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Neuro-cognitive development of semantic and syntactic bootstrapping in 6- to 7.5-year-old children

Neelima Wagley[*], **James R. Booth**
Department of Psychology and Human Development, Vanderbilt University, Nashville, USA

Abstract

The present study examined the longitudinal relations of brain and behavior from ages 6–7.5 years old to test the bootstrapping account of language development. Prior work suggests that children's vocabulary development is foundational for acquiring grammar (e.g., semantic bootstrapping) and that children rely on the syntactic context of sentences to learn the meaning of new words (e.g., syntactic bootstrapping). Yet, little is known about the dynamics underlying semantic and syntactic development as children enter elementary school. In a series of preregistered and exploratory analyses, we tested how semantic and syntactic behavioral skills may influence the development of brain regions implicated in these processes, i.e. left posterior middle temporal gyrus (pMTG) and inferior frontal gyrus (pars opercularis, IFGop), respectively. Vice-a-versa, we tested how these brain regions may influence the development of children's semantic and syntactic behavioral skills. We assessed semantic (N = 26) and syntactic (N = 30) processes behaviorally and in the brain when children were ages 5.5–6.5 years old (Time 1) and again at 7–8 years old (Time 2). All brain-behavior analyses controlled for T1 autoregressive effects and phonological memory. Exploratory hierarchical regression analyses suggested bi-directional influences, but with greater support for syntactic bootstrapping. Across the analyses, there was a small to medium effect of change in variance in models where semantics predicted syntax. Conversely, there was medium to large change in variance in models where syntax predicted semantics. In line with prior literature, results suggest a close relationship between lexical and grammatical development in children ages 6–7.5 years old. However, there was more robust evidence for syntactic bootstrapping, suggesting that acquisition of phrase structure in school age children may allow for more effective learning of word meanings. This complements prior behavioral studies and suggests a potential shift in the early reliance on semantics to later reliance on syntax in development.

Keywords

Language development; Neurocognitive; Bootstrapping; Semantics; Syntax; Longitudinal design

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[*]Corresponding author. neelima.wagley@vanderbilt.edu (N. Wagley).

Author Credit Statement

Neelima Wagley: Conceptualization, Methodology, Formal analysis, Original draft James Booth: Conceptualization, Methodology, Review & Editing; Supervision; Funding acquisition.

Data and code availability statement

This dataset is part of a larger longitudinal study assessing the neurocognitive processes of language development in children. The complete dataset can be found on OpenNeuro.org (Wang et al., 2021).

1. Introduction

Traditional theories of language proposed autonomous models of syntax and semantics, where grammar is acquired and represented independently from knowledge of word meanings (Chomsky, 1965; 2014). In contrast, others have suggested that grammatical development is directly tied to lexical knowledge (Bannard, Lieven, & Tomasello, 2009; Bates & Goodman, 2001; Goodman & Bates, 2013). Jackendoff's (1997; 2007) Parallel Architecture perspective posits that semantic and syntactic processes are reciprocal and concurrent in nature. According to this perspective, semantic and syntactic representational systems are thought to be distinct but mutually constraining in comprehension (Culicover & Jackendoff, 2005). A core question in this theoretical debate is how the systems for meaning and grammar interact to support language competence across development.

One mechanism that characterizes this dynamic relationship is the *bootstrapping* account of language development (e.g., Abend et al., 2017; Pinker, & MacWhinney, 1987). Decades of research in child language acquisition suggest that children's vocabulary development is foundational for acquiring grammar (i.e., *semantic bootstrapping*; Bates & Goodman, 1997; Dale et al., 2000; Marchman & Bates, 1994). For example, early vocabulary size is positively associated with children's later mean length utterance (MLU), suggesting that early learned words may help facilitate the later production of different forms of morphosyntactic structures (e.g., Marchman & Bates, 1994; Marchman, Martínez-Sussmann, & Dale, 2004). Children also rely on the syntactic context of sentences to learn the meaning of new words (i.e., *syntactic bootstrapping;* Fisher, Gertner, Scott, & Yuan, 2010; Gleitman, 1990; Gleitman & Gillette, 1999; Landau & Gleitman, 1985; Naigles, 1990). For example, based on the structure of a sentence such as "Do you know what it means to latt? " or "Have you ever seen any latt? ", children can infer whether the novel word refers to a verb or even a subclass of nouns, such as mass nouns (Brown, 1957). Most behavioral studies examining this reciprocal relationship emphasize the importance of early vocabulary knowledge in bootstrapping grammatical development in younger children, particularly prior to age three (Marchman & Bates, 1994; Marchman et al., 2004). Yet, little is known about the dynamics underlying semantic and syntactic development as children enter elementary school and are learning to comprehend more complex language and text. The present study examines semantic and syntactic bootstrapping mechanisms in an understudied period of development, in children ages 6–7.5 years old.

Only a handful of studies have longitudinally examined the relations between semantic and syntactic development in (pre)school-aged children. Using cross-lagged correlational analyses, Moyle, Weidmer, Evans & Lindstrom (2007) assessed lexical and grammatical development in typically developing (TD) and late-talking children at five points between ages 2–5.5 years old. They found evidence in support for bi-directional bootstrapping in TD children between ages 2–3.5 years old but not in the older children or in children who were late talkers. Caglar-Ryend, Eklund, & Nergård-Nilssen (2019) conducted a longitudinal multiple-wave design and assessed vocabulary and grammar skills at seven time points between 1.5–6 years old. Cross-lagged path analysis indicated evidence for both semantic and syntactic bootstrapping across this period of development. In younger children, paths between vocabulary to grammar were significant between 1.5–2 years old (32% of variance explained) and 2.5–3 years old (34% of variance explained). Further, grammar at age 2 explained 14% of the variance in vocabulary at 2.5 years old. Finally, in older children, cross-lagged associations between grammar to vocabulary were significant for ages 3.5–4.5 years old (11% of the variance explained) and 4.5–6.0 years old (38% of the variance explained; Caglar-Ryend et al., 2019). These results support the bi-directional nature of language bootstrapping, yet show that as children get older, there may be a sequential shift in the early reliance on semantics to later reliance on syntax (Brinchmann et al., 2019). Brinchmann, Braeken, & Lyster (2019) also found a small, direct contribution from grammar to vocabulary in a sample of children from 4–5 years old. However, there was no association in either direction from 5–6 years old. Lastly, Blom & Boerma (2019) examined receptive vocabulary and sentence repetition skills across three timepoints, at ages 5–6, 6–7, and 7–8 years old, in children with Developmental Language Disorders (DLD) and typically developing peers. The authors found that syntactic skills predicted lexical skills from ages 5–7 years old, but only in children with DLD. Overall, prior developmental research suggests that there may be a greater role of syntactic bootstrapping in older children. However, much of this research has focused on behavioral designs and only two of these studies (e.g., Brinchmann et al., 2019; Caglar-Ryend et al., 2019) have controlled for children’s initial skill levels.

Neural sensitivity to semantic and syntactic features of language develops early in life (e.g., Benavides-Varela & Gervain 2017; Friedrich & Friederici, 2005; 2006). A recent review of electrophysiological studies assessing lexical-semantic and syntactic processes in children suggests that the N400 index for semantics emerges early around 9 months old, before aspects of the grammar are acquired (Morgan, van der Meer, Vulchanova, Blasi, & Baggio, 2020). This is thought to be followed by the later emergence of syntactic operations between 30 and 36 months old (indexed by the (E)LAN and P600 effects; Oberecker & Friederici, 2006; Oberecker, Friedrich, & Friederici, 2005). Neurobiological models of language in adults and children widely reognize localization of lexical-semantic processes in the middle temporal gyrus (MTG) and the orbitalis/triangularis region (BA 45/47) of the inferior grontal gyrus (IFG), and syntactic-structure processes in the opercularis region the left IFG (BA 44) and the posterior superior temporal gyrus (STG; Binder, Desai, Graves, & Conant, 2009; Brauer & Friederici, 2007; Hagoort & Indefrey, 2014; Skeide et al., 2014; Skeide & Friederici, 2016; Wu, Vissiennon, Friederici, & Brauer, 2016). Our regions of interest were chosen based on the previous literature. No prior study has examined the neural bases of semantic and syntactic processes in relation to language bootstrapping longitudinally.

We chose IFGop for its role in syntactic processing based on the findings from Brauer & Friederici (2007) who observed selective engagement of the left BA 44 in Broca’s area during the processing of syntactic phrase structure violations in children ages 5–6 years old. Additionally, Wu et al. (2016) found that five-year-old children with better syntactic proficiency showed greater activation in the left IFGop during a sentence comprehension task with demands on syntactic cues. These findings are consistent with the prior work on the neurobiology of syntax with older children (Skeide et al., 2014) and adults (e.g., Hagoort & Indefrey, 2014). Similarly, we chose pMTG for its role in semantic processing as Wang, Rice, & Booth (2020) found evidence of neural specialization for semantic processing in this region in children ages 5–6 years old. They used MVPA analyses to examine semantic and syntactic processes using the same sentence stimuli as in the present study. This is consistent with the prior work on the neurobiology of semantic processing (e.g., Binder et al., 2009; Friederici and Gierhan, 2013). The IFGop and pMTG are two regions within a larger network involved in sentence comprehension (Enge, Friederici, & Skeide, 2020; Friederici et al., 2012; Skeide et al., 2014). For example, there is evidence that the STG and IFG pars orbitalis/triangularis are also involved in lexical-semantic and syntactic processing. However, unlike the adult literature, there is limited evidence to support semantic and syntactic specialization in the developing brain. Thus, our examination of the pMTG and IFGop is an initial effort towards increasing our understanding of the neurocognitive models of language comprehension over development.

