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Linguistic Inability or Poor Performance: Dissociating Scalar Implicature Generation and Mismatch in the Developing Brain

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Behavioral investigations of the acquisition of *some* have shown that children favor its logical interpretation (*some and possibly all*). Adults, however, use the pragmatic interpretation (*some but not all*) derived by a scalar implicature. Certain experimental manipulations increase children's rates of adult-like responses, indicating that children are capable of computing implicatures. A functional MRI (fMRI) study examining adults linked the left inferior frontal gyrus (IFG) to implicature computation, and prefrontal regions, the left middle frontal gyrus (MFG), and medial frontal gyrus (MeFG), to processing the mismatch between implicatures and the context in which they were presented. In the current fMRI study, we aimed to determine whether children's failure to give pragmatic interpretations to *some* results from a failure in implicature computation or in implicature-mismatch processing. We explored children's brain activations with the same experimental task administered to adults. In a region-of-interest analysis, children showed an activational pattern similar to the one observed in adults in the left IFG with increased activations for the implicature conditions. By contrast, in the left MFG, children showed decreased activation for the mismatched implicatures compared with matched and no implicature conditions. No difference between the conditions was observed in the MeFG. For both implicature conditions, no activation in the left IFG was observed when comparing adults and children directly. However, for mismatched implicatures, adults showed greater activation in the prefrontal regions compared with children. Our results suggest that children may have an adult-like computation of implicatures (even when their behavior does not necessarily indicate that), but they fail in resolving implicature-mismatch situations.

Keywords: language acquisition, semantics, neurolinguistics, fMRI, scalar implicatures

In the first years of their lives, children acquire language quickly and effortlessly. Talking to a typically developing 4-year-old reveals that children that age have remarkable communication skills. However, some aspects of language use seem to be difficult even for 6-year-olds (or even older). One example is the ability to make inferences beyond the literal and logical meaning of utterances (e.g., Bernicot, Laval, & Chaminaud, 2007; Huang & Snedeker, 2009; Noveck, 2001; Pexman & Glenwright, 2007). Such pragmatic inferences are common in any language, and children come across them frequently. Consider Example 1 in the following text. The adult reader probably infers that some *but not all* of the toys were out of the box. But, in fact, the logical meaning of *some* includes the stronger member of the same scale, *all*/*every*. That is, the logical meaning of *some* is *some and possibly all*, as can be seen in Example 2. In that example, the adult reader is not likely to get the pragmatic interpretation of *some but not all*.

Example 1. Some toys are out of the box.

Example 2. If some toys are out of the box, you cannot get dessert after dinner.

The phrase *but not all* that is added to the meaning of the sentence in Example 1 occurs via a meaning enrichment mechanism called *scalar implicature*. Formal semantics maintains that weak scalar expressions form ordered scales with stronger expressions of the same type (e.g., *some, many, most, all/every*; other scales are *or, and*; the numbers line; or adjectives like *warm, hot*; e.g., Gazdar, 1979; Grice, 1975; Horn, 1972). Scalar implicatures occur through the consideration of the scalar alternatives of a scalar expression positioned at the weaker end of the scale (e.g., *some*). Via this mechanism, language users infer that the stronger alternatives (e.g., *every/all*) do not hold, thus reaching a stronger interpretation of the weak scalar expression (e.g., *some but not all*).

Developmental studies, although not without disagreement, seem to suggest that adults tend to use the pragmatic interpretation of *some* (i.e., *some but not all*), whereas children favor its logical

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meaning (i.e., *some and possibly all*; e.g., Guasti et al., 2005; Huang & Snedeker, 2009; Noveck, 2001; Smith, 1980). For example, when presented with underinformative statements, such as "Some giraffes have long necks," French-speaking children and adults responded differently: adults were more likely than children (8-year-olds and 10-year-olds) to reject these statements based on the pragmatic interpretation of *some* and other scalar expressions (Noveck, 2001). It is important to note that underinformative statements present a case of implicature mismatch as they are logically true but pragmatically incorrect (because it is known that *every* giraffe has a long neck). Several studies, using the same or similar judgment tasks in different languages, showed this different response pattern between adults and children with various weak scalar expressions (Braine & Rumain, 1981; Chierchia, Crain, Guasti, Gualmini, & Meroni, 2001; Feeney, Scrafton, Duckworth, & Handley, 2004; Foppolo, Guasti, & Chierchia, 2012; Guasti et al., 2005; Smith, 1980; Verbuk & Shultz, 2010). Hendriks et al. (2009) reported no age affect in the rates of enriched responses (in Dutch), comparing a group of 5- through 9-year-olds with older children (two groups ages 10–14 and 15–19 years) and adults. However, it is very likely that age effects in the younger group are not present because this group includes children older than the age of acquisition for scalar implicatures (which is assumed to be before the age of 7; e.g., Foppolo et al., 2012; Katsos & Bishop, 2011).

The pattern of behavior with scalar implicatures, where adults and children respond differently, has also been shown in an online visual world paradigm using eye tracking, which eliminates the need to make overt judgments on the truth value of statements (Huang & Snedeker, 2009). In this task, children also failed to exhibit an adult-like response with *some*. Whereas adults reliably shifted their looks to the target after encountering the word *some* (which corresponded to the pragmatic interpretation), children did so only after encountering a disambiguating phonological cue that helped them decide between the pragmatic and the semantic interpretations of the sentence they had heard.

This evidence seems to suggest that children do not compute scalar implicatures to derive the pragmatic interpretation of scalar expressions. However, several studies have shown that under certain experimental settings, children have higher rates of adult-like responses. For example, when adding a short training session using underinformative statements without scalar expressions (e.g., "a little animal with four legs" to describe a dog), children's rates of pragmatic adult-like responses for weak scalar expressions increased (7-year-olds in Guasti et al., 2005; 5-year-olds in Papafragou & Musolino, 2003). The training was presumed to draw the attention of the participants to the goals of the experiment. Increased rates of the pragmatic interpretation of *some* were also observed with an action-based, rather than a verbal judgment, task performed by 5- and 7-year-olds (Pouscoulous, Noveck, Politzer, & Bastide, 2007). Additionally, when required to choose between a statement with a weak scalar (e.g., *or*), and a statement with the stronger alternative of that scalar (e.g., *and*), children properly used the pragmatic interpretation to make their decision (Chierchia et al., 2001). In the same vein, when children were asked to use a 3-point scale to judge underinformative statements, rather than give a binary (true/false) judgment, they performed like adults, rating underinformative statements with the middle score (Katsos & Bishop, 2011).

