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Brain structural correlates of complex sentence comprehension in children

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ABSTRACT

Prior structural imaging studies found initial evidence for the link between structural gray matter changes and the development of language performance in children. However, previous studies generally only focused on sentence comprehension. Therefore, little is known about the relationship between structural properties of brain regions relevant to sentence processing and more specific cognitive abilities underlying complex sentence comprehension. In this study, whole-brain magnetic resonance images from 59 children between 5 and 8 years were assessed. Scores on a standardized sentence comprehension test determined grammatical proficiency of our participants. A confirmatory factory analysis corroborated a grammar-relevant and a verbal working memory-relevant factor underlying the measured performance. Voxel-based morphometry of gray matter revealed that while children's ability to assign thematic roles is positively correlated with gray matter probability (GMP) in the left inferior temporal gyrus and the left inferior frontal gyrus, verbal working memory-related performance is positively correlated with GMP in the left parietal operculum extending into the posterior superior temporal gyrus. Since these areas are known to be differentially engaged in adults' complex sentence processing, our data suggest a specific correspondence between children's GMP in language-relevant brain regions and differential cognitive abilities that guide their sentence comprehension.

1. Introduction

Compared to other species, humans show a prolonged phase of brain functional specialization that allows the brain to be shaped by postnatal experience. This delayed time course in brain maturation provides more time for learning processes (Johnson, 2001), and the delayed prefrontal maturation is especially suggested to be an adaptation of the human brain necessary for the development of social and linguistic conventions (Thompson-Schill et al., 2009). Although children acquire basic principles of their native language incredibly fast, the ability to process complex sentences develops rather late. In developmental literature, it is discussed whether this can be attributed to lack of linguistic competence (e.g., Sheldon, 1974; Tavakolian, 1981), lack of experience (e.g., Diessel and Tomasello, 2005), or limitations in processing capacities (e.g., Goodluck and Tavakolian, 1982). However, the relation between the physical growth of the brain and development of cognitive milestones such as complex sentence processing remains largely unclear. Brain volume drastically increases early in life, and at 6 years of age children have reached approximately 90% of the adult brain volume (Courchesne et al., 2000; Lenroot and Giedd, 2006; Reiss et al., 1996). This structural increase originates from exceeding progressive changes such as an overgrowth of cell bodies (Petanjek et al., 2008), dendritic sprouting (Simonds and Scheibel, 1989), and an overgrowth of synaptic connections (Huttenlocher and de Courten, 1987; Rakic et al., 1986) in the gray as well as myelination (Yakovlev and Lecours, 1967) in white matter compartments. However, during preadolescence, the developmental pattern of gray matter is inverted and maturation is generally defined as a loss of gray matter density (Giedd et al., 1999; Giedd and Rapoport, 2010; Gogtay et al., 2004; Gogtay and Thompson, 2010; Lenroot and Giedd, 2006; Raznahan et al., 2011; Sowell et al., 2003; Taki et al., 2013). Onset and rate of gray matter loss is region-specific and follows a functional maturation sequence, starting with gray matter reduction in early-maturing primary sensorimotor areas, followed by gray matter reduction in late-maturing higher-order association areas (Gogtay et al., 2004; Brain Development Cooperative Group, 2012). While progressive changes in the cortical development are assumed to provide the basis for neural plasticity and thus maximal learning opportunities (Johnson, 2001; Simonds and Scheibel, 1989), regressive changes in the cortex, such as synaptic pruning (Rakic et al.,

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1986), have been related to a decline of the brain's ability to adapt to environmental input during development (Huttenlocher, 2002).

As the phylogenetic evolutionary development of the brain has been associated with the evolvement of language, it is suggested that the ontogenetic maturation, especially of the prefrontal cortex, can be related to language acquisition (e.g., Thompson-Schill et al., 2009). Prior structural imaging work found initial evidence for the link between structural gray matter changes and the development of language performance in children: Infants' gray matter maturation of the right cerebellum and the right hippocampus was found to correlate with later language competence (Deniz Can et al., 2013). The receptive and productive phonological skills of children aged between 5 and 11 years correlate with measurements of gray matter probability (GMP) in the left inferior frontal gyrus (IFG; Lu et al., 2007). In teenagers aged between 12 and 17 years, gray matter of the left supramarginal gyrus and left posterior temporal regions correlate with vocabulary knowledge (Richardson et al., 2010). However, no study to date closely examined gray matter maturation in relation to the processing of syntactically complex sentences. Frontal and parietal areas have been shown to be involved in complex sentence processing (for a review, see Friederici, 2011). With regard to brain structure, the frontal and parietal lobe demonstrate an increase of gray matter during childhood (Giedd et al., 1999; Lenroot et al., 2007; Matsuzawa et al., 2001; Shaw et al., 2008) and an onset of gray matter loss around 9.6 years (frontal) and 10.7 years (temporal) of age (Tanaka et al., 2012).

