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Left prefrontal cortex activation during sentence comprehension covaries with grammatical knowledge in children

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ABSTRACT

Children's language skills develop rapidly with increasing age, and several studies indicate that they use language- and age-specific strategies to understand complex sentences. In the present experiment, functional magnetic resonance imaging (fMRI) and behavioral measures were used to investigate the acquisition of case-marking cues for sentence interpretation in the developing brain of German preschool children with a mean age of 6 years. Short sentences were presented auditorily, consisting of a transitive verb and two case-marked arguments with canonical subject-initial or non canonical object-initial word order. Overall group results revealed mainly left hemispheric activation in the perisylvian cortex with increased activation in the inferior parietal cortex (IPC), and the anterior cingulate cortex (ACC) for object-initial compared to subject-initial sentences. However, single-subject analysis suggested two distinct activation patterns within the group which allowed a classification into two subgroups. One subgroup showed the predicted activation increase in the left inferior frontal gyrus (IFG) for the more difficult object-initial compared to subject-initial sentences, while the other group showed the reverse effect. This activation in the left IFG can be taken to reflect the degree to which adult-like sentence processing strategies, necessary to integrate case-marking information, are applied. Additional behavioral data on language development tests show that these two subgroups differ in their grammatical knowledge. Together with these behavioral findings, the results indicate that the use of a particular processing strategy is not dependent on age as such, but rather on the child's individual grammatical knowledge and the ability to use specific language cues for successful sentence comprehension.

Introduction

At the most basic level, children's sentence interpretation requires the acquisition of distinctive characteristics of their native language. Children have to develop a strategy to unveil the meaning of a word in the context of other words. Thereby, one of the major challenges in language acquisition is to detect reliable linguistic regularities (Bates et al., 1988; Jackendoff, 2002) and cues in order to identify "who is doing what to whom" in a sentence. But which features are initially used as a cue to determine this so-called thematic relationship in a sentence? A study by Slobin and Bever (1982) tested native-speaking English, Italian, Serbo-Croatian, and Turkish children, and concluded that the first cue used by children is their language's most valid one. These results are in line with the competition model postulated by Bates et al. (1984), Bates and MacWhinney (1987, 1989), which states that how fast a child acquires a specific cue for their target language depends on the strength of the cue, and this, in turn, depends on the consistency and frequency of this information.

An important cue to identify thematic relationships in sentences is word order. However, in contrast to languages such as English, German allows a relatively free word order and therefore, additional information is often needed to identify relational information between the arguments in a sentence. Thus, German children have to learn that, in addition to word order, other cues like morphological case-markers and semantic features (e.g., animacy) convey crucial information. Information carried by the case-marking cue can be illustrated by considering the following example:

(1) a. Der Vater ruft den Sohn.
[the father]$_{\text{nominative(NOM)}}$ calls [the son]$_{\text{accusative(ACC)}}$
The father calls the son.
b. Den Sohn ruft der Vater.
[the son]$_{\text{ACC}}$ calls [the father]$_{\text{NOM}}$
The father calls the son.

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Whether the first argument in the transitive sentence (1b) functions as a subject or an object depends on morphological markings (case-markings) and contains a reference to the thematic role in the context. The nominative case "der" indicates "der Vater" as the subject and, crucially, as the actor in the sentence. The accusative case-marked by the finite article "den" points to the object and undergoer of the scenario. Above all, word order does not provide any cue for the interpretation of (1a) and (1b). However, even if case-marking is a frequent cue in German, its availability is rather low since, in many cases, noun phrases are ambiguously case-marked, e. g. feminine and neuter singular nouns as well as plural noun phrases, as in the following example:

(2) Die Mutter ruft die Tochter.
[the mother]$_{NOM/ACC}$ calls [the daughter]$_{NOM/ACC}$

Assuming, no context is given, as in example (2), word order is the only cue for role assignment in ambiguous sentences. Accordingly, the acquisition of word order should precede the acquisition of German case-marking due to higher availability of the former and, therefore, highest cue strength (Bates and MacWhinney, 1989; Slobin and Bever, 1982).

Behavioral comprehension studies with German-speaking children that presented sentences with manipulated word order and additional information (e.g., case-marking and animacy), support this theory, and reported a relatively late acquisition of case-marking as a cue to argument interpretation (Chan et al., 2009; Dittmar et al., 2008; Lindner, 2003; Primus and Lindner, 1994; Schaner-Wolles, 1989). Dittmar et al. (2008) tested German-speaking children in a pointing task. The results indicated that children are not able to reliably process solely morphological information before the age of 7. Furthermore, while 2-year-olds needed word order and case-marking information in combination to correctly identify the actor of an action presented in the test sentence, 5-year-old children could use the word-order cue alone, but not the information provided by case-marking alone. Nevertheless, findings from an EEG-study by Schipke et al. (in press) investigated the neurophysiological underpinnings of processing case-marked topicalized object noun phrases in German-speaking children at the age of 3;0, 4;6 and 6;0, as well as in adults. The event-related potential (ERP) results suggested that three-year-olds consult word order for sentence interpretation, whereas children at the age of 4;6 were already sensitive to case-marking, although they did not use it for interpretation. Nevertheless, the ERP effects in the group of 6-year-olds indicated that the underlying processes react to object-initial noun phrases similar to adults, but they still have problems when it comes to integrating the second noun phrase for interpretation.

In short, the studies reviewed indicate that children's awareness of which cues will help them to process even non prototypical sentences in their native language develops with increasing age, and that children do not detect the strength of case-marking information, as a language cue in German, before the age of five to six.

To our knowledge, no functional resonance imaging (fMRI) study has investigated the brain areas which subserve acquisition of case-marking cues for argument interpretation in unambiguously case-marked object-initial sentences in young children. However, extensive data are available from fMRI studies investigating syntactic processing in adults. These studies have examined processing of syntactic complexity in adults by varying the argument hierarchies in languages that provide additional information relevant for argument interpretation (e.g., case-marking). Syntactic processes seem to be subserved mainly by the left inferior frontal gyrus (IFG) and the left superior temporal gyrus and sulcus (STG/STS). Both areas show stronger activation for the processing of grammatically more complex sentences (e.g., scrambling) than sentences with canonical word order (Ben-Shachar et al., 2004; Bornkessel et al., 2005; Friederici et al., 2006; Grewe et al., 2005; Obleser et al., 2011; Röder et al., 2002). Interestingly, imaging data indicate that activation within the left IFG (BA 44) increases parametrically with syntactic complexity, operationalized as the number of permutations of case-marked arguments in a sentence (Friederici et al., 2006).

