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# Functional organization of the language network in three- and six-year-old children

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## ABSTRACT

The organization of the language network undergoes continuous changes during development as children learn to understand sentences. In the present study, functional magnetic resonance imaging and behavioral measures were utilized to investigate functional activation and functional connectivity (FC) in three-year-old (3yo) and six-year-old (6yo) children during sentence comprehension. Transitive German sentences varying the word order (subject-initial and object-initial) with case marking were presented auditorily. We selected children who were capable of processing the subject-initial sentences above chance level accuracy from each age group to ensure that we were tapping real comprehension. Both age groups showed a main effect of word order in the left posterior superior temporal gyrus (pSTG), with greater activation for object-initial compared to subject-initial sentences. However, age differences were observed in the FC between left pSTG and the left inferior frontal gyrus (IFG). The 6yo group showed stronger FC between the left pSTG and Brodmann area (BA) 44 of the left IFG compared to the 3yo group. For the 3yo group, in turn, the FC between left pSTG and left BA 45 was stronger than with left BA 44. Our study demonstrates that while task-related activation was comparable, the small behavioral differences between age groups were reflected in the underlying functional organization revealing the ongoing development of the neural language network.

## 1. Introduction

When children acquire language, they are confronted with the challenge to decode the relationship between the entities of an utterance, which requires identification of the specific grammatical and thematic roles each entity plays. To do so, they have to detect the linguistic cues and regularities that the particular language provides. In a transitive sentence, for instance, they have to identify the action and discriminate the actor from the patient of the action. Several cues are available to decode the relationship between noun phrases in a sentence (e.g., case marking, word order, animacy hierarchy). The weighting of these cues varies across language. A popular framework used to explore the acquisition of linguistic cues, the Competition Model (Bates, 1982; MacWhinney et al., 1984), proposes that consistency and frequency of a cue in a given language determine how early it will be learned. In a German transitive sentence like (1a), the word order indicates the first argument as the agent and the second as the patient, which coincides with the case marking cue expressed at the determiners of the noun phrases. The determiner *der* in German marks the nominative (NOM) singular (SING) case and assigns the agent role to the first noun, whereas the accusative (ACC) marking *den* on the second noun phrase indicates the patient role. In sentence (1b) that conveys the same semantic information, however, word order and case marking cues would suggest competing interpretations, in which case the latter is the reliable solution.

(1a) Der Fuchs trägt den Wolf.
  The [NOM.SING] fox carries the [ACC.SING] wolf.
  “The fox carries the wolf”.
(1b) Den Wolf trägt der Fuchs.
  The [ACC.SING] wolf carries the [NOM.SING] fox.
  “The fox carries the wolf”.

Assumptions of the Competition Model about the consecutive acquisition of such cues are supported by several behavioral observations. Dittmar et al. (2008) showed that two-year-old German children were capable of interpreting prototypical transitive sentences above chance level when word order and case marking cues were consistent. Moreover, Chan et al. (2009) extended this finding by demonstrating the transition of cue reliance towards word order in three age groups (2;6, 3;6 and 4;6) with the highest use of word order in the oldest group while the youngest still relied on a combination of two cues (word order

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and animacy). From the age of five, case marking becomes more pivotal for sentence interpretation than word order (Lindner, 2003; Schanerwolles, 1989), and children could rely on case marking over word order when the two cues conflicted only by the age of seven (Dittmar et al., 2008). These behavioral findings highlight two critical periods for the transition of cue acquisition: sentence comprehension relies more on word order at the ages of two to four and case marking becomes more prominent at the ages of five to seven.

In the context of syntactic cue processing, two brain regions have been consistently observed in the adult brain: the posterior part of the left superior temporal gyrus/sulcus (pSTG/pSTS) and a subdivision of the left inferior frontal gyrus (IFG), Brodmann area (BA) 44 (pars opercularis). These regions have been reported repeatedly in language studies dealing with the need to process syntactic relationships, such as reading sentences containing syntactic movement operations (Ben-Shachar et al., 2004), reading sentences opposed to word lists (Humphries et al., 2005; Snijders et al., 2009), or reading sentences with different levels of syntactic complexity (Friederici, 2011; Friederici et al., 2009; Santi and Grodzinsky, 2010). The left pSTG has been suggested to fulfill an integrative role in verb-argument-dependent information (i.e., lexico-semantic features of a verb which determine the predictability of an argument) in natural language processing (Friederici, 2011, 2012) and is often reported together with activation of the left IFG in experimental paradigms varying the degree of syntactic complexity (e.g., the number of embedded structures). The left IFG is an important region involved in complex syntactic processing and has been shown to be involved in processing of recursion (i.e., the ability of linguistic structure to contain itself) (Friederici et al., 2009). In another study, Friederici et al. (2006b) also demonstrated BA 44 as being sensitive to the degree of syntactic manipulation in grammatical sentences but insensitive to ungrammatical sentences that involved violations of phrase structure. This is concordant with findings on artificial grammar learning, in which BA 44 repeatedly showed activation for syntactic operations in expressions without lexical content (Bahlmann et al., 2006, 2007, 2008; Friederici et al., 2006a). Whereas activation of the left BA 44 is mostly found for syntactic processes, the more anterior part of the left IFG, namely BA 45 (pars triangularis), is thought to subserve semantic processing (Friederici, 2002, 2011; Newman et al., 2003, 2010; Wu et al., 2016). For instance, it has been interpreted as being involved in processing thematic aspects of verb semantics in a study by Newman et al. (2003), in which the presence of an extra verb elicited activation in BA 45 whereas activation for agreement violations was found in BA 44.

Recent studies have focused more on the functional interplay of the language network. A functional relationship between the left IFG and pSTG in the adult brain was shown earlier in resting state functional connectivity (FC) studies (Cordes et al., 2000; Kelly et al., 2010; Muller and Meyer, 2014; Zhu et al., 2014). Another study examined the low-frequency components of task activation residuals and showed connectivity between the left pSTG and BA 44 in language over non-language experiments (Lohmann et al., 2010). As indicated in studies on functional localization (e.g., Ben-Shachar et al., 2004; Friederici et al., 2006a), there is established knowledge of a general functional relationship between these two regions but only few studies investigated how FC is modulated by task requirements. Yue et al. (2013) found that FC between the left BA 44 and pSTG was higher in a sentence comprehension task requiring active responses compared to passive listening. In another study, FC between the left BA 45 and pSTG was found to be higher for intelligible compared to unintelligible speech processing (Ge et al., 2015). The functional relation between frontal and temporal regions of the language network has been described as a top-down relationship (Skeide and Friederici, 2016). One aspect of top-down processing may be that it focuses on task relevant components of the input and is thought to increase as development advances (Bitan et al., 2006, 2009). These latter findings indicate task responsiveness of the mature language network, although its particular role and possible modulations regarding syntactic processing remain to be further investigated.

Accounts have been made to track the development of the language network with age and to link them to behavioral changes. As demonstrated in a study on syntactic and semantic interaction in three- to ten-year-old children (Skeide et al., 2014), the specialization of the language network is gradually established as development progresses. The authors investigated sentence comprehension in children from three age groups (ages of three to four, six to seven, and nine to ten) using a picture matching task in which syntactic complexity and semantic plausibility of relative clauses were varied. An interaction of syntax and semantics was observed in the left mid to posterior STG for the youngest group of three- to four-year-olds. In addition to an interaction, the group of six- to seven-year-olds also showed a main effect of syntax in the left pSTG, whereas only the older children (nine- to ten-year-olds) showed an adult-like main effect of syntax in the left IFG (including BAs 44/45). Moreover, several developmental studies on language processing have shown that the neural organization undergoes several changes accompanied by behavioral changes. Nunez et al. (2011) found a correlation between syntactic proficiency and activation in the left BA 44 for the processing of complex syntax in children aged between seven and fifteen, with those who performed better in a standardized language task showing more prominent activation. Knoll et al. (2012) observed that activation of the left BA 44 was dependent on the grammatical capabilities of the children, and only the more proficient group of children showed adult-like activation for object-initial compared to subject-initial sentences. Wu et al. (2016) also reported a positive correlation between syntactic capability and brain activation in the left BA 44 and left pSTG/pSTS for processing non-canonical object-initial sentences in five-year-old children. These studies all showed that the correlation between behavioral proficiency and activation in the left fronto-temporal regions was independent of age.

