# The scaffolding of individual variability in language processing by domain-general neural networks

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**Abstract:**

Language processing is supported by distributed neural systems. Yet most research examines these systems at the population-average level, obscuring how individual cognitive differences shape language-related brain activity. In this study, we combined comprehensive cognitive assessments and task-based fMRI in a large sample of healthy adults (N = 205) to examine how variability in linguistic knowledge, working memory, processing speed, and non-verbal reasoning influenced neural responses in four language tasks: lexical decision, picture naming, sentence comprehension, and sentence production. All tasks engaged canonical left-lateralized language regions. However, individual differences in cognitive skills were not associated with modulations within commonly activated regions, but rather with modulations in domain-general systems outside traditional perisylvian language areas, mainly the default mode and dorsal attention networks. Notably, activations in these domain-general regions were predominantly negatively correlated with cognitive skills, indicating that individuals with lower cognitive skills draw on these broader neural resources more than higher-skilled individuals, possibly as a compensatory mechanism. These results reveal that while canonical language regions are consistently engaged during language tasks, the recruitment of domain-general systems acts as a variable resource modulated by individuals' cognitive skills. Overall, our findings demonstrate that individual cognitive profiles determine how distributed brain systems are dynamically engaged to scaffold language processing.

## INTRODUCTION

Producing even a single word engages a cascade of tightly coordinated processes, ranging from conceptualizing an intended message and retrieving the appropriate lexical item to assembling its phonological or gestural components into a precise motor plan (Dell, 1986; Levelt et al., 1999; Nozari, 2025). At the sentence level, these demands escalate: speakers must encode thematic roles (e.g., agent and patient), organize syntactic structure, and mark the communicative focus of the utterance (Roelofs & Ferreira, 2019). Comprehension poses similarly complex challenges. Listeners must rapidly decode the incoming linguistic signal, integrate it with prior knowledge, and construct a coherent mental representation of the intended message in real time (Ferreira & Henderson, 1991; Magnuson et al., 2020; Norris & McQueen, 2008; Pickering, 2003).

Successfully accomplishing these linguistic operations relies not only on access to domain-specific linguistic knowledge, i.e. vocabulary and grammatical knowledge (Dąbrowska, 2018; McConnell, 2023), but also on domain-general cognitive skills, including working memory, processing speed, and non-verbal reasoning. Working memory supports the maintenance and manipulation of transient conceptual and linguistic representations during both comprehension and production (Acheson & MacDonald, 2009; Daneman & Merikle, 1996; Huettig & Janse, 2016; Piai & Roelofs, 2013; Shao et al., 2012). For instance, it enables the retention of morphosyntactic structures and lexical items that are necessary for resolving long-distance dependencies (Lewis & Vasishth, 2005; Nicenboim et al., 2015) and for integrating information across clause boundaries in complex sentences (Fedorenko et al., 2006). Processing speed, defined as the efficiency with which cognitive operations are executed (Kail & Salthouse,

1994), constrains the ability to decode sensory input and plan linguistic output in real time. It is therefore critical for tasks requiring rapid temporal coordination, such as distinguishing phonemes in fast speech streams (Chang et al., 2010; Christiansen & Chater, 2016) and retrieving and sequencing lexical candidates during fluent speech production (Fuhrmeister et al., 2024). Non-verbal reasoning contributes to conceptual integration by supporting the construction of intended meaning beyond the literal words, the resolution of semantic ambiguities, the interpretation of metaphors, and the generation of discourse-level inferences (Engelhardt et al., 2017; Kazmerski et al., 2003).

Importantly, domain-specific and domain-general skills vary substantially across individuals, raising the question of how such variability contributes to differences in language processing. Psycholinguistic research has consistently documented individual differences in language processing strategies and performance that are linked to cognitive skills. Individuals with higher working memory capacity process syntactically complex sentences more efficiently (Just & Carpenter, 1992), while faster processing speed is associated with stronger linguistic prediction in a visual world paradigm (Huettig & Janse, 2016). Similarly, children with higher non-verbal reasoning skills differentiate semantic and syntactic violations more rapidly (Hampton Wray & Weber-Fox, 2013). Together, these findings demonstrate that language performance is not determined by linguistic knowledge alone but is scaffolded by the flexible recruitment of domain-general cognitive resources that differ across individuals.

While there is mounting behavioral evidence for interindividual differences in language processing and growing interest in their neural correlates (Balboni et al., 2025; Feng et al., 2021; Liu et al., 2024), neurobiological investigations of language have largely emphasized shared

neural mechanisms across speakers and listeners (Giglio et al., 2022; Menenti et al., 2011; Segaert et al., 2012). This focus on population-level averages has typically led to individual variability being treated as noise, rather than as a source of insight into the mechanisms that support flexible language use (Seghier & Price, 2018). As a result, fundamental questions remain unresolved: 1) How are individual differences in cognitive skills reflected in neural activity during language processing? 2) Where in the brain do these differences primarily manifest; within canonical language regions, or in domain-general areas outside these regions?

Addressing these questions is essential for developing comprehensive models of language processing that account for the interactions between domain-specific language systems and the broader cognitive architecture (Kidd et al., 2018). Understanding how individual variability in cognitive skills relate to language processing offers valuable insight into the functioning of the language system and typical language development, enhances our understanding of language-related disorders, and opens new avenues for tailoring educational or clinical interventions based on individual cognitive profiles.

To this end, we combined behavioral and neuroimaging approaches in the largest sample of healthy participants to date (N = 205) for characterizing individual differences in language processing. Participants' cognitive skills were assessed across four domains: domain-specific **linguistic knowledge,** and three domain-general skills, namely **processing speed, working memory**, and **non-verbal reasoning**. Additionally, during fMRI scanning, participants completed four language tasks: **auditory lexical decision, picture naming, sentence comprehension,** and **sentence production**, designed to tap different linguistic levels (words and sentences), sensory input modalities (auditory and visual) and task demands (comprehension and

production). By relating interindividual variability in cognitive skills to variability in task-evoked brain activity, we aim to elucidate the cognitive and neural architecture that supports flexible language use across individuals.

## METHODS

### Participants

A total of 205 healthy young adults, who were native Dutch speakers, participated in the study (age range: 18-30; mean age = 23 years; 149 females; 28 left-handed; 3 ambidextrous). Participants were recruited from the pool of individuals who had completed a recent behavioral study ((Hintz et al., 2025), *see Behavioral Testing*). Inclusion criteria were as follows: (1) fluent Dutch speakers; (2) normal hearing and normal vision or corrected-to-normal vision; (3) no history of brain operations or epilepsy; (4) fulfill the safety criteria to go into the MRI scanner. Several participants were excluded due to anatomical anomalies, poor task performance, or missing behavioral data, resulting in the following final sample sizes: Lexical decision (n = 193), picture naming (n = 190), sentence comprehension (n = 192), and sentence production (n = 192). The study was approved by the local ethics committee, and written informed consent was obtained in accordance with the Declaration of Helsinki.

### Behavioral Testing

All participants were drawn from a larger pool of 748 individuals who had previously completed a comprehensive behavioral study designed to assess interindividual differences in linguistic knowledge, linguistic processing skills and domain-general cognitive skills using an extensive test battery (Hintz et al., 2025). Six participants completed the behavioral battery on-

site (two-hour sessions on two separate days) while the remaining 199 participants completed the same battery online (four one-hour sessions of on four separate days). For the present study, we used latent factor scores derived from the domain-specific linguistic knowledge tests and from cognitive tasks assessing three domain-general skills: processing speed, working memory, and non-verbal reasoning (**Table 1** provides an overview of the administered tests). Tests targeting linguistic processing abilities (i.e., word- and sentence-level comprehension and production) were not included in the analyses reported here and were distinct from the language tasks performed during fMRI. For a detailed description of the behavioral test battery, testing procedures, and factor-score derivation, we refer to the original publication (Hintz et al., 2025).

***Table 1:*** *Behavioral tests included in the battery used to assess the four cognitive skills*

| Linguistic Knowledge | Processing Speed | Working Memory | Non-verbal Reasoning |
|---|---|---|---|
| Peabody picture vocabulary test | Auditory simple reaction time | Digital forward span | Raven's advanced progressive matrices |
| Antonym production | Auditory choice reaction time | Digital backward span | |
| Idiom recognition | Letter comparison speed | Corsi forward block clicking | |
| Spelling test | Visual simple reaction time | Corsi backward block clicking | |
| Author recognition test | Visual choice reaction time | | |
| Prescriptive grammar test | | | |

## fMRI Testing

All participants attended a single three-hour laboratory session, divided into two halves. In the first half, they completed the **lexical decision** and **picture naming** tasks, and in the second half, they performed the **sentence comprehension** and **sentence production** tasks. Participants also listened passively to two 4-minute stories, one at the end of each session half, but data from the stories were not analyzed in this study.