These findings clearly indicate that children have the capacity to compute scalar implicatures. It is still unclear why they do not show this capacity in standard judgment tasks, and what linguistic and cognitive factors elicit the pragmatic responses under the various experimental manipulations presented earlier. It has been suggested that children fail to give pragmatic responses in standard judgment tasks due to their limited computational resources (Guasti et al., 2005; Pouscoulus & Noveck, 2009), because they cannot access the scalar alternatives of the weak scalar expression (i.e., they cannot make the connection between *some* and *all*; Barner, Brooks, & Bale, 2011) or because they are willing to accept pragmatic violation but not logical violations (Katsos & Bishop, 2011).

In the present study, we aimed to explore the source of children's non-adult-like behavior with scalar implicatures in standard judgment tasks, focusing on the mismatch between the implicature and the context. Our investigation is based on a functional MRI (fMRI) study with adults, where we tested the processing of scalar implicatures and were able to dissociate between scalar implicature computation and the processing of mismatched scalar implicatures (Shetreet, Chierchia, & Gaab, 2014a). In that study, we examined the processing of implicatures in adults looking for similarities and differences between mismatch implicature (e.g., the sentence "Some giraffes have balloons" presented with a picture in which all of the giraffes had balloons), matched implicature (e.g., same sentence presented with a picture in which some but not all of the giraffes had balloons), and no implicature (e.g., using sentences including *every* with both picture types) conditions (see Table 1). Table 2 summarizes our two main findings of Shetreet et al. (2014a): (a) Both mismatched and matched implicatures showed increased activation in the left inferior frontal gyrus (IFG; Brodmann area [BA] 47) when compared with the no-implicature conditions. Thus, this region, which has a well-known role in semantic processing (Dapretto & Bookheimer, 1999; Hagoort, 2005; Hagoort, Baggio, & Willems, 2009; Homae,

Table 1
Summary of Results From Shetreet et al. (2014a): Conditions

Condition	Sentence	Picture
Mismatched scalar implicature: (*some*ALL)	Some mice have grapes.	ALL of the mice have grapes
Matched scalar implicature: (*some*SOME)	Some lions are skating.	SOME lions are skating
(someNONE)	Some monkeys are on the couch.	NONE of the monkeys are on the couch
No implicature:		
(*every*ALL)	Every penguin is on the bus.	ALL of the penguins are on the bus
(*every*SOME)	Every rabbit has keys.	SOME rabbits have keys

Table 2
Summary of Results From Shetreet et al. (2014a): Main Results

Comparison	Activated region
Implicature computation: someALL > everyALL and someSOME > everyALL	Left IFG (BA 47)
Implicature mismatch: someALL > someSOME and someALL > someNONE	Left MFG (BA 10) Left MeFG/ACC

Note. IFG = inferior frontal gyrus; BA = Brodmann area; MFG = middle frontal gyrus; MeFG = medial frontal gyrus; ACC = anterior cingulate.

Hashimoto, Nakajima, Miyashita, & Sakai, 2002; Sakai, 2005; see also meta-analysis studies, e.g., Binder, Desai, Graves, & Conant, 2010; Bookheimer, 2002; Fiez, 1997), was linked to implicature computation. (b) Two regions in the prefrontal cortex, the left anterior middle frontal gyrus (MFG) and medial frontal gyrus (MeFG)/anterior cingulate (ACC), were activated by mismatched implicatures but not by the matched- and no-implicature conditions. Thus, these regions were linked to the processing of the mismatch between the implicature and the context (i.e., the picture). Interestingly, these regions have been previously linked to high cognitive functions, such as conflict monitoring, cognitive control, and truth value judgment (Carter & van Veen, 2007; Mansouri, Tanaka, & Buckley, 2009; Wendelken, Nakhabenko, Donohue, Carter, & Bunge, 2008; Wolfensteller & von Cramon, 2011).

In the developing brain, the regions that were linked to scalar implicature processing in adults, the left IFG, and the left anterior MFG and MeFG/ACC, are assumed to have different trajectories. Based on longitudinal studies, it is suggested that the maturation of the frontal lobes proceeds from posterior regions toward the anterior regions (e.g., Gogtay et al., 2004). This finding suggests that the IFG, which is more posterior than the other two regions, matures earlier. Furthermore, the development of cognitive functions agrees with the suggested pattern of brain maturation, as language processing (which is linked to posterior frontal regions and temporal regions) develops earlier than executive functions and attention (which are linked to the prefrontal cortex; e.g., Best, Miller, & Jones, 2009).

In the present fMRI study, we examined the brain activations of 6-year-old children while they were performing a task designed to test the processing of scalar implicatures (and which was used with the adults in Shetreet et al., 2014a). Brain activations in the developing brain provide an implicit measurement for children's computation of scalar implicature, as it is independent from their actual behavior. This investigation can thus help uncover the source for the behavioral differences between adults and children with respect to scalar implicatures. Specifically, we wanted to determine whether children's logical non-adult-like behavior with scalar implicatures is rooted in their limited ability to compute implicatures or in their failure to process the mismatch between the implicature and its context.

It should be noted that the current study was not designed to distinguish between logical and pragmatic responders. Instead, we aimed to determine whether children's brain activations resemble those of adults when they encounter the quantifier *some* in match and mismatch contexts. To do so, we examined in children the implicature computation and implicature-mismatch processing components in brain regions previously identified in adults for these components. We performed a region of interest analysis in children, as well as direct comparisons between children and adults. In both, we focused our attention on the left IFG (BA 47), left MFG, and the MeFG/ACC. If children fail to produce adult-like responses with scalar implicatures due to linguistic processes related to implicature computation, activations in the left IFG should not follow the activation pattern observed in adults. However, if children master implicature computation and fail to produce adult-like responses with implicatures because of a failure in the processing of mismatched contexts, we should detect activations in the prefrontal regions (the left MFG and the MeFG/ACC) that differ from those observed in adults.