While the development of the language network has gained increasing attention over the past ten years, research on its functional interplay especially in the context of syntactic processing remains sparse. Few studies investigating resting state functional connectivity in children reported a functional relationship between the left IFG and pSTS. Xiao et al. (2016a) found FC between the left BA44 and pSTS in five-year-old children associated with their understanding of object-initial transitive sentences assessed by an offline picture selection task and that this functional network develops with increasing syntactic abilities over one year from age 5 to age 6 (Xiao et al., 2016b). In a causal connectivity analysis in six- to fifteen-year-old children, Wilke et al. (2009) reported that in a “beep” story passive listening task (in which keywords were replaced by sinus tones) the left inferior frontal region (including BA 44) and the left posterior region (including pSTG) induced the strongest effect on other regions. However, they differed in the amount of input they received: lowest in the frontal and highest in the posterior regions. In addition, the development of structural connections also allows us to draw inferences on the information flow in the language network during different developmental stages. In a diffusion-weighted imaging study, Skeide et al. (2015) showed that fractional anisotropy (FA) of the dorsal pathway (connecting the left BA 44 and the left pSTG via the arcuate fasciculus) was significantly higher in six- to seven-year-olds compared to three- to four-year-olds, whereas the ventral route (connecting the left BA 45 and the left pSTG via the inferior fronto-occipital fasciculus) showed no difference in FA values between these age groups. Another series of studies also reported relatively late maturation of the arcuate fasciculus. Perani et al. (2011) demonstrated that in newborns the ventral pathway was already present, whereas the connection of the left BA 44 to the left pSTG was only detectable in seven-year-old children (Brauer et al., 2011, 2013). These findings suggest that the dorsal route from BA44 to pSTG needs a certain maturation status in order to be fully employed for sentence processing, while the ventral route from BA45 to pSTG is engaged for these processes already at younger ages.

The present study aims to reveal the functional relationships underlying syntactic processing in the developing brain. We investigated the functional network subserving sentence comprehension at two developmental stages in three- and six-year-old children, ages at which word order and case marking cues may be used differently with word order preceding case marking. Moreover, considering the abovementioned evidence from functional and structural connectivity studies, we expect to find differences in FC between the groups of six-year-olds and three-year-olds. We hypothesize that six-year-olds would show stronger connectivity between the left BA 44 and the left pSTG compared to three-year-olds, while the latter group would rely more on the connection between the left BA 45 and the left pSTG.

## 2. Material and methods

### 2.1. Participants

Initially 55 children aged six and seventy-six children aged three were recruited from an internal participant database as well as via letter announcements in local kindergartens. All children had a monolingual German familial background. A questionnaire was completed by the parents to assure that the children had no history of psychological, medical or neurological diseases, or any hearing impairments. Experimental procedure was explicated to the parents in an informative briefing. They declared written consent to their children's participation in the study, and the children gave verbal assent prior to the experiment. The study was approved by the Ethical Review Board of the University of Leipzig.

Testing young children in the scanner is not always easy, particularly when they are awake as in the present study. Here they were required to attentively listen to 60 sentences presented during fMRI scanning and to lie still during the entire scanning session which lasted 7 min. A number of children were not able to lie still and complete the entire session.

In the group of six-year-old (6yo) children, 6 children had to be excluded due to extensive movement during the fMRI-scanning session to more than 3 mm at any translation axis or 5° at any rotation. Ten children were excluded for not completing at least 60% of the experimental trials and additional 5 children were not considered for analysis because of missing behavioral data. Additional children were excluded from the final analyses as they were left-handed or ambidextrous. Five children were left-handed (i.e., handedness score $< -40$ in the modified version of the Edinburgh Handedness Inventory (Oldfield, 1971)) and three were ambidextrous (handedness score between −40 and 40). Among these children, we examined the lateralization of brain activation for the basic sound (i.e., sentence conditions) against baseline (i.e., null events) contrast, and further excluded three left-handed and two ambidextrous children as they had right-lateralized activation or no activation at all.

In the group of three-year-olds (3yo), several children had to be excluded for the following reasons: 19 children due to non-compliance in either the mock-up or the scanning sessions, 3 having tympanic tubes after being recruited to the study, 11 due to extensive movement (using similar criteria as for the six-year-olds), and 22 for not completing at least 60% of the experimental trials.

As a result, we had 29 children in the group of 6yo (15 females; age $M$=78.6 months, $SD$=3.4; handedness score $M$=64.8, $SD$=44.6) and 21 in the group of 3yo (12 females; age $M$=43.4 months, $SD$=3.4; handedness score $M$=63.4, $SD$=23.3) for the final analysis.

In addition, we also invited 22 adults (11 females; age range: 21–35 years, $M$=26.5, $SD$=3.7; handedness score: $M$=92.3, $SD$=8.4) to participate in this study, and their brain responses served as a reference model for functional localization of regions of interest (ROIs) for later analyses. We had to exclude one participant from the adult's group who was exposed to the stimuli before in a related EEG-study due to experimenter error.

### 2.2. Behavioral assessment

Standardized behavioral assessment of all children was conducted and used to ensure appropriate homogeneity and development stage of the participants. General language competence was assessed using a short version of “Test zum Satzverstehen bei Kindern” (Siegmüller et al., 2011). The Mottier test (Mottier, 1951) and forward and backward digit span tests (Kaufman et al., 2003) were conducted to assess phonological and general working memory abilities of the children.

### 2.3. Stimuli and task

We manipulated word order with case marking cues in an auditory sentence comprehension task. For the experimental stimuli, the factor WORDORDER was set up by two variations of transitive sentences in German: subject-initial and object-initial sentences. Only animate and grammatically masculine nouns were used as they unambiguously display nominative (NOM) or accusative (ACC) case marking at their preceding determiner (examples 2a/b). For the creation of the experimental stimuli, the German corpora Child Language Data Exchange System (CHILDES) and SETK-2 (Grimm et al., 2000) were consulted to obtain appropriate verbs and nouns. We selected verbs that (1) were transitive verbs, (2) did not require an instrument or a further object for physical interaction, and (3) were not particle verbs. Furthermore, each word did not have more than two syllables. The sentences were recorded by a trained female native German speaker in a child-directed manner. The recorded sentences were digitized (44.1 kHz, 32-bit sampling rate, mono) and normalized to the root mean squared amplitude.

(2a) Der Hund schiebt den Tiger.
[the dog]$_{\mathrm{NOM}}$ pushes [the tiger]$_{\mathrm{ACC}}$.
The dog pushes the tiger.
(2b) Den Tiger schiebt der Hund.
[the tiger]$_{\mathrm{ACC}}$ pushes [the dog]$_{\mathrm{NOM}}$.
The dog pushes the tiger.

### 2.4. fMRI testing

Before entering the MR device, children were familiarized with the experimental setup during a practice session in a mock MR scanner no more than seven days before the actual scanning session. The experimenter instructed the children as follows: “I'm going to play some short stories to you. You have to listen carefully who is doing what to whom. Afterwards there will be a riddle on those stories”. They were instructed to lie still inside of the mock scanner, and they received verbal feedback via headphones regarding their movement. Similar sentences containing different verbs and nouns from the experimental stimuli were used in the mock-up session. After the practice, children were asked questions about which animals and actions they could recall. Only children who passed the mock-up session were invited to participate in the experiment.

