of several cues carried by the components to determine which participant in a sentence is the actor of an action expressed by the verb, thereby helping with interpretation. Take an English sentence "*she plays the piano*" for example. One could use several cues in the sentence to identify *she* as the agent to play and *the piano* as the patient to be played, such as (1) animacy hierarchy—an animate noun *she* is more likely to act upon an inanimate noun *the piano*; (2) "subject–verb–object" word order—the noun before the verb (i.e., *she*) is the subject, and the noun after the verb (i.e., *the piano*) is the object; (3) case marking—the first noun *she* is a subject pronoun but not an object pronoun (i.e., *her*). While it seems to be an automatic process for adults to interpret sentences by assigning different weights to the available cues (MacWhinney et al., 1984), sentence comprehension is nonetheless a challenging task for the developing cognitive system (Bates et al., 1984).

According to the competition model, the age of acquisition of a sentential cue is determined by its cue validity, which is jointly influenced by cue availability and cue reliability in the target language (Bates and MacWhinney, 1982; Bates et al., 1984). Mastery of these cues only occurs gradually over time during language development (Bates et al., 1984; Chan et al., 2009; Dittmar et al., 2008). For the German language, previous behavioral studies have demonstrated that German-speaking children show primacy in the acquisition of animacy cues, followed by word order, and do not rely on case marking over other cues until the age of seven or later (Chan et al., 2009; Dittmar et al., 2008; Lindner, 2003). The late acquisition of syntactic case marking may be attributed to its low validity in German particularly due to lower availability of unambiguous case marking (Mahlstedt, 2007). Other studies have also suggested that semantic information directly influences syntactic analysis in children's sentence processing (Deutsch et al., 1999; Friederici, 1983). Hence, semantic cues seem to play a more important role for children compared to adults during sentence comprehension (MacWhinney et al., 1984).

Apparently, sentence comprehension is achieved by integrating the syntactic and semantic information provided. Evidence from functional neuroimaging studies with adults has shown that while syntactic and semantic processing both involve a left-lateralized fronto-temporal network, each function seems to be supported by segregated regions in the brain (Friederici et al., 2000; Newman et al., 2003, 2010; Ni et al., 2000). While the pars opercularis of the left inferior frontal gyrus (IFG), that is, Brodmann Area (BA) 44, and the left posterior superior temporal gyrus/sulcus (posterior STG/STS) have been reported to show increased activation for processing more complex syntactic sentences compared to

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http://dx.doi.org/10.1016/j.neuroimage.2015.10.036
1053-8119/© 2015 Published by Elsevier Inc.

less complex sentences (Constable et al., 2004; Friederici, 2011; Friederici et al., 2009; Grewe et al., 2007; Kinno et al., 2008; Mack et al., 2013; Makuuchi et al., 2009; Meltzer et al., 2010; Santi and Grodzinsky, 2010), sentential semantic processing has been shown to be subserved by pars triangularis (BA 45) and pars orbitalis (BA 47) of the left IFG as well as the left posterior STS (Binder et al., 2009; Bruffaerts et al., 2013; Grewe et al., 2007; Mestres-Missé et al., 2008; Newman et al., 2010; Rodd et al., 2005). These neuroimaging findings from adults provide a valuable neurocognitive model of language against which the development of semantic and syntactic processing in children can be discussed.

Yet the neural network underlying sentence processing in young children has only been sparsely investigated. Existing studies suggest that functional segregation in the fronto-temporal regions in children is not as crisp as in adults. Using transitive sentences containing either syntactic or semantic violations, Brauer and Friederici (2007) demonstrated that while adults showed function-specific activation in the left STG and the frontal operculum for syntactic as compared with semantic processing, five- to six-year-old children recruited largely overlapped activation in the left STG and bilateral IFG. Skeide et al. (2014) used correct sentences in a sentence–picture matching task with manipulations of syntactic complexity and semantic plausibility, and demonstrated that three- to four-year-old children showed no main effect, but only interaction effects between syntax and semantics in the mid and posterior portion of STG. In addition to interaction effects, six- to seven-year-old children also started to show main effects of syntax and semantics in the mid to posterior STG/STS, but children at the ages of nine to ten had a segregated main effect of syntax in the left IFG and a main effect of semantics in the anterior STG/STS. This study provides strong neural evidence that children do not process syntax independently from semantics in sentence interpretation until the age of ten.

Moreover, there are a number of studies that report cortical activation for syntactic processing to be associated with children's behavioral performance. In children aged between seven and fifteen years, it was found that the activation in the left IFG in response to syntactic processing increased with above average proficiency of syntactic skills independent of age (Nuñez et al., 2011). In another study with children between four and six years of age, it was shown that even in these young children, a subgroup with better syntactic knowledge already showed enhanced activation in the left BA 44 for non-canonical object-first sentences compared to canonical subject-first sentences (Knoll et al., 2012). These studies indicate that the neural representation underlying language processing is dependent on the development and maturation of the brain, which in turn is correlated with children's linguistic skills. A direct correlation between the brain's functional development of four language-related regions as well as the structural maturation between these and the syntactic processing skills between the ages of three to ten years has recently been demonstrated by Skeide et al. (2015).