**Lexical Decision Task:**

**Stimuli.** The stimuli consisted of 80 existing Dutch nouns, 80 pseudowords and 20 quilts. The 80 existing words were chosen to differ in the word frequency on a continuum ranging from Zipf frequency values of 2.15 – 5.27, with a mean Zipf frequency of 3.71 (van Heuven et al., 2014). Additionally, the stimuli were selected based on several other psycholinguistic variables, including prevalence (> 0.959), word length (4 - 9 letters and 1 – 4 syllables), phonological neighborhood density (0 - 26), and phonological neighborhood frequency (0 – 3362.93). The 80 pseudowords for this task were generated by modifying the existing words using Wuggy software (Keuleers & Brysbaert, 2010). Recordings of all the existing words and pseudowords were produced by one female speaker of Dutch. From the 80 existing words, 20 were selected (by sampling evenly from the full frequency range) to be transformed into "quilts", to be used as baseline trials. Specifically, these quilts were created by dividing real word recordings into segments of 30 ms in length, which were then concatenated in a semi-random order. This semi-random concatenation of segments was performed such that it maximized the cross-correlation between the original and quilted waveforms. This quilting procedure was based on the "Sound Quilting Toolbox" (Norman-Haignere et al., 2015), which essentially disrupted sound properties of audio stimuli on longer timescales, while approximately preserving them on shorter timescales. This means that quilted stimuli maintained their low-level auditory features (i.e., their speech-specific spectrotemporal structure), without any recognizable phonotactic or lexical features.

**Procedure.** Participants performed the auditory lexical decision task in the scanner with an event-related design, consisting of two runs: 40 word, 40 pseudoword and 10 quilt trials per run. There was a short break of 30 s between the two runs while the scanner continued collecting

the data. The trial structure was as follows: participants were presented with a red fixation cross in the middle of the screen for 250 ms, indicating the beginning of a trial, followed by the presentation of the auditory stimulus (word, pseudoword, or quilt). The trial length including the auditory input was 2750 ms. Participants were instructed to press the "yes" button with their left index finger when hearing an existing word and press the "no" button with their left middle

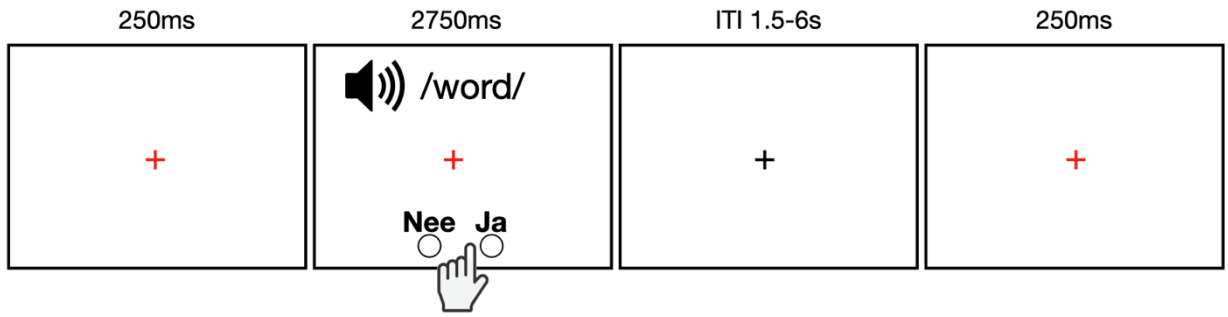


***Figure 1:*** *Example trial structure for the auditory lexical decision task*

finger when hearing non-existing words or quilts. After the response was given, the red fixation cross turned black. The inter-trial interval was jittered between 1.5 s to 6 s in steps of 1.5 s, 2.1 s on average (**Figure 1**). The order of trials was pseudo-randomized, but the same order was used for all participants. "OptSeq" software was used to randomize and optimize the order of trials and the inter-trial interval (https://surfer.nmr.mgh.harvard.edu/optseq/) (Dale, 1999). The whole task including the 30 s pause lasted approximately 13 min.

**Analysis.** At the individual subject level, three regressors of interest (trials of words, pseudowords, and quilts) that were responded to correctly, along with a regressor for incorrectly responded trials, were modeled using the Hemodynamic Response Function (HRF). A fifth regressor accounted for the 30 s pause halfway through the task. For the group level analysis, we focused on the **Words > Quilts** contrast, as these two conditions were acoustically similar. This comparison helped control for low-level acoustic properties and isolate neural activity specifically related to linguistic processing. At the group level, we investigated how individual

differences in cognitive skills influenced activation patterns. A random-effects analysis was conducted, using each participant's contrast images as random factors. Four behavioral factor scores were included as covariates of interest: linguistic knowledge, auditory processing speed, working memory, and non-verbal reasoning. Gender and handedness were also included as covariates of no interest.

**Picture Naming Task:**

**Stimuli.** The stimuli consisted of 80 pictures of common objects, 20 nameless objects and 20 scrambled pictures. The 80 pictures were taken from the Bank of Standardized Stimuli (Brodeur et al., 2010). All pictures were colored photographs located on a square white background, with equal dimensions and an equal digital resolution of 300 x 300 pixels. The objects were selected such that the name of the objects ranged in the word Zipf frequency values (range 2.06-4.84). Twenty of the 80 pictures were scrambled and used as baseline stimuli (Wilson et al., 2009). Specifically, scrambled pictures were generated by dividing the intact pictures into a 20*20 grid of small squares (each 15*15 pixels), and by randomly rearranging the positions of these small squares. The resulting scrambled pictures were thus similar to the original pictures in terms of low-level visual features and complexity, but without any recognizable parts or objects. The twenty original pictures used for scrambling were selected by sampling evenly from the visual complexity distributions in all pictures, whilst ensuring that the selection had sufficient variation in terms of color schemes. Twenty nameless objects were selected from other studies that used such objects in their studies (Bürki et al., 2012; Takashima et al., 2014) to be included as a baseline condition. This condition required the visual processing

of picture stimuli and generating a verbal response ("Niks") without engaging in accessing, retrieving, or preparing lexical representations for production.

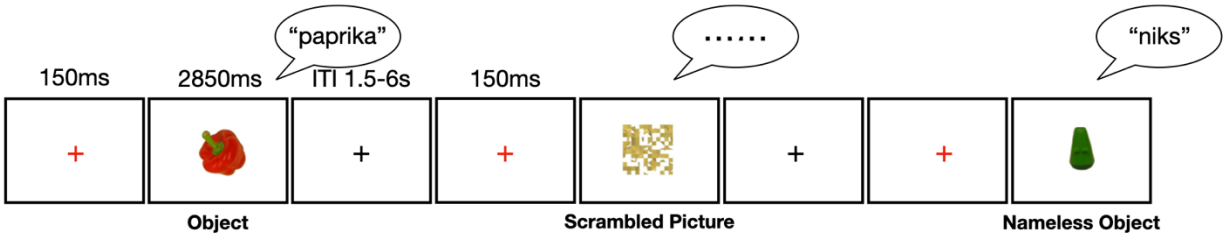


***Figure 2:*** *Example trial structure for the picture naming task*

**Procedure.** The run consisted of two halves with each half having 40 objects, 10 nameless objects, and 10 scrambled pictures with a 30 sec pause in between while the scanner continued to acquire volumes. Participants were instructed to name the object using one word, without articles, in singular form, and not using diminutives. If participants saw a nameless object, they were instructed to say "Niks" ("nothing" in Dutch). For the scrambled pictures, participants were instructed to stay silent. The trial structure was as follows: a black cross appeared in the middle of the screen for 150 ms, indicating the beginning of a trial, followed by the presentation of the visual stimulus (object, nameless object, or scrambled picture). The picture presentation was fixed to 2850 ms. During the trial period, participants were instructed to verbally make a one-word response or stay silent in case of scrambled pictures. The inter-trial interval was jittered between 1.5 s to 6 s in steps of 1.5 s, 2.4 s on average (**Figure 2**).

**Analysis.** As regressors of interest, correct trials for object, nameless object, and scrambled picture conditions, and incorrect trials of all conditions pooled together, and a fifth regressor to account for the pause halfway through the task were included. Furthermore, motion-related nuisance regressors were added to the model in the same way as the auditory lexical decision mentioned above. For the group level analysis, we focused on the **Object > Nameless**

**Object** contrast, as participants responded by speaking in both conditions. This comparison helped control for low-level motor properties and isolate neural activity specifically related to linguistic processing. At the group level, a random-effects analysis was conducted, using each participant's contrast images as random factors. Four behavioral factor scores were included as covariates of interest: linguistic knowledge, visual processing speed, working memory, and non-verbal reasoning. Gender and handedness were also included as covariates of no interest.

**Sentence Comprehension Task:**

**Stimuli.** 80 sentences were selected from a published data set Mother Of Unification Studies (MOUS) created by Schoffelen et al. (Schoffelen et al., 2019) and were used in a study by Uddén et al. (Uddén et al., 2022). All sentences varied between 9 and 15 words in length, and they were relatively unconstrained in terms of syntactical structure. Forty-six of the 80 selected sentences contained a relative clause (58%), whereas 34 did not (42%). Word frequencies for each word in each sentence were retrieved from SUBTLEX-NL (Keuleers & Brysbaert, 2010), and converted to the Zipf scale (van Heuven et al., 2014). For each sentence, we calculated the average Zipf frequency, as well as the minimum Zipf of all words within each sentence. For the word list condition, 140 words were randomly selected from the above list of sentences. These words were distributed amongst 20-word lists with seven words in each list. The mean Zipf frequency values of the words per list and the minimum Zipf frequency value within the list was similar to that of the sentence condition on average. In 20% of the cases (16 trials for sentence condition, and 4 trials for word list condition), a question followed on the screen, which focused on the content of the sentence, or whether the word was mentioned in the preceding sentence / list. (e.g. "Was a profession mentioned?", "Was the word 'barkeeper' mentioned?").