The experiment consisted of 70 trials: 30 sentences per condition (subject-initial and object-initial sentences) and 10 null events. The order of the trials was pseudo-randomized with the constraint of no more than 3 trials of the same condition in a row. Each trial lasted for 6 s resulting in an experiment length of 7 min. The onsets of trials were randomly jittered at 0, 500, 1000 and 1500 ms after the beginning of the first scan. Stimuli were presented auditorily via MR-compatible headphones. Each sentence presentation was accompanied by the presentation of two pictures arranged vertically depicting the two animals named in the sentence via LCD-goggles. The pictures of the subject and object nouns were randomized in their position and the looking direction of the animals (i.e., left or right). During the null events, a blank screen was presented. No responses were required during the fMRI task. The total session including preparation time and the acquisition of anatomical images lasted for approximately 40 min.

### *2.5. Post-scan behavioral testing*

Subsequent to the fMRI session, children performed a behavioral picture matching task in a separate room. The experimenter sat next to the child and introduced the task: “Now, I am going to play some short stories, like the one you already heard. You are going to show me which picture fits to that story.” The sentences were a subsample of the experimental stimuli, consisting of eight items per condition. They were presented using a laptop and speakers in a pseudorandomized order.

### *2.6. Imaging data acquisition*

Imaging data were acquired on a 3 T Magnetom Trio Tim scanner (Siemens, Erlangen, Germany) with a 12-channel head coil. An echo planar imaging sequence was used to acquire functional images with the following parameters: repetition time (TR)=2 s, echo time (TE) =30 ms, flip angle (FA)=90°, field of view (FOV)=192 mm, matrix size 64×64, in-plane resolution 3×3 $\text{mm}^2$, slice thickness 3 mm, and 28 axial slices acquired bottom-up sequentially with 0.99-mm gaps between slices. For anatomical reference, an MPRAGE sequence (TR 1480 ms, TE 3.46 ms, FA 10°, matrix size 240×256, resolution 1×1×1.5 $\text{mm}^3$) was used to obtain T1-weighted images covering the whole-brain.

### *2.7. Behavioral data analysis*

The accuracy rate of the post-scan behavioral picture matching task was computed, and one-sample *t*-tests were conducted in each age group to determine if the average performance was significantly above chance level (i.e., 50%) in each condition. We conducted a 2 (AGE)×2 (WORDORDER) mixed-design ANOVA to investigate age and word order effects on behavioral performance. To identify the participants who were reliably involved in the task and performed above chance level, we used a binomial test in each participant in the subject-initial condition. Previous literature suggests that children are capable of processing sentences in which word order and case marking are not conflicting (Chan et al., 2009; Dittmar et al., 2008). While not all children at three and six years of age have mastered the use of case marking cues to resolve object-initial sentences, they should be capable of understanding simple subject-initial transitive sentences. Therefore, the performance of the subject-initial condition would serve as a suitable check for us to determine engagement of the children in the task. Only those participants whose accuracy in the subject-initial condition was significantly above the chance level were considered for the following behavioral and functional data analysis. One sample *t*-tests assured that both age groups performed above chance level in both experimental conditions. Hereafter a 2 (AGE)×2 (WORDORDER) mixed-design ANOVA was set up to investigate age and word order effects on behavioral performance.

### *2.8. Imaging data analysis*

We used the Statistical Parametric Mapping software (SPM8; http://www.fil.ion.ucl.ac.uk/spm/) to preprocess and analyze the fMRI data. All of the functional images were slice-timing corrected, using the middle slice in the acquisition order as the reference slice. All volumes were realigned to the first volume to correct for head movement, and each participant's T1-weighted image was coregistered with the mean functional image. For the children, a study-specific anatomical template, which encompassed the T1-weighted images from three- and six-year-old children, was created using the template creation script (builtemplateparallel.sh) of the Advanced Normalization Tools (ANTs, (Avants et al., 2011)). For template creation, each age group consisted of 14 participants matched in gender (8 females) and the monthly distribution of age as possible. The T1-weighted images were segmented using the tissue probability maps of the study-specific template for children and the standard MNI template for adults. Subsequently all images were normalized and smoothed with a Gaussian Kernel of 6 mm full-width at half-maximum.

For statistical analysis, a general linear model was set up to analyze condition effects of functional data at the whole brain level. The blood oxygen level dependent signal was modeled using the canonical hemodynamic response function with time derivatives. Realignment parameters were included in the design matrix as regressors of non-interest to control for variances induced by head movement. At the individual-level, contrast images were computed for the two conditions against the silent baseline. For group-level analysis, flexible factorial designs were set up to investigate condition specific effects in each group. To perform a group comparison, planned *t*-tests were performed for word order contrast (i.e. object-initial vs. subject-initial sentences) between groups. The WORDORDER-contrast of the adults group was set up to illustrate the brain responses evoked by the experimental stimulation as a basis for ROI-definition. Therefore, we decided for this specific contrast to adopt a more liberal cluster-defining threshold (CDT) of $p < 0.005$ and a cluster-level FWE-corrected threshold of $p < 0.05$.

### *2.9. Region of interest analysis*

Subsequently, a priori defined language-related ROIs chosen on the basis of adult language studies discussed in the introduction (left BA 45, left BA 44, and posterior portion of the left STG) were obtained using the segmentation tool *recon* on a standard T1-template in FreeSurfer (https://surfer.nmr.mgh.harvard.edu/). For the ROI of the left posterior STG, the left STG was split by the middle point along the y-axis and the posterior part was taken as the ROI mask of pSTG. Those images were used to mask activation maps of the WORDORDER contrast (i.e., object-initial > subject-initial sentences) of the adults control group. The coordinates of the peak activation inside of these masks was used as centers to create 4-mm spheres. The FSL non-linear transformation tool *fnirt* (Andersson et al., 2007) was applied to obtain transformation matrices which projected from the standard MNI-template to the study-specific children template. Via these matrices the ROIs were transformed into the space of the children template. The resulting ROIs were used to extract individual subject's percent signal change (PSC) for each condition using MarsBaR (Brett et al., 2002). In analogy to the whole brain analysis, the PSC of the silence condition was subtracted from that of the particular sentence condition to obtain a condition-specific contrast with an explicit baseline. A mixed-design ANOVA (age group×word order×ROI) was conducted.

### *2.10. Functional connectivity analysis*

The CONN toolbox (Whitfield-Gabrieli and Nieto-Castanon, 2012) was used for functional connectivity analysis on the preprocessed data of the two experimental conditions. The design matrices from the individual-level analysis in SPM8 were imported to define stimulus onsets and duration of conditions. Next, additional preprocessing was done to model the BOLD signal by regressing out variance contributed by the realignment parameters, the white matter and the cerebrospinal fluid by using CompCor component-based noise correction (Behzadi et al., 2007). A ROI-to-ROI bivariate correlation analysis was per-

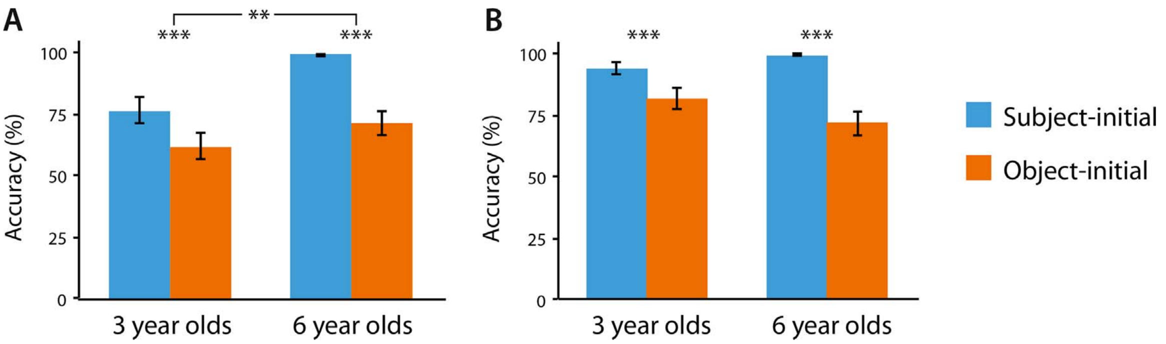

**Fig. 1.** Behavioral performance in the picture matching task from (A) the whole groups including all participants and (B) groups only including participants who performed above chance level in the subject-initial condition. Error bars represent standard deviation of the sample. Asterisks indicate significance levels: **$p < 0.005$,***$p < 0.001$.

formed using our a priori ROIs (4 mm spheres in the left BA 44, BA 45 and pSTG). A three-way model including the factors of age group, condition and ROI was set up to examine differences in correlations. In order to obtain condition-specific time series, the original ones were weighted by the corresponding HRF-convolved regressors. The subsequent results are reported at a significance level of $p < 0.05$, FDR-corrected.