The current study used functional magnetic resonance imaging (fMRI) to specify the neural correlates underlying processing of syntactic canonicity and of semantic animacy, as well as the interaction between these, during auditory sentence comprehension in the developing and mature brain. In a sentence listening paradigm, we manipulated case marking as the syntactic cue and animacy hierarchy as the semantic cue. Five-year-old children were selected to compare with adults as children at this age are already sensitive to the animacy hierarchy but have only started to learn case marking cues. This allows us to examine whether children with different levels of syntactic knowledge, independent of age, may show different patterns of neural activation for syntactic processing and how this interacts with animacy information. Adults were chosen as the control group as their neural responses would serve as a reference model for sentence comprehension under the task manipulation. Moreover, in the current study, analyses tested for whole brain effects as well as for anatomically defined a priori regions-of-interest (ROIs) in the perisylvian areas that have been identified relevant for processing sentence comprehension in previous studies as described above, namely the pars opercularis and pars triangularis in the left IFG, the left posterior STS, and the left posterior STG (Bahlmann et al., 2007; Ben-Shachar et al., 2003; Binder et al., 2009; Bornkessel et al., 2005; Bruffaerts et al., 2013; Constable et al., 2004; Friederici, 2011; Friederici et al., 2009; Grewe et al., 2007; Kinno et al., 2008; Makuuchi et al., 2009; Mestres-Missé et al., 2008; Moro et al., 2001; Musso et al., 2003; Newman et al., 2010; Obleser et al., 2007; Rodd et al., 2005; Röder et al., 2002; Saur et al., 2008; Tyler et al., 2005).

Materials and methods

Participants

Fifty-six children at the age range of 5;1 to 5;11 were initially recruited. A number of children had to be excluded from the study for the following reasons: two children showed incidental findings; eleven did not finish the fMRI task; three were ambidextrous or left-handed (scores ≤ 20 in the modified version of Edinburgh Handedness Inventory (Oldfield, 1971)); three had large movement during fMRI scanning exceeding 3 mm at any translation axis and/or 3° at any rotation. Consequently, data from thirty-seven children were preprocessed and analyzed. A group of sixteen adults served as a control group. After individual-level analyses, activation maps contrasting all individual sentence conditions versus the silence condition (rest) were examined as a basic activation check, which were expected to show activation in the bilateral auditory cortices as the sentences were auditorily presented. Seven children and one adult were excluded from group-level analyses as they did not show any activation in the auditory cortices for this baseline contrast even at the threshold of $p < 0.05$ (uncorrected). As a result, the final group-level analyses consisted of thirty children (ten boys, age range 5;1–5;11, $M = 5;6$, SD = 0;3.45; handedness scores range 40–100, $M = 78.1$, $SD = 17.8$) and fifteen adults (eight males; age range 21–32, $M = 25.5$, $SD = 3.27$; handedness scores range 36.8–100, $M = 83.0$, $SD = 16.9$). All participants were native German speakers, and had no history of medical, psychiatric or neurological disorders. Written informed consent was obtained from all adult participants and the parents of the children. Children gave verbal assent prior to participation. The study was approved by the Institutional Review Board of the University of Leipzig.

Task design and materials

In German language, case marking in the article of the noun phrase indicates the subject (nominative case) and the object (here: accusative case). While canonical sentences are subject-first, German as a free word order language also possesses non-canonical object-first sentences. Stimulus materials consisted of 150 five-word German sentences composed of two noun phrases (NPs) and one verb (V) following a NP–V–NP structure. Only grammatically masculine nouns were used, for which case marking variation of the nominative and accusative forms is unambiguous. The sentences varied in two factors: syntactic case marking and semantic animacy hierarchy. Case marking variation was used to introduce canonical subject-first and non-canonical object-first sentences that differed by syntactic structure but not by semantic content. Animacy hierarchy of the nominatives and the accusatives in the NPs was defined with three levels as neutral hierarchy (animate agent and animate patient, AA), prototypical hierarchy (animate agent and inanimate patient, AI), and non-prototypical hierarchy (inanimate agent and animate patient, IA). The manipulation of case marking and animacy hierarchy factors resulted in a 2 × 3 within-subjects designed experiment composed of six conditions: C-AA, C-AI, C-IA, NC-AA, NC-AI, and NC-IA (see Table 1 for examples of sentences). Each condition consisted of 25 sentences, and each sentence lasted for 3.29 s on average ($SD = 0.02$ s). For both children and adults, the

Please cite this article as: Wu, C.-Y., et al., Preschoolers' brains rely on semantic cues prior to the mastery of syntax during sentence comprehension, NeuroImage (2015), http://dx.doi.org/10.1016/j.neuroimage.2015.10.036