All sentences were additionally characterized in terms of syntactic complexity, as well as word count. The syntactic complexity of each sentence was assessed using a left-branching complexity measure from a dependency structure (Kapteijns & Hintz, 2021; Uddén et al., 2022). We used a left-branching unification score, which counts the number of left-branching dependents that are closed at each word in a dependency structure (for example, in the sentence "the customer left", one dependency relation (determiner to noun) is closed at "customer", and one relation (subject to verb) is closed at "left"). The scores were summed across all words in a sentence, reaching a total unification score for each sentence.

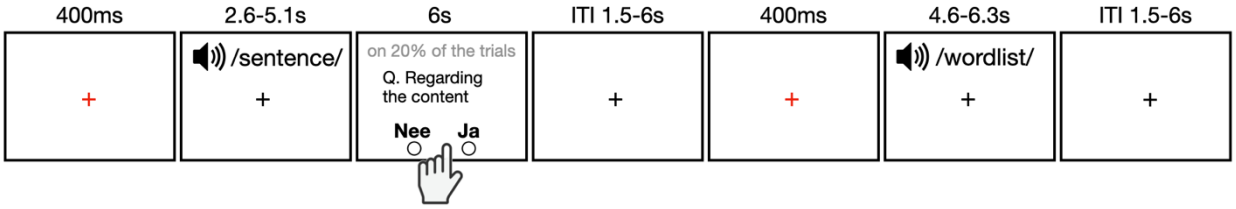


***Figure 3:*** *Example trial structure for the sentence comprehension task*

**Procedure.** On each trial, participants first saw a fixation cross in the middle of the screen for 500 ms, indicating the start of a trial. This was followed by the presentation of a spoken sentence on task trials, or a spoken random word lists on the baseline trials. The eighty spoken sentences had an average duration of 4063 ms (range 2588 - 5147) and 20-word lists had an average duration of 5443 ms (range 4609 – 6277 ms). Participants were instructed to listen to the sentences carefully and to keep their attention on the task, twenty percent of the stimuli (i.e., 16 sentences and 4-word lists) were followed by a visually presented comprehension question on sentence trials or a memory probe question on word list trials. Participants were instructed to make a "yes" or "no" judgment as quickly and accurately as possible by pressing a button associated with left index (yes) or left middle finger (no), while the question remained visible on

the screen for 6 s. The inter-trial intervals were jittered between 1.5 s to 6 s, 2.4 s on average (**Figure 3**). The order of trials was pseudo-random and the same for each participant. Halfway through the run, there was a 30 s pause where the participants were instructed to stay still in the scanner. The experiment lasted approximately 17.6 min.

**Analysis.** Two regressors of interest (sentence condition, wordlist condition) and two control regressors (question and pause) were modelled together with the motion-related nuisance regressors. All experimental conditions were modeled by convolving the onset times for the sentences, word lists, and questions with the hemodynamic response function (HRF). The pause regressor was modelled using the onset of the pause with a duration of 30 s. For the group level analysis, we focused on the **Sentences > Wordlist** contrast. A second model was tested in which left-branching (LB) unification scores were included as a parametric modulator for the sentence condition, after controlling for sentence length (word count) (Kapteijns & Hintz, 2021). At the group level, for both models, a random-effects analysis was conducted using each participant's contrast images as random factors. Four behavioral factor scores were included as covariates of interest: linguistic knowledge, auditory processing speed, working memory, and non-verbal reasoning. Gender and handedness were also included as covariates of no interest.

**<u>Sentence Production Task</u>:**

**Stimuli.** The stimuli were adapted from the set of photographs used in the studies by Menenti et al. (Menenti, Petersson, et al., 2012; Menenti, Segaert, et al., 2012). The stimulus set included 30 images depicting a single person shaded in yellow performing an action, 30 images showing two people (a man and a woman) engaged in an action with one shaded in yellow and the other in blue, and 30 additional images featuring the same pair performing actions with the

color assignments swapped between the man and the woman. In addition, 30 intransitive, 30 active and 30 passive sentences, and two phrases spoken by a native Dutch young male were used. In total there were 30 active trials, 30 passive trials, 30 intransitive trials and 24 phrase trials (baseline) (**Figure 4A**).

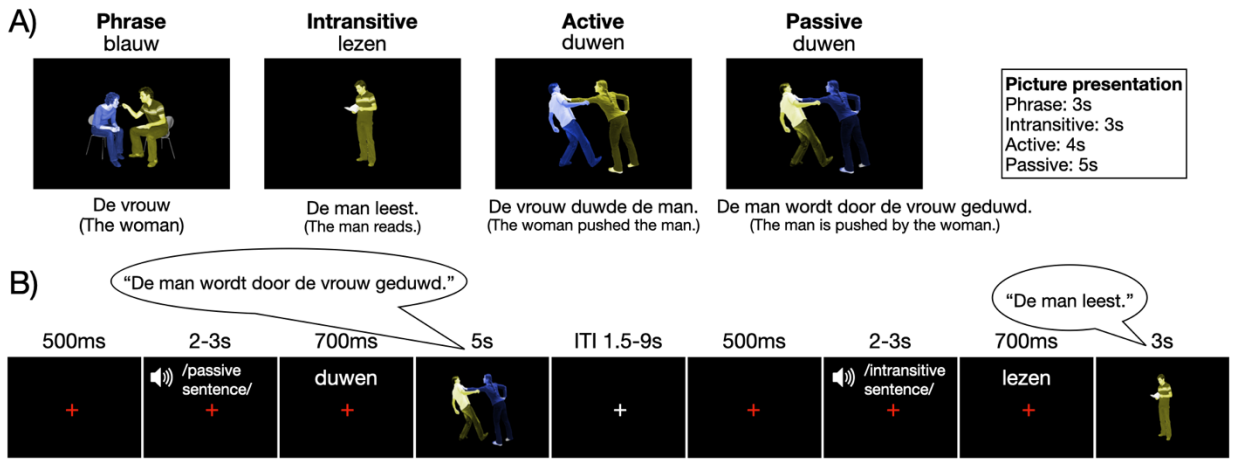


***Figure 4:*** *Example **A.** stimuli and **B.** trial structure for the sentence production task*

**Procedure.** In order to guide the active vs. passive voice production in the experimental trials (transitive events), we implemented a combination of structural priming and the so-called stoplight paradigm, as described by Menenti et al. (Menenti, Segaert, et al., 2012). That is, the pictures were preceded by an audio recording of a sentence that featured the same syntactic voice as the target sentence, using a different verb to prime the participant. The participants were not instructed to copy the sentence structure of the audio material but were instructed to produce one sentence per picture using the verb on the screen and mentioning the yellow person first. This coerced the production of active (e.g. The woman pushed the man – when the woman was yellow) and passive (e.g. The man was pushed by the woman – when the man was yellow) sentences. We included the auditory priming sentence in our paradigm as the pilot study had shown that the participants were more likely to produce the less preferred passive sentences

when preceded by a passive priming sentence. The actor on the intransitive condition (e.g. The man yawns) was always shaded in yellow. For the baseline phrase condition, a color-word, either "geel (yellow)" or "blauw (blue)" was presented instead of a verb. The participants were instructed to name the person in that color (e.g., "de man (the man)" or "de vrouw (the woman)"). The preceding audio for this phrase condition was either "de man of de vrouw (the man or the woman)" or "de vrouw of de man (the woman or the man)".

The trial began with a fixation cross for 200 ms in the middle of the screen. Then, while the fixation cross remained in view, they heard the priming sentence (between 1000 and 3000 ms in duration), which indicated the structure of the target sentence (active, passive, or intransitive). Then, the target verb or the color word was presented visually for 500 ms, followed by another fixation cross lasting 200 ms. After that, the target picture was presented, and participants had to describe the event as quickly and accurately as possible, using the color coding in the picture. The inter-trial interval was jittered between 1.5 seconds and 9 seconds, with an average of 2.7 seconds (**Figure 4B**). The order of trials was pseudo-random and the same for each participant, such there was always an intransitive condition or a phrase condition in between an active or a passive condition except for six instances where the passive condition was directly followed by an active condition (4 times) or a passive condition (2 times). The experiment consisted of two halves with a 30 s break in between. The conditions were divided equally between the two halves and the whole experiment lasted for approximately 20 min.