## 3. Results

### 3.1. Behavioral results

One-sample $t$-tests revealed that performance in the picture matching task was significantly above chance level (50%) for all conditions in both age groups (for subject-initial sentences, 3yo: $M$=76.8%, SD=24.1%, $t$(20)=5.09, $p < 0.001$; 6yo: $M$=99.6%, $SD$=2.3%, $t$(28)=115.0, $p < 0.001$; for object-initial sentences, 3yo: $M$=62.5%, $SD$=25.6%, $t$(20)=2.23, $p < 0.05$; 6yo: $M$=71.7%, $SD$=27.4%, $t$(28)=4.27, $p < 0.001$) (Fig. 1A). A mixed-design ANOVA with a between-subjects factor AGE (3yo and 6yo) and a within-subjects factor WORDORDER (subject-initial and object-initial) revealed a main effect for AGE, $F$(1, 48)=9.886, $p < 0.005$, and a main effect for WORDORDER, $F$(1, 48)=33.123, $p < 0.001$. The interaction of both factors showed a marginally significant effect, $F$(1, 48)=3.434, $p$=0.07. The resolution of that interaction revealed that 6yo children performed better than 3yo in the subject-initial condition $t$(48)=4.31, $p < 0.001$, whereas no age difference was found in the object-initial condition $t$(48)=1.21, $p$=.234.

In order to make sure that subsequent data analysis did not include participants who were guessing, did not pay attention to the task, or were using other inappropriate strategies, we used a binomial test to identify the participants whose accuracy was above chance level in the subject-initial condition. Test results indicated that while all 6yo performed above chance level in the subject-initial condition, the accuracy rate of ten participants of the 3yo group was not significantly different from chance level. Therefore, 29 participants of 6yo (15 females; age $M$=78.97 months, $SD$=3.6; handedness score $M$=65) and 11 participants of 3yo (7 females; age $M$=43.5 months, $SD$=3.8; handedness score $M$=68.3) were selected for the subsequent fMRI analyses. One-sample $t$-tests showed that both selected groups performed above chance level in both experimental conditions (for subject-initial sentences, 3yo: $M$=94.3%, $SD$=8.6%, $t$(10)=17.1, $p < 0.001$; for object-initial sentences, 3yo: $M$=81.8%, $SD$=14.1%, $t$(10) =7.48, $p < 0.001$;) (Fig. 1B). A mixed-design ANOVA revealed a main effect for WORDORDER, $F$(1, 38)=20.506, $p < 0.001$. An interaction of both factors was marginally significant ($F$(1, 38)=2.968, $p$=0.093). Accordingly to the whole group analysis the resolution of the interaction in the subsamples showed that the main effect of WORDORDER is driven by a marginal age effect in the subject-initial condition, $t$(38)=2, $p$=0.072, whereas the object-initial condition did not show age differences, $t$(38)=−1.52, $p$=.137.

### 3.2. Functional MRI results

In the whole-brain analysis using a flexible factorial design, the effect of WORDORDER in the adults comprised of greater activation for the object-initial compared to subject-initial conditions in the left anterior insula covering the left IFG, the left superior frontal gyrus (SFG), and the left pSTG, with a cluster-extent threshold (CDT) of $p < 0.005$ and a cluster-level FWE-corrected threshold of $p < 0.005$ (Fig. 2, Table 1). It should be noted that the left pSTG cluster did not survive at a more conservative CDT of $p < 0.001$, while the left-lateralized frontal activation comprising the clusters in the left anterior insula and the left SFG were still observed (see Supplementary Materials, Fig. S1 and Table S1). The clusters were masked with a priori defined anatomical ROIs. The coordinates of the peak activation inside of each ROI were used to derive 4-mm sphere masks (see coordinates in Table 2). These spheres were then transformed into the space of the study-specific children's template.

The 6yo group who performed above chance level showed similar activation patterns for the subject-initial and object-initial conditions, including the bilateral STG/STS, occipital areas V1/2, and the left IFG. No clusters were found at the whole-brain level for the contrast of object-initial against subject-initial ("WORDORDER") conditions. A similar pattern was observed in 3yo participants who performed above chance level (see Fig. 3). The planned $t$-tests for the WORDORDER contrast between age groups did not show any significant group differences.

### 3.3. ROI results

A three-way mixed-design ANOVA (AGE×WORDORDER×ROI)

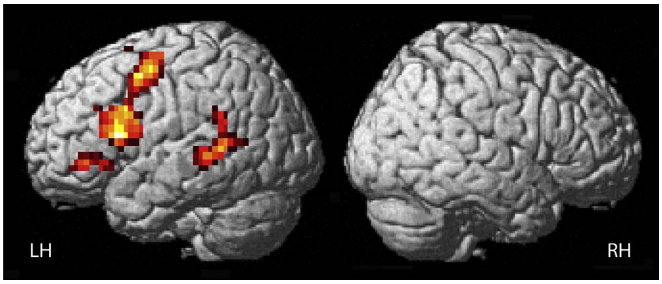

**Fig. 2.** Whole brain activation map for the main effect of WORDORDER in adults (i.e., object-initial > subject-initial sentences). (CDT $p < 0.005$, cluster ≥139 voxels, equivalent to cluster-level FWE-corrected $p < 0.005$).

**Table 1**
Activation clusters of the main effect of WORDORDER in adults (object-initial > subject-initial conditions).

| Hemisphere | Region | x | y | z | Cluster size | z Value |
|---|---|---|---|---|---|---|
| Left | Anterior insula | −27 | 20 | 6 | 570 | 4.89 |
| Left | Superior frontal gyrus | −3 | 8 | 58 | 226 | 4.85 |
| Left | Posterior superior temporal gyrus | −60 | −46 | 6 | 139 | 3.75 |

*Note*. Coordinates are in the MNI space. (CDT $p < 0.005$, cluster≥139 voxels, equivalent to cluster-level FWE-corrected $p < 0.005$).

**Table 2**
Activation peaks of the main effect of WORDORDER in adults within a priori ROI masks.

| Hemisphere | Region | BA | x | y | z |
|---|---|---|---|---|---|
| Left | pSTG | 22 | −60 | −46 | 10 |
| Left | Pars opercularis | 44 | −45 | 17 | 14 |
| Left | Pars triangularis | 45 | −45 | 35 | −2 |

*Note*. Coordinates are in the MNI space.

showed an interaction between WORDORDER and ROI, $F(2,\ 37) = 4.09$, $p < 0.01$. Post-hoc analyses resolving this interaction revealed a simple effect of WORDORDER in the left pSTG, where the object-initial condition showed higher activation than the subject-initial condition, $F(1,\ 38) = 9.49$, $p < 0.005$ (Fig. 4). No effects were found for BA 44 and BA 45.

### 3.4. FC results

Time-course correlation coefficients between ROIs for each participant were used to set up a general linear model (GLM) with three factors (AGE×WORDORDER×ROI). The model showed a significant three-way interaction, $F(1,\ 38) = 6.75$, $p = 0.013$ (FDR-corrected). Resolving the interaction revealed between-group differences where 6yo showed stronger connectivity between left BA 44 and left pSTG ($r = 0.22$, $p < 0.001$, FDR-corrected) in the subject-initial condition than 3yo ($r = 0.04$, $p = 0.52$, FDR-corrected), $t(38) = 2.15$, $p = .038$ (FDR-corrected) (Fig. 5). Furthermore, the within-group comparison in 3yo indicated marginally stronger connectivity between the left BA 45 and pSTG ($r = 0.21$, $p < 0.005$, FDR-corrected) compared to the connectivity between the left BA 44 and pSTG ($r = 0.04$, $p = 0.53$, FDR-corrected) in the subject-initial condition, $t(10) = 2.07$, $p = 0.046$ (FDR-corrected).