Method

Participants

Twelve 6-year-old children (mean age = 6 years, 0 months, *SD* = 0 years, 3 months; range: 5 years, 9 months–6 years, 4 months; eight girls and four boys) participated in the study. All of the children met our eligibility criteria, including being native English-speaking and right-handed, as well as having normal hearing and no history of cognitive, motor, developmental, or language difficulties or brain injury. Children were recruited through the Research Participant Registry of the Laboratories of Cognitive Neuroscience in Boston Children's Hospital. All of our participants came from a middle or high socioeconomic status and were Caucasian. The study was approved by the Institutional Review Board of Boston Children's Hospital. Verbal assent and informed consent were obtained from each participant and his or her caregiver, respectively. All families received gift cards to compensate for their participation. Three additional participants were excluded from the analysis due to low performance in the experimental task, one participant was excluded due to extensive movement, and another one due to a technical problem. All in all, we scanned 17 children, but only 12 were included in the fMRI analysis.

Language and Cognitive Assessments

All children completed language and cognitive standardized testing which took place on a different day than the fMRI session (eight children performed the testing session before the MRI session and four children after). Assessments included the Kaufman Brief Intelligence Test (KBIT-2, Kaufman & Kaufman, 2004) to test for verbal and nonverbal intelligence, the Digits Forward and Digits Backward subtests from the Test of Memory and

Learning (TOMAL-2, Reynolds & Bigler, 2007) to test for working memory, and the Clinical Evaluation of Language Fundamentals (CELF-4, Semel, Wiig, & Secord, 2003) to test for core language abilities. All the participants scored within or above the average range (Table 3).

Materials and Procedure

One hundred sentences were used in this experiment. Sentences included a quantifier, *some* or *every*, with a noun in the subject position. All of the words in the sentences had an Age-of-Acquisition earlier than 5 years (as determined by the MacArthur–Bates Communicative Development Inventories; Dale & Fenson, 1996). We balanced the words across conditions by using the same words in different combinations (e.g., "Some elephants are drinking," "Every elephant is dancing," and "Every giraffe is drinking"). The sentences described an action performed by the subject (e.g., "Every elephant is dancing"), the location of the subject (e.g., "Some zebras are on the boat"), or a possession of the subject (e.g., "Some giraffes have balloons"). Sentences were presented auditorily. A female who is a native speaker of American English recorded the sentences in random order across conditions.

These sentences were used in two tasks, an experimental task (a meaning-matching task) and a control task (a voice-matching task). We piloted the two tasks with a different sample of 6-year-olds to ensure that 6-year-old children could perform the tasks adequately.

Meaning-matching task. In this sentence-picture matching task, participants heard a sentence while looking at a picture and were asked to decide if the sentence matched the picture. Pictures were used to determine a context for the sentences. All of the pictures included five individuals of the same type (e.g., five giraffes, or five girls). There were three types of pictures: pictures where all of the individuals had the same property that was stated in the sentence (e.g., five mice with grapes; Figure 1A), pictures where three of the individuals had the same property (e.g., three skating lions; Figure 1B), and pictures where none of the individuals had that property (e.g., no monkey on a couch; Figure 1C).

We designed five conditions by combining the two sentence types (with *some* or *every*) and the three picture types (ALL, SOME, or NONE; Figure 1):[1] (a) *some*ALL—*some* sentences with ALL pictures: This is the implicature-mismatch condition which includes both the implicature computation and the implicature-mismatch processing; (b) *some*SOME—*some* sentences with SOME pictures: This is the matched implicature condition which includes only the implicature computation; (c) *some*NONE—*some* sentences with NONE pictures: it is unclear whether this condition includes implicature computation (because the truth value of the sentence can be successfully determined on either the logical or the pragmatic construal); (d) *every*ALL—*every* sentences with ALL pictures; and (e) *every*SOME—*every* sentences with SOME pictures. Conditions (d) and (e) do not include any implicature-related processes, as they include a strong scalar expression. Each condition was sampled 20 times (with a total of 100 sentences). There were no differences in the duration of the sentences across the five conditions, $F(4, 99) = 0.83$, $p = .51$; $\eta_p^2 = .03$.

Table 3
Scores in Behavioral Tests

Test	Mean	*SD*	Range
Kaufman Brief Intelligence Test (KBIT-2)			
IQ Composite standard score	115.2	14.0	94–136
Verbal subtest standard score	118.7	13.0	102–144
Test of Memory and Learning (TOMAL-2)			
Digits Forward standard score	10.7	2.3	7–16
Digits Backward standard score	12.2	1.3	10–15
Clinical Evaluation of Language Fundamentals (CELF-4)			
Core Language Index standard score	125.2	13.8	96–142

Note. For KBIT-2, standard scores between 85 and 115 are considered to be in the average range. For TOMAL-2, standard scores between 7 and 13 are considered to be in the average. For CELF-4, standard scores between 85 and 115 are considered to be in the average.

Voice-matching task. This task was used as a control task to set the baseline activation for auditory, lexical, and syntactic processing, as well as for decision making. We asked the participants to match the voice of the speaker(s) of the sentence to a picture of the speaker(s). Thus, no access to the semantics/pragmatics of the sentences was needed in order to give a response. For this task, we chose a random sample of the sentences that were used in the experimental task. The sentences were spoken by a woman, an alien, or both.[2] The alien voice was created by an audio manipulation in GoldWave program. The pictures in this task included a detailed scene with a woman, an alien, or both. Each picture and each sentence were presented once for each participant. For example, when presented with a picture of a woman and an alien (Figure 2), participants were expected to respond with "match" if the sentence spoken by a woman had the last word spoken by an alien, but with "no match" if the sentence was spoken only by a woman. All of the sentences including the alien voice were fillers and were not included in the analysis. There were 20 control sentences and 20 fillers.

In both tasks, each picture was presented for 4 s. The sentence was played with the initial display of the picture, and a response was required after the ending of the sentence. Rest trials with a fixation cross were also included and displayed for 4 s. Trial randomization was determined by optseq (available at http://www.freesurfer.net/optseq). The meaning-matching task was presented in two separate runs with 10 trials for each condition in each run. The voice-matching task was presented in a single run with all 20 sentences of each condition. Each run lasted approximately 4.5 min. The order of the presentation of the runs was counterbalanced between subjects. Stimuli were delivered to the participants using Presentation software (Version 14.9). All responses and reaction times were recorded.