**Analysis.** At the single subject level, we modelled three levels of syntactic complexity (intransitive, active, and passive) and one baseline condition (phrase) for all correctly produced trials, and three control regressors, one accounting for the prime sentence period, one accounting for all incorrect trials, and one for the pause block. For the group level analysis, we focused on

the **Sentences > Phrases** contrast. In a second model, we modelled four regressors, one for correct trials, one for incorrect trials, one for the prime sentence period and one for the pause block. Furthermore, we incorporated a parametric modulator, which assigned weights to the syntactic complexity in a linear fashion (-1.5 for phrase condition, -0.5 for intransitive, 0.5 for active, and 1.5 for passive sentence conditions) to the correct trial condition. Both models included motion related nuisance regressors like the other three tasks. At the group level, for both models, a random-effects analysis was conducted using each participant's contrast images as random factors. Four behavioral factor scores were included as covariates of interest: linguistic knowledge, visual processing speed, working memory, and non-verbal reasoning. Gender and handedness were also included as covariates of no interest.

**MRI Protocols and Preprocessing**

MRI data were acquired using 3T Magnetom Prisma MR scanners. For functional scans, a multiband multi-echo sequence with a 32-channel head coil was used. Noise-cancelling headphones were used for presenting the auditory stimuli and reducing scanner noise and auditory responses were recorded with noise cancellation filtering. The following settings were used: TR = 1.50 s, TE1 = 13.4 ms, TE2 = 34.8 ms, TE3 = 56.2 ms, flip-angle = 75°, slice thickness = 2.5 mm, FOV = 210 mm, resolution = 2.5 x 2.5 x 2.5 $mm^3$, slice matrix size = 84 x 84. For structural scans, MPRAGE T1-weighted anatomical scans at 1 mm isotropic resolution were acquired with a repetition time of 2000 msec, an echo time of 2.03 msec, a flip angle of 8°, and a field of view of 256 × 256 × 192 mm. All collected data (DICOM files) were converted to BIDS compatible format using bidscoiner (vers. 3.7.4 https://github.com/Donders-Institute/bidscoin). Functional data were further preprocessed using fmriprep (v22.1.1), with

added function of normalizing to MNI152NLinAsym template with the voxel size of 2 $mm^3$, and calculating the motion related independent components using AROMA function (Pruim et al., 2015). All scans were smoothed with 4 mm kernel FWHM using SPM12 function (www.fil.ion.ucl.ac.uk/spm/software/spm12/).

**Laterality Index Calculation**

To quantify hemispheric lateralization for each language task, laterality indices (LIs) were calculated for each participant based on participant-level T-maps. For each contrast image, voxels exceeding a T-value of 3.13 (corresponding to p = 0.001, two-tailed) were considered suprathreshold and included in the calculation. For each participant, LI was computed as

$$\mathbf{LI = (SumT_L - SumT_R) / (SumT_L + SumT_R)},$$

where $SumT_L$ and $SumT_R$ denote the sum of T-values across suprathreshold voxels in the left and right hemispheres, respectively. LI values ranged from −1 to +1, with negative values indicating right-lateralized activation and positive values indicating left-lateralized activation. At the group level, one-sample t-tests against zero were performed to assess whether lateralization was consistent across participants. Effect sizes were quantified using Cohen's d, calculated as the mean LI divided by the standard deviation of LI across participants.

## RESULTS

### Individual Variability in Cognitive Skills

Individual test scores from the behavioral battery were combined into factor scores for linguistic knowledge, auditory and visual processing speed, and working memory following the procedure described in Hintz et al. (Hintz et al., 2025). In contrast, a factor score was not computed for non-verbal reasoning, as this domain was assessed using a single measure: accuracy on the Raven's Advanced Progressive Matrices test, which yields only non-negative values. To make this measure more comparable to the factor score distributions of the other cognitive domains, the Raven accuracy scores were standardized by z-scoring. (**Figure 5**).

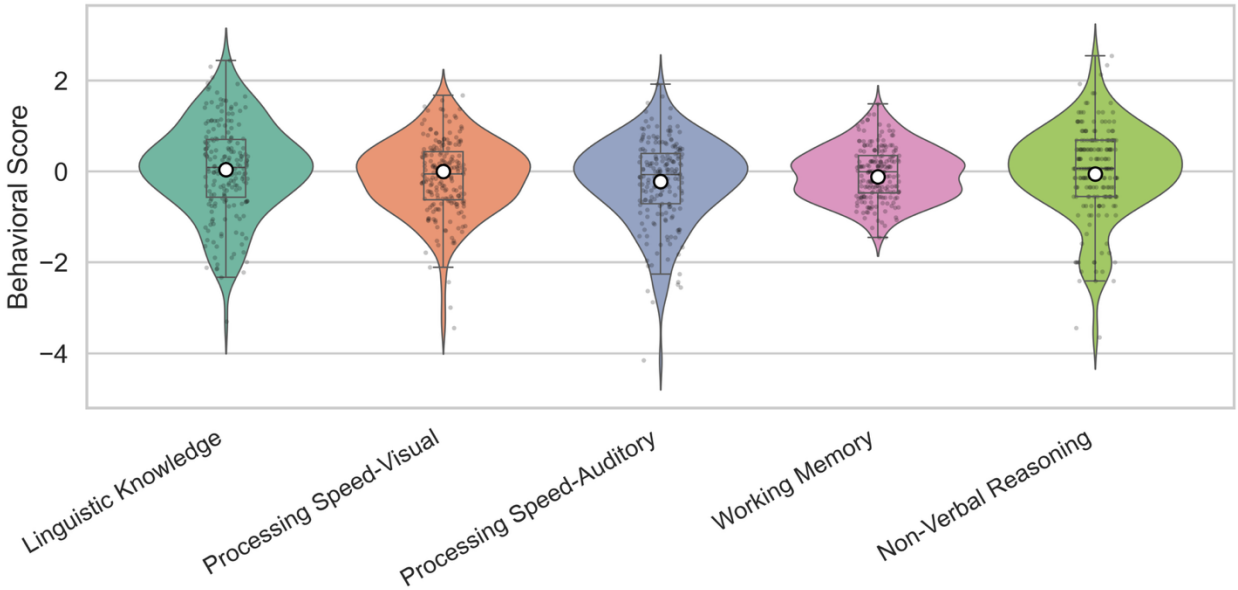


***Figure 5: Distribution of behavioral scores across participants for different cognitive skills.*** *Violin plots show the full distribution of individual scores for each cognitive skill, with overlaid boxplots indicating the median and interquartile range. Individual data points are jittered for visibility, and white markers with vertical lines represent the mean ± 95% confidence interval. Linguistic knowledge, processing speed, and working memory scores represent factor scores derived from multiple tests, whereas the non-verbal reasoning score corresponds to the z-scored accuracy on the Raven's Advanced Progressive Matrices test.*

### Behavioral Results of the fMRI Language Tasks

Participants were required to make active responses during all four language tasks performed in the scanner, either through button presses (lexical decision and sentence

comprehension) or overt speech (picture naming and sentence production). These responses were analyzed to confirm participant engagement and task compliance. Accuracy scores were consistently high across all tasks and conditions (> 90%, **Supplementary Table 1**), indicating that participants were attentive and reliably followed the task instructions.

**Neural Results of the fMRI Language Tasks**

We conducted two complementary group-level analyses to examine neural activation patterns during the four language tasks: one aimed at identifying **common activation across participants**, and the other aimed at identifying neural responses associated with **individual differences** in cognitive skills.

We examined a targeted contrast of interest within each language task to isolate specific linguistic processes. For the lexical decision task, we focused on the ***Word > Quilt*** contrast. The Quilt stimuli retained the low-level auditory features of real words but lacked recognizable phonotactic or lexical structure, allowing this contrast to control for basic auditory input while isolating brain regions involved in phonological and lexical processing. In the picture naming task, we used the ***Object > Nameless Object*** contrast. Because both conditions required spoken responses, this comparison controlled for general speech-related motor activity and highlighted regions specifically engaged in lexical access and semantic processing. For the sentence comprehension task, we examined the ***Sentence > Wordlist*** contrast. Only the Sentence condition contained coherent syntactic and semantic structure, making this contrast sensitive to higher-level integration processes. Finally, in the sentence production task, we analyzed the ***Sentence > Phrase*** contrast. As both conditions involved speech production, this contrast

isolated neural regions involved in generating full, syntactically structured and semantically integrated utterances, beyond the demands of producing isolated phrases.

In addition, for the sentence comprehension and sentence production tasks, we examined how brain activity was modulated by **syntactic complexity** using parametric analyses. In sentence comprehension, we modeled activation as a function of left-branching unification demands to identify regions sensitive to structure building. In sentence production, we used a linear modulator to capture increasing syntactic complexity across conditions (simple phrases < intransitive < active < passive sentences), revealing regions that support the construction of increasingly complex syntactic representations.

**Common activations across individuals:**

Focusing first on common activation patterns, a whole-brain comparison of the four language tasks revealed both overlapping and task-specific neural activation profiles. For each task contrast, group-level statistical T-maps were thresholded to identify significant positive activations ($T > 3.13$, $p < 0.001$ uncorrected). The extent of activation, measured by the number of suprathreshold voxels, varied across tasks: picture naming elicited the broadest activation (47,417 voxels), followed by sentence production (38,184), lexical decision (32,595), and sentence comprehension (32,424). To systematically characterize these activation patterns and identify anatomical regions most strongly engaged by each task, mean T-values were extracted from 116 regions of interest defined by the Automated Anatomical Labeling (AAL) atlas (Tzourio-Mazoyer et al., 2002) (**Figure 6A**).