The aim of the current study is to examine the longitudinal relations of brain and behavior from ages 6–7.5 years old to test the bootstrapping account of language development. To examine these mechanisms, we tested how semantic and syntactic behavioral skills influence the development of brain regions implicated in these processes, i.e., the left posterior Middle Temporal Gyrus (pMTG) and Inferior Frontal Gyrus (pars opercularis, IFGop), respectively. Vice-a-versa, we tested how these brain regions influence the development of children's semantic and syntactic behavioral skills. Using hierarchical regression analyses, we tested two hypotheses examining semantic bootstrapping: (1) semantic skills at age 6 will predict IFGop activation for syntax at 7.5 years old, (2) activation in the pMTG for semantics at age 6 will predict syntactic skills at 7.5 years old, and two hypotheses examining syntactic bootstrapping: (3) syntactic skills at age 6 will predict pMTG activation for semantics at 7.5 years old, and (4) activation in the IFGop for syntax at age 6 will predict semantic skills at 7.5 years old. Although we expect bi-directional bootstrapping based on the previous literature, given the older participant in our sample, we expect syntactic bootstrapping to be more apparent.

2. Materials & Methods

The study hypotheses and analytical plan were preregistered through Open Science Framework after data cleaning but prior to beginning the data analyses (see https://osf.io/gaqk6/).

2.1. Participants

The semantic task included twenty-six participants (15 females) and the syntax task included thirty participants (20 females). Participants were 5.5–6.5 years old (M = 5.90, SD = 0.20) at Time 1 (T1) and 7–8 years old (M = 7.54, SD = 0.29) at Time 2 (T2) of data collection. Participants were selected from a larger longitudinal study assessing the neurocognitive processes of language development in children ages 5–10 years old. The original sample included 51 participants who completed at least part of the fMRI session of the semantic task at both time points and 78 participants who completed at least part of the fMRI session of the syntax task at both time points. Among these participants, 25 and 48 were excluded for each task respectively for missing data, poor in-scanner performance, or excessive movement (see details below).

All participants met the following inclusionary criteria: (1) primarily right-handed assessed using five actions of writing, drawing, picking-up, opening, and throwing; score ≥ 3 indicates right-handedness; (2) main-stream English speaker, assessed using the Diagnostic Evaluation of Language Variation (DELV) Part 1 Language Variation Status (Seymour et al., 2003); (3) no clinical diagnosis of neurological, psychiatric or developmental disorders as reported in parent questionnaire; and (4) normal hearing and normal/corrected vision as reported in parent questionnaire. We used the Clinical Evaluation of Language Fundamentals (CELF-5, Wiig, Semel, & Secord, 2013) to assess language ability and Kaufman Brief Intelligence Test, Second Edition (KBIT-2, Kaufman and Kaufman, 2004) to assess nonverbal IQ. All children in the final sample scored greater than or equal to a standard score of 80 on the CELF-5 Core Language Score and KBIT-2 Non-verbal Scale subtest.

Caregivers and children completed informed consent and assent forms before participation. Caregivers were compensated $20 per session, and participants were compensated a rate of $20/hour. Additionally, participants earned tickets over the course of the testing sessions that could be redeemed for toys and books. All study procedures were approved by the Institutional Review Board.

2.2. Procedure

Participants completed behavioral and fMRI tasks over the course of 4 to 6 visits at each time point. First, participants completed standardized behavioral assessments while caregivers completed developmental history questionnaires. Next, participants completed a practice MRI session in a mock scanner. This allowed participants to become familiar with the in-scanner tasks as well as the scanning environment. Lastly, participants completed the fMRI sessions. Mean (standard deviation) number of days between T1 and T2 are as follows: semantic task fMRI = 604.27(115.92) and standardized testing = 567.08(92.69); syntax task fMRI = 597.70(79.05) and standardized testing = 571.77(74.96). For N = 26 of the semantic task, the average number of days between the behavioral tasks and the fMRI session was 72 (SD = 46) at T1 and 109 (SD = 58) at T2. For N = 30 of the syntax task, the average number of days between the behavioral tasks and the fMRI session was 57 (SD = 50) at T1 and 74 (SD = 52) at T2. Participants in the current study completed data collection within a single grade (e.g., end of preschool, in kindergarten), in the summer in between kindergarten to first grade, or in first grade.

2.3. Behavioral Assessments

We used the CELF-5 language composite scores to index semantic and syntactic skills at both time points. The Language Content Index (LCI) was used to measure semantic skills and is a composite of the Linguistic Concepts, Word Classes, and Following Directions subtests of CELF-5. The Language Structure Index (LSI) was used to measure syntax skills and is a composite of the Sentence Comprehension, Word Structure, Formulating Sentences, and Recalling Sentences subtests of CELF-5. Composite scores combine the individual subtest scaled scores (mean of 10, standard deviation of 3). Scores from the LCI and LSI composites were entered into the regression analyses.

Phonological memory was measured using raw scores on the CTOPP-2 Phonological Memory Composite Score (Comprehensive Test of Phonological Processing), a composite of the Memory for Digits and Non-word Repetition subtests (Wagner et al., 1999). Prior research suggests there are significant associations between phonological memory and language comprehension and production (e.g., Delage et al., 2019; Lopez-Barroso et al., 2011). In particular, individual abilities in word segmentation, grammar-rule learning, and vocabulary have been related to children's phonological memory capacity (Gathercole & Baddeley, 1990; Swanson, Zheng, & Jerman, 2009). Thus, to exclude potential confounding effects, we included phonological memory as a covariate of no interest in our analyses.

2.3.1. fMRI Tasks of Syntax & Semantics—Participants completed two auditory sentence judgment tasks in the MRI scanner. On both tasks, a trial consisted of a sentence presented binaurally through MRI compatible earphones (Sensimetrics, Model S14). Participants were instructed to respond to all trials as quickly and accurately as possible using their right index finger for a "yes " response their right middle finger for a "no " response. Experimental tasks were the same as previously reported in Wang, Rice, & Booth (2020).

All sentence stimuli in the syntax and the semantic task had the following structure: An optional carrier phrase ("Last week "/ "Every day ") + subject and verb phrase (e.g., "She baked ") + number and object (e.g., "two cakes "). The sentences included one of the following four verb forms: (1) third-person present tense (–s); (2) present progressive copula (be); (3) auxiliary verb (do); and (4) simple past tense (–ed). Each condition had five sentence stimuli for each verb form (see below for condition details). Stimuli were matched across all conditions in each task in terms of the written word frequency (Masterson, Stuart, Dixon, & Lovejoy, 2010; Balota et al., 2007), the number used (one/two/three/four/five/six), the subject used (he/she/they), the number of syllables (6–8), and the frequency of "not " usage in the sentences.

Semantic Task.: The semantic task included three experimental conditions: Strongly Congruent (SCon) – based on the high association strength values between the verb and the object (0.28–0.81, M = 0.41, SD = 0.12), Weakly Congruent (WCon) – based on the low association strength values between the verb and the object (0.02–0.19, M = 0.11, SD = 0.05), and Incongruent (InCon) – based on no semantic association between the verb and the object. The association strength values between the verb and the object in the sentence were defined using the Forward Cue-to-Target Strength (FSG) values from the University of South Florida Free Association Norms (http://w3.usf.edu/FreeAssociation/, Nelson et al., 2004). Participants were instructed to judge whether "the way she speaks makes sense". In addition to the experimental conditions, the task included a perceptual condition (Control) in which participants heard two frequency-modulated white noise bursts ("shh-shh ") and were instructed to press the 'yes' response. Stimuli duration ranged between 2748 and 4520 ms and was followed by a 1875–3450 ms jittered response interval. The length of trials (3000–4530 ms) was equated across conditions.

There were no significant differences across conditions within or across runs in terms of verb forms and sentence length (*ps* > .902). There were no significant differences in the average word frequency, average word length, and number of syllables across conditions within runs (SCon vs. WCon: *ps* > .241; SCon & WCon vs. InCon: *ps* > .077) or across runs (SCon: *ps* > .136; WCon: *ps* > .547; InCon: *ps* > .473, linguistic characteristics drawn from the English Lexicon Project, Balota et al., 2007).

Syntax Task.: The syntax task included three experimental conditions: grammatically correct (Gram) - sentence without grammatical errors, Plurality Violation (PVio) - sentence with a mismatch between the number and object by either adding an "s " or omitting an "s " in the object noun word, and Finiteness Violation (FVio) – sentence with inconsistency between the subject and verb phrase by either adding an inflection or omitting/substituting an inflection/auxiliary verb (see Table 1 for examples). Participants were asked to judge whether "the way she speaks sounds right." Participants also completed the perceptual control condition as described above. Stimuli duration ranged between 2740 and 4972 ms and was followed by a 1234–4611 ms jittered response interval. The length of trials (5174–8422 ms) was equated across conditions.

There were no significant differences across all conditions within or across runs in terms of verb forms and sentence length (*ps* > .489). There were no significant differences in the average word frequency, average word length, and number of syllables across conditions within runs (FVio vs. PVio: *ps* > .172; FVio & PVio vs. Gram: *ps* > .122) or across runs (FVio: *ps* > .306; PVio: *ps* > .235; Gram: *ps* > .331, linguistic characteristics drawn from the English Lexicon Project, Balota et al., 2007).

All sentence stimuli were recorded by a female native English speaker in a sound booth using Audacity and edited using Praat. For each task, there were 20 trials per condition, totaling 80 trials evenly divided into two runs. Each run lasted around 4.5 min. The four conditions were pseudorandomized so that there were no more than five of the same responses in a row. A blue circle appeared simultaneous to the auditory presentation of the stimuli, and children were asked to look at this circle. The blue circle changed to yellow to provide a 1000 msec warning for the participants to respond, if they hadn't already, before moving onto the next trial.

The sentence stimuli for the semantic and syntax tasks were very similar in duration, however the syntax task trial lengths were slightly longer. This is due to a programming error that resulted in certain trials in the syntax task having shorter or longer response intervals as compared to the semantic trials. However, the stimuli lengths were well matched across experimental conditions and across tasks. Additionally, the behavioral response data of the in-scanner task suggests that even the shortest response interval is likely to be sufficient for the participants to respond. Thus, the minimal difference in trial length should not affect the comparison of the two tasks.