So far, we know little about the neural network involved in the processing of syntactically more complex sentences in young children. In a neuroimaging study by Brauer and Friederici (2007), a syntactic and semantic violation paradigm, including a judgment task was auditorily presented to 6-year-old German children. The results showed a significant overlap for syntactic and semantic processing. For older children, Nuñez et al. (2011) found a relation between syntactic proficiency and activation in the left IFG, superior frontal gyrus (SFG), and middle frontal gyrus (MFG) independent of age. Moreover, in English-speaking children at the age of 7;2 to 15;8, they observed that the amount and extent of activation within the right IFG during syntactic processing (versus rest) was negatively correlated with cortical thickness in this region, which suggests a shift from the right to the left hemisphere during this age. A comparison of brain activation during syntactic processing versus semantic processing revealed activation in Brodmann area (BA) 44 for older children (above the age of 10.7 years), but not for younger children in the group. Another study (Yeatman et al., 2010) tested children at the age of 10 to 16, and while they did not find IFG activation at the group level, a post-hoc analysis demonstrated a higher involvement of the IFG in children with better receptive language skills, as tested outside the scanner.

Taken together, these findings suggest that sentence processing in children between the ages of 7 and 16 involves brain areas (especially IFG/MFG/STG) that were also found in fMRI studies investigating syntactic processing in adults. However, the studies in children often failed to find significant results at the group level, indicating a high variance in language proficiency that is not related to a specific age. Rather, several studies found that activation in the left IFG correlated with individual language skills (Nuñez et al., 2011; Yeatman et al., 2010).

In the present study, we aim to investigate the neural basis of syntactic processing of German preschool children using canonical and non canonical sentences. The specific goal was to examine the use of case-marking when assigning the role of the arguments in sentences. The experimental paradigm included transitive sentences with varying syntactic complexity, which have been successfully used before in an ERP study with 3- to 6-year-old German-speaking children (Schipke et al., in press). Due to high individual differences reported in recent developmental studies (Nuñez et al., 2011; van Ettinger-Veenstra et al., 2010; Yeatman et al., 2010), a closer look at the single-subject level should provide additional information concerning the individual developmental level. Hence, extensive behavioral testing was conducted to quantify children's performance with respect to receptive grammar skills.

Material and methods

Participants

Thirty-three healthy children between 4;8 and 6;8 years of age took part in the experiment. Before their participation, parental informed consent was obtained for all children. Eleven children were excluded due to the following reasons: low scores on a language development test for reception of grammar (TROG-D, Fox, 2008), movement artifacts or brain anomalies. The final sample for the fMRI experiment consisted of 22 children (nine female), mean age 5;9, range 4;8 to 6;8 years-old. All children were monolingual German speakers and had no neurological, medical, or psychological disorders and no contraindications to obtaining an MRI scan. No child was left-handed but six children were ambidextrous (modified version of Oldfield, 1971). Group statistics with and without these six children did not suggest that this group was an outlier, therefore these data remained in the final analysis.

Materials

For the behavioral part of the experiment, we used 24 sentences of the same type that were successfully applied in a previous behavioral and ERP study (Schipke et al., in press), for example:

(1a) Der Hund küsst den Tiger.
[the dog]$_{NOM}$ kisses [the tiger]$_{ACC}$
The dog kisses the tiger.
(1b) Den Tiger küsst der Hund.
[the tiger]$_{ACC}$ kisses [the dog]$_{NOM}$
The dog kisses the tiger.

Using this type of sentence, *we aimed to* investigate the acquisition of the case-marking cue for argument interpretation. Other cues (e.g., animacy and prosody for argument interpretation) were excluded. Nouns and their combining transitive verbs were chosen after a pretest with 30 children (ten 3-year-olds, ten 5-year-olds, and ten 6-year-olds) to ensure that all preschoolers knew the relevant words and named every actor and its action consistently.

In the behavioral part of the study we used 12 sentences with a subject-initial (1a) structure and 12 sentences with an object-initial (1b) structure. All nouns corresponding to animals, were masculine, thus belonging to the strong declination type. In German, nominative and accusative are unambiguously case-marked for masculine nouns only, by the case-marking of the definite article preceding the noun. Thus, in our experiment, all nominal constituents in a sentence were unambiguously marked for accusative or nominative by the definite article. For the behavioral test sentences, six nouns and six verbs were used. Every animal occurred equally as often as an agent, as an undergoer, and in interaction with other animals.

Corresponding pictures were created using Adobe illustrator and featured two animals engaging in a particular action. Animals were controlled for size and position within the picture frame. The illustration of the action performed by one of the two animals was counterbalanced in order to equally show the agent to the right or to the left of the undergoer. Thus, each picture card contained two pictures in a counterbalanced order aligned on the horizontal axis, i.e., a picture corresponding to the respective test sentence and another picture with the actor and undergoer in a reversed version.

For the fMRI experiment, the same sentences as in the behavioral experiment were used. In addition, another six pretested transitive verbs were included making a total of 48 test sentences, 24 in the subject-initial condition and 24 in the object-initial condition. Furthermore, grammatically violated sentences with double nominative or double accusative were included in the presentation order to minimize the predictability of the next type of sentence structure.

Participants were presented with mildly child-directed spoken sentences. All sentences were recorded in a soundproof chamber by a trained female speaker. After recording, sentences were digitized (44.1 kHz/16 bit sampling rate, mono) and normalized in root mean squared amplitude. The last noun phrase was afterwards cross-spliced to assure comparability and to avoid prosodic cues. The resulting audio files had a mean duration of 2368 ms (SD = 134 ms), and did not differ between conditions ($t(46) < 1$).

Procedure

All children participated in a testing session to assess language skills, handedness, and hearing. A receptive language development test was employed (the TROG-D, Fox, 2008). All children that were included in our final fMRI sample showed normal language development as assessed by the TROG-D.