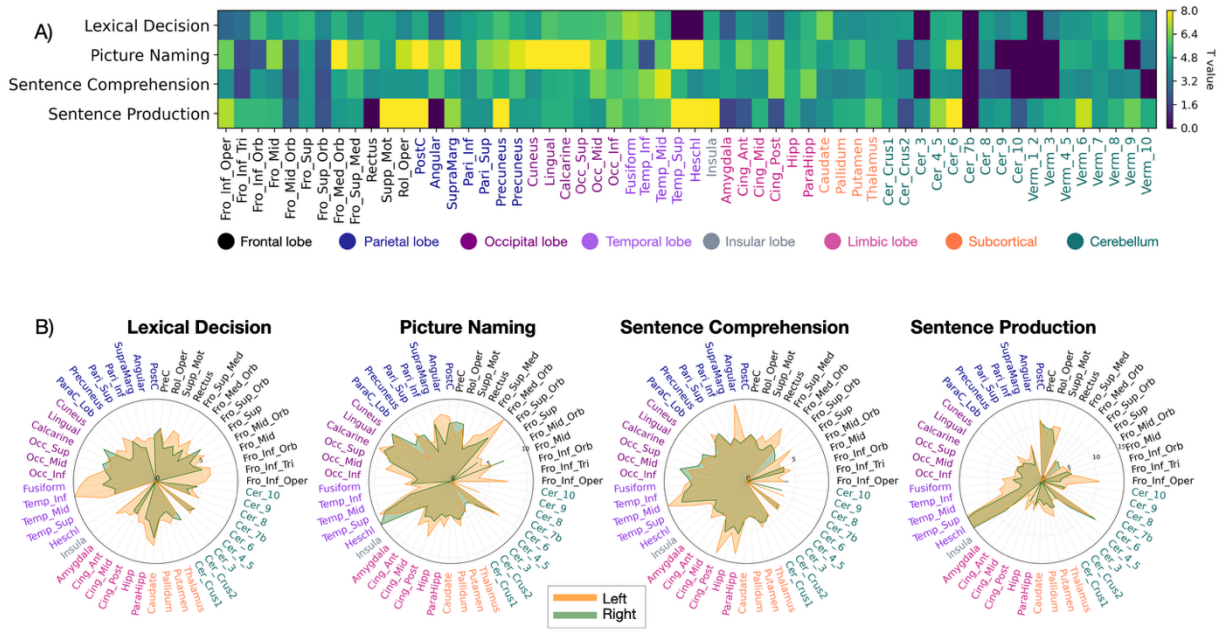


***Figure 6: Distribution of significant voxel activations across anatomical regions calculated using group-level T-maps.*** ***A.*** *Mean T-values of significant voxels averaged for each Region of Interest (ROI) and language task combined across both hemispheres.* ***B.*** *Hemispheric comparison of mean T-values of significant voxels averaged for each ROI and language task (Left vs. Right Hemisphere).*

To compare the activation patterns for each language task between the left and right hemispheres, we computed a laterality index (LI) for each task with positive LI values indicating left-lateralization (see *Laterality Index Calculation*). All four language tasks demonstrated significant left-hemisphere asymmetry in activation, consistent with the broadly observed left-lateralization of language processing in the brain (Knecht et al., 2000; Price, 2012). However, the degree of lateralization varied by task, indicating that different tasks modulated the relative contributions of the two hemispheres. The sentence production (LI = 0.24, t= 17.77, $p < 0.001$, Cohen's d = 1.28 ) and lexical decision (LI = 0.24, t = 8.66, $p < 0.001$, Cohen's d = 0.62) tasks showed the strongest left-lateralization, followed closely by picture naming (LI was 0.22, t= 11.98, $p < 0.001$, Cohen's d = 0.87) and sentence comprehension (LI = 0.20, t= 8.92, $p < 0.001$, Cohen's d = 0.64) (see **Figure 6B** for group-level comparisons).

To identify common activation clusters for each task contrast, we applied a voxel-wise threshold of $p < 0.001$, followed by cluster-level Family-Wise Error (FWE) correction to control for multiple comparisons (**Figure 7, Supplementary Table 2**). The **lexical decision** task elicited the largest activation cluster centered in the posterior portion of the left inferior temporal gyrus (ITG), extending into the posterior middle temporal gyrus (MTG) and inferior parietal lobule (IPL). Strong activation was also observed in the inferior frontal gyrus (IFG), centered in pars orbitalis (Hagoort et al., 2004). This pattern aligns with findings from previous meta-analyses of speech perception comparing spoken words and pseudowords, which identified a similar network supporting phonological processing and lexical-semantic access to extract meaning from spoken words (Binder et al., 2009; Davis & Gaskell, 2009).

Activation in the posterior ITG and MTG was observed also during the **sentence comprehension** task. However, unlike the lexical decision task, which primarily engages word-level comprehension, we also observed robust bilateral activation of the temporal poles (anterior temporal lobe, ATL). This pattern aligns with previous studies comparing sentence comprehension to unstructured word lists, highlighting the ATL's role in processing syntactic structure and combinatorial semantics (Bemis & Pylkkänen, 2011; Giglio et al., 2024; Humphries et al., 2005; Snijders et al., 2009). Additionally, we observed activation in the language and precuneus during sentence comprehension. These regions, typically implicated in episodic memory retrieval (Cavanna & Trimble, 2006; Rugg & Vilberg, 2013), have also been reported to be recruited during tasks that require encoding sentence content into memory (Hasson et al., 2007). This is consistent with our task design, in which participants answered comprehension or memory probe questions on selected trials.

Tasks that required overt articulation, namely **picture naming** and **sentence production**, robustly engaged bilateral frontal motor and sensorimotor regions, including the precentral gyrus, postcentral gyrus, and IFG, consistent with the demands of motor planning and execution. Notably, both tasks also elicited extensive activation in the right auditory cortex, encompassing Heschl's gyrus and extending into the superior temporal gyrus (STG), indicating a prominent role for auditory feedback monitoring during speech production. Sentence production further recruited the supplementary motor area (SMA) and pallidum, supporting their involvement in motor sequence control and coordination (Hertrich et al., 2016). Meanwhile, picture naming elicited significant activation in occipital regions, including the calcarine cortex, cuneus, lingual gyrus, and occipital gyrus, reflecting the visual processing demands of the task necessary for object recognition.

**Activations that reflect individual differences:**

Next, we identified neural responses associated with individual differences in cognitive skills, i.e. linguistic knowledge, processing speed, working memory, and non-verbal reasoning. To do this, we conducted group-level analyses using participants' behavioral scores in these four cognitive domains as covariates. Significant activation clusters were defined using a voxel-wise threshold of $p < 0.001$, followed by cluster-level FWE correction. This analysis revealed several clusters where activation levels varied systematically with cognitive skill levels (**Clusters 1–14** in **Table 2** and **Figure 7**). These 'individual variability clusters' were distributed across both hemispheres and, notably, the majority (11 of 14) showed a negative correlation with cognitive skills, indicating that higher-skilled participants exhibited lower neural activation in these regions.

We then examined the anatomical locations of these clusters relative to the group-level common activation maps to determine whether they were colocalized with shared activation regions or located outside them. To quantify this relationship, we calculated the percentage of spatial overlap between each cluster and the common activation map for the different language tasks. Overall, overlap was limited, occurring in only 5 of 14 clusters (**Table 2, Figure 7**). Most overlap was observed for the lexical decision task, involving one cluster in the SMA, one in the IFG, and two in the cerebellum. Additionally, for sentence production, only one cluster in the IPL showed overlap, while all remaining clusters across tasks fell entirely outside the shared activation regions. These results suggest that individual variability in language processing manifests largely through the activation of distinct brain regions, rather than modulation within regions commonly engaged across participants.