Only participants who completed both runs for the semantic task and, separately, both runs for the syntax task at both time points were included in the analysis (N = 1 was excluded for incomplete semantic task runs). For the semantics task at both timepoints, all participants completed the two runs within the same scanning session. For the syntax task at T1, two participants completed run 1 and run 2 on two separate sessions that were a week apart. For the syntax task at T2, one participant completed run 1 and run 2 on two separate sessions that were 48 days apart.[1]

Those who scored within an acceptable accuracy range and had no response bias were included in the analysis. Acceptable accuracy was defined as at least 50% in the perceptual control condition and at least 40% on the SCon condition for Semantic task and Gram condition for Syntax task. These conditions were the easiest and required a ‘yes’ response. The lack of response bias was defined by no greater than a 40% difference in accuracy between the SCon and InCon conditions for the semantics task and between the Gram and FVio conditions for the Syntax task. The InCon and FVio conditions were the most difficult conditions and required a ‘no’ response. Participants (N = 7 for semantics and N = 723 for syntax) were excluded for not meeting the task performance criteria. The 23 participants who were excluded based on syntax task performance had comparable KBIT-2 Non-Verbal scores (*M* = 7104, *SD* = 714) as the final sample of 30 participants (*M* = 7110, *SD* = 714; *t* (47) = 71.46, *p* = 7.151. As a group, this final sample had a slightly higher CELF Core Language Scores (*M* = 7122, *SD* = 711) as compared to the group excluded based on syntax task performance (*M* = 7112, *SD* = 717), *t* (37) = 72.42, *p* = 7.021).

2.4. fMRI Data Acquisition

Images were acquired using 3-T Siemens Skyra MRI scanner with a 64-channel head coil. Functional images were acquired using a susceptibility T2-weighted single-shot EPI method with the following parameters: TR = 71250 ms, TE = 730 ms, FOV = 7256 × 256 mm, matrix size = 7128 × 128, bandwidth = 71776 Hz/Px, slice thickness = 72 mm without gap, number of slices = 756, voxel size = 72 × 2 × 2 mm, flip angle = 780°, multiband acceleration factor = 74. Slices were acquired interleaved from foot-to-head. A high-resolution T1-weighted structural image was also acquired using the following parameters: TR = 71900 ms, TE = 72.43 ms, FOV = 7256 × 256 mm, matrix size = 7256 × 256, bandwidth = 7180 Hz/Px, slice thickness = 71 mm, number of slices = 7192, voxel size = 71 mm isotropic, flip angle = 79°, acceleration factor = 72.

2.5. fMRI Data Preprocessing & Analysis

2.5.1. Preprocessing—fMRI data was analyzed using SPM12 (http://www.fil.ion.ucl.ac.uk/spm). First, functional images were realigned to their mean functional image across runs. Using CerebroMatic, the anatomical images were segmented and warped to a pediatric template of children between the ages of 5.5–8 years old (Wilke et al., 2017). Next, the mean functional images were co-registered to the skull-stripped anatomical image and then normalized to the pediatric template and smoothed using a 6 mm isotropic Gaussian kernel.

ArtRepair (http://cibsr.stanford.edu/tools/human-brain-project/artrepair-software.html) was used to identify outlier volumes among the functional images. Outlier volumes were defined as volumes exceeding 1.5 mm volume-to-volume head movement in any direction, head

[1]For the 12 participants who completed both the semantic and syntax fMRI tasks, the average number of days in between the tasks was 18 (SD = 17) at T1 and 53 (SD = 30) at T2.

movement greater than 5 mm in any direction from the mean functional image, or deviations of more than 4% from the global mean signal. Volumes identified as outliers were replaced with interpolated values from the adjacent volumes. No more than 10% of the volumes from each run and no more than six consecutive volumes for any individual were interpolated in this way. Six motion parameters estimated in the realignment step were entered in the first-level modeling as regressors and the repaired volumes were deweighted (Mazaika et al., 2009). 17 participants for the semantics task and 24 participants from the syntax task were excluded from analysis for excessive movement. One participant from the syntax task was also excluded for poor image quality (i.e., ghosting and insufficient brain coverage).

2.5.2. First-level Analysis—First-level statistical analyses were performed on individual participants' data using the general linear model as implemented in SPM12. The first level model included ten regressors for each run, one for each of the experimental conditions (Semantic: SCon, WCon, InCon; Syntax: Gram, FVio, PVio), one for the control condition, and six nuisance regressors for the realignment parameters. The following contrast maps were estimated for each task, SCon > Control for semantics and Gram >Control for syntax. The contrasts were chosen based on prior analyses by Wang, Rice, & Booth (2019). Specifically, both the SCon and Gram conditions required the same response (pressing the 'yes' button) thus avoiding potential effects related to different 'yes' and 'no' responses and both conditions were 'correct' sentences with no grammatical or lexical anomalies, thus avoiding potential effects related to processing error sentences. All correct and incorrect trials were included in the analysis and modeled using a canonical hemodynamic response function.

2.5.3. Region of Interest (ROI) Masks—Two regions of interest were chosen based on prior findings on semantic and syntactic processing in this age group (e.g., Brauer & Friederici, 2007; Wang et al., 2020). Anatomical masks for left middle temporal gyrus and left inferior frontal gyrus (pars opercularis, IFGop) were defined using the automated anatomical labeling (aal) atlas and the WFU pickatlas toolbox (Maldjian et al., 2003, see Figure 1). The MarsBar toolbox (Brett et al., 2002) was used to isolate an anatomical mask consisting of the posterior half of the left middle temporal gyrus (pMTG; y = 7–33). For each participant at each timepoint, the average beta value for each task condition was extracted from the top 100 activated voxels (*t* value regardless of significance) within each tasks' ROI mask. For the semantic task, top voxels were extracted from within the pMTG anatomical mask associated with the SCon > Control contrast. For the syntax task, top voxels were extracted from within the IFGop anatomical mask associated with the Gram > Control contrast. The average beta values were entered into the regression analyses. See Fig. 1 for the spatial distribution and overlap of voxels across participants within each anatomical mask.

2.6. Analytic Approach

Two hierarchical regression analyses examined semantic bootstrapping. First, we computed a regression with phonological memory at T1 and brain activation for Gram > Control in the IFGop at T1 entered into the model as covariates of no interest and semantic skill T1 as the independent variable. The dependent measure was brain activation for Gram > Control in the IFGop at T2. Second, we computed a regression with phonological memory at T1 and syntax skill at T1 entered into the model as covariates of no interest and brain activation for SCon > Control in the pMTG at T1 as the independent variable. The dependent measure was syntax skill at T2.

Two hierarchical regression analyses examined syntactic bootstrapping. First, we computed a regression with phonological memory at T1 and brain activation for SCon > Control in the pMTG at T1 entered into the model as covariates of no interest and syntax skill at T1 as the independent variable. The dependent measure was brain activity for SCon > Control in the pMTG at T2. Second, we computed a regression with phonological memory at T1 and semantic skill at T1 entered into the model as covariates of no interest and brain activation for Gram > Control in the IFGop at T1 as the independent variable. The dependent measure as semantic skill at T2. All analyses were run in SPSS Statistics v26 (IBM Corp 2019).

For the pre-registered analyses, semantic behavioral skill is measured using the scaled score on the CELF-5 Language Content Index and syntax behavioral skill is measured using the scaled score on the Language Structure Index.

3. Results

Performance on the semantic and syntax tasks and standardized behavioral measures are reported in Table 2. For both imaging tasks, participants showed a significant increase in task accuracy from T1 to T2 across the three experimental sentence conditions ($p < .05$). There were no differences in measures of language skills from T1 to T2, except for the measure of semantic skills. There was a significant decrease in the Language Content Index score from T1 to T2, likely because the composite scores are an aggregate scaled score which is normed using age-matched cohort data. The decrease in performance from T1 to T2 indicates that the current sample of children in our study are developing their semantic skills at a slower rate than their cohort of peers. At the individual level, there is a significant increase in the raw scores from T1 to T2 for all subtests of the LCI (all paired t-statistics are $p < .01$), suggesting growth in skills overtime.

3.1. Preregistered Analyses

Hierarchical regression analyses revealed no evidence in support of either semantic or syntactic bootstrapping (see Table 3). Across the models tested, there was little to no change in percent variance explained between semantic and syntax brain activation and skill after accounting for autoregressive effects and phonological memory at T1. Semantic skills at T1 accounted for less than 1% variance in IFGop activation for syntax at T2 ($F(1,26) = .03$, $p = 96$). Brain activation in pMTG for semantics at T1 accounted for less than 1% variance in syntax skills at T2 ($F(1,22) = .19$, $p = .67$). Similarly, syntax skills at T1 accounted for less than 1% variance in pMTG activation for semantics at T2 ($F(1,22) = .02$, $p = .87$). Lastly, IFGop activation for syntax at T1 accounted for less than 1% of the variance in semantic skills at T2 ($F(1,26) = .08$, $p = .77$).

3.2. Bivariate Correlations

Bivariate correlations between the study variables are reported in Table 4. Brain activation in the pMTG during the semantic task was negatively related to semantic skills ($r = -.11$), yet positively related to syntax skills ($r = .21$) at T1. At T2, the relation between brain activation in the pMTG and semantic skills ($r = -.17$) was equal to the relation between pMTG and syntax skills ($r = -.17$). In addition, brain activation in the IFGop during the syntax task was similarly related to syntax skill ($r = .27$) as semantic skills ($r = .28$) at T1. This pattern was also observed for brain-behavior correlations at T2 between IFGop activation and syntax ($r = -.04$) and semantic ($r = .08$) skills. These correlations indicate that our method of selecting voxels for each task were not differentially sensitive to semantic versus syntactic skills. Thus, we used an alternate approach for identifying voxels in the subsequent exploratory analyses.