## 4. Discussion

With the present study we provide evidence that despite the similar level of task proficiency together with comparable functional activation patterns, the underlying neural mechanisms of sentence processing change as development progresses. While previous studies mainly focused on the functional localization of brain regions involved in syntactic processing or the structural changes accompanying behavioral changes (Brauer and Friederici, 2007; Knoll et al., 2012; Nunez et al., 2011), our study is, to the best of our knowledge, the first to show differences in the functional interplay of the language network in young children processing syntactic structures. Both 6yo and 3yo children showed a main effect of WORDORDER in the left pSTG. However, by correlating the time series of three a priori ROIs (the left BA 44, BA 45, and pSTG), we found that the 6yo showed stronger FC between the left pSTG and left BA 44 compared to the 3yo in the subject-initial condition. Moreover, in the same condition the 3yo showed marginally stronger FC between the left pSTG and left BA 45 compared to the FC between the left pSTG and left BA 44. Our experiment thereby demonstrated that age differences in functional connectivity between brain regions of the language network could be detected although local activations were comparable.

Our results indicate that 6yo children were capable of interpreting transitive object-initial sentences quite well using case marking cues, and their behavioral performance (subject-initial: 99.6%, object-initial: 71.7%) was consistent with findings by Knoll et al. (2012) who found similar accuracy rates (subject-initial: M=94.1%; object-initial: M=70.6%; age range: 4.8–6.8 years). Overall the group of 3yo children performed on average less accurately than the 6yo children, but their performance was above chance level for subject-initial (76.8%) and for

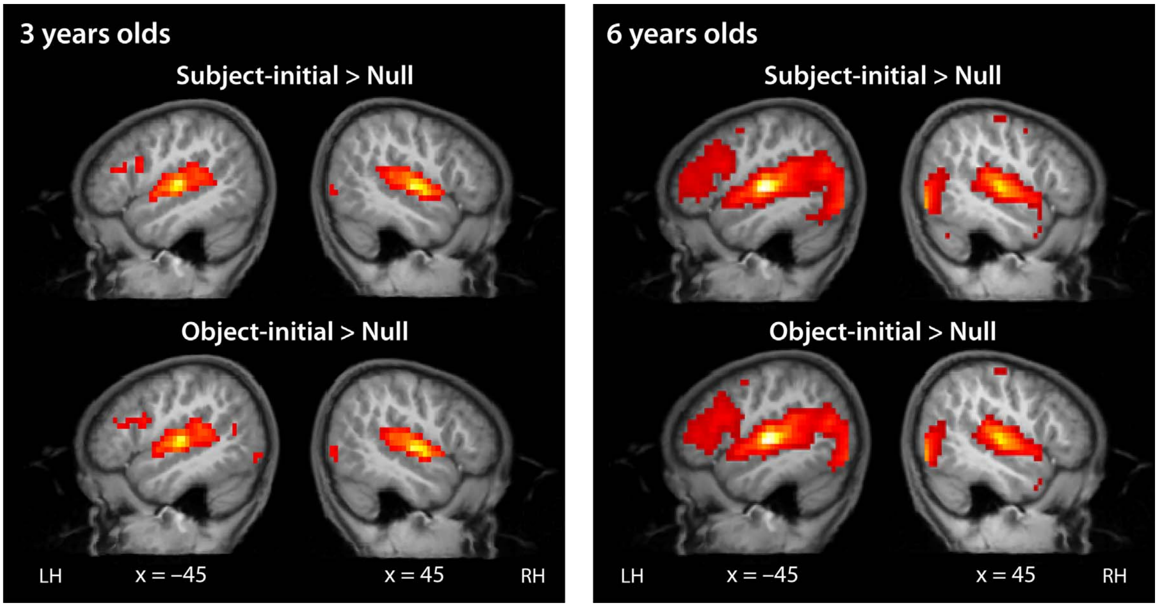

**Fig. 3.** Activation of sentence conditions contrasted to baseline (null events) mapped onto the study-specific template in three-year-old (N=11) and six-year-old (N=29) children who performed above chance level ($p < 0.05$, FWE-corrected).

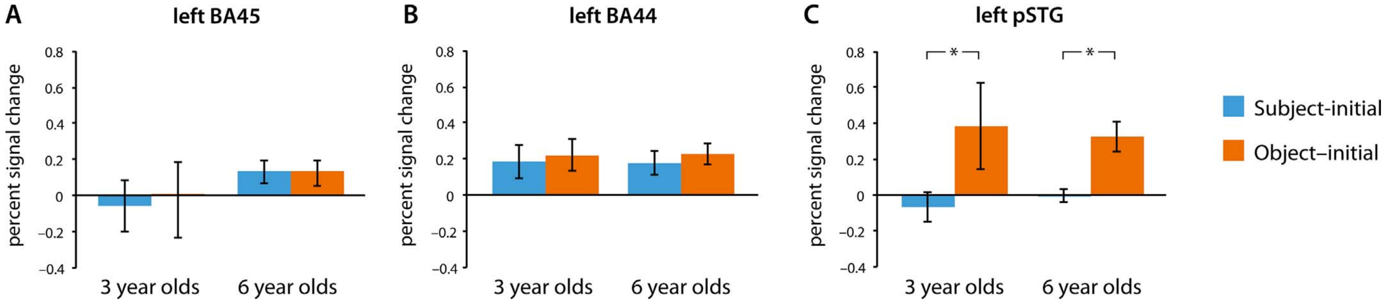

**Fig. 4.** Percent signal change (PSC) for subject- and object-initial conditions for 3-year-old and 6-year-old children in three regions of interest: (A) left BA 45, (B) left BA 44, and (C) posterior superior temporal gyrus (pSTG). We found a main effect of word order in the left pSTG. Error bars show ± 1 SEM. $^*p < 0.05$.

object-initial (62.5%) sentences. However a marginal interaction of WORDORDER and AGE reflects that developmental differences to be displayed in the subject-initial sentences (6yo=99.6%, 3yo=76.8%) rather than in the object-initial sentences (6yo=71.7%, 3yo=62.5%). For those participants who reached above chance level accuracy in the subject-initial condition, the 3yo had overall comparable performance as the 6yo, although a marginally significant interaction remained which could be attributed to a small group difference in the subject-initial sentences (6yo=99.6%, SD=2.3%, 3yo=94.3%, SD=8.6%) but not in the object-initial sentences (6yo=71.7%, SD=27.4%, 3yo=81.8%, SD=14.1%). Former studies reported varying age ranges at which children were capable of making reliable (i.e., above chance level) interpretation of object-initial sentences. The performance of our 3yo children might seem to be better than those previously reported. Some studies found that children only started to process this kind of complex sentences at the age of five (Chan et al., 2009; Lindner, 2003), while others did not report above chance-level understanding from children before the age of seven (Schipke et al., 2012). Skeide et al. (2014) using a lead-in sentence, however, reported that even children between 3 and 4 years of age were capable of processing more complex sentences than the ones used in the present study. In a picture matching task children showed above chance-level performance on subject- as well as object-relative clauses. These varied findings seem to suggest that the age when children start to make use of case marking might be influenced by the difficulty of the tasks. When task demands are high like in act-out paradigms (Chan et al., 2009) or paradigms that involve novel verbs (Dittmar et al., 2008), children might have poorer performance. Our results showed that some children as early as 3 years of age have just begun to understand transitive sentences using case marking even when case marking conflicted with word order cues. One may argue that the small sample size of the 3yo group may be a potential limitation that warrants replication of the results. However, similar results have been found in another investigation, in which a group of 3yo children also performed above chance level on a similar task (Dissertation by Anna Strotseva-Feinschmidt).