Prior to the MRI scan, participants went through a training session using a mock scanner procedure (Raschle et al., 2009, 2012). The training included an age-appropriate introduction to the

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[1] Other conditions were also included in the adults study by Shetreet et al. (2014a), including an *every*NONE condition. The conditions were excluded from the current study to allow for shorter fMRI scanning. In our experience, fMRI scanning periods shorter than 5 min are better suited for young children. Including more conditions in this experiment would have resulted in longer periods of scanning.

[2] Because voice matching can be performed by only hearing the first word in the sentence, we decided to include sentences that were spoken by two speakers. This way, participants had to listen to the entire sentence before making a response.

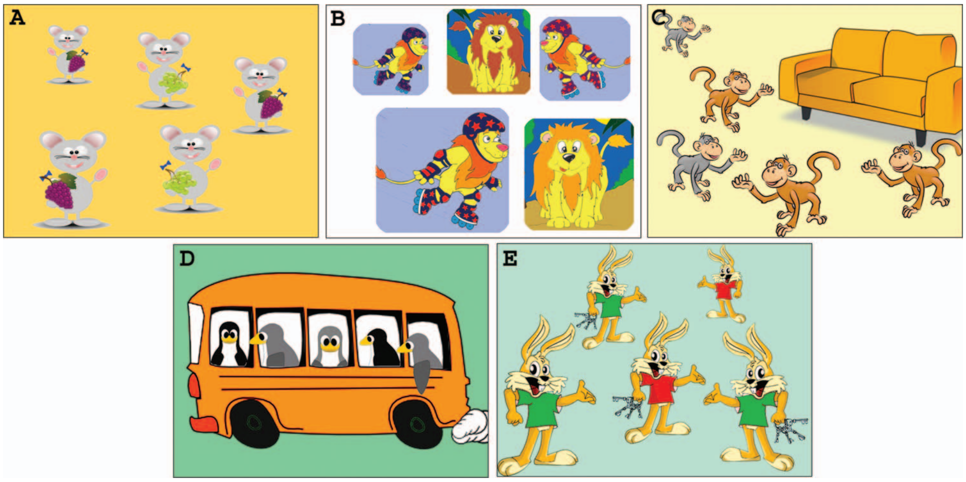

Figure 1. Examples for pictures used in the experimental task (meaning-matching task**)**. Picture A was presented with the sentence "Some mice have grapes" (for the mismatched implicature condition); Picture B with the sentence "Some lions are skating" (for the matched implicature condition); Picture C with "Some monkeys are on the couch"; Picture D with "Every penguin is on the bus"; and Picture E with "Every rabbit has keys." See the online article for the color version of this figure. Adapted from "When Three Is Not Some: On the Pragmatics of Numerals," by E. Shetreet, G. Chierchia, and N. Gaab, 2014, *Journal of Cognitive Neuroscience, 26*, p. 857. Copyright by MIT Press.

MRI machine, explaining the importance of staying still, and getting comfortable within the scanner. Using instruction videos, the experimenter confirmed that the child understood the tasks. Next, the child practiced the tasks using sentences and pictures that were not used in the experiment itself. We did not include mismatch scenarios in the practice of the meaning-matching task. The entire session, including the training and the MRI scan, lasted approximately 2 hr.

Figure 2. An example for a picture used in the control task (voice-matching task**)**. This picture shows a woman and an alien and was presented with the sentence "Some monkeys are on the *couch*" where the last word (*couch*) was spoken by "an alien" (a voice manipulation), and the rest of the sentence was spoken by a woman (for a match response). See the online article for the color version of this figure. Adapted from "When Three Is Not Some: On the Pragmatics of Numerals," by E. Shetreet, G. Chierchia, and N. Gaab, 2014, *Journal of Cognitive Neuroscience*, *26*, p. 858. Copyright by MIT Press.

Data Acquisition

MRI scans were obtained in a whole-body 3-tesla Siemens Trio MR scanner (Siemens; Erlangen, Germany). Functional MRI was performed using a gradient-echo $T2^*$-weighted echo-planar-imaging interleaved sequence with 127 whole-brain images in each run. Images obtained were 32 sagittal slices 4-mm thick, covering the whole of the cerebrum and most of the cerebellum. Our acquisition parameters were field of view (FOV) = 192; matrix size = 64 × 64; repetition time (TR) = 2,000 ms; echo time (TE) = 30 ms; and flip angle = 90°.

Data Analysis

Image analysis was performed using Statistical Parametric Mapping (Version 8; SPM8). Functional images from each subject were slice-time-corrected for interleave acquisition, motion-corrected, normalized, and spatially smoothed using a Gaussian filter (4-mm kernel). For normalization, the SPM Montreal Neurological Institute (MNI) adult template was employed to keep to template constant across analysis.[3] We chose the MNI template due to the fact that a region of interest (ROI) analysis based on coordinates obtained using this template was performed (see

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[3] Other approaches for normalization of pediatric fMRI data have been used. One prominent approach employed in comparing adults and children is the use of a customized template based on an average of anatomical images of both adults and children participating in the study (e.g., Burgund et al., 2002; Kang, Burgund, Lugar, Peterson, & Schlaggar, 2003). We applied this approach for the comparison between adults and children in the current study as well. The results of this analysis are reported in footnote 4.

Muzik, Chugani, Juhász, Shen, & Chugani, 2000, for use of the SPM adult template with child population). Artifact detection was employed individually for each participant's data using the Artifact Detection Tool (ART; Version 2011-07) software. Volumes with movement threshold higher than 3 mm and rotation threshold higher than 0.05 radians were excluded from the analysis. None of the subjects who were include in the final analysis had more than 10% excluded volumes.

Data from individual subjects were analyzed using a general linear model (GLM; Friston et al., 1994) with high-pass filtered at 128 s. Events were modeled with the onset of the sentence/picture (which was the same for both) and with the duration of the entire trial (4 s) to capture processes of implicature computation and the decision making, which is relevant to the mismatch processing. We used response accuracy as a covariate for each experimental condition separately. For the *some*ALL condition, we defined the adult-like response to be correct (see the Results section for further discussion on using this response as a regressor). Head motion parameters and outlier volumes (as determined by the ART software) were added as regressors.