3.3. Exploratory Analyses 1

In the first set of exploratory analyses, we changed two variables from the preregistered design to increase specificity in the measurement of semantic and syntactic processing behaviorally and in the brain.

Based on the results of the bivariate correlations, we changed the method used to identify activated voxels. All preprocessing and first-level analyses remained the same. Next, we computed group-level correlation analyses in SPM for each task at each timepoint between brain activation and skill. Specifically, group-level fMRI analysis for the semantic task (SCon > Control) at T1 was correlated with semantic skill (LCI) at T1. Group-level analysis for the syntax task (Gram > Control) at T1 was correlated with syntax skill (LSI) at T1. The same was repeated for brain and skill measures at T2. For each group-level analysis, we extracted coordinates of the top 100 most correlated voxels within the pre-defined anatomical masks. Following, for each participant, we extracted beta values for each contrast of interest from the identified 100 voxels. The average of these top voxels for each participant, task, and time point were entered into the hierarchical regression. T1 and T2 group-level activations are shown in Fig. 2.

Initially, we operationalized semantic and syntactic behavioral skills using CELF-5 language composite scores, which captured a broad range of language skills. In the exploratory analyses, we examined the bootstrapping mechanisms using a specific CELF-5 subtest. In particular, we chose one semantic and one syntax subtest with the highest correlation coefficient across T1 and T2 measurements, suggesting the most stable relationship within each skill across time. For semantics, we used Word Classes (T1-T2 $r = .53$) which assesses children's knowledge and relationship between words based on semantic class features. In comparison, the other semantics related subtests had relatively weaker T1-T2 correlations (Linguistic Concepts $r = .46$, Following Directions $r = .37$). For syntax, we used Recalling Sentences (T1-T2 $r = .86$) which assesses children's competence for sentence structure and is a reliable measure used in identifying language disorders (Wiig et al., 2013). In comparison, the other syntax related subtests had weaker T1-T2 correlations (Formulating Sentences $r = .27$, Word Structures $r = .43$, and Sentence Comprehension $r = .32$). Additionally, in comparison to the composite scores, the subtest scores are more strongly correlated with the in-scanner task performance, particularly at T2. Correlations between in-scanner semantics task performance (overall accuracy) and semantics-related standardized assessments are as follows: LCI (r = .01) and Word Classes subtest (r = . 11) at T1; LCI (r = .26) and Word Classes subtest (r = .31) at T2. Correlations between the in-scanner syntax task performance (overall accuracy) and the syntax-related standardized assessments are as follows: LSI (r = .16) and Recalling Sentences subtest (r = .09) at T1; LSI (r = .10) and Recalling Sentences subtest (r = .34) at T2. This data provides further evidence in support of our decision to test the bootstrapping models using the subtest scores in the exploratory analyses. T1 and T2 group-level activations using the subtest scores are shown in Fig. 2.

3.4. Exploratory analyses with language composite scores

Bivariate correlations based on the revised method of voxel selection are reported in Table 5. As expected, based on the method of voxel selection, brain activation in the pMTG during the semantics task was related to semantic skills more so than syntax skills at T1 and T2. Similarly, brain activation in the IFGop during the syntax task was related to syntax skills more than semantic skills at T1 and T2. These differences in brain-behavior correlations between syntax and semantics were more pronounced for the subtest scores as compared to the language composite scores (e.g., pMTG T1 correlated with LCI T1 (r = .65) and LSI T1 (r = .54) versus Word Classes T1 (r = .53) and Recalling Sentences T1 (r = .16); see Table 5. This indicates that the newly identified voxels are not correlated to the same degree with the alternate construct of interest and are differentially sensitive to semantic versus syntactic skills.

Regression analyses using the language composite scores revealed evidence in support of syntactic bootstrapping (see Table 6). There was a large effect of percent variance change between syntax skills at T1 and semantic brain at T2. Syntax skills at T1 accounted for an additional 21.9% of the variance in pMTG activation at T2, after controlling for pMTG activation and phonological memory at T1 (F(1,22) = 6.36, p = .019). In the parallel brain to skill model, IFGop activation for syntax at T1 accounted for an additional 2.9% of the variance in semantic skill at T2, after controlling for semantic skills and phonological memory at T1 (F(1,26) = 1.19, p = .285). Regarding semantic bootstrapping, there was a small change in percent variance between semantic skills at T1 and syntax brain at T2. Semantic skills at T1 accounted for an additional 3.8% of the variance in IFGop activation at T2, after controlling for IFGop activation and phonological memory at T1 (F(1,26) = 1.08, p = .309). In the parallel brain to skill model, pMTG activation for semantics at T1 accounted for less than 1% of the variance in syntax skills at T2, after controlling for syntax skills and phonological memory at T1 (F(1,22) = .06, p = .812).

3.5. Exploratory analyses with language subtest scores

Regression analyses using language subtest scores indicated evidence in support for bi-directional influences (see Table 6 and Fig. 3). Regarding syntactic bootstrapping, there was a medium effect of change in variance between syntax skills at T1 and semantic brain at T2. Syntax skills at T1 accounted for an additional 5.4% percent of the variance in pMTG activation for semantics at T2, after controlling for pMTG activation and phonological memory at T1(F(1,22) = 1.32, p = .263). In the parallel brain to skill model, IFGop activation for syntax at T1 accounted for an additional 1.5% of the variance in semantic skill at T2, after controlling for semantic skills and phonological memory at T1(F(1,26) = .62, p = .439). Regarding semantic bootstrapping, there was a medium effect of change in variance between semantic skills at T1 and syntax brain at T2. Semantic skills at T1 accounted for an additional 8.1% of the variance in IFGop activation for syntax at T2, after controlling for IFGop activation and phonological memory at T1 (F(1,26) = 2.43, p = .131). In the parallel brain to skill model, pMTG activation for semantics at T1 accounted for less than 1% of variance in syntax skills at T2, after controlling for syntax skills at T1 and phonological memory (F(1,22) = .23, p = .637).

3.6. Exploratory Analyses 2

In the second set of exploratory analyses, we tested whether the bootstrapping effect generalizes to processing grammatically incorrect (FVio > Control) or semantically anomalous (InCon > Control) sentences (i.e., "no " response experimental conditions). Sentences with semantic or syntactic violations place different demands on language and cognitive processes (Davis & Rodd, 2011; Haggort & Indefrey, 2014). This may lead to variations in the amount of brain activation and variations in the localization of these effects (e.g., Kuperberg et al., 2003). Similar to the first exploratory analyses, we used group-level brain and behavior correlations to identify activated voxels. Further, we computed hierarchical regressions using both language composite and subtest scores. Group-level activations using the violation sentences are shown in Fig. 2 and bivariate correlations among these set of variables are presented in Table 7.

3.7. Exploratory analyses using anomalous sentences and language composites

Regression analyses with the anomalous sentences and language composite scores indicated support for syntactic bootstrapping (see Table 8). There was a medium effect of change in variance between syntax skill at T1 and semantic brain at T2. Syntax skills at T1 accounted for an additional 6.7% percent of the variance in pMTG activation for semantics at T2, after taking into account pMTG activation and phonological memory at T1 (F(1,22) = 1.67, p = .210). In the parallel brain to skill model, IFGop activation for syntax at T1 explained less than 1% of the variance in semantic skill at T2, after controlling for semantic skills and phonological memory at T1(F(1,26) = .34, p = .562). Regarding semantic bootstrapping, there was a small effect of change in variance between semantic skill at T1 and syntax brain at T2. Semantic skills at T1 accounted for an additional 1.6% of the variance in IFGop activation for syntax at T2, after taking into account IFGop activation and phonological memory at T1 (F(1,26) = .48, p = .496). In the parallel brain to skill model, pMTG activation for semantics at T1 accounted for less than 1% of the variance in syntax skills at T2, after controlling for syntax skills at T1 and phonological memory (F(1,22) = .12, p = .731).

3.8. Exploratory analyses using anomalous sentences and language subtests

Regression analyses with the anomalous sentences and language subtests indicated evidence in support for bi-directional influences (see Table 8 and Fig. 3). Regarding syntactic bootstrapping, there was a medium effect of change in variance between syntax skills at

T1 and semantic brain at T2. Syntax skills at T1 accounted for an additional 8.0% percent of the variance in pMTG activation for semantics at T2, after taking into account pMTG activation and phonological memory at T1 ($F(1,22) = 1.94$, $p = .177$). In the parallel brain to skill model, IFGop activation for syntax at T1 explained less than 1% of the variance in semantic skill at T2, after controlling for semantic skills and phonological memory at T1($F(1,26) = .06$, $p = .801$). Regarding semantic bootstrapping, there was a medium effect of change in variance between semantic skill at T1 and syntax brain at T2. Semantic skills at T1 accounted for an additional 6.8% of the variance in IFGop activation for syntax at T2, after taking into account IFGop activation and phonological memory at T1 ($F(1,26) = 2.1$, $p = .159$). In the parallel brain to skill model, pMTG activation for semantics at T1 accounted for less than 1% of the variance in syntax skills at T2 after controlling for syntax skills and phonological memory at T1 ($F(1,22) = .41$, $p = .530$).

3.9. Exploratory Analyses 3

In the third exploratory analyses, we computed two skill to brain models to test the selectivity of our prior bootstrapping effects. Specifically, we tested whether the prior semantic bootstrapping trends are specific to syntax task activation in the IFGop and not semantics-related activation in the IFGop. Similarly, we tested whether the prior syntactic bootstrapping trends are specific to semantic task activation in the pMTG and not syntax-related activation in the pMTG. To do so, we used the top 100 most correlated voxels from the exploratory analyses with the 'yes' response sentences and the CELF-5 subtest scores: SCon > Perceptual correlated with Word Classes raw score within pMTG mask and Gram > Perceptual correlated with Recalling Sentences raw score within IFGop mask. Next, for each participant, we extracted the beta values from the same top voxels in the alternate ROI and task contrast: SCon > Perceptual in IFGop (semantic task activation in syntax ROI) and Gram > Perceptual in pMTG (syntax task activation in semantic ROI). The average of these top voxels for each participant were entered into the hierarchical regression.