***Table 2: 'Individual variability clusters' where fMRI activation covaried with cognitive skills.*** *The* ***fMRI Contrast/Modulation*** *column specifies the experimental condition contrast or parametric modulator used for each language task.* ***P-FWE*** *denotes the cluster-level Family-Wise Error–corrected significance level.* ***Cluster size*** *is reported in number of voxels.* ***x, y, z*** *columns indicate the MNI coordinates of the peak voxel within each cluster.* ***Overlap*** *percentages quantifies the spatial overlap between the cluster and the group-level common activation map. SMA: Supplementary motor area, RO: Rolandic Operculum, IFG op.: Inferior frontal gyrus opercularis, MTG: Middle temporal gyrus, AG: Angular gyrus, IPL: Inferior parietal lobule, med. SFC: Medial superior frontal cortex, ACC: Anterior cingulate cortex*

| Cluster Number | fMRI Contrast/ Modulation | Cognitive Skill | Correlation Direction | Cluster Location | P-FWE | Cluster Size | x | y | z | Overlap with common activation |
|---|---|---|---|---|---|---|---|---|---|---|
| **Lexical Decision** | | | | | | | | | | |
| 1 | Word-Quilt | Linguistic Knowledge | Negative | SMA (right) | 0 | 151 | 4 | -4 | 68 | 24% |
| 2 | Word-Quilt | Linguistic Knowledge | Negative | RO (right) | 0.041 | 53 | 62 | 8 | 12 | 0 |
| 3 | Word-Quilt | Processing Speed | Positive | Cerebellum Crus I (right) | 0.007 | 74 | -38 | -50 | -30 | 26% |
| 4 | Word-Quilt | Processing Speed | Positive | Cerebellum VI (right) | 0.049 | 51 | 22 | -58 | -20 | 96% |
| 5 | Word-Quilt | Non-verbal Reasoning | Negative | IFG op. (left) | 0.044 | 52 | -58 | 14 | 12 | 23% |
| **Picture Naming** | | | | | | | | | | |
| 6 | Object-Nameless Object | Processing Speed | Negative | MTG (left) | 0.032 | 58 | -48 | -56 | 4 | 0 |
| 7 | Object-Nameless Object | Working Memory | Negative | Precuneus (left) | 0.053 | 52 | 0 | -66 | 42 | 0 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sentence Comprehension** | | | | | | | | | | |
| 8 | Sentence-Wordlist | Processing Speed | Positive | Cuneus (right) | 0.001 | 104 | 4 | -78 | 40 | 0 |
| 9 | Syntactic Complexity | Linguistic Knowledge | Negative | Precuneus (right) | 0.055 | 47 | 18 | -56 | 32 | 0 |
| 10 | Syntactic Complexity | Processing Speed | Negative | AG (right) | 0.05 | 48 | 28 | -60 | 40 | 0 |
| **Sentence Production** | | | | | | | | | | |
| 11 | Sentence-Phrase | Working Memory | Negative | Precuneus (left) | 0.01 | 78 | -6 | -64 | 40 | 0 |
| 12 | Syntactic Complexity | Linguistic Knowledge | Negative | IPL (left) | 0.054 | 54 | -38 | -38 | 50 | 85% |
| 13 | Syntactic Complexity | Non-verbal Reasoning | Negative | med. SFC (left) | 0.046 | 56 | -14 | 52 | 0 | 0 |
| 14 | Syntactic Complexity | Non-verbal Reasoning | Negative | ACC (right) | 0.046 | 56 | 12 | 40 | 2 | 0 |

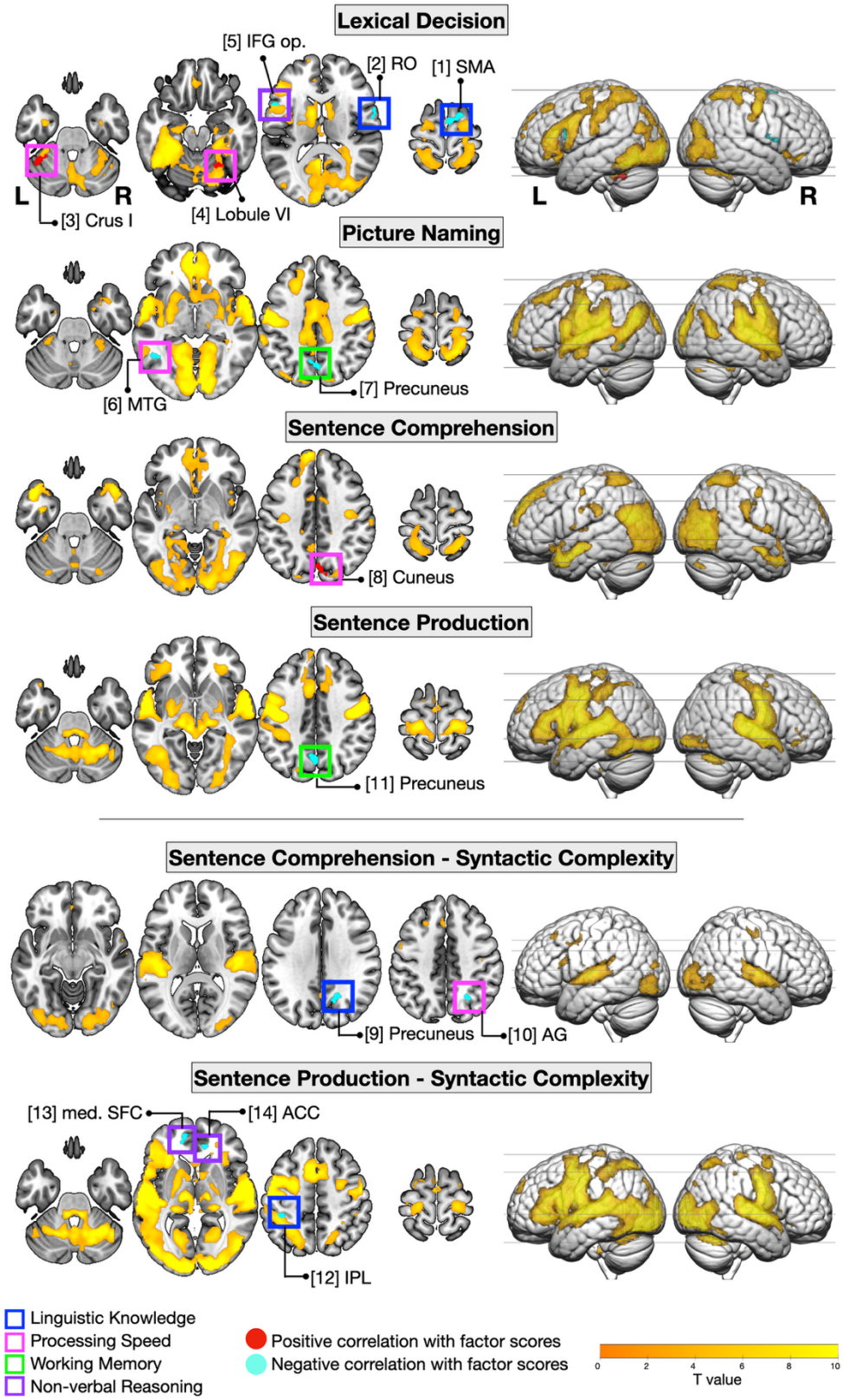
Lexical Decision
[5] IFG op.
[2] RO
[1] SMA
L
R
[3] Crus I
[4] Lobule VI
Picture Naming
[6] MTG
[7] Precuneus
Sentence Comprehension
[8] Cuneus
Sentence Production
[11] Precuneus
Sentence Comprehension - Syntactic Complexity
[9] Precuneus
[10] AG
Sentence Production - Syntactic Complexity
[13] med. SFC
[14] ACC
[12] IPL
Linguistic Knowledge
Processing Speed
Working Memory
Non-verbal Reasoning
Positive correlation with factor scores
Negative correlation with factor scores
0
2
4
6
8
10
T value

***Figure 7: fMRI activation patterns for common effects and individual differences.*** *Yellow indicates group-level common activation patterns across contrasts and parametric modulators for each language task. Four axial slices are displayed for each task, with rendered brains indicating slice positions. Red and blue clusters denote regions where activation correlates with behavioral scores (Red = positive correlation; Blue = negative correlation). These clusters are highlighted by colored square frames, where the color of the frame indicates the specific cognitive skill associated with the effect. Cluster numbers 1-14 correspond to those in* ***Table 2****. RO: Rolandic Operculum, IFG op.: Inferior frontal gyrus opercularis, SMA: Supplementary motor area, MTG: Middle temporal gyrus, AG: Angular gyrus, ACC: Anterior cingulate cortex, med. SFC: Medial superior frontal cortex, IPL: Inferior parietal lobule*

**Brain networks underlying individual variability in language processing:**

To gain insight into the large-scale brain systems that contribute to individual variability in language processing, we next examined how the previously identified clusters, in which activation during language tasks covaried with cognitive skills, mapped onto established functional networks. Specifically, we quantified the spatial overlap between each 'individual variability cluster' (**Clusters 1-14** in **Table 2** and **Figure 7**) and the seven canonical Yeo networks (Thomas Yeo et al., 2011): Visual Network (VN), Somatomotor Network (SMN), Dorsal Attention Network (DAN), Ventral Attention Network (VAN), Limbic Network (LN), Frontoparietal Network (FPN), and Default Mode Network (DMN). The Yeo networks provide a well-established and widely used functional parcellation of the cortex, offering a principled framework to characterize how individual variability relates to large-scale neurocognitive systems.

Across tasks, several clusters showed a substantial degree of overlap with the **DMN**, highlighting its central role in supporting the high-level cognitive operations that contribute to language processing. Three clusters overlapped strongly with the **DAN** and two with **VAN**, pointing to the role of attentional control. The **FPN** was also extensively involved, particularly during syntactically demanding sentence processing tasks. In contrast, none of the clusters overlapped with the **LN** (**Figure 8**).