To familiarize the children with the experimental setting and scanner noise, each child also underwent a simulated scanner session in a mock MR scanner. Stimuli similar to, but not identical to, the experimental stimuli were used for familiarization. To practice lying still in the scanner, each child got verbal and visual feedback via headphones and a motion sensor during the session. Each child was given a clear instruction before the practice scan and was reminded that there would be a post-scanning survey with specific questions about the sentences they heard.

Before the actual fMRI session, children had the chance to accustom themselves to the environment and the scanner. They were reminded to lie still and listen to the sentences, and that after the scanner session, they had to answer test questions about the sentences that they would hear in the scanner. The test procedure including behavioral and fMRI data acquisition encompassed a total of 2–3 h and was distributed over 2 days. The scanning session was scheduled on average two weeks after the behavioral session that also included the mock scanner training.

fMRI testing

All children completed a 16 minute run consisting of 120 events: 24 sentences per condition (subject-initial and object-initial sentence structure) plus 24 grammatically violated sentences, and 24 null events, presented in an event-related, pseudo-randomized design according to the following constraints: (1) No more than two consecutive trials belonging to the same stimulus condition, and (2) no more than four consecutive trials containing either correct or incorrect stimuli. The stimuli were presented acoustically via headphones while a screensaver, that didn't involve any kind of human or animal action, was presented via LCD display glasses. The 120 events lasted 6 seconds each (i.e. 3 scans of TR = 2000 ms), with a randomly varied onset jitter of 0, 400, 800, 1200 or 1600 ms.

Post-scan behavioral testing

After the scan session, a behavioral picture-matching test was carried out. Children sat together with the experimenter in a separate room and first familiarized themselves with the animal pictures by naming each animal separately. Next, the task was introduced: “Now, I am going to show you a picture card with two pictures on it. I am going to ask you to find a picture for me”. Then the first picture card was presented on the table and the experimenter would ask the child: “Show me …” followed by the test sentence. All test sentences were taken from the experimental material of the scanner session. Number of correct pointing was counted. The experimenter repeated each test sentence maximally twice. The order of the test sentences was pseudo-randomized.

fMRI data acquisition

Twenty-six axial slices (3 mm thickness, 1 mm inter-slice distance, FOV 19.2 cm, data matrix 64 × 64 voxels, in plane resolution of 3 × 3 mm) were acquired every 2 s during functional measurements (BOLD sensitive gradient EPI sequence, TR = 2 s, TE = 30 ms, flip angle 90°, acquisition bandwidth = 100 kHz) with a 3 Tesla scanner (Siemens TRIO, Germany).

After functional imaging, a T1-weighted 3D magnetization-prepared rapid gradient-echo (MP-RAGE) sequence (data matrix 256 × 256, TR = 1.48 s, TE = 3.46 ms, TI = 7.4 s, flip angle 10°, bandwidth 190 kHz, space resolution 1 × 1 × 1.5 mm) was acquired with a non-slice-selective inversion pulse followed by a single excitation of each slice. These anatomical data were used to co-register functional images before normalized to a representative brain image of one of the children. This brain was previously rotated into the stereotactic coordinate system and transformed to a standard size (Talairach and Tournoux, 1988). Therefore, it served as a template for normalization and anatomical ROI definition.

fMRI data analysis

Functional imaging data processing was performed using the software package LIPSIA (Lohmann et al., 2001). Functional data were first corrected for motion artifacts and entered into a distortion correction using a field-map scan (only one child was analyzed without this latter step, because no field-map scan was available). Movement correction was allowed up to 3 mm (one voxel). Subjects were excluded if head movement exceeded this range. To correct for the temporal offset, data were corrected for slicetime acquisition differences using cubic-spline interpolation. Low frequency signal changes and baseline drifts were removed by applying a temporal high pass filter to remove frequencies below 1/70 Hz. A spatial smoothing filter with a kernel of 6.0 mm^3 FWHM was applied.

The anatomical images acquired during the functional session were transformed to a standard size by linear scaling and then co-registered with the reference brain by an additional non-linear normalization known as 'demon matching' (Thieron, 1998). The transformation parameters obtained from this step were subsequently applied to the preprocessed functional images.

Using the software package LIPSIA, the statistical evaluation was based on a least-squares estimation using the general linear model for serially autocorrelated observations (Friston, 1994). The design matrix was generated with a synthetic hemodynamic response function (Friston et al., 1998; Josephs et al., 1997) and their temporal and dispersion derivatives. To take the autocorrelation of the data into account for statistical evaluation, a two-pass whitening procedure was performed (Worsley et al., 2002). Movement correction parameters were included into the model as regressors. For each participant, three contrast images were generated to represent the main effects of each of the correct conditions contrasted to baseline (null events), and furthermore, the effect of object-initial sentences compared to subject-initial sentences.

Subsequent random-effects group analysis consisted of a one-sample *t*-test across the contrast images of all participants to indicate whether observed effects were significantly distinct from zero. The resulting t-statistics were transformed to standard normalized distribution. To protect against false-positive activations, a multiple comparison correction tested for cluster size (number of voxel) and the minimal p-value per cluster, based on Monte Carlo simulations. The Monte Carlo simulation generates voxels at a rate equal to the significant criterion specified, proportional to the total number of voxels in the dataset, and calculates a cluster size that corresponds to the true false-positive rate for these conditions. A combination of single voxel probability thresholding on the one hand, and cluster size and cluster-z value thresholding on the other, was used to take account of the possibility that even small clusters may be true activations if the effect is strong enough (Lohmann et al., 2008). Using 1000 iterations, a minimum cluster size at $z > 2.57$ was determined in order to arrive at a corrected p-value of $p < .05$.