Regression analyses with the alternate ROI and task contrast indicated evidence in support for the selectivity the semantic bootstrapping effects in the IFGop and the syntactic bootstrapping effects in the pMTG (see Table 9). Regarding semantic bootstrapping, our prior analyses with 'yes' response (grammatically correct and semantically plausible) sentences and CELF subtests indicated that semantic skill at T1 accounted for an additional 8% of the variance in IFGop activation for syntax at T2. The current exploratory analyses indicates that semantic skill at T1 accounted for only 2% of the variance in IFGop activation for semantics at T2, after taking into account the IFGop activation and phonological memory at T1 ($F(1,22) = .51$, $p = .482$). Similarly, regarding syntactic bootstrapping, our prior analyses indicated that syntax skill at T1 accounted for an additional 5% of the variance in pMTG activation for semantics at T2. The current exploratory analyses indicates that syntax skill at T1 accounted for less than 1% of the variance in pMTG activation for syntax at T2, after controlling for pMTG activation and phonological memory at T1 ($F(1,26) = .16$, $p = .688$).

4. Discussion

The aim of the present study was to examine the longitudinal relations of brain and behavior from 6–7.5 years old to test the semantic and syntactic bootstrapping account of language development. Results from the preregistered analyses indicated no evidence in favor of either semantic or syntactic bootstrapping mechanisms. Results from the exploratory analyses indicated bi-directional influences, but with greater support for syntactic bootstrapping. Findings extend prior work suggesting that acquisition of phrase structure in school age children may allow for the more effective learning of word meanings (e.g., Blom & Boerma, 2019; Caglar-Ryend et al., 2019). The current findings complement prior behavioral studies showing reliance on lexical knowledge to facilitate grammatical development in younger children.

In line with prior evidence in younger children, our results indicate a close relationship between lexical and grammatical development in children ages 6–7.5 years old. However, we observed more robust evidence for syntactic bootstrapping (see Table 10). Across the models tested, there was a small to medium effect of change in variance in models where semantic skills at T1 predicted IFGop activation for syntax at T2. Conversely, there was medium to large change in variance in models where syntax skills at T1 predicted pMTG activation for semantics at T2. Prior behavioral literature emphasizes the importance of vocabulary knowledge in bootstrapping grammatical development in younger children (e.g., Marchman & Bates, 1994; Marchman et al., 2004). Our results suggest a greater influence of grammatical skills on the development of lexical knowledge in older children. These results align with previously reported behavioral findings from Caglar-Ryend et al. (2019). The authors observed a shift in the association of early vocabulary knowledge with subsequent grammar between ages 1.5 to 3 years old followed by the reverse between ages 3.5 to 6 years old. Our results extend the previous findings to show evidence for syntactic bootstrapping that persists between ages 6 to 7.5 years old.

Both experience and brain maturation are likely to result in earlier development of semantics than syntax, and therefore greater early semantic bootstrapping and later syntactic bootstrapping. Around age 4–6 years old, children experience more advanced grammatical growth (e.g., Guasti, 2017; Tomblin and Zhang, 2006). As children enter elementary school, their language interactions include more complex conversations and increased experiences with text. The syntactic structure of written language is more varied and complex than that of spoken language. The advancement in grammatical skills through reading achievement may contribute to this shift in greater syntactic bootstrapping during elementary school (Braginsky et al., 2015; Brinchmann et al., 2019; Hood, Conlon, & Andrews, 2008; Sénéchal & LeFevre, 2002; Traxler, 2005).

In parallel, neurobiological models of language development posit that comprehension processes in younger children are likely to be supported by early developing temporal lobe structures, enabling direct mapping of sound to meaning (e.g., Hickok & Poeppel, 2004; Skeide & Friederici, 2016). As the frontal lobe matures in older children, comprehension is increasingly supported by functionality of the inferior frontal gyrus and its role in syntactic computations (e.g., Friederici et al., 2012; Hahne, Eckstein, & Friederici, 2004;

Skeide & Friederici, 2016). In line with this developmental model, prior studies have shown evidence of semantic specialization in the temporal lobe, including the pMTG, in children as young as 5 to 6 years old (e.g., Wang et al., 2020; Weiss, Cweigenberg, Booth, 2018). In contrast, evidence in support of IFGop specialization for syntactic processes at this age have been inconsistent (e.g., Brauer & Friederici, 2007; Wang et al., 2020). Skeide & Friederici's (2016) development model suggest that functional selectivity in the frontal lobe for sentence-level syntactic information may not distinct from semantics until later in development, between ages 7 to 9 years old (Brauer & Friederici, 2007; Nunez et al., 2011). Our results suggest a stronger effect of grammatical skills on meaning-based language comprehension in the temporal lobe in older children. We found little evidence in this age group of the effect of children's lexical-semantic skills on syntax-based language comprehension in the frontal lobe.

We chose to focus on the pMTG and IFGop as they are implicated in semantic and syntactic processing, respectively. In addition to pMTG and IFGop, neural models of language suggest that the ventral IFG (pars triangularis and orbitalis) is important in semantic access (e.g., Binder et al., 2009; Ferstl et al., 2008) and the posterior STG is involved in the integration of semantics and syntax (e.g., Rodd et al., 2015; Skeide & Friederici, 2016; Vigneau et al., 2006; Wang et al., 2020). A recent meta-analysis of fMRI studies on language comprehension in children revealed consistent activation in bilateral STG and the left ventral IFG (Enge, Friederici, & Skeide, 2020). Based on these findings, we could also expect to observe syntactic bootstrapping effects in the ventral IFG. Specifically, children's knowledge of phrase structure may guide the more efficient access of semantic information and thus more strongly recruit the pars triangularis/orbitalis regions of the IFG. Further, we could also expect bi-directional effects of language bootstrapping in the STG. During processes of semantic and syntactic integration, we would expect semantic skills to predict activation in the STG for syntax and reciprocally, syntax skills to predict activation in the STG for semantics. While the current study does not aim to distinguish between processes of representation versus access, a closer examination of the fronto-temporal network can help further our understanding of the mechanisms underlying language comprehension and its development (e.g., (Hoffman et al., 2018).

Across the analyses, models in which brain activation at T1 predicted behavior at T2 yielded little to no evidence in favor of either bootstrapping mechanism. Behavioral skills at T1 are a strong predictor of behavioral skills at T2, because of the stability of individual differences in behavior across this time period. After controlling for the effects of behavioral skills at T1, brain activity at T1 accounted for little variance in T2 behavior. The brain to skill models in our analyses indicate that there is little predictive utility of the brain measures above and beyond behavioral measures in explaining unique variance in semantic and syntactic skills overtime (at least for these measures and this sample). However, the skill to brain models indicated that behavioral measures explained additional variance above and beyond brain measures in predicting neural processes overtime. Longitudinal research using cross-lagged designs allows us to infer causal directionality (Kearney, 2017). However, a shortcoming of many prior behavioral studies that have used predictive models is that they have not controlled for children's initial skill levels (e.g., Blom & Boerma, 2019; Moyle et al., 2007).

By accounting for autoregressive relations in the present study, we are able to draw better inferences about bidirectional influences in children's semantic and syntactic development.

Additionally, a significant contribution of the current study is that we used both brain and behavioral measures to systematically test questions of language bootstrapping. Our ROIs were chosen based on prior work in children ages 5–6 years old that had established specificity for semantic and syntactic processes to some degree in the left MTG (Wang et al., 2020) and IFG (Brauer & Friederici, 2007), respectively. In our exploratory analyses, we used brain-behavior correlations at each time point to identify the top correlated voxels for each language construct. Accordingly, brain activation for the semantic task within the pMTG mask was more correlated with semantic, compared to syntactic, behavioral skills at T1 and T2. Similarly, brain activation for the syntax task within the IFGop mask was more correlated with syntax, compared to semantic, behavioral skills at T1 and T2. This approach allowed us to isolate the regions for processing semantic and syntactic features and capture the individual differences in sensitivity to different aspects of linguistic processing.

Our exploratory analyses testing for language bootstrapping used semantically plausible and implausible as well as grammatical and ungrammatical sentences (see Figure 3). We tested whether effects generalize to processing sentences with a ‘yes’ response to those with a ‘no’ response. Across all exploratory analyses, the pattern of results converge to support the interdependence of lexical and grammatical development, with stronger evidence in support for syntactic bootstrapping. We also tested the selectivity of these effects in the IFGop and pMTG by examining within-construct behavior to brain relationships (e.g., semantic behavioral skill predicting semantic task activation in the IFGop and syntax behavioral skill predicting syntax task activation in the pMTG). Results from this analysis show evidence in support for the selectivity of the semantic bootstrapping effects in the IFGop and the syntactic bootstrapping effects in the pMTG. Although promising, our analyses are exploratory and these results need to be replicated. Nevertheless, the consistency in our results across all analyses using different brain and behavioral measures is encouraging.

The pre-registered and exploratory analyses in the current study assessed brain-behavior relations overtime. In our sample, only 12 participants completed both the semantic and syntax fMRI tasks at both time-points. Thus, differences in the relative strength of semantic and syntactic bootstrapping effects could be due individual differences between the samples included in either task. Future studies with a larger sample size could also test effects of bootstrapping within brain-to-brain or skill-to-skill analyses. Testing of these alternate models may be more sensitive at capturing effects of semantic and syntactic bootstrapping in comparison to a brain-to-skill model. In the current study, the correlations between the standardized behavioral assessments (either the composite scores or subtests) and the in-scanner task performance (overall accuracy or conditions of interest accuracy) are modest. This suggests construct validity is lacking given that both the behavioral and imaging tasks are expected to measure the same (semantic or syntactic) construct. The standardized/normed assessment likely better captures individual differences in skill whereas brain activation during the in-scanner task is perhaps a better index of one type of semantic or grammatical feature in one region within a network of regions known to contribute to semantic and syntactic skills.