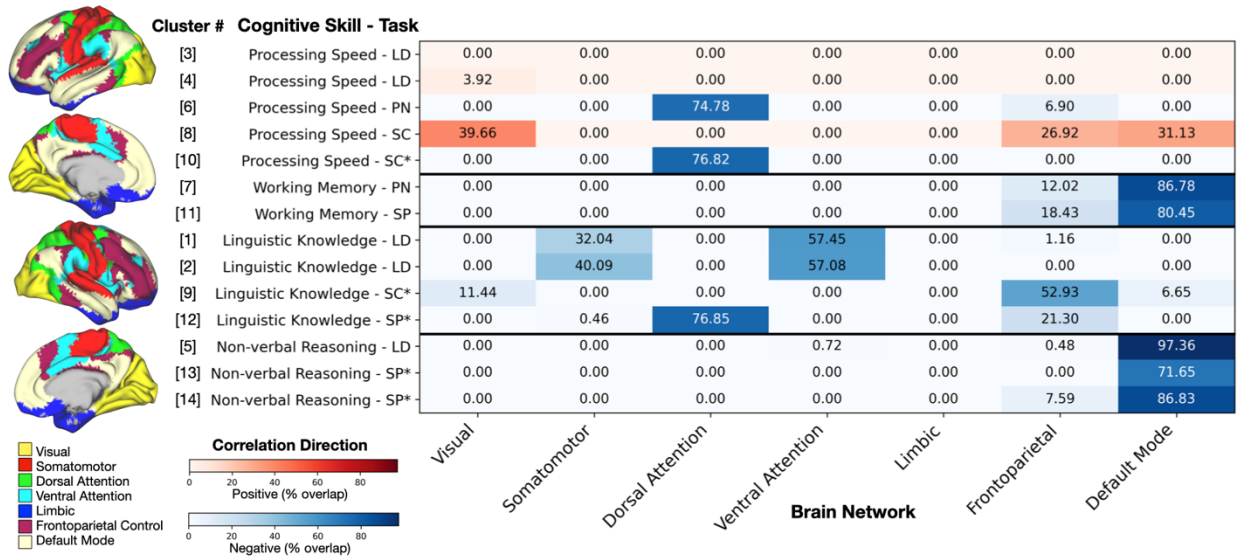


***Figure 8: Spatial overlap of fMRI clusters reflecting individual variability with the seven canonical Yeo networks.*** *Cluster numbers correspond to those in* ***Table 2*** *and* ***Figure 7****. Shades of red and blue indicate the magnitude of positive and negative correlations, respectively, between activation in each cluster and participants' behavioral scores for different cognitive skills. LD: Lexical Decision, PN: Picture Naming, SC: Sentence Comprehension, SC*: Sentence Comprehension-Syntactic Complexity, SP: Sentence Production, SP*: Sentence Production-Syntactic Complexity*

Distinct profiles emerged when we examined how patterns of network overlap appeared across the four cognitive domains. Clusters associated with **linguistic knowledge** exhibited a dispersed profile, overlapping primarily with attention networks (DAN and VAN), the FPN, and the SMN. Anatomically, these clusters encompassed right frontal motor regions (SMA and rolandic operculum), the precuneus, and the inferior parietal cortex (**Table 2**, **Figures 7–8**). Similarly, clusters in which activation covaried with **processing speed** were broadly distributed across the VN, DAN, FPN, and DMN, and anatomically located in the cerebellum, left MTG, and right posterior parietal regions (including the cuneus and angular gyrus). In contrast, the remaining cognitive skills showed much more selective network profiles. Clusters associated with **working memory** appeared only during overt speech production tasks and were primarily located in the left precuneus, substantially overlapping the DMN (>80% overlap) and FPN.

Finally, clusters associated with **non-verbal reasoning** exhibited the most focused network profile. These clusters localized to the medial prefrontal/anterior cingulate cortex and the IFG (opercularis), showing up to 97% overlap with the DMN.

## DISCUSSION

Our study examined how individual differences in cognitive skills are reflected in neural activity during language processing. While all language tasks reliably engaged classical left-lateralized language regions, variability related to linguistic knowledge and domain-general cognitive skills was primarily expressed in brain areas outside the perisylvian language system, most prominently in regions associated with default-mode and dorsal attention networks. Notably, individuals with lower cognitive skill levels showed stronger engagement of these domain-general regions than higher-skilled individuals, suggesting compensatory recruitment of broader neural resources to support language processing.

All four language tasks consistently engaged canonical left-lateralized language regions (Hagoort & Indefrey, 2014; Indefrey, 2018; Turker et al., 2023), accompanied by robust recruitment of the right hemisphere that varied according to the specific task at hand. Sentence production, for example, elicited slightly stronger left-lateralized activation (LI = 0.24) than word-level production demands in the picture naming task (LI = 0.22), consistent with models proposing greater left-hemisphere dominance for connected speech compared to single-word processing (Peelle, 2012; Poeppel, 2014). Nevertheless, right-hemisphere regions including Heschl's gyrus, the superior temporal gyrus (STG), and the cerebellum were also strongly activated during overt production, underscoring the contribution of bilateral systems to sensorimotor coordination and speech monitoring (Ozker et al., 2022, 2024). Although both

sentence production and picture naming relied on visually presented stimuli, picture naming additionally elicited strong right-hemisphere visual activation, possibly reflecting the increased object-recognition demands of the task (Price et al., 2005). In contrast to the production tasks, auditory comprehension exhibited a different pattern of lateralization: word-level processing in the lexical decision task showed stronger left lateralization (LI = 0.24), whereas sentence comprehension recruited relatively more bilateral networks (LI = 0.20). Together, these findings reinforce the view that hemispheric asymmetry for language is dynamic and shaped by input modality (visual vs. auditory), task demands (production vs. comprehension), and linguistic level (word vs. sentence processing)(Bradshaw et al., 2017; Turker et al., 2023).

Importantly, individual variability in language processing did not manifest within these shared patterns of task-related activation. Instead, correlations between brain activity and cognitive skills revealed that individual variability was largely expressed in regions outside commonly activated language regions. Most activation clusters associated with cognitive skills showed minimal overlap with group-level activation maps and were predominantly negatively correlated with cognitive skills. This pattern indicates that broader neural systems, rather than shared language-dominant regions, account for much of the variability across individuals. The predominance of negative correlations further suggests that individuals with lower cognitive skills rely more heavily on these broader resources to support language processing, whereas higher-skilled individuals achieve comparable performance with reduced auxiliary engagement.

Characterizing these effects within the framework of large-scale functional brain networks provided additional insight into where and how individual variability emerges. Clusters associated with **linguistic knowledge** spanned multiple networks, revealing a consistent pattern

of reduced engagement with increasing cognitive skill levels. During lexical decision tasks, higher linguistic knowledge was associated with reduced activation in frontal motor regions overlapping with the ventral attention network (VAN) and sensorimotor network (SMN), implying that individuals with more extensive linguistic knowledge recognize words more automatically, requiring less attentional or motor simulation effort. Conversely, individuals with lower linguistic knowledge may recruit these regions more strongly, possibly reflecting compensatory strategies such as increased attentional effort or subvocal rehearsal. A similar pattern emerged in the frontoparietal network (FPN) and dorsal attention network (DAN) during the processing of syntactically complex sentences: higher linguistic knowledge corresponded to reduced activation, indicating that individuals with lower linguistic knowledge rely more heavily on domain-general control functions, whereas higher-skilled individuals draw on more efficient, specialized linguistic representations, allowing them to parse complex sentences with fewer cognitive-control demands.

Clusters associated with **processing speed** also spanned a broad range of networks, including regions involved in sensorimotor coordination, visuospatial processing, and multisensory integration, with overlap across the visual network (VN), DAN, FPN and default mode network (DMN). This widespread network involvement suggests that rapid language processing depends on the coordinated interaction between perceptual systems and domain-general control mechanisms that support flexible integration across modalities. Notably, positive correlations between cognitive skill levels and neural activity were rare and were observed only for processing speed. Specifically, individuals with higher processing speed showed greater cerebellar activation during auditory lexical decision, possibly reflecting the contribution of cerebellar mechanisms related to timing, prediction, or coordination in supporting rapid lexical

access (Gilligan & Rafal, 2019; Pleger & Timmann, 2018). A second positive association was observed during sentence comprehension, with higher-skilled individuals showing greater activation in the cuneus. Although primarily a visual region, the cuneus overlaps with both the FPN and DMN and is known to be engaged during auditory language tasks that evoke visual imagery (Olivetti Belardinelli et al., 2009). This finding suggests that individuals with higher processing speed may leverage visual imagery as an additional strategy to facilitate sentence comprehension.

In contrast to the broad network involvement observed for linguistic knowledge and processing speed, **working memory** and **non-verbal reasoning** showed more selective engagement, primarily involving the DMN. Working memory skills were particularly linked to speech production tasks, with focused activation in the precuneus, a DMN hub associated with internally oriented cognition, memory integration, and construction of mental representations (Cavanna & Trimble, 2006; Sestieri et al., 2011). Because both production tasks in our study relied on visually presented stimuli, increased precuneus activation in individuals with lower working memory capacity may reflect a greater reliance on DMN-mediated processes to transform visual input into mental representations that support verbal planning and short-term retention (Fernandino & Binder, 2024). Similarly, non-verbal reasoning was negatively associated with DMN engagement, particularly in the medial prefrontal and anterior cingulate cortices, regions implicated in abstraction, strategic reasoning, and goal maintenance (Andrews-Hanna et al., 2014). These findings indicate that low-level reasoning skills modulate engagement with linguistic input, even in the absence of explicit problem-solving demands when the task is primarily linguistic.