Region of interest analysis

In a subsequent region of interest (ROI) analysis we focused on the left IFG, because we expected a significant difference in the contrast of object-initial compared to subject-initial. Other fMRI studies found evidence that this area is activated by syntactic complexity in adults and children (Ben-Shachar et al., 2004; Bornkessel et al., 2005; Friederici et al., 2006; Nuñez et al., 2011; Röder et al., 2002; Yeatman et al., 2010). However, this effect was not replicated in all studies and often only ROI analysis could unveil activation differences in this region (Ben-Shachar et al., 2004). The representative brain image of one of the children previously used for co-registration served as a template to define the ROIs. They were anatomically defined using a Lipsia tool (vledit) to draw two ROIs based on anatomy, covering two subregions of Broca's area in the left IFG, i.e. BA 44 and BA 45, respectively (Fig. 3A). The areas were identified by visual inspection of the macrostructural information of the brain. For BA 44, the opercular part of the IFG was selected between precentral gyrus, lateral fissure, inferior frontal sulcus, and ascendant ramus. For BA 45, the triangular part of the IFG was selected between inferior frontal sulcus, lateral fissure, ascendant ramus, and horizontal ramus. Regions of interest were analyzed by direct statistical comparison between the object-initial and the subject-initial condition. To do so, the percent signal change (PSC) was calculated per condition as a function of time (averaged across all subjects) and analyzed for mean PSC per condition in a time window from 3 to 10 s post stimulus onset (also averaged across all subjects) in a repeated-measures GLM including Greenhouse–Geisser correction. Additional ROI analyses were conducted to investigate individual differences. Following the same protocol, clusters of activation in the anterior cingulate cortex (ACC) and left IPC were also analyzed in order to investigate group differences.

Pilot study in adults

To pretest our paradigm, a pilot fMRI study in adults ($N = 22$, age range of 21 to 33 years) with identical stimuli material and exactly the same protocol was conducted before the children study. In the fMRI experiment a passive listening task was used that had the advantage of targeting relatively normal language processing and exclude task-specific processes that could interfere with the data. Nevertheless, many fMRI studies in adults that found stronger activation for the processing of grammatically more complex sentences predominantly included an active task already during the scan session (e.g., a comprehension task in Ben-Shachar et al., 2004; Bornkessel et al., 2005; Friederici et al., 2006; or error detection Röder et al., 2002). Because the fMRI study in children would have no in-scanner task, a preceding piloting in adults was conducted to ensure that our fMRI paradigm

Table 1
Overview of significant clusters, random-effects contrast, thresholded to $p < .05$, corrected. Talairach coordinates. Table shows following contrasts: (a) subject-initial > baseline, (b) object-initial > baseline, and (c) object-initial > subject-initial. ACC = anterior cingulate cortex, ant = anterior, CC = cingulate cortex, IFG = inferior frontal gyrus, IPC = inferior parietal cortex, MTG = middle temporal gyrus, PCC = posterior cingulate cortex, PHG = parahippocampal gyrus, post = posterior, STG = superior temporal gyrus, TP = temporal pole.

Hemisphere	Region	BA	X	Y	Z	Cluster size	z value
a. Subject-initial > baseline							
Right	STG	22	55	−15	9	38,421	7.73
Left	STG	22	−44	−24	9	42,012	7.22
Left	TP	38	−35	21	−21	189	5.33
Left	Thalamus		−14	−27	0	2214	4.40
Left	CC	26/29	−2	−48	15	756	3.74
	Brain stem		1	−33	−3		3.68
Right	IFG	BA 45	37	21	9	405	3.44
b. Object-initial > baseline							
Right	STG	22	52	−15	9	113,643	7.61
Left	STG	22	−44	−24	9		7.43
Right	Thalamus		13	−24	0		5.16
Left	Thalamus		−17	−27	0		5.08
Left	IFG	45	−47	18	21	1836	4.68
Left	IFG	Ant. insula	−38	27	3		3.74
	Cerebellum		−2	−48	−15	1053	4.06
Left	CC	26/29	−5	−51	18	1701	4.03
Left	PHG		−26	−6	−36	594	3.86
Left	ACC	24	−14	3	30	2646	3.82
Right	ACC	24	13	18	30	27	3.13
Right	PCC	31	4	−33	33	243	3.43
Right	CC	31	25	−54	12	81	3.38
Left	SFG	8	−2	15	51	189	3.43
Left	SFG	6	−2	3	54	108	3.10
c. Object-initial > subject-initial							
Right	ACC	24/32	16	21	33	1971	4.76
Left	IPC	40/39	−47	−57	39	2349	4.02
Left	MTG	21	−50	−36	−3	135	3.61
Left	Post STG	22	−38	−42	21	27	3.51

would evoke the predicted effect in the left IFG for syntactically more complex object-initial sentences compared to subject-initial sentences.

Because the focus of the present study was on Broca's area, the cytoarchitectonic probabilistic maps of the Juelich database (Amunts et al., 1999) were used to build two regions of interest (ROI) for BA 44 and BA 45. These ROIs were thresholded to $p = .05$ to avoid an overlap of these two areas. These two ROIs were analyzed by direct statistical comparison between the object-initial and the subject-initial sentences in a repeated-measures GLM including Greenhouse–Geisser correction. There was found a significant main effect of factor *ROI* ($F(1,21) = 7.3$, $p = .01$) and a significant interaction of factor *ROI* by *word order* ($F(1,21) = 4.3$, $p = .05$). A closer examination revealed a significant main effect of *word order* in BA 44 ($t(21) = -2.2$, $p = .04$). These results confirmed the hypothesis for the planned study in children and validated the paradigm with a passive listening task.

Results

Behavioral results

In the receptive language test (TROG-D), 14 children performed within the expected T-score of 50 ± 10 and eight children performed above this mean result for this age group. In the behavioral test conducted after the scanner session, mean accuracy for the subject-initial condition on the picture task was 94.1% (SD 8.2) and for the object-initial condition 70.6% (SD 23.8), suggesting a significant advantage for subject-initial sentences ($t(21) = 4.4$, $p < .001$). Importantly, however, children performed significantly above chance in both conditions (subject-initial: $t(21) = 25.3$, $p. < .001$; object-initial: $t(21) = 4.1$, $p < .001$). Mean accuracy for subject-initial sentences was correlated with age ($r = .6$, $p = .003$) while for object-initial sentences it was not ($r = -.04$, n.s.). No significant correlations were found between the results of the TROG-D, the performance in the post-scan behavioral test, age and, sex.