Functional activation patterns of the sentence conditions against the silent baseline were in line with previous findings. The activation was observed in the left IFG as well as the bilateral occipital areas V1 and V2 extending along the STG/STS in both children groups. Both conditions reflect the task demands of our experimental stimulation. Numerous studies in adults have reported the left IFG and left STG activation in the context of language processing (Bahlmann et al., 2007; Ben-Shachar et al., 2004; Friederici et al., 2006b). In addition to the activation in language-related areas and regions subserving auditory processing, we also observed activation in the occipital lobe. This could most likely be attributed to the pictures of animals that were presented during the experiment. Activation in the primary visual and association areas have been reported in naming, picture-sentence matching, audio-visual paired association, and perception tasks (Dick et al., 2010; Kinno et al., 2008; Okada et al., 2013; Smith et al., 2013).

More importantly, the expected activation of the left pSTG for the WORDORDER contrast reflected the role of this region in complex sentence processing as reported in the literature. The posterior portion of the superior temporal gyrus has been reported previously to subserve syntactic processing in children (Skeide et al., 2014; Wu et al., 2016) as well as in adults (Friederici et al., 2009; Grodzinsky and Friederici, 2006; Santi and Grodzinsky, 2010). The absence of an age effect in the left pSTG is in line with our expectations suggested by Skeide et al. (2014). In their study, children between three to four years of age show an interaction between syntax and semantics in the left pSTG. In the older group of six- to seven-year-olds, they observed main effects for syntax and semantics as well as an interaction in the left pSTG. Their findings might suggest that syntactic processing mainly engage the left pSTG for children before the age of seven. The pSTG has been assigned an integrating role with respect to the syntactic information related to verb-argument structures. The absence of a WORDORDER effect in the frontal areas might be attributed to less specialization at the age of our participants (Skeide et al., 2014; Wu et al., 2016), and therefore these regions still showed a non-distinct activation level for both complexity conditions.

Taking the language network of adults as a reference model, we investigated the dynamics of the neural network in developing lan-

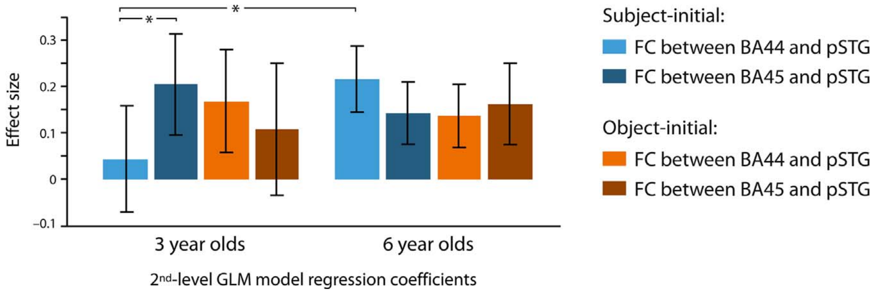

**Fig. 5.** Effect sizes for correlational analyses between left BA 44, BA 45 and posterior STG. $^*p < 0.05$.

guage processors. We were particularly interested in the interplay between the left inferior frontal and posterior superior temporal areas. The finding that 6yo showed higher functional connectivity of the left pSTG with BA 44 compared to 3yo suggests that 3yo have not yet established this connection. Overall the FC pattern corresponds with previous findings in which FC between the left inferior frontal and left posterior superior temporal regions was observed for the processing of complex syntactic structures like object-cleft sentences (den Ouden et al., 2012). This fronto-temporal network has been interpreted as serving top-down mechanisms in argument assignment and sentence interpretation, where the left IFG exerts control over temporal regions (Friederici, 2012; Makuuchi and Friederici, 2013). Besides, effective connectivity investigations tried to provide more cognitive description of the observed patterns. The relationship of top-down control of the left IFG over the pSTG has been reported in non-syntax tasks even across modalities (visual vs. auditory) as the ability to suppress interference from task-irrelevant information (Bitan et al., 2006, 2009). In a study by Bitan et al. (2009), they interpreted the directional influence that the left IFG exerted on the left temporal cortex as the cognitive control processes, which enhanced the focus of the temporal cortex on task-relevant input. They further found that modulatory control of the left IFG over the temporal region increased with age. Skeide and Friederici (2016) stated that this modulation already begins by the age of four but evolves gradually and slowly. Although the present analysis does not provide information about the directionality of information flow, the results of these former studies may hint on how the observed connections may modulate the regions involved. Considering the marginal interaction in the behavioral performance that was driven by a small age effect in the subject-initial but not in the object-initial conditions, we assume that the age differences in FC were mainly reflected in the subject-initial condition. As there were no behavioral differences in the object-initial condition between the age groups, the use of top-down information from the left BA 44 to left pSTG might still be variable in both groups thereby causing variance that masks a possible age effect. Nevertheless, the data suggest that a functional connection between the left BA 44 and posterior temporal regions is established by the age of 6 but not yet consistently used in object-initial contexts. This interpretation is consistent with previous results of FC in resting state fMRI data and its correlation with the development of sentence comprehension abilities at this age (Xiao et al., 2016b).

Another explanation for the difference in FC between age groups could be the ongoing maturation of the arcuate fasciculus (AF), a dorsal white matter tract linking the inferior frontal with the posterior temporal regions (Catani et al., 2002, 2005; Gierhan, 2013; Rilling et al., 2008). This link has been shown to be crucial for language processing (Wilson et al., 2011), and it matures at a later developmental stage (Brauer et al., 2013, Broce et al., 2015; Friederici, 2009; Skeide et al., 2015) as the AF is not yet trackable in infants (Brauer et al., 2013). Broce et al. (2015) showed a positive correlation between age and fractional anisotropy measures in children aged between 5 and 8, indicating that the AF is still developing at that age. Moreover, while the dorsal pathway connecting the left BA 44 and pSTG via AF matures later, a ventral pathway connecting the left BA 45 and the posterior temporal cortex has been found to be present at birth (Brauer et al., 2013). Our findings of the stronger FC of the left BA 45 and pSTG compared to that of BA 44 and pSTG for subject-initial sentences in 3yo might suggest that younger children rely on the ventral pathway before the dorsal pathway is fully developed. Further analysis using diffusion weighted imaging have to show whether there are age- and/or performance-dependent differences in the presence of the AF in these populations.

When dealing with young populations, developmental researchers face several limitations and challenges which should be acknowledged and will be briefly discussed. We are aware that the number of dropouts from the recruited sample in the present study especially in 3yo might seem high at first glance – out of 76 children we managed to acquire 21 complete datasets and only included 11 participants for the fMRI analyses. Many 3yo children were excluded for different reasons, such as non-compliance in the mock-up or the scanning sessions, failure to complete at least 60% of the experiment, or extensive movement. While the high exclusion rate in the current study may posit a question in terms of generalizability of the findings, it also speaks for our efforts in ensuring a pleasant experimental experience for the young children by respecting their will to continue or to end their participation at any time, and reflects our efforts in providing adequate data quality by excluding data with extensive head movement. Apparently, researchers face higher challenges to ensure data quality in children studies compared to adult studies. Dropout rates of 50% have been reported previously for five-year-old children even with careful preparation (Byars et al., 2002; Wilke et al., 2003). To reduce dropout rates and to increase data quality in studies with young children, we suggest that motivation of the young participants is not only a key point to task engagement and thus to the measured signal, but also to compliance in terms of controlling head movement (Power et al., 2012). For conducting (fMRI-) investigations in very young children, a careful preparation of an age-adequate experimental design is as essential as to familiarize the children with the procedure (Raschle et al., 2012; Thomason, 2009). With the limitations functional neuroimaging in young children has to deal with, it is important to keep generalizability in mind. As technology and experience in the field of pediatric neuroimaging progresses, future studies will have to replicate and extend the present findings in a larger sample.