We also aim to extend these findings to a separate and older cohort of children. While results of the current study indicated stronger evidence in favor of syntactic bootstrapping, we also observed evidence for semantic bootstrapping (see Table 10). Examining children from 7.5–9 years old could further inform our understanding of the trajectory of semantic and syntactic development. In the older age group, we expect to see more robust evidence for syntactic bootstrapping. Prior behavioral research suggests that a certain level of grammatical development may be necessary in order to make use of syntactic cues to word meaning (Hollich et al., 2000). It would also be informative to investigate if language bootstrapping is modulated by the language ability of the children. Previous studies have shown that syntactic skills predicted semantic skills in school age children with developmental language disorder (Blom & Boerma, 2019), whereas syntactic growth did not predict lexical development in preschool children who were late talkers (Moyle et al., 2007). This suggests that not only age, but also language proficiency may modulate the degree of bootstrapping; thus, higher grammatical skill may be necessary for robust syntactic bootstrapping.

In conclusion, the present study is the first to examine the neurocognitive mechanisms of semantic and syntactic bootstrapping longitudinally in children ages 6 to 7.5 years old. A series of preregistered and exploratory hierarchical regression analyses indicated bi-directional influences, but with greater support for syntactic bootstrapping. Our results complement prior behavioral studies and together suggests a potential shift in the early influence of semantic bootstrapping in preschoolers to later influence of syntax bootstrapping in school age children.

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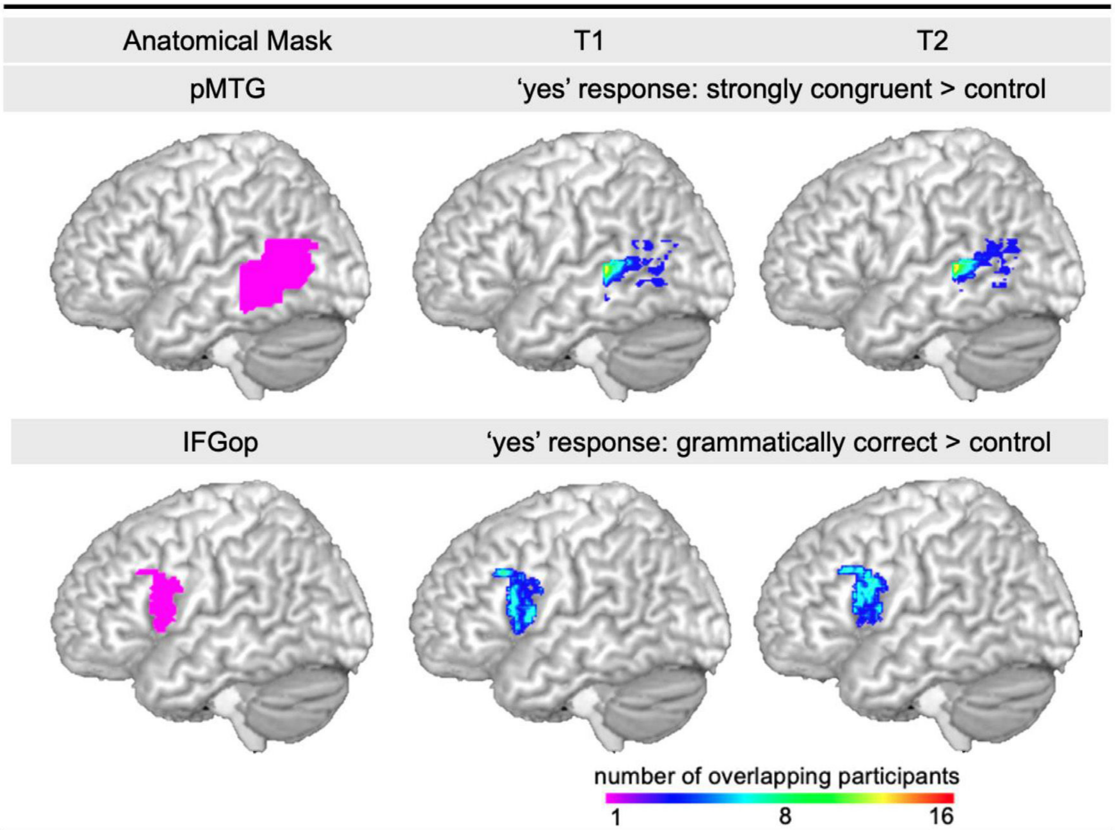

Fig. 1.

Anatomical masks of posterior middle temporal gyrus (pMTG) and inferior frontal gyrus (par opercularis, IFGop) and the spatial overlap across participants within each region-of-interest at each timepoint. The color gradient shows the number of participants with overlapping voxels for the 'yes' response trial types: strongly congruent > control in pMTG and grammatically correct > control in the IFGop.

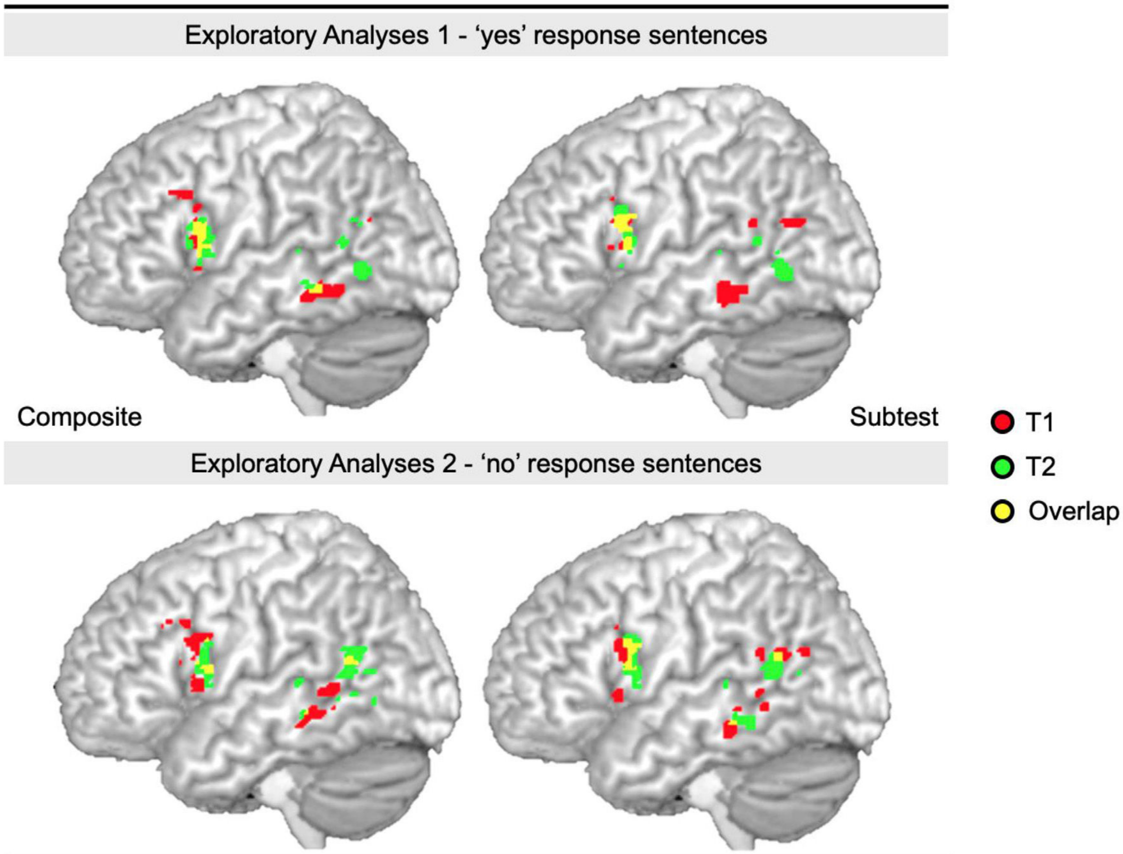

Fig. 2.

Group-level activations showing T1 (red), T2 (green), and T1-T2 overlap (yellow) within each region-of-interest. Top row shows activations for Exploratory Analyses 1 using 'yes' response sentences (strongly congruent > control in pMTG and grammatically correct > control in the IFGop) correlated with language composite (left) and subtest (right) scores. Bottom row shows activations for Exploratory Analyses 2 using 'no' response sentences (incongruent > control in the pMTG and finiteness violation > control in the IFGop) correlated with language composite (left) and subtest (right) scores.