Functional MRI results

The main effects of subject-initial and object-initial conditions (compared to baseline) revealed a similarly activated network in both conditions, including the STS/STG bilaterally, bilateral medial geniculate body, brainstem, and isthmus of cingulate gyrus, with more extended cluster activation for the object-initial condition in the anterior and posterior cingulate gyrus (Table 1, Fig. 1A). In both contrasts, the activation in the right IFG formed part of the larger right STG cluster. The left IFG was only activated for object-initial, but not for subject-initial sentences (Table 1, Fig. 1B).

The direct comparison of object-initial versus subject-initial sentences ("word order") revealed mainly left hemispheric activation. The area of activation comprised the IPC, particularly the supramarginal gyrus (SMG) and angular gyrus (AG); posterior STG (pSTG); MTG; and the left and right ACC (Table 1, Fig. 2A).

Region of interest results

In the repeated-measures GLM focusing on the left IFG the interaction of *ROI* by *word-order* effect in the group including 22 children approached significance ($F(1, 21) = 3.7$, $p = .07$). As displayed in Fig. 3A, BA 44, but not BA 45, showed more activation for object-initial than for subject-initial sentences, but neither in BA 44 nor in BA 45 a significant main effect was found.

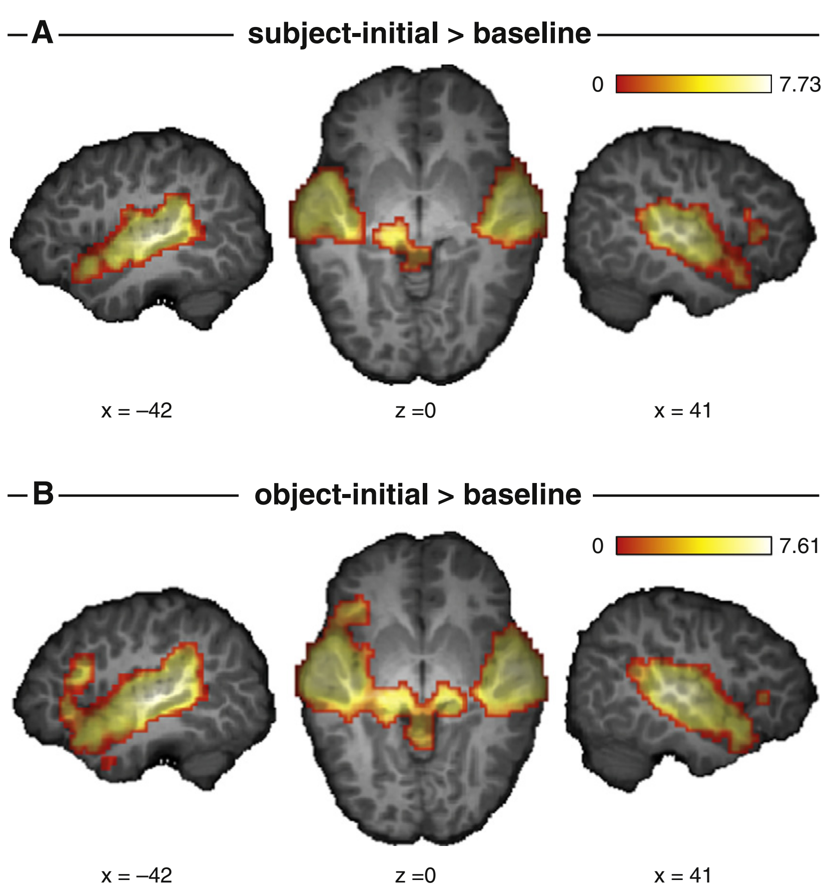

Fig. 1. Main effects contrasted to baseline (null events) mapped on the best brain. (A) Observed activations for subject-initial sentences in all children. (B) Observed activations for object-initial sentences in all children. All activations are thresholded to $p < .05$, corrected.

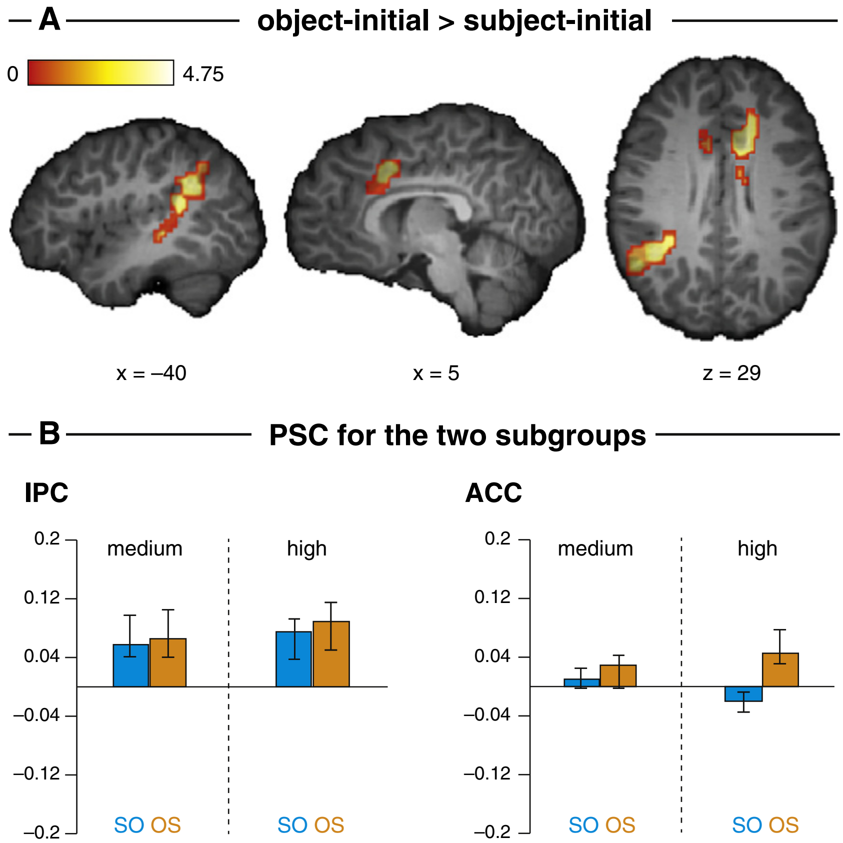

Fig. 2. (A) Observed activation for object-initial (OS) vs. subject-initial sentences (SO) in all children mapped on the best brain. All activations are thresholded to $p<.05$, corrected. (B) Percent signal changes (PSC) for a 3–10 s averaged time window in the two subgroups (medium and high-performing children). Error bars represent ±1 between-subjects Standard error of the mean (SEM). Blue bars refer to subject-initial sentences and orange bars to object-initial sentences. Illustrated are two regions of interest. Abbreviations: IPC = inferior parietal cortex; ACC = anterior cingulate cortex.