Our study was set up to explore FC at two specific stages in language development (use of word order cues and use of case marking cues). Follow-up studies need to examine the trajectory of FC development, for instance, via broader cross-sectional or longitudinal studies. Moreover, future studies will have to investigate how other cues (e.g., animacy, subject-verb agreement) shape the FC of the language network during development. Finally, the directionality of connections within the language network remains to be explored by effective connectivity or dynamic causal modeling analysis.

## 5. Conclusion

The present study provides evidence that children even from the age of three start to use case marking as a possible strategy to help sentence interpretation. Here, we demonstrate that beyond the general activation in the fronto-temporal language network, age-related changes occur in the functional connectivity within this language network which can be linked to changes in behavioral performance. Our findings shed light on a locus of ongoing development within the language network.

## Conflict of interest

The authors declare that there are no conflicts of interest.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2016.08.014.

## References

Andersson J.L., Jenkinson M., Smith S. FMRIB Analysis Group of the University of Oxford; 2007. Non-linear Registration, aka SPATIAL Normalisation FMRIB Technical Report TR07JA2.

Avants, B.B., Tustison, N.J., Song, G., Cook, P.A., Klein, A., Gee, J.C., 2011. A reproducible evaluation of ANTs similarity metric performance in brain image registration. Neuroimage 54 (3), 2033–2044.

Bahlmann, J., Schubotz, R.I., Friederici, A.D., 2008. Hierarchical artificial grammar processing engages Broca's area. Neuroimage 42 (2), 525–534.

Bahlmann, J., Heim, S., Schubotz, R., Friederici, A., 2006. FMRI investigation of the processing of linear and hierarchical structures: an artificial grammar task. J. Psychophysiol. 20 (4), 317-317.

Bahlmann, J., Rodriguez-Fornells, A., Rotte, M., Munte, T.F., 2007. An fMRI study of canonical and noncanonical word order in German. Hum. Brain Mapp. 28 (10), 940–949.

Bates, E.M., B., 1982. Functionalist approaches to grammar. In: Wanner, L., E.G. (Ed.), Language Acquisition: The State of the Art. Cambridge University Press, New York.

Behzadi, Y., Restom, K., Liau, J., Liu, T.T., 2007. A component based noise correction method (CompCor) for BOLD and perfusion based fMRI. Neuroimage 37 (1), 90–101.

Ben-Shachar, M., Palti, D., Grodzinsky, Y., 2004. Neural correlates of syntactic movement: converging evidence from two fMRI experiments. Neuroimage 21 (4), 1320–1336.

Bitan, T., Cheon, J., Lu, D., Burman, D.D., Booth, J.R., 2009. Developmental increase in top-down and bottom-up processing in a phonological task: an effective connectivity, fMRI study. J. Cognit. Neurosci. 21 (6), 1135–1145.

Bitan, T., Burman, D.D., Lu, D., Cone, N.E., Gitelman, D.R., Mesulam, M.M., Booth, J.R., 2006. Weaker top-down modulation from the left inferior frontal gyrus in children. Neuroimage 33 (3), 991–998.

Brauer, J., Friederici, A.D., 2007. Functional neural networks of semantic and syntactic processes in the developing brain. J. Cognit. Neurosci. 19 (10), 1609–1623.

Brauer, J., Anwander, A., Friederici, A.D., 2011. Neuroanatomical prerequisites for language functions in the maturing brain. Cereb. Cortex 21 (2), 459–466.

Brauer, J., Anwander, A., Perani, D., Friederici, A.D., 2013. Dorsal and ventral pathways in language development. Brain Lang. 127 (2), 289–295.

Brett, M., Anton, J.-L., Valabregue, R., Poline, J.-B., 2002. Region of interest analysis using an SPM toolbox. Paper presented at the 8th International Conference of Functional Mapping of the Human Brain, Sendai, Japan.

Broce, I., Bernal, B., Altman, N., Tremblay, P., Dick, A.S., 2015. Fiber tracking of the frontal aslant tract and subcomponents of the arcuate fasciculus in 5-8-year-olds: relation to speech and language function. Brain Lang. 149, 66–76.

Byars, A.W., Holland, S.K., Strawsburg, R.H., Bommer, W., Dunn, R.S., Schmithorst, V.J., Plante, E., 2002. Practical aspects of conducting large-scale functional magnetic resonance imaging studies in children. J. Child Neurol. 17 (12), 885–890.

Catani, M., Jones, D.K., Ffytche, D.H., 2005. Perisylvian language networks of the human brain. Ann. Neurol. 57 (1), 8–16.

Catani, M., Howard, R.J., Pajevic, S., Jones, D.K., 2002. Virtual in vivo interactive dissection of white matter fasciculi in the human brain. Neuroimage 17 (1), 77–94.

Chan, A., Lieven, E., Tomasello, M., 2009. Children's understanding of the agent-patient relations in the transitive construction: cross-linguistic comparisons between Cantonese, German, and English. Cognit. Linguist. 20 (2), 267–300.

Cordes, D., Haughton, V.M., Arfanakis, K., Wendt, G.J., Turski, P.A., Moritz, C.H., Meyerand, M.E., 2000. Mapping functionally related regions of brain with functional connectivity MR imaging. Am. J. Neuroradiol. 21 (9), 1636–1644.

Dick, A.S., Solodkin, A., Small, S.L., 2010. Neural development of networks for audiovisual speech comprehension. Brain Lang. 114 (2), 101–114.

Dittmar, M., Abbot-Smith, K., Lieven, E., Tomasello, M., 2008. German children's comprehension of word order and case marking in causative sentences. Child Dev. 79 (4), 1152–1167.

Friederici, A.D., 2002. Towards a neural basis of auditory sentence processing. Trends Cognit. Sci. 6 (2), 78–84.

Friederici, A.D., 2009. Pathways to language: fiber tracts in the human brain. Trends Cognit. Sci. 13 (4), 175–181.

Friederici, A.D., 2011. The brain basis of language processing: from structure to function. Physiol. Rev. 91 (4), 1357–1392.

Friederici, A.D., 2012. The cortical language circuit: from auditory perception to sentence comprehension. Trends Cognit. Sci. 16 (5), 262–268.

Friederici, A.D., Makuuchi, M., Bahlmann, J., 2009. The role of the posterior superior temporal cortex in sentence comprehension. Neuroreport 20 (6), 563–568.

Friederici, A.D., Bahlmann, J., Heim, S., Schubotz, R.I., Anwander, A., 2006a. The brain differentiates human and non-human grammars: functional localization and structural connectivity. Proc. Natl. Acad. Sci. USA 103 (7), 2458–2463.

Friederici, A.D., Fiebach, C.J., Schlesewsky, M., Bornkessel, I.D., von Cramon, D.Y., 2006b. Processing linguistic complexity and grammaticality in the left frontal cortex. Cereb. Cortex 16 (12), 1709–1717.

Ge, J.Q., Peng, G., Lyu, B.J., Wang, Y., Zhuo, Y., Niu, Z.D., Gao, J.H., 2015. Cross-language differences in the brain network subserving intelligible speech. Proc. Natl. Acad. Sci. USA 112 (10), 2972–2977.

Gierhan, S.M.E., 2013. Connections for auditory language in the human brain. Brain Lang. 127 (2), 205–221.

Grodzinsky, Y., Friederici, A.D., 2006. Neuroimaging of syntax and syntactic processing. Curr. Opin. Neurobiol. 16 (2), 240–246.

Grimm, H., Aktas, M., Frevert, S., 2000. Sprachentwicklungstest für zweijährige Kinder (SETK-2) Hogrefe. Göttingen.

Humphries, C., Love, T., Swinney, D., Hickok, G., 2005. Response of anterior temporal cortex to syntactic and prosodic manipulations during sentence processing. Hum. Brain Mapp. 26 (2), 128–138.

Kaufman, A.S., Kaufman, N.L., Melchers, P., 2003. K-ABC—Kaufman assessment battery for children. In: S. Zeitlinger (Ed.). Frankfurt am Main, Germany.