We computed individual contrasts between the experimental conditions and between the experimental conditions and the control condition. For the group level, one-sample *t* tests and two-sample *t* tests were computed using these contrast images. Analyses at the group level were carried out with the threshold of $p <$ .005 and cluster size of $k > 10$ voxels. Correction at the cluster level was applied using family-wise error correction ($p_{\mathrm{FWE}}) < .05$.

We further performed an ROI analysis, with ROIs that were defined based on areas observed in the conjunction analysis of the individual comparisons of *some*ALL with each of the *every* conditions in an adult sample in Shetreet et al. (2014a). We focused on the left IFG (BA 47), left MFG, and medial frontal gyrus (MeFG), which were specifically linked to the processing of implicatures. Using MarsBar (MARSeille Boîte À Région d'Intérêt; Brett, Antoine, Valabregue, & Potine, 2002), a toolbox for SPM, we defined a sphere around the peak MNI coordinates of each of these areas as reported in Shetreet et al. The sphere size was selected based on the size of the original areas, with a 10-mm sphere for the left MFG and 5-mm sphere for the other regions (Figure 3). At the subject level, we computed the contrast between each condition (*some*ALL, *some*SOME, *some*NONE, *every*ALL, and *every*SOME) and the control (baseline) task condition. Average contrast estimates for all five contrasts were extracted from the ROIs using MarsBar, and planned comparisons were performed to compare the *some* conditions with the *every* conditions.

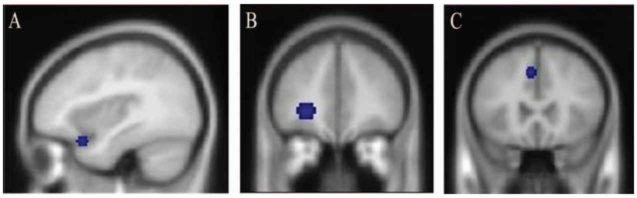

Figure 3. Regions of interest (indicated by black spots in the print journal and by dark blue spots in the online version) defined based on clusters of activations observed in adults while performing the same task (Shetreet et al., 2014a): (A) the left inferior frontal gyrus, (B) left anterior middle frontal gyrus, and (C) medial frontal gyrus/anterior cingulate. See the online article for the color version of this figure.

Adult Sample

Data from the 13 adults (eight females and five males, ages 19–30 years, mean age 23.4) who participated in Shetreet et al. (2014a) were included in this study in order to perform direct comparisons between children and adults. All of the adults were right-handed, native English speakers without neurological, hearing, or language impairment. They gave informed consent prior to the experiment and were compensated for their participation.

The adult participants, like the children, performed meaning-matching and control tasks. However, they were presented with more trials and more conditions (e.g., *every*NONE condition). For a detailed report on the task, see Shetreet et al. (2014a). For the current study, preprocessing and data analysis were performed as detailed for the child sample.

We directly compared adults and children and therefore examined the differences between their head movements. We calculated the average of each of the six motion parameters obtained for each subject in the motion correction analysis in SPM. We then performed a 2×6 repeated-measurement analysis of variance (ANOVA) with group (two levels) and movement (six levels, repeated). No significant main effect for group, $F(1, 23) = 0.209$, $p = .652$, or movement, $F(5, 115) = 0.361$, $p = .140$, was observed. The interaction between group and movement also failed to reach statistical significance, $F(5, 115) = 0.583$, $p = .713$.

Results

In-Scanner Performance

In the experimental task (the meaning-matching task), all 12 child participants performed above chance as determined by the binomial test. For this test, we considered only the four conditions for which there was one possible correct response (i.e., we did not include the *some*ALL condition, for which both "match" and "no-match" responses are acceptable). For the *some*ALL, six children responded with significantly more match responses (logical responders), two gave more no-match responses (pragmatic responders), and the remaining four gave mixed responses. An ANOVA test was used to determine that there were no significant differences in reactions times and accuracy between the experimental conditions, $F(8, 4) = 3.43$, $p = .12$, $\eta_p^2 = .87$; and $F(8, 4) = 2.19$, $p = .23$, $\eta_p^2 = .81$, respectively. Mean accuracy was 7.5, 7.6, 8, 6, and 7.1 for the *some*ALL, *some*SOME, *some*NONE, *every*ALL, and *every*SOME, respectively. Mean reaction time was 2.9, 2.7, 2.9, 2.6, and 2.9 for the *some*ALL, *some*SOME, *some*NONE, *every*ALL, and *every*SOME, respectively.

The control task yielded lower performance, with only six out of the 12 participants showing above-chance performance. The control task was used only to determine baseline activations for basic auditory, lexical, and syntactic processing compared with the experimental task in the ROI analysis. We, therefore, decided to use a different criterion for exclusion. We calculated the number of miss responses on this task and excluded children who had more than 25% miss trials. All of the participants included in the analysis performed in accordance with this criterion.

fMRI Results

We analyzed the data from both logical and pragmatic responders together. This was done based on several considerations. First, when we defined the logical response as the correct response in the response accuracy regressor of the *some*ALL condition, the pattern of results in the ROI analysis was identical to the results observed (as detailed later) when we defined the pragmatic response as the correct response in this regressor (with only small variations in the significant p values obtained when using each response type in the regressor). This clearly suggests that the response type did not significantly affect brain activations in the examined regions. Additionally, an event-related potentials (ERP) study showed no differences in brain activations between a group of logical adult responders and a group of pragmatic adult responders (Noveck & Posada, 2003). Finally, the two responder types were also grouped together for the fMRI analysis in our adult study (see Shetreet et al., 2014a, for our considerations). Thus, grouping the responder types in the current study would follow the adult study more carefully.

A whole brain analysis did not show any significant activations. Therefore, we performed a more sensitive analysis, an ROI analysis. Such an analysis allowed us to focus on specific regions defined by a priori hypotheses, thus eliminating the need to correct for a variety of multiple comparisons and increasing the statistical power of the analysis. We focused on the left IFG (BA 47), left MFG, and medial frontal gyrus (MeFG), which were linked to the processing of scalar implicatures in adults.