Closer inspection of the single-subject data revealed two distinct patterns of activation in the overall group. A subgroup of children ($n=11$) showed the predicted increased activation for object-initial sentences compared to subject-initial sentences, while a second subgroup ($n=11$) showed the reversed effect with stronger activation for subject-initial compared to object-initial sentences. Importantly, each child showed suprathreshold activation in only one of these two contrasts. Thus, we were able to group children unambiguously on the basis of their activation patterns.

Due to high individual differences reported in recent developmental studies (Nuñez et al., 2011; van Ettinger-Veenstra et al., 2010; Yeatman et al., 2010), we statistically tested post-hoc for a factor that could explain the different activation pattern. A significant difference between the two groups was found in the children's performance in an independent grammar test (TROG-D) ($t(20)=-2.3$, $p=.03$; one subgroup had an average performance of 61% and the other subgroup 82%). Based on this result, the children were divided by median on their result in the TROG-D. Two-sample t-tests revealed no differences between medium and high-performing group for sex, age, and post-scan behavioral picture task results. But importantly, the performance in the object-initial sentences in the post-scan picture task was found significantly above chance level only for the subgroup that performed high in the independent grammar test ($t(9)=4.5$, $p<.001$; $t(9)<1$).

A post-hoc repeated-measures GLM was performed with a within-subject factors *ROI* (BA 44 vs. BA 45) and *word order* (subject-initial vs. object-initial) and the new between-subject factor *group* (using the mean PSC per condition in the initially defined ROIs as the dependent measure). This analysis showed a tendency of a main effect of factor *ROI* ($F(1,18)=4.0$, $p=.06$), a significant interaction of factor *word order* by *group* ($F(1, 18)=5.6$, $p=.03$) and a marginally significant threefold interaction of factor *ROI* by *word order by group* ($F(1, 18)=4.2$, $p=.06$; Table 2). A closer examination revealed a significant interaction of *word order* by *group* only in BA 45 ($F(1,18)=7.0$, $p=.02$; Fig. 3B). Based on our prediction that only high-performing children would show an adult-like pattern of higher activation in object-initial compared to subject-initial sentences in BA 44, planned t-tests were conducted. The results suggest a trend towards higher activation for object-initial sentences compared to subject-initial sentences solely in high-performing children (BA 44: high-performing subgroup, $t(9)=-2.0$, $p=.08$; medium-performing subgroup, $t(9)<1$).

In order to investigate whether these group differences were confined to the IFG solely, or transferable to other regions, additional post-hoc tests (GLM, with the same factors as above) were performed on the mean PSC in the ACC and left IPC, respectively, cluster of activation of the whole group analysis. Main effects for *word order* were found only in the frontal areas (ACC: $F(1,18)=8.0$, $p=.01$; IPC: $F(1,18)<1$; Fig. 2B, Table 2).

In sum, word-order differences were observed in adjacent areas in the left frontal cortex. More importantly, only the group of children with a general higher grammatical knowledge showed an adult-like pattern of activation (larger activation for object-initial compared to subject-initial sentences) in the left IFG. A repeated-measure GLM was performed to test this directly. Therefore, anatomical ROIs for BA 44 and BA 45 were defined for the adult template image (same approach as described in section *Region of interest analysis*). Comparing adults from the pilot study to the medium-performing group, significant differences were found for the interaction of *ROI* by *group* ($F(1,30)=9.4$, $p=.01$), *word order* by *group* ($F(1,30)=5.7$, $p=.02$) and for the threefold interaction of *ROI* by *word order* by *group*

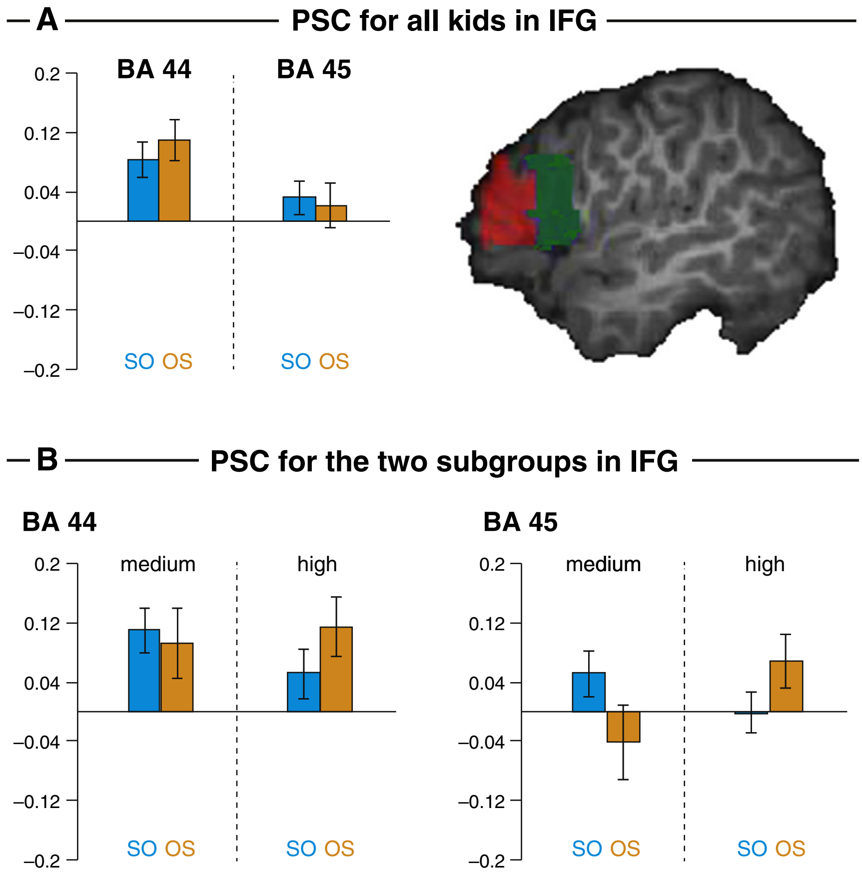

Fig. 3. (A) Percent signal changes (PSC) for a 3–10 s averaged time window for the two subregions of the left IFG (BA 44 and BA 45) in all children. Error bars represent ±1 between-subjects Standard error of the mean (SEM). Figure shows anatomical defined IFG ROIs (BA 44 in green and BA 45 in red). (B) Percent signal changes for a 3–10 s averaged time window for the two subgroups (medium and high-performing children) in BA 44 and BA 45. Error bars represent ±1 between-subjects Standard error of the mean (SEM). Blue bars refer to subject-initial sentences (SO) and orange bars to object-initial sentences (OS).