Kelly, C., Uddin, L.Q., Shehzad, Z., Margulies, D.S., Castellanos, F.X., Milham, M.P., Petrides, M., 2010. Broca's region: linking human brain functional connectivity data and non-human primate tracing anatomy studies. Eur. J. Neurosci. 32 (3), 383–398.

Kinno, R., Kawamura, M., Shioda, S., Sakai, K.L., 2008. Neural correlates of noncanonical syntactic processing revealed by a picture-sentence matching task. Hum. Brain Mapp. 29 (9), 1015–1027.

Knoll, L.J., Obleser, J., Schipke, C.S., Friederici, A.D., Brauer, J., 2012. Left prefrontal cortex activation during sentence comprehension covaries with grammatical knowledge in children. Neuroimage 62 (1), 207–216.

Lindner, K., 2003. The development of sentence-interpretation strategies in monolingual German-Learning children with and without specific language impairment. Linguistics 41 (2), 213–254.

Lohmann, G., Hoehl, S., Brauer, J., Danielmeier, C., Bornkessel-Schlesewsky, I., Bahlmann, J., Friederici, A., 2010. Setting the frame: the human brain activates a basic low-frequency network for language processing. Cereb. Cortex 20 (6), 1286–1292.

MacWhinney, B., Bates, E., Kliegl, R., 1984. Cue validity and sentence interpretation in English, German, and Italian. J. Verbal Learn. Verbal Behav. 23 (2), 127–150.

Makuuchi, M., Friederici, A.D., 2013. Hierarchical functional connectivity between the core language system and the working memory system. Cortex 49 (9), 2416–2423.

Mottier, G., 1951. Der Mottier-test. über untersuchungen zur sprache lesegestörter kinder. Folia Phoniatr. 3 (1951), 170–177.

Muller, A.M., Meyer, M., 2014. Language in the brain at rest: new insights from resting state data and graph theoretical analysis. Front. Hum. Neurosci. 8.

Newman, S.D., Ikuta, T., Burns, T., Jr., 2010. The effect of semantic relatedness on syntactic analysis: an fMRI study. Brain Lang. 113 (2), 51–58.

Newman, S.D., Just, M.A., Keller, T.A., Roth, J., Carpenter, P.A., 2003. Differential effects of syntactic and semantic processing on the subregions of Broca's area. Brain Res. Cognit. Brain Res. 16 (2), 297–307.

Nunez, S.C., Dapretto, M., Katzir, T., Starr, A., Bramen, J., Kan, E., Sowell, E.R., 2011. fMRI of syntactic processing in typically developing children: Structural correlates in the inferior frontal gyrus. Dev. Cognit. Neurosci. 1 (3), 313–323.

Okada, K., Venezia, J.H., Matchin, W., Saberi, K., Hickok, G., 2013. An fMRI study of audiovisual speech perception reveals multisensory interactions in auditory cortex. Plos One 8, 6.

Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9 (1), 97–113.

den Ouden, D.B., Saur, D., Mader, W., Schelter, B., Lukic, S., Wali, E., Thompson, C.K., 2012. Network modulation during complex syntactic processing. Neuroimage 59 (1), 815–823.

Perani, D., Saccuman, M.C., Scifo, P., Anwander, A., Spada, D., Baldoli, C., Friederici, A.D., 2011. Neural language networks at birth. Proc. Natl. Acad. Sci. USA 108 (38), 16056–16061.

Power, J.D., Barnes, K.A., Snyder, A.Z., Schlaggar, B.L., Petersen, S.E., 2012. Spurious but systematic correlations in functional connectivity MRI networks arise from subject motion. Neuroimage 59 (3), 2142–2154.

Raschle, N., Zuk, J., Ortiz-Mantilla, S., Sliva, D.D., Franceschi, A., Grant, P.E., Gaab, N., 2012. Pediatric neuroimaging in early childhood and infancy: challenges and practical guidelines. Ann. N. Y. Acad. Sci. 1252, 43–50.

Rilling, J.K., Glasser, M.F., Preuss, T.M., Ma, X.Y., Zhao, T.J., Hu, X.P., Behrens, T.E.J., 2008. The evolution of the arcuate fasciculus revealed with comparative DTI. Nat. Neurosci. 11 (4), 426–428.

Santi, A., Grodzinsky, Y., 2010. fMRI adaptation dissociates syntactic complexity dimensions. Neuroimage 51 (4), 1285–1293.

Schanerwolles, C., 1989. Strategies in acquiring grammatical relations in German – Word-order or case marking. Folia Linguist. 23 (1–2), 131–156.

Schipke, C.S., Knoll, L.J., Friederici, A.D., Oberecker, R., 2012. Preschool children's interpretation of object-initial sentences: neural correlates of their behavioral performance. Dev. Sci. 15 (6), 762–774.

Siegmüller, J., Kauschke, C., van Minnen, S., Bittner, D., 2011. Test zum Satzverstehen von Kindern (TSVK)—Eine profilorientierte Diagnostik der Syntax. In: U. F. Verlag (Ed.): Elsevier GmbH, Munich.

Skeide, M.A., Friederici, A.D., 2016. The ontogeny of the cortical language network. Nat. Rev. Neurosci. 17 (5), 323–332.

Skeide, M.A., Brauer, J., Friederici, A.D., 2014. Syntax gradually segregates from semantics in the developing brain. Neuroimage 100, 106–111.

Skeide, M.A., Brauer, J., Friederici, A.D., 2015. Brain functional and structural predictors of language performance. Cereb. Cortex.

Smith, J.F., Braun, A.R., Alexander, G.E., Chen, K., Horwitz, B., 2013. Separating lexical-semantic access from other mnemonic processes in picture-name verification. Front Psychol. 4, 706.

Snijders, T.M., Vosse, T., Kempen, G., Van Berkum, J.J.A., Petersson, K.M., Hagoort, P., 2009. Retrieval and unification of syntactic structure in sentence comprehension: an fMRI study using word-category ambiguity. Cereb. Cortex 19 (7), 1493–1503.

Thomason, M.E., 2009. Children in non-clinical functional magnetic resonance imaging (fMRI) studies give the scan experience a "thumbs up". Am. J. Bioeth. 9 (1), 25–27.

Whitfield-Gabrieli, S., Nieto-Castanon, A., 2012. Conn: a functional connectivity toolbox for correlated and anticorrelated brain networks. Brain Connect. 2 (3), 125–141.

Wilke, M., Lidzba, K., Krageloh-Mann, I., 2009. Combined functional and causal connectivity analyses of language networks in children: a feasibility study. Brain Lang. 108 (1), 22–29.

Wilke, M., Holland, S.K., Myseros, J.S., Schmithorst, V.J., Ball, W.S., 2003. Functional magnetic resonance imaging in pediatrics. Neuropediatrics 34 (5), 225–233.

Wilson, S.M., Galantucci, S., Tartaglia, M.C., Rising, K., Patterson, D.K., Henry, M.L., Gorno-Tempini, M.L., 2011. Syntactic processing depends on dorsal language tracts. Neuron 72 (2), 397–403.

Wu, C.-Y., Vissiennon, K., Friederici, A.D., Brauer, J., 2016. Preschoolers' brains rely on semantic cues prior to the mastery of syntax during sentence comprehension. Neuroimage 126, 256–266.

Xiao, Y., Friederici, A.D., Margulies, D.S., Brauer, J., 2016a. Development of a selective left-hemispheric fronto-temporal network for processing syntactic complexity in language comprehension. Neuropsychologia 83, 274–282.

Xiao, Y., Friederici, A.D., Margulies, D.S., Brauer, J., 2016b. Longitudinal changes in resting-state fMRI from age 5 to age 6years covary with language development. Neuroimage 128, 116–124.

Yue, Q., Zhang, L., Xu, G., Shu, H., Li, P., 2013. Task-modulated activation and functional connectivity of the temporal and frontal areas during speech comprehension. Neuroscience 237, 87–95.

Zhu, L.L., Fan, Y., Zou, Q.H., Wang, J., Gao, J.H., Niu, Z.D., 2014. Temporal reliability and lateralization of the resting-state language network. Plos One 9, 1.