In the left IFG, we tested the differences between sentences that induce implicatures and those that do not. Comparing the mismatched and matched implicature conditions (*some*ALL and *some*SOME) with the no implicature conditions (*every*ALL and *every*SOME) conditions showed increased activations in the left IFG of children, $t(11) = 3.86$, $p = .001$, $d = 2.33$ (Figure 4A). We also assessed the activations of the *some* conditions separately using repeated-measures ANOVA. This showed a significant main condition effect, $F(4, 44) = 4.49$, $p = .004$, $\eta_p^2 = .29$. Using planned comparisons, we found that each of the *some* conditions showed increased activation in this area compared with the *every* conditions: $F(1, 11) = 6.4$, $p = .02$, $\eta_p^2 = .37$; $F(1, 11) = 13.7$, $p = .003$, $\eta_p^2 = .55$; and $F(1, 11) = 11.6$, $p = .006$, $\eta_p^2 = .51$. for the *some*ALL, *some*SOME and *some*NONE, respectively. Thus, our results show an activation pattern similar to the one observed in the adult brain (as reported in Shetreet et al., 2014a), with increased activations for implicature conditions when compared with no-implicature conditions (although see the later discussion of the *some*NONE condition).

In the left MFG, we tested the differences between mismatched and matched implicatures, as well as between the mismatched implicatures and the no-implicatures conditions. In this region, children showed less activation for the mismatched implicatures (*some*ALL) condition than for the matched implicatures (*some*SOME) condition, $t(11) = 4.8$, $p < .001$, $d = 2.9$ (Figure 4B). Furthermore, the mismatched implicatures showed less activation than the no-implicature (*every*) conditions, $t(11) = 3.0$, $p = .006$, $d = 1.8$. In the MeFG, no significant difference was found in the comparisons, $t(11) = 0.43$, $p = .33$, $d = 0.26$, for the comparison between mismatched and matched implicatures and $t(11) = 1.58$, $p = .07$, $d = 0.95$, for the comparison between mismatched and no-implicature conditions. Thus, the pattern of activation in these regions in the developing brain differs from the pattern of activation observed in the adult brain (as reported in Shetreet et al., 2014a).

We also calculated the correlations between the rates of pragmatic responses, the language scores in the standardized tests and the brain activations estimates for the *some*ALL condition. We did not find a significant correlation between the rates of pragmatic responses for the *some*ALL condition and the Core Language score of the CELF ($r = .25$, $p = .21$), nor between the rates of pragmatic responses and the activations for the *some*ALL condition in left IFG ($r = .15$, $p = .31$) or the left MFG ($r = .15$, $p = .31$). Interestingly, however, the activations in the left IFG correlated with the CELF Core Language scores ($r = .72$, $p = .003$). This result can be expected because the left IFG is considered a classic language region.

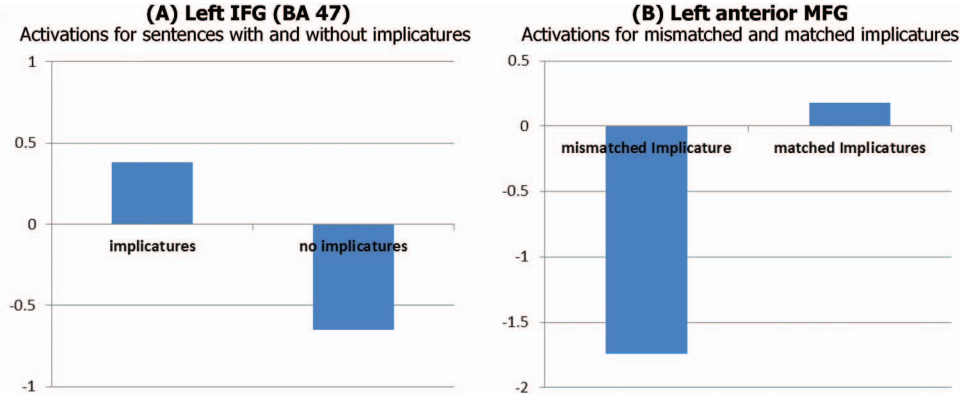

Figure 4. Extent of activation (A) for scalar implicatures versus no scalar implicatures conditions in the left inferior frontal gyrus (IFG), and (B) for the mismatched scalar implicatures versus matched scalar implicatures in the left middle frontal gyrus (MFG). Note that the contrast estimates were defined based on a contrast between each condition and the control condition. That is, all conditions were compared to the same baseline. Therefore, the difference between the conditions should be considered, rather than their absolute values. BA 47 = Brodmann area 47. See the online article for the color version of this figure.

Table 4
Areas of Activations in the Comparison Between Adults and Children on the Mismatched and Matched Implicature Conditions

Region/comparison	*x*	*y*	*z*	*k*	*t* max
Mismatched scalar implicatures					
Adults > children					
Left/medial prefrontal cortex, including left anterior MFG (BA 10) & MeFG/ACC (BA 32)	−15	38	6	230	4.52
Right superior/middle frontal gyri (BA 10)	24	47	14	72	4.22
Left precuneus/posterior cingulate	−15	−49	30	207	6.33
Right precuneus/posterior cingulate	12	−46	26	165	4.49
Cerebellum	−18	−67	−26	1529	8.06
Children > adults					
Left precentral gyrus	−12	−31	70	131	4.86
Matched scalar implicatures					
Adults > children					
Cerebellum	−9	−81	−28	514	5.08
Left middle temporal/occipital gyrus	−30	−70	−6	191	4.57
Children > adults					
Left precentral gyrus	−15	−31	70	347	5.13

Note. Carried out with threshold $p < .005$, cluster size of $k > 10$ voxels, and cluster correction of family-wise error correction (p_{FWE}) < .05. max = maximum; MFG = middle frontal gyrus; BA = Brodmann area; MeFG = medial frontal gyrus; ACC = anterior cingulate.

Finally, we directly tested the differences between children and adults. We compared children from the current study and adults from our previous study (Shetreet et al., 2014a) in the two critical conditions of this study: the mismatched scalar implicature (*some*ALL) condition and the matched scalar implicatures (*some*SOME) condition. For the mismatch implicature condition (compared with the control condition), we observed increased activation for adults compared with children in prefrontal areas, including the left and right MFG and the MeFG/ACC (see Table 4 and Figure 5), as well as in the cerebellum and occipital/parietal regions.[4] For the matched implicature condition, we observed increased activation for adults compared with children in the cerebellum, as well as occipital/posterior temporal regions (Table 3 and Figure 5). In both conditions, increased activations for children compared with adults were observed in the precentral gyrus. It is important to note that we did not identify activation differences between the two groups in the left IFG (BA 47) in any of those comparisons.[5] Thus, the comparison between adults and children further suggests that there is no difference between the groups in the activation of the left IFG (a region that was previously linked to implicature computation). There is, however, a significant difference in prefrontal regions (regions that were previously linked with the processing of implicature mismatch).