($F(1,30) = 4.3$, $p = .05$). The high-performing group compared to adults showed only a significant main effect of *word order* ($F(1,30) = 9.3$, $p = .01$). These findings confirmed the assumption that only the high-performing group employs adult-like sentence comprehension strategies that are mirrored in the left IFG.

Table 2
Results of repeated-measures GLM for (a) specific ROIs with within-subject factors ROI and word order (subject-initial vs. object-initial) and (b) with between-subject factor group or (c) just word order, and between-subject factor group.

ROI	Effect	df	f value	p value
a. All children				
IFG	ROI (BA 44 and BA 45)	1,21	2.998	n.s.
	Word order	1,21	.081	n.s
	ROI*word order	1,21	3.715	.068
b. Medium vs. high-performing children				
IFG	ROI (BA 44 and BA 45)	1,18	4.003	.061
	ROI*group	1,18	1.011	n.s.
	Word order	1,18	.059	n.s.
	word order*group	1,18	5.610	.029
	ROI*word order	1,18	2.933	n.s.
	ROI*word order*group	1,18	4.188	.056
c. Medium vs. high-performing children				
ACC	Word order	1,18	7.995	.011
	Word order*group	1,18	2.483	n.s.
IPC	Word order	1,18	.433	n.s.
	Word order*group	1,18	.033	n.s.

Discussion

The present study set out to investigate the acquisition of case-marking cues for argument interpretation in preschool children using fMRI and behavioral measures. Our results suggest a broad heterogeneity within 5- to 6-year-old children related to sentence processing. Irrespective of age, only the group with high receptive grammatical competence showed an adult-like pattern with stronger activation for object-initial sentences compared to subject-initial sentences. This is a pattern often reported in fMRI studies in adults (Bornkessel et al., 2005; Friederici et al., 2006; Rogalsky et al., 2008, for a recent review see Friederici, 2011), and also confirmed by our statistical analysis that found differences only between the medium-performing children and adults. Furthermore, left frontal areas are found to be activated for the more demanding non canonical sentence structure in general, with a specification of the left IFG for sentence comprehension already in children.

The behavioral results suggest that preschool children are able to process case-marking information even in object-initial sentences. However, their responses were less accurate in object-initial (71%) as compared to subject-initial constructions (94%). In spite of this, in both conditions children performed above chance level. The results are in contrast to other studies (Lindner, 2003; Schipke et al., in press) where children at this age were found to perform not significantly above chance level for object-initial sentences. Our findings indicate that children at this age are already sensitized to case-marking cues, but they have not yet completely integrated these into their grammatical knowledge. Therefore, they do not entirely rely on this information for sentence interpretation.

As expected, activations for both conditions contrasted to a silent baseline (Fig. 1) were observed mainly bilaterally along the entire STG/STS. In contrast to subject-initial sentences, object-initial sentences showed a more extended activation including the ACC/PCC and left IFG. The latter activation is generally in line with previous findings that found IFG activation for language processes. Although this area is extensively studied, its role in sentence processing is still debated (Friederici et al., 2006, 2010; Grodzinisky and Santi, 2008; Just et al., 1996; Rogalsky and Hickok, 2011; Stromswold et al., 1996). It is still not entirely clear what kinds of processes are subserved by Broca's area. While some researcher claim that this area is relevant for syntactic processes (Caplan et al., 2000, 2008; Friederici et al., 2010; Makuuchi et al., 2009; for an overview see Grodzinisky and Friederici, 2006), others suggest it is partly associated with working memory mechanisms that are related to language processes (Fiebach et al., 2004, 2005) or simply rehearsal (Rogalsky and Hickok, 2011). In addition, the left IFG is further divided into different subregions that are associated with different aspects of sentence processing: whereas BA 44 is taken to be linked with syntactic structure building (Friederici, 2002), BA 45/47 is associated supporting semantic processes (Bookheimer, 2002; Friederici, 2002; Hagoort, 2005). More recently area 45 has been subdivided receptor-architectonically in an anterior portion (45a) and a posterior portion (45b) with the latter bordering area 44 (Amunts et al., 2010).

Considering that object-initial sentences are expected to be more syntactically complex than subject-initial sentences, the activation in the left IFG for object-initial sentence contrasted to baseline was predicted. The subject-initial condition did not activate this region. However, in contrast to other studies that found activation in BA 44 for syntactic complexity in adults (Bornkessel et al., 2005; Friederici et al., 2006; Rogalsky et al., 2008), the activation in the present study was observed in BA 45. Brodmann's area 45 is argued to be more engaged during sentence comprehension in 6- to 7-year-old children than in adults, possibly because the dorsal white-matter connecting BA 44 to the temporal region is not yet fully matured at this age (Brauer et al., 2011). Rather, a ventral connection targeting BA 45 might serve as an additional connection within the language network, as reflected by stronger functional activation in BA 45 in children (Brauer et al., 2011).