Sentence comprehension crucially depends on determining the thematic relationship of noun phrases, that is, on identifying who is doing what to whom. While in English, word order provides a reliable cue for assigning thematic roles to noun phrases (i.e., agent, theme and goal), in German, the assignment additionally depends on processing morphological information such as case-marking. Behaviorally, it has been reported that German-speaking children cannot reliably process this kind of morphological information up to the age of 7 years (Dittmar et al., 2008; Schipke et al., 2012). In addition, several studies found that before 7 years of age, children do not demonstrate reliable subvocal rehearsal that increase verbal working memory capacity and, consequently, facilitate complex sentence processing (e.g., Gathercole et al., 2004; Gathercole and Hitch, 1993).

To elucidate on the missing link between brain structural properties of cortical regions relevant for complex sentence processing and the establishment of grammatical proficiency, we investigated the interrelation between GMP in language-relevant brain areas and specific cognitive abilities underlying complex sentence comprehension. To do this, whole-brain magnetic resonance images from 59 children aged between 5 and 8 years were assessed and analyzed using voxel-based morphometry (VBM). We determined grammatical proficiency by scores attained from grammar-specific subtests of the German version of the Test for the Reception of Grammar (TROG-D; Fox, 2006): Here, only sentences that required specific morphological and syntactic knowledge were included in the analysis. To segregate different contributions of grammatical knowledge and verbal working memory capacity to the comprehension of complex sentences, a principal component analysis was run on the participants' behavioral data. To investigate a relation between these two factors and GMP on whole-brain level, a multiple regression analysis was performed. Finally, since the maturation of the prefrontal cortex has been associated with the development of linguistic conventions (Thompson-Schill et al., 2009) and the processing of syntactically complex sentences typically engages the left IFG (for a review, see Friederici, 2011), additional correlational analyses were restricted to this specific region.

2. Methods

2.1. Participants

Children were recruited through letter announcements in local kindergartens and schools. Interested parents were invited for an informative meeting about the experiment and procedures. They gave informed written consent and children gave verbal assent prior to assessment and scanning. Children's parents filled out a questionnaire to ensure all participants were monolingual German speakers, had no neurological, medical, or psychological disorders, and no contraindications for obtaining a magnetic resonance imaging (MRI) examination.

Ten children had to be excluded from the study because of too much head movement during the anatomical scan ($N = 8$) or brain anomalies ($N = 2$). Eventually, data from 28 children aged between 5 and 6 years (mean age: 5;11 years; range: 5;1 to 6;8 years; 13 boys and 15 girls) and 21 children aged between 7 and 8 years (mean age: 7;11; range: 7;1 to 8;9; 11 boys and 10 girls) were analyzed. Our group of children had a normal range of sequential processing skills in the verbal and visual domain (mean = 105; standard deviation = 12.05) administered by the Kaufman Assessment Battery for children (K-ABC; Kaufman et al., 1994). The socioeconomic status (SES) of our group was determined by maternal education converted into the International Standard Classification of Education (ISCED 11, UNESCO Institute for Statistics, 2012). As with many other developmental studies, the group was weighted towards a high SES with 30% of the parents having upper-secondary education or post-secondary non-tertiary education (ISCED 3 and 4), 21.3% of the parents having short-cycle tertiary education or a Bachelor's degree (ISCED 5 and 6), 43.8% of the parents having a Master's degree (ISCED 7), and 3.8% having a doctoral degree (ISCED 9; general distribution of educational attainment in Germany: 50% ISCED 3/4; 8.6% ISCED 5/6; 13.6% ISCED 7; 1.1% ISCED 8; Bildungsbericht 2014, n.d.). The Research Ethics Committee of the University of Leipzig (Leipzig, Germany) approved the procedure and protocol of the study.

2.2. Assessment of grammatical proficiency and verbal working memory

Children's language comprehension skills were determined by the TROG-D (Fox, 2006). This is a standardized sentence comprehension test for children aged between 3 and 11 years. The comprehension of increasingly complex sentence structures is assessed by 21 grammatical constructions comprising four test items resulting in a final set of 84 items. Sentences are presented auditorily, and the child is asked to point to one out of four pictures whereby incorrect pictures depict either deviating lexical or grammatical interpretations.

We employed the Mottier Test (Mottier, 1951) to assess the children's verbal working memory abilities. Children had to listen to pseudowords with an increasing number of syllables and repeat them immediately after the presentation. For constant presentation, test items were recorded by a trained female speaker and subsequently digitized (44.1 kHz/16 bit sampling rate, mono), normalized according to the root-mean-square amplitude of all files, and presented via headphones. To make the procedure more suitable for children, we presented stimuli in form of a repetition game. Participants were introduced to a parrot on the screen who told them to repeat the items exactly how he pronounced them. To prevent lexicalization of the pseudowords during repetition, children were told that they cannot know the words they would hear since the parrot speaks a foreign parrot language. Children's responses were recorded via a portable mini disk recorder (Sony, Ft. Myers, FL, USA). These tests and an abridged version of the test for handedness