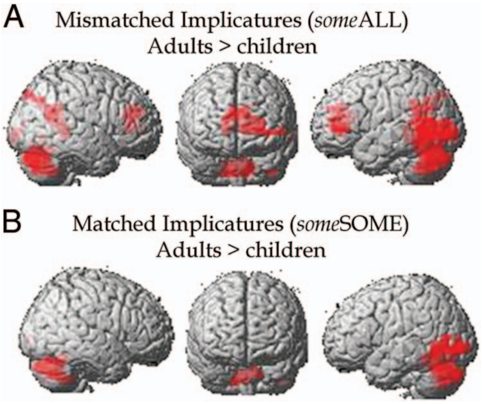

Figure 5. Activation differences (indicated by cloudy gray areas in the print journal and by red patches in the online version) between adults and children on (A) the mismatched scalar implicature condition (someALL) (compared with the control condition) and (B) the matched implicature condition (someSOME) (compared with the control condition) $p < .005$, cluster size of $k > 10$ voxels, and cluster correction of family-wise error correction (p_{FWE}) < .05. See the online article for the color version of this figure.

Discussion

This is the first neuroimaging study to assess the neural processing of scalar implicatures in young children. Young children tend to use the logical interpretation of underinformative statements, such as “Some giraffes have long necks,” and accept them

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[4] Using a customized template based on an average of anatomical images of both the adults and children to normalize the data, we saw a very similar pattern of results to the ones obtained when normalizing with the SPM MNI template: adults showed increased activations compared with children in prefrontal regions (including the left MFG and ACC) and in posterior regions (including the cerebellum and occipital regions) for mismatched implicatures (the *some*ALL condition). Increased activations for adults compared with children were observed in posterior regions only (cerebellum and occipital/temporal regions) for matched implicatures (the *some*SOME condition). In both of these comparisons, no activations were observed in the left IFG (BA 47), just as observed when using the SPM MNI template.

[5] Because uncorrected thresholds are often used in pediatric data sets due to lower signal-to-noise ratio and high interindividual variance (e.g., Thomason, Burrows, Gabrieli, & Glover, 2005), we also performed the comparisons between adults and children using an uncorrected threshold. This resulted in more clusters of activation in all of the comparisons reported previously. It should be noted that even when we used an uncorrected threshold, no activations were observed in the left IFG in any of the comparisons.

as correct. Such behavior differs from that of adults who prefer the pragmatic interpretation derived by scalar implicatures as they reject underinformative statements (e.g., Braine & Rumain, 1981; Chierchia et al., 2001; Feeney et al., 2004; Foppolo et al., 2012; Guasti et al., 2005; Noveck, 2001; Smith, 1980; Verbuk & Shultz, 2010).

We explored children's brain activations in regions that were previously identified with processing implicatures in an adult sample. We argued that in adults, the left IFG (BA 47) was involved in the computation of scalar implicatures (Shetreet et al., 2014a). This assumption was based on the shared activation of mismatched and matched implicatures. The children in the current study showed a similar pattern of activation in this region, as increased activations were observed for both mismatched and matched implicatures (the *some*ALL and *some*SOME conditions, respectively) compared with no-implicature conditions (the *every* conditions). Furthermore, no differences in a direct comparison between adults and children were observed in the left IFG on either of the implicature conditions. These findings seem to suggest that children compute scalar implicatures with the *some* conditions. Remarkably, this did not result in adult-like behavior with underinformative statements, as most of the children in this study did not respond pragmatically to the implicature mismatch condition. If so, this would suggest that children's logical (non-adult-like) behavior with implicatures does not occur because they fail to compute the implicatures, as has been suggested (e.g., Noveck, 2001). To determine the reasons for children's logical behavior, we should therefore look at other processes involved in producing pragmatic responses to underinformative statements.

Two prefrontal regions, the left anterior MFG and the MeFG, were also observed in our adult study (Shetreet et al., 2014a) adult study. These regions were linked to the processing of implicature mismatch because they were activated by mismatched implicatures, but not by matched ones. Based on previous neuroimaging studies, we proposed that the mismatch processing in the anterior MFG is associated with truth evaluation in yes/no judgment tasks (Wendelkenet al., 2008) or response strategy (Wolfensteller & von Cramon, 2011) and that the MeFG plays a role in conflict monitoring and conflict detection (Bartholow et al., 2005; Carter et al., 1998; Carter & van Veen, 2007; Mansouri et al., 2009). The pattern of activations in children in these regions differed from the pattern reported in the adult sample. Adults showed increased activation in these regions compared with children in the mismatched implicature condition. The ROI analysis further confirmed these differences: In the left anterior MFG, children showed the opposite pattern from the one observed in adults, as mismatched implicatures (*some*ALL) yielded lower activations compared with matched implicatures (*some*SOME), as well as the no-implicature conditions (*every*). In the MeFG, no difference between the conditions was observed in children. Because the activation in the IFG suggests that children compute implicatures, it seems reasonable to conclude that children's non-adult-like behavior with scalar implicatures results from a malfunction in the processing of the implicature mismatch.

The neurocognitive results found in our study suggest that children's logical behavior with scalar implicatures is rooted in their cognitive abilities rather than in their linguistic skills. That is, children compute the implicature when encountering a statement with a weak scalar. However, the developing cognitive system fails to form an adult-like response when faced with the two possible interpretations of sentences with *some*, in a context where one interpretation is true (*some* means *some and possibly all*) and the other one is false (*some* means *some but not all*). Although we found a correlation between children's scores in a receptive core language standardized test (CELF) and the activation in the left IFG, we did not find any correlation between these two measures and the rates of pragmatic responses. This seems to suggest that the rate of pragmatic responses is not linked to linguistic abilities.