The present data specify this view somewhat: they imply that enhanced BA 45 activation might also reflect a different strategy used by children compared to adults. While adults use case-marking information as a cue in complex sentences to access the thematic roles to the arguments, preschool children have not reached this proficiency level yet. Their performance in the post-scan picture test for the object-initial condition was, though above chance, significantly below their performance for the subject-initial condition. Thus, the current data suggest that case-marking is a cue which preschool children are aware of, but that they have not yet completely integrated this knowledge in order to use it fully in sentence processing. Instead, other kinds of information (i.e., semantic cues) are probably employed for sentence interpretation. An indication for this strategy stems from reports provided by our participants after they completed the task. When being asked about the sentences, a number of children refused some sentences because of their semantic content (“You can not comb a bird. The bird has no hair.”; “You can not touch the hedgehog, it has spines.”). Earlier imaging studies in adults found the BA 45 part of the left IFG more active for sentences containing real-world knowledge violations compared to those that did not (Hagoort et al., 2004). However, assuming that BA 45 may contribute to sentence comprehension in terms of working memory (Fiebach et al., 2005), the current activation may indicate, that even in short sentences, children struggle to analyze object-initial sentences on the first pass.

Functional MRI results in the present study further revealed mainly left hemispheric activation for object-initial versus subject-initial sentences comprising the IPC (particularly the supramarginal and angular gyrus); the pSTG; the MTG; and the ACC. Activation in BA 45 that had been found only in the object-initial condition contrasted to baseline, was not confirmed in the direct contrast between the both conditions.

Activation in the ACC has been typically observed in studies that investigate cognitive control, for example, conflict monitoring during cognitive tasks (Barch et al., 2001; Botvinick et al., 2001, 2004; Carter et al., 1998). Activation is usually enhanced when participants produce errors or detect a salient violation of expectancy. With respect to our results, the ACC activation could be interpreted as violation of an expectancy of a canonical subject-initial sentence structure.

Activation of left IPC and pSTG are consistent with previous studies that found those areas activated during sentence processing in children and adults (Ahmad et al., 2003; Booth et al., 2000; Yeatman et al., 2010). Yeatman et al. found the pSTG activated for syntactically complex versus easy sentences and suggested that children recruit this area for the comprehension of syntactically complex sentences. These findings are also consistent with previous findings in adults (Friederici et al., 2009; Newman et al., 2010; Santi and Grodzinisky, 2010). Activation in the left MTG and SMG are associated with supporting semantic processes (Binder et al., 2009; Kotz et al., 2002; Price et al., 1997), and especially the MTG is suggested a critical region for lexical semantic integration (Hickok and Peoppel, 2007). This expending activation from IPC to MTG for object-initial sentences provides indirect evidence that the children drew semantic information instead of only morphological information to process this sentence structure.

Furthermore, we found in the region of interest analysis for BA 44 and BA 45 a significant interaction of *word order* and the two subregions within the left IFG (Fig. 3A). As individual differences have been reported in developmental studies before (Nuñez et al., 2011; van Ettinger-Veenstra et al., 2010; Yeatman et al., 2010), we performed post-hoc analyses at the single-subject level that revealed two distinct activation patterns (i.e., two subgroups) within the overall group. A subgroup (half of the children) showed the predicted increased activation in the object-initial compared to subject-initial sentences. However, the other half of the children showed the opposite effect with stronger activation for subject-initial sentences. Interestingly, differences between the two subgroups were found in their language abilities. Only the group with a high grammatical knowledge showed in the left IFG a pattern of activation in an adult-like manner (Friederici et al., 2006; Rogalsky et al., 2008). These findings are in line with other developmental studies that found correlations between language skills and IFG activation strength (Nuñez et al., 2011; Yeatman et al., 2010). Although the ROI analysis in all children indicated that BA 44 is more strongly involved in sentence processing in general, no differences were found between the subgroups for the factor *word order* in this area. Planned *t*-test suggested a trend towards high activation for object-initial sentences compared to subject-initial sentences in the high-performing group. Clear significant differences between factors *word order* and *group* were only found in BA 45. This could point to the use of different strategies depending on grammatical knowledge in the children.

Interestingly, differences in the left IFG were found, for subject-initial sentences, between two subgroups of children. In the subgroup of medium performers, this area was more activated for canonical sentences, than in the subgroup of children with higher receptive language skills. Only the latter subgroup showed the expected larger activation for more complex sentences in contrast to canonical sentences. We believe that, the different findings in the left IFG could be due to strategies children use for sentence processing. Instead of only using case-marking information, they search for other cues that help to process the sentences, for instance semantic cues, suggested by different pattern of activation in BA 45. The results of the post-scan picture task also support this conclusion: Only the high-performing subgroup performed above chance in object-initial sentences. In general, the data suggest, that even if the medium-performing subgroup is already sensitized to case-marking, they do not constantly use this information to process the object-initial sentence.

To elucidate the differences between the subgroups we took a closer look into the activated regions in frontal and parietal lobe. The overall picture was similar in the analyzed ROIs (IPC, and ACC). Although, an increase in activation in the object-initial sentences in all areas was observable, a main effect of condition was found in the frontal areas exclusively (ACC; Fig. 2B). Based on previous studies that suggested ACC activation to represent error detection and enhanced need for cognitive control, we assume the ACC activation for non canonical sentences to be associated with reorganization of the maintained information and predicting subject and verb information, which is more demanding for object-initial sentences.

Conclusion

This functional MRI study in children between five and six years of age (a developmental stage at which they start using case-marking information) shows that there is a considerable amount of heterogeneity within this age group, and that this heterogeneity is directly reflected in differential patterns of inferior frontal cortex activation. Some children already use case-marking information for sentence interpretation reliably by this age, while others do not: They rely instead on additional cues to process sentences. Our functional neuroanatomical and behavioral data indicate that different strategies are employed when it comes to using case-marking information for sentence processing, depending on the children's receptive grammatical knowledge.

Both high and medium-performing subgroups show a similar effect in frontal areas that might reflect a general cognitive control effect. Additionally, the more demanding object-initial sentences more strongly involved the ACC, an area that is commonly attributed to executive functions (e.g. error predictions). Interestingly, a different pattern of activation is found in the left IFG, suggesting that this area is more sensitive to sentence structure comprehension itself. Furthermore, activations in the left IFG seem to indicate the degree to which adult-like sentence comprehension strategies are already employed. While medium-performing children do not reliably use case-marking cues for syntactic integration processes, high-performing children do. Their language system is not challenged by subject-initial sentence constructions anymore, but for object-initial constructions, the left IFG comes into play to integrate all informative cues. Thus, it seems that our experiment has pinpointed a pivotal phase when children are already sensitized to grammatical cues but differ in their individual ability to integrate them for successful sentence comprehension.

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