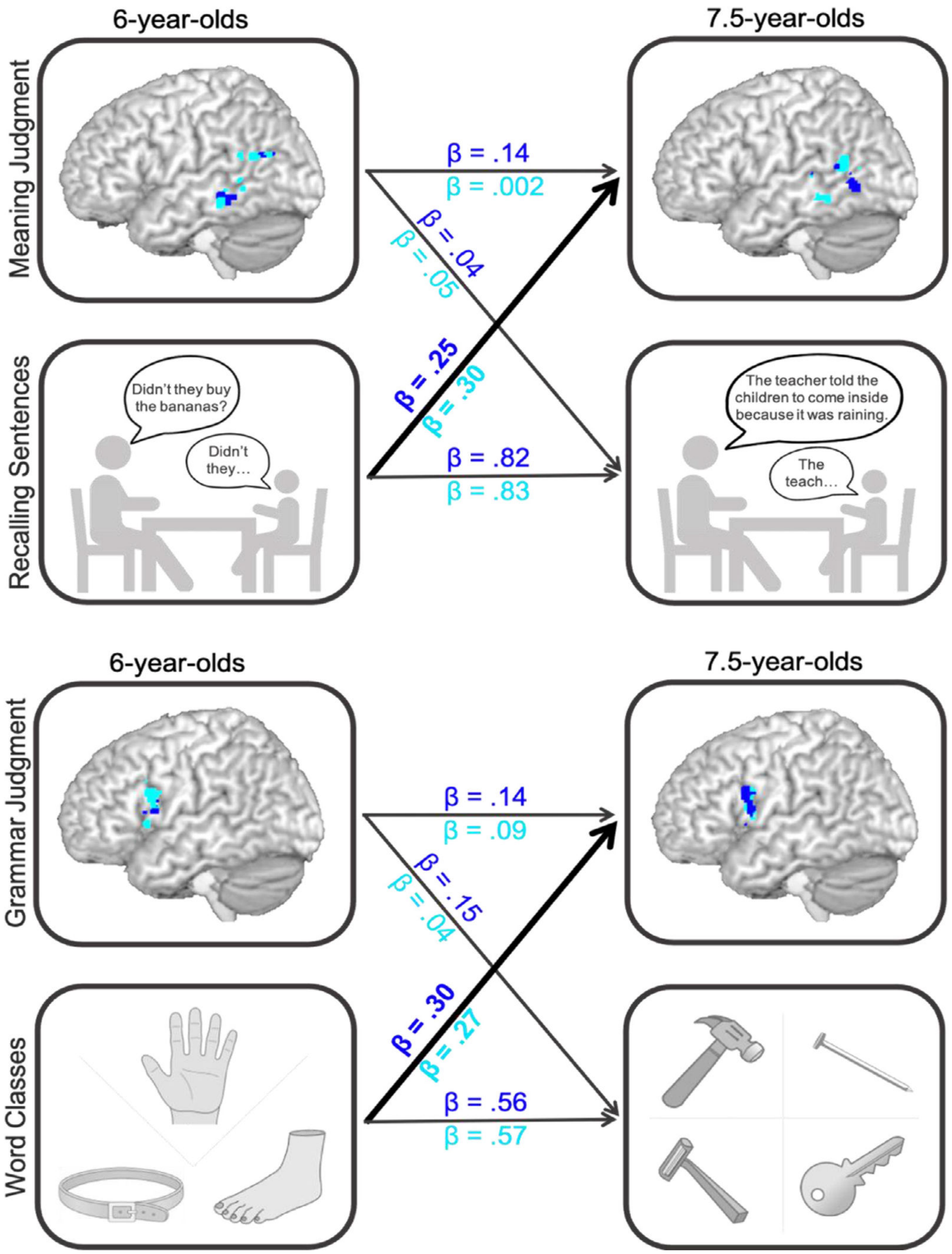

Fig. 3.

Summary of the beta coefficients from Exploratory Analyses 1 & 2 using language subtest scores. Brain activations in dark blue reflect ‘yes’ response sentence conditions (strongly congruent > control in pMTG and grammatically correct > control in the IFGop) and brain activations in light blue reflect ‘no’ response sentence conditions (semantically incongruent > control in pMTG and finiteness violation > control in the IFGop). Bold path highlights the skill to brain syntactic (top) and semantic (bottom) bootstrapping relationship.

Table 1

Examples of the stimuli from the sentence judgment tasks.

Task	Response	Condition	Example
Semantic	*yes*	Strongly congruent (SCon)	She is singing one song
	yes	Weakly congruent (WCon)	They are building one house
	no	Incongruent (InCon)	Last week, they chopped two phones
	yes	Perceptual (Control)	"Sh – Sh"
Syntax	*yes*	Grammatically correct (Gram)	Every day, he learns six words
	no	Plurality violation (PVio)	She is opening two window
	no	Finiteness violation (FVio)	They not climb one hill
	yes	Perceptual (Control)	"Sh – Sh"

Table 2

Performance on in-scanner tasks and standardized assessments for participants who completed the semantic task (N = 26; top) and syntax task (N = 30, bottom).

		N = 26			
		M(SD)		*t, p*	*r,p*
		T1	T2		
Semantic	SCon	77.5 (13.3)	85.6 (12.1)	−2.52, .018	.18, .308
Task[a]	WCon	65.6 (15.6)	75.6 (15.4)	−2.63, .014	.22, .595
	InCon	82.9 (16.2)	90.6 (10.3)	−2.29, .030	.22, .303
	Control	95.2 (6.7)	98.1 (2.8)	−1.99, .057	−.03, .746
CELF-5[b]	Language Content Index (LCI)	40.6 (6.7)	37.2 (5.7)	3.31, .002	.66, .000
	Language Structure Index (LSI)	51.1 (7.8)	49.3 (7.6)	1.29, .207	.59, .000
	Word Classes	14.8 (2.9)	14.2 (2.8)	1.27, .216	.53, .000
	Recalling Sentences	13.6 (2.5)	13.1 (3.0)	1.81, .083	.90, .000
CTOPP-2[c]	Phonological Memory	22.9 (3.7)	-	-	
		N = 30			
		M(SD)		*t,p*	*r,p*
		T1	T2		
Syntax	Gram	68.7 (15.9)	81.3 (9.5)	−4.95, .000	.49, .015
Task[a]	PVio	80.7 (11.3)	90.3 (8.7)	−3.64, .001	−.04, .720
	FVio	69.5 (13.5)	79.8 (13.0)	−3.37, .002	.20, .756
	Control	94.5 (6.9)	98.0 (3.5)	−2.33, .027	−.10, . 489
CELF-5[b]	Language Content Index (LCI)	40.6 (6.6)	37.8 (5.3)	2.72, .011	.55, .000
	Language Structure Index (LSI)	52.7 (6.7)	50.8 (6.4)	1.68, .103	.53, .000
	Word Classes	14.1 (2.9)	14.7 (2.2)	−1.19, .242	.58, .000
	Recalling Sentences	13.8 (2.4)	13.7 (2.4)	.49, .625	.81, .000
CTOPP-2[c]	Phonological Memory	23.0 (4.0)	-	-	-

Note.

[a] Percent accuracy

[b] Scaled score

[c] Raw score

Table 3

Results of the preregistered hierarchical regression analyses.

	T1 Semantic Skill → T2 Syntax Brain				*T1 Syntax Skill → T2 Semantic Brain*			
	IFGop T2	*β*	R^2	ΔR^2	pMTG T2	*β*	R^2	ΔR^2
Model 1	Phono. Memory T1	−.403*			Phono. Memory T1	−.306		
	IFGop T1	.157	.177		pMTG T1	.672***	.472**	
Model 2	Phono. Memory T1	−.400*			Phono. Memory T1	−.296		
	IFGop T1	.160			pMTG T1	.676***		
	LCI T1	−.011	.177	.000	LSI T1	−.027	.472**	.001
	T1 Semantic Brain → T2 Syntax Skill				*T1 Syntax Brain → T2 Semantic Skill*			
	LSI T2	*β*	R^2	ΔR^2	LCI T2	*β*	R^2	ΔR^2
Model 1	Phono. Memory T1	.323			Phono. Memory T1	.191		
	LSI T1	.465*	.438**		LCI T1	.500**	.340**	
Model 2	Phono. Memory T1	.332			Phono. Memory T1	.191		
	LSI T1	.476*			LCI T1	.486**		
	pMTG T1	−.071	.442**	.005	IFGop T1	.048	.342*	.002

* $p < .05$

** $p < .01$

*** $p < .001$

Table 4

Bivariate correlations between study variables from the pre-registered analyses using subject-level top activated voxels within each region-of-interest. Highlighted values indicate brain-behavior correlations of interest for constructs of syntax and semantics.

Semantic Task Participants (N = 26)							
	1.	2.	3.	4.	5.	6.	7.
1. Phono. Memory T1	-						
2. LCI T1	.45	-					
3. LSI T1	.39	.78	-				
4. LCI T2	.35	.66	.64	-			
5. LSI T2	.50	.57	.59	.74	-		
6. pMTG T1	.18	−.11	.21	−.03	.09	-	
7. pMTG T2	−.18	−.23	−.003	−.17	−.17	.62	-
Syntax Task Participants (N = 30)							
	1	2	3	4	5	6	7
1. Phono. Memory T1	-						
2. LCI T1	.28	-					
3. LSI T1	.33	.58	-				
4. LCI T2	.33	.55	.65	-			
5. LSI T2	.46	.34	.53	.64	-		
6. IFGop T1	.08	.28	.27	.20	−.03	-	
7. IFGop T2	−.39	−.08	−.04	.08	−.04	.12	-

Table 5

Bivariate correlations between study variables from exploratory analyses 1 using group-level brain-behavior correlations to identify activated voxels using language composite (top half) and subtest (bottom half) scores. These analyses used the ‘yes’ response sentence conditions (strongly congruent > control in pMTG and grammatically correct > control in the IFGop). Highlighted values indicate brain-behavior correlations of interest for constructs of syntax and semantics.

	Semantic Task Participants (N = 26)								*Syntax Task Participants (N = 30)*						
	1.	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**		**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**
1. Phono. Memory T1	-							1. Phono. Memory T1	-						
2. LCI T1	.45	-						2. LCI T1	.28	-					
3. LSI T1	.39	.78	-					3. LSI T1	.33	.58	-				
4. LCI T2	.35	.66	.64	-				4. LCI T2	.33	.55	.65	-			
5. LSI T2	.50	.57	.59	.74	-			5. LSI T2	.46	.34	.53	.64	-		
6. pMTG T1	.38	.65	.54	.57	.41	-		6. IFGop T1	.26	.56	.60	.47	.11	-	
7. pMTG T2	−.13	.08	.29	.28	.21	−.13	-	7. IFGop T2	.22	0	.13	.35	.45	.01	-
	1.	2.	3.	4.	5.	6.	7.		1.	2.	3.	4.	5.	6.	7.
1. Phono. Memory T1	-							1. Phono. Memory T1	-						
2. Word Classes T1	.27	-						2. Word Classes T1	.25	-					
3. Recalling Sent. T1	.34	.32	-					3. Recalling Sent. T1	.55	.33	-				
4. Word Classes T2	.34	.53	.57	-				4. Word Classes T2	.16	.58	.41	-			
5. Recalling Sent. T2	.51	.45	.90	.54	-			5. Recalling Sent. T2	.52	.35	.81	.37	-		
6. pMTG T1	.44	.53	.16	.41	.27	-		6. IFGop T1	.57	.30	.64	.28	.013	-	
7. pMTG T2	−.16	.13	.16	.25	.14	.04	-	7. IFGop T2	.16	.34	.47	.33	.43	.23	-

Table 6

Results of Exploratory Analyses 1 using group-level brain-behavior correlations to identify activated voxels using language composite (top half) and subtest (bottom half) scores. These analyses used the ‘yes’ response sentence conditions (strongly congruent > control in pMTG and grammatically correct > control in the IFGop).