Our account is in line with findings from behavioral studies of the acquisition of scalar implicatures. Children's performance with scalar implicatures seems inconsistent: although many studies report that children favor the logical interpretation of *some* and other weak scalar expressions (Braine & Rumain, 1981; Chierchia et al., 2001; Feeney e al., 2004; Foppolo et al., 2012; Guasti et al., 2005; Huang & Snedeker, 2009; Noveck, 2001; Smith, 1980; Verbuk & Shultz, 2010), there is ample evidence showing that children are capable of computing implicatures and producing adult-like pragmatic responses (Chierchia et al., 2001; Guasti et al., 2005; Katsos & Bishop, 2011; Papafragou & Musolino, 2003; Papafragou & Tantalou, 2004; Pouscoulous et al., 2007). When children do compute implicatures, it is usually following some kind of experimental manipulation. If, as suggested by our account, children generally compute implicatures but have difficulty making a decision between the two interpretations of the sentence they heard, they are expected to be sensitive to various methodological aspects that help them decide between the two interpretations. That is, experimental manipulations improve children's rate of adult-like responses, not by promoting the computation of scalar implicatures (because they are computed anyway), but rather by indicating to the child which is the preferred interpretation. Indeed, most of the experimental manipulations that improved children's rates of adult-like responses highlighted the level of informativeness of the sentence (Chierchia et al., 2001; Guasti et al., 2005; Katsos & Bishop, 2011; Papafragou & Musolino, 2003; Papafragou & Tantalou, 2004). For example, training trials with underinformative statements without scalar expressions (e.g., "a little animal with four legs" to describe a dog) may have increased the rates of pragmatic responses to implicatures by indicating to the child that the informativeness of the sentence should guide his or her choice between the two possible interpretations. Our account, therefore, suggests that experimental manipulations operate through a modification of cognitive components that are responsible for children's responses, and not through the linguistic system.

On the other hand, when no clear direction to one of the interpretations of a sentence with *some* is given, children show logical behavior. This was shown, for example, in a statement evaluation task where no visual supplements or specific context were given (e.g., Noveck, 2001). Our results cannot provide a clear answer to the question of why children favor, by default, the logical interpretation of weak scalar expressions over the pragmatic one. Further research is needed to explore this question. Here, we suggest a few possible explanations for this phenomenon. Children may give more logical responses, accepting underinformative statement as true, because they have a "yes" bias. Note, however, that it was found that, with regard to object and face knowledge, 5- and 6-year-olds do not show such bias (Okanda & Itakura, 2010, 2011). Alternatively, children (and adults who give logical responses; e.g., in Noveck, 2001) may obey the principle of charity. According to this principle, language users would prefer to choose one interpretation that makes the sentence true over another interpretation (Quine, 1960). A similar explanation is given by the pragmatic tolerance account (Katsos & Bishop, 2011), which argues that children give logical responses to sentences with *some* not because they are linguistically incapable of computing the implicatures, but because they are willing to accept pragmatic violations (i.e., they are pragmatically tolerant). One final suggestion to explain children's logical responses concerns switching between interpretations. The logical meaning of *some* is initially accessed. Later on, the pragmatic interpretation becomes available. It is possible that children keep the first interpretation because it is too cognitively costly to revise their meaning assignment. Huang and Snedeker (2009) noted that children improve their rates of adult-like performance with scalar implicatures around the time they improve in cognitive control, which is important for the reanalysis of sentence meaning. Furthermore, Foppolo et al. (2012) argued that children's performance in various tasks involving scalar implicatures is influenced, among other things, by their ability to switch strategy.

Finally, we would like to discuss the finding regarding the *some*NONE condition. Unlike adults, children showed increased activations in the left IFG for this condition (compared with the *every* conditions). It is possible that during the course of scalar implicatures acquisition, changes occur in the way that scalar implicatures are computed as they attuned to the effects of the context. It might be that in the first stages of acquisition, children compute the implicature whenever a weak scalar expression is encountered, thus showing increased activations for all the *some* conditions in the left IFG (which is linked to implicature computation). By the end of the acquisition process, they learn that some statements can be verified just on the basis of the lower boundary defined by the logical meaning of the scalar expression (i.e., *some* expresses any quantity greater than none), and therefore, that the sentences in the *some*NONE condition should be rejected without computing the implicature. This will result in the adult pattern of brain activation (observed in Shetreet et al., 2014a), where no difference was observed between the *some*NONE and the *every* conditions in the left IFG.

To test scalar implicatures, we used the quantifier scale with *some* and *every*. The same mechanism is assumed for other scales as well (e.g., the [or, and] scale). Therefore, we predict that other weak scalar items will show similar patterns of results in both adults and children (although see Shetreet, Chierchia, & Gaab, 2014b, for results regarding the numbers scale). To confirm this prediction, other scalar items should be tested using fMRI.

We have suggested that children compute scalar implicatures in the same way that adults do on the basis of their pattern of brain activation. However, some methodological limitations should be considered. (a) Our pediatric sample included logical, pragmatic, and mixed responders (and the adult sample in Shetreet et al., 2014a also included both logical and pragmatic responders). As described in the beginning of the fMRI section in Results, we took several considerations into account when performing the analysis with all the responder types combined (this included performing analysis with both pragmatic and logical responses as the accurate response to the mismatch implicature condition and an ERP study that did not show differences between logical and pragmatic responders). Additionally, as also mentioned in the Results section, the activation in the left IFG did not correlate with the number of pragmatic responses. However, further fMRI research examining the different activation patterns for logical and pragmatic responses will be extremely valuable. (b) Our control voice-matching task did not yield above-chance performance in children. However, this task was used only for determining baseline activation for basic auditory and lexical processing. Therefore, the performance on this task is not expected to critically affect the results of the ROI analysis. (c) In the children's data, we focused on results from a selective ROI analysis. This type of analysis explores activations in a priori defined sets of brain regions, and therefore no inferences about activations in other regions can be made.

To summarize, we addressed the question of the acquisition of scalar implicatures from a new angle. Implicit brain measurements indicate that 6-year-old children compute scalar implicatures, even though they do not use the pragmatic interpretation that results from this computation. Brain activations further suggest that children's non-adult-like behavior with underinformative statements is linked to the processing of implicature mismatch, and that this (based on the location of the activation) seems to be related to higher cognitive functions, such as conflict monitoring, cognitive control, or truth value judgment. To determine the mechanism that guides children's behavior with scalar implicatures and pragmatic interpretations, future research testing the correlations between children's rates of scalar-implicature-dependent interpretation, their cognitive abilities, and their performance on other linguistic ambiguities across their language development is needed.

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