Across all cognitive domains, the DMN and DAN emerged as the networks most consistently associated with individual differences. Lower working memory and non-verbal reasoning skills were linked to increased DMN activation, whereas lower linguistic-knowledge and processing speed skills corresponded to increased DAN activation. The DMN is thought to play a central role in language processing by integrating multimodal information into coherent, internally generated representations of meaning. During language tasks, it supports the construction of conceptual and semantic models that link words to prior knowledge and context (Fernandino & Binder, 2024). Reduced DMN activation observed in individuals with higher working memory and non-verbal reasoning skills, suggests that they can access and manipulate linguistic representations with less reliance on broad, integrative mechanisms. In contrast, individuals with lower skills may depend more heavily on DMN-mediated processes to maintain and bind information. Similarly, increased DAN activation in individuals with lower linguistic knowledge or slower processing speed likely reflects compensatory attentional control. Attentional networks have long been implicated in language processing, supporting the selective allocation of attention to semantic categories (Cristescu et al., 2006) and to specific acoustic features such as pitch, intonation, lexical tone, and prosodic focus (Hill & Miller, 2010; Kristensen et al., 2013; Li et al., 2010; Wang et al., 2009). Greater engagement of these networks in lower-skilled individuals likely reflects the need for sustained attentional support to extract linguistic cues and integrate information over time, processes that higher-skilled individuals perform more automatically and efficiently.

Overall, these findings demonstrate that the neural architecture of language processing is modulated by individual differences in cognitive skills. While group-level maps are consistent with the centrality of core areas for language (Fedorenko & Thompson-Schill, 2014; Hagoort,

2017; Hertrich et al., 2020), these core linguistic systems are scaffolded by cognitive skill-related modulations in domain-general networks. Our results underscore that language processing is an inherently dynamic, multi-network phenomenon, reconfiguring network involvement to meet the shifting computational demands of the linguistic task at hand and the cognitive capacities of each individual.

## CONCLUSION

By combining cognitive profiling with task-based fMRI in a large sample, our study highlights how individual cognitive skills modulate the neural architecture of language processing, revealing a dynamic interplay between core language regions and domain-general systems shaped by sensory modality, motor demands, and linguistic complexity. While canonical left-lateralized language areas are consistently recruited across diverse tasks, interindividual differences in linguistic knowledge, processing speed, working memory and non-verbal reasoning are primarily reflected in the flexible engagement of distributed networks beyond the perisylvian cortex. These findings suggest that the neural architecture of language is shaped not only by linguistic competence but also by broader cognitive traits that influence how language is internally represented, maintained, and executed. We provide evidence that language processing is deeply embedded within broader neural systems that support abstraction, attention, memory and control. This integrative framework advances our understanding of language as a distributed and adaptive function, tailored to the cognitive skills of each individual. It also underscores the importance of considering how language is scaffolded by general cognitive architecture, with implications for future research on the neural basis of language in both typical and atypical

populations, as well as for applied contexts such as language education, assessment, and rehabilitation.

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## SUPPLEMENTARY MATERIAL

***Supplementary Table 1:*** *Behavioral accuracy scores of the fMRI language tasks averaged across participants*

| Language Task | Condition | Mean Accuracy Score (%) |
|---|---|---|
| **Lexical Decision** | Word | 94 |
| | Pseudoword | 91 |
| | Quilt | 100 |
| **Picture Naming** | Object | 94 |
| | Nameless Object | 98 |
| | Scrambled Picture | 100 |
| **Sentence Comprehension** | Sentence | 96 |
| | Wordlist | 94 |
| **Sentence Production** | Active | 95 |
| | Passive | 94 |
| | Intransitive | 96 |
| | Phrase | 96 |

***Supplementary Table 2:*** *Significant fMRI group-level activation clusters across different language task contrasts and modulators (thresholded at a voxel-wise level of p < 0.001, with cluster-level Family-Wise Error correction at p < 0.05)*

| fMRI Contrast | Cluster Location | Cluster Size | x | y | z |
|---|---|---|---|---|---|
| **Lexical Decision** | | | | | |
| Word-Quilt | temporal_inf_L | 162920 | -48 | -56 | -16 |
| | precentral_R | 4912 | 46 | -14 | 48 |
| | frontal_inf_orb_L | 4163 | -32 | 32 | -10 |
| | parietal_inf_L | 2810 | -34 | -44 | 52 |
| | caudate_L | 2761 | -8 | 10 | 4 |
| | frontal_inf_orb_R | 334 | 34 | 36 | -8 |
| | frontal_sup_L | 236 | -16 | 36 | 46 |
| | frontal_sup_medial_L | 166 | -6 | 56 | 38 |
| | putamen_L | 160 | -28 | -6 | -10 |
| | rolandic_oper_L | 72 | -38 | -6 | 16 |
| | hippocampus_R | 69 | 20 | -16 | -16 |
| | postcentral_L | 53 | -24 | -28 | 66 |
| | cingulum_mid_R | 51 | 8 | 4 | 30 |
| **Picture Naming** | | | | | |
| Object-Nameless Object | heschl_R | 458090 | 58 | -10 | 6 |
| | temporal_mid_R | 684 | 50 | -64 | 12 |
| | frontal_sup_R | 210 | 24 | 10 | 58 |
| | frontal_inf_orb_L | 112 | -30 | 36 | 12 |
| | vermis_8 | 74 | 2 | -72 | -36 |
| | thalamus_L | 70 | -14 | -18 | 4 |
| | cerebellum_crus1_R | 61 | 32 | -78 | -34 |
| | temporal_inf_L | 56 | -44 | -36 | -18 |
| **Sentence Comprehension** | | | | | |
| Sentence-Wordlist | temporal_pole_mid_L | 210590 | -46 | 10 | -30 |
| | frontal_sup_medial_L | 3789 | -8 | 56 | 38 |
| | precuneus_R | 3636 | 10 | -54 | 62 |
| | temporal_pole_mid_R | 1566 | 46 | 14 | -32 |
| | precentral_R | 386 | 38 | -12 | 44 |
| | supramarginal_L | 276 | -62 | -30 | 28 |
| | postcentral_L | 176 | -38 | -14 | 46 |
| | thalamus_L | 150 | -2 | -16 | 6 |
| | vermis_7 | 118 | -2 | -72 | -30 |
| | cerebellum_crus1_R | 94 | 32 | -74 | -34 |
| | cingulum_mid_R | 93 | 12 | 2 | 42 |
| | caudate_L | 83 | -20 | -34 | 22 |
| | cingulum_mid_L | 81 | -4 | 6 | 38 |
| | cerebellum_crus1_L | 70 | -30 | -80 | -32 |
| | vermis_9 | 67 | -2 | -60 | -36 |
| | cingulum_ant_R | 53 | 22 | 26 | 20 |
| Syntactic complexity | temporal_sup_L | 1942 | -50 | -20 | 80 |
| | heschl_R | 1784 | 50 | -18 | 8 |
| | lingual_R | 1225 | 18 | -88 | -10 |
| | occipital_inf_L | 816 | -36 | -82 | -12 |
| | temporal_inf_L | 116 | -40 | -40 | -18 |
| | supp_motor_area_L | 103 | -2 | 20 | 48 |
| | frontal_mid_L | 95 | -30 | 30 | 48 |
| | postcentral_R | 95 | 44 | -22 | 52 |
| | cingulum_ant_L | 87 | -2 | 42 | -6 |
| | precuneus_R | 69 | 2 | -56 | 34 |
| | frontal_inf_oper_L | 64 | -56 | 14 | 20 |
| | precentral_L | 62 | -54 | 2 | 42 |
| | occipital_mid_L | 54 | -32 | -90 | 16 |
| **Sentence Production** | | | | | |
| Sentence-Phrase | heschl_R | 336430 | 48 | -16 | 8 |
| | supp_motor_area_L | 3010 | -2 | 2 | 64 |
| | frontal_inf_orb_R | 872 | 36 | 32 | -10 |
| | precentral_R | 166 | 28 | -4 | 48 |
| | pallidum_R | 132 | 28 | -10 | -4 |
| Syntactic complexity | temporal_sup_L | 373420 | -46 | -24 | 10 |
| | heschl_R | 4839 | 48 | -18 | 8 |
| | postcentral_R | 459 | 20 | -30 | 60 |
| | insula_R | 359 | 32 | 20 | 6 |
| | precentral_R | 333 | 28 | -4 | 48 |
| | parietal_sup_R | 775 | 18 | -64 | 56 |
| | cingulum_mid_L | 94 | -8 | -14 | 40 |
| | frontal_sup_medial_L | 135 | -6 | 58 | 36 |
| | caudate_L | 72 | 0 | 20 | 4 |
| | caudate_R | 68 | 18 | 26 | 16 |
| | occipital_sup_R | 64 | 28 | -72 | 26 |