	T1 Semantic Skill → T2 Syntax Brain				*T1 Syntax Skill → T2 Semantic Brain*			
	IFGop T2	β	R^2	ΔR^2	pMTG T2	β	R^2	ΔR^2
Model 1	Phono. Memory T1	.235			Phono. Memory T1	−.092		
	IFGop T1	−.048	.052		pMTG T1	−.100	.026	
Model 2	Phono. Memory T1	.200			Phono. Memory T1	−.215		
	IFGop T1	−.172			pMTG T1	−.366		
	LCI T1	.238	.089	.038	LSI T1	.574*	.244	.219*
	T1 Semantic Brain → T2 Syntax Skill				*T1 Syntax Brain → T2 Semantic Skill*			
	LSI T2	β	R^2	ΔR^2	LCI T2	β	R^2	ΔR^2
Model 1	Phono. Memory T1	.323			Phono. Memory T1	.191		
	LSI T1	.465*	.438***		LCI T1	.500**	.340**	
Model 2	Phono. Memory T1	.314			Phono. Memory T1	.168		
	LSI T1	.443*			LCI T1	.391*		
	pMTG T1	.047	.439***	.001	IFGop T1	.207	.369**	.029
	T1 Semantic Skill → T2 Syntax Brain				*T1 Syntax Skill → T2 Semantic Brain*			
	IFGop T2	β	R^2	ΔR^2	pMTG T2	β	R^2	ΔR^2
Model 1	Phono. Memory T1	.037			Phono. Memory T1	−.228		
	IFGop T1	.211	.054		pMTG T1	.143	.044	
Model 2	1 Phono. Memory T1	.004			Phono. Memory T1	−.310		
	IFGop T1	.138			pMTG T1	.138		
	Word Classes T1	.300	.135	.081	Recalling Sent. T1	.247	.098	.054
	T1 Semantic Brain → T2 Syntax Skill				*T1 Syntax Brain → T2 Semantic Skill*			
	Recalling Sent. T2	β	R^2	ΔR^2	Word Classes T2	β	R^2	ΔR^2
Model 1	Phono. Memory T1	.232*			Phono. Memory T1	.015		

	Recalling Sent. T1	.822***	.858***		Word Classes T1	.577**	.338**	
Model 2	Phono. Memory T1	.213*			Phono. Memory T1	−.066		
	Recalling Sent. T1	.821***			Word Classes T1	.550**		
	pMTG T1	.043	.859***	.001	IFGop T1	.154	.353**	.015

* $p < .05$

** $p < .01$

*** $p < .001$

Table 7

Bivariate correlations between study variables from Exploratory Analyses 2 using group-level brain-behavior correlations to identify activated voxels using language composite (top half) and subtest (bottom half) scores. These analyses used the ‘ no’ response sentences (semantically incongruent > control in pMTG and finiteness violation > control in the IFGop). Highlighted values indicate brain-behavior correlations of interest for constructs of syntax and semantics.

	Semantic Task Particpants (N = 26)						
	1.	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**
1. Phono. Memory T1	-						
2. LCI T1	.45	-					
3. LSI T1	.39	.78	-				
4. LCI T2	.35	.66	.64	-			
5. LSI T2	.50	.57	.59	.74	-		
6. pMTG T1	.30	.51	.35	.40	.21	-	
7. pMTG T2	.07	.19	.31	.31	.22	.22	-
	1.	2.	3.	4.	5.	6.	7.
1. Phono. Memory T1	-						
2. Word Classes T1	.27	-					
3. Recalling Sent. T1	.34	.32	-				
4. Word Classes T2	.34	.53	.57	-			
5. Recalling Sent. T2	.51	.45	.90	.54	-		
6. pMTG T1	.16	.51	−.10	−.02	.01	-	
7. pMTG T2	.10	.10	.30	.52	.22	−.03	-

	Syntax Task Particpants (N = 30)						
	1.	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**
1. Phono. Memory T1	-						
2. LCI T1	.28	-					
3. LSI T1	.33	.58	-				
4. LCI T2	.33	.55	.65	-			
5. LSI T2	.46	.34	.53	.64	-		
6. IFGop T1	.28	.41	.53	.34	.22	-	
7. IFGop T2	.34	.25	.24	.45	.49	.20	-
	1.	2.	3.	4.	5.	6.	7.
1. Phono. Memory T1	-						
2. Word Classes T1	.25	-					
3. Recalling Sent. T1	.55	.33	-				
4. Word Classes T2	.16	.58	.41	-			
5. Recalling Sent. T2	.52	.35^	.81	.37	-		
6. IFGop T1	.41	.14	.56	.12	.37	-	
7. IFGop T2	.29	.33	.45	.35	.52	.20	-

Table 8

Results of Exploratory Analyses 2 using group-level brain-behavior correlations to identify activated voxels using language composite (top half) and subtest (bottom half) scores. These analyses used the ‘no’ response sentences (semantically incongruent > control in pMTG and finiteness violation > control in the IFGop).

	T1 Semantic Skill → T2 Syntax Brain				*T1 Syntax Skill → T2 Semantic Brain*			
	IFGop T2	β	R^2	ΔR^2	pMTG T2	β	R^2	ΔR^2
Model 1	Phono. Memory T1	.308			Phono. Memory T1	.005		
	IFGop T1	.120	.129		pMTG T1	.215	.047	
Model 2	Phono. Memory T1	.282			Phono. Memory T1	−.086		
	IFGop T1	.070			pMTG T1	.142		
	LCI T1	.140	.145	.016	LSI T1	.291	.114	.067
	T1 Semantic Brain → T2 Syntax Skill				*T1 Syntax Brain → T2 Semantic Skill*			
	LSI T2	β	R^2	ΔR^2	LCI T2	β	R^2	ΔR^2
Model 1	Phono. Memory T1	.323			Phono. Memory T1	.191		
	LSI T1	.465*	.438**		LCI T1	.500**	.340**	
Model 2	Phono. Memory T1	.335			Phono. Memory T1	.173		
	LSI T1	.481*			LCI T1	.463*		
	pMTG T1	−.060	.441**	.003	IFGop T1	.103	.348*	.009
	T1 Semantic Skill → T2 Syntax Brain				*T1 Syntax Skill → T2 Semantic Brain*			
	IFGop T2	β	R^2	ΔR^2	pMTG T2	β	R^2	ΔR^2
Model 1	Phono. Memory T1	.245			Phono. Memory T1	.111		
	IFGop T1	.104	.092		pMTG T1	−.048	.013	
Model 2	Phono. Memory T1	.184			Phono. Memory T1	.000		
	IFGop T1	.092			pMTG T1	.002		
	Word Classes T1	.269	.160	.068	Recalling Sent. T1	.305	.093	.080
	T1 Semantic Brain → T2 Syntax Skill				*T1 Syntax Brain → T2 Semantic Skill*			
	Recalling Sent. T2	β	R^2	ΔR^2	Word Classes T2	β	R^2	ΔR^2
Model 1	Phono. Memory T1	.232*			Phono. Memory T1	.015		

	Recalling Sent. T1	.822***	.858***		Word Classes T1	.577**	.338**	
Model 2	Phono. Memory T1	.220*			Phono. Memory T1	−.003		
	Recalling Sent. T1	.831***			Word Classes T1	.575**		
	pMTG T1	.052	.860***	.003	IFGop T1	.045	.339*	.002

* $p < .05$

** $p < .01$

*** $p < .001$

Table 9

Results of Exploratory Analyses 3 using group-level brain-behavior correlations to identify top corelated voxels using subtest scores and the alternate ROI. These analyses used the ‘yes’ response sentences (semantically congruent > control in IFGop and grammatically correct > control in the pMTG).

	T1 Semantic Skill → T2 Syntax Brain			
	IFGop T2 - for semantic task	*β*	R^2	ΔR^2
Model 1	Phono. Memory T1	.133		
	IFGop T1	.068	.029	
Model 2	Phono. Memory T1	.064		
	IFGop T1	.128		
	Word Classes T1	.165	.051	.022
	T1 Syntax Skill → T2 Semantic Brain			
	pMTG T2 - for syntax task	*β*	R^2	ΔR^2
Model 1	Phono. Memory T1	.003		
	pMTG T1	.074	.006	
Model 2	Phono. Memory T1	−.056		
	pMTG T1	.095		
	Recalling Sent. T1	.098	.012	.006

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Table 10

Summary of results showing change in percent variance (ΔR^2) from all regression analyses examining semantic and syntactic bootstrapping. Operationalization of variables for each analysis is described below.

	Preregistered	**Exploratory 1**		**Exploratory 2**		**Exploratory 3**
	top voxels based on subject-level activations	***top voxels based on group-level correlation with skill***		***top voxels based on group-level correlation with skill***		***top voxels based on group-level correlation with skill & alternate ROI***
	'yes' response sentences analyses using composite scores	***'yes' response sentences***		***'no' response sentences***		***'yes' response sentences***
		composite scores	***subtest scores***	***composite scores***	***subtest scores***	***subtest scores***
Semantic Skill → Syntax Brain	<1%	4%	8%	2%	7%	2%
Semantic Brain → Syntax Skill	<1%	<1%	<1%	<1%	<1%	-
Syntax Skill → Semantic Brain	<1%	22%	5%	7%	8%	<1%
Syntax Brain → Semantic Skill	<1%	3%	2%	<1%	<1%	-