The Language of Thought is not Language: Evidence from Formal Logical Reasoning

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The human capacity for **logical reasoning** lies at the heart of our ability to learn and think about the world, as well as engage in formal thought (e.g., mathematical reasoning). The format of the mental representations that mediate thought remains debated: thoughts can be expressed symbolically, schematically, diagrammatically, in mathematical or formal expressions, but can also be cast into a linguistic format. According to one popular hypothesis about the representational format of thoughts—the "language of thought" (**LOT**) hypothesis (Fodor, 1975)—thoughts are composed of smaller atomic pieces in a structured format with hierarchical relations between the component elements, just like programs are built out of a small collection of operations, or sentences are built out of words. Some have further explicitly argued that the language of thought is natural language (e.g., Chomsky, 1993, 1995; Davidson, 1967, 1975; Dennett, 1991, 1996, 2017; Carruthers, 2002; for earlier claims, see Wittgenstein, 1921), presumably due to the analogous hierarchical structure (**Figure 1**) which commonly exists in systems with elements that combine to form compositional structures.

We here challenge the claim that language is the medium of thought using a combination of neuroimaging in healthy adults and behavioral investigations of patients with severe aphasia. We examine two paradigmatic types of logical reasoning which require LOT: induction and deduction, applied to formal rules. **First,** we use a formal rule induction paradigm (Rule et al., 2024) where participants are presented with an input number list and the output list (e.g., 1 4 7 → 7 4 1), and are asked to infer the underlying transformation rule. They can then test their hypothesis on a new input list, until they guess the correct rule. The rules involve a combination of mathematical, list, and structural operations, and require a formal representation (in e.g., first-order logic or lambda calculus) to solve (**Table 1**). **Second**, we use a formal deduction paradigm (Coetzee & Monti, 2018) where participants are presented with a classic syllogism consisting of two premises and a conclusion (e.g., i) If A is B, then A is also C. ii) A is not C. <u>Therefore</u>, A is not B), and are asked to infer if the conclusion is valid. In order to properly answer if the conclusion follows from the premises, participants must have a formal representation of all three propositions: the necessary implications of the premises, and the criteria for the satisfaction of the conclusion (**Table 2**).

In **Experiment 1A,** we measured healthy adults' brain responses using fMRI while they performed the rule induction task; in the critical trials, participants were guessing the outputs but did not know what the rule was. We operationalized the solution or 'got it' trial as the point at which participants guessed the output correctly and never made another error for that rule, as a heuristic for the induction period (pre-solution) and application period (post-solution). The response in the language brain areas (Fedorenko et al., 2024; see <u>Methods</u>) to the induction contrast was low, close to the low-level baseline (**Figure 2A**). Instead, another system—the Multiple Demand (MD) system (Duncan, 2010; Duncan et al., 2020), which has been implicated in goal-directed behaviors and associated with general fluid intelligence (e.g., Woolgar et al., 2010)—showed a robust response to the rule induction task, and stronger responses during the induction period, compared to the period after participants had figured out the rule (**Figure 2B**). Thus, the language areas in healthy adults are not engaged much during formal rule induction.

Next, in **Experiment 1B**, we asked whether the rule induction task can be performed without the language system by testing two individuals with global aphasia. These participants have sustained massive damage to the Perisylvian language cortex (**Figure 4**) and display severe language difficulties in both comprehension and production across modalities (**Supp. Table 1**). In spite of this severe linguistic impairment, one participant (age=50) performed better on the rule induction task than a group of n=40 age-matched control participants, and the other (age=78) performed similarly to the controls (**Figure 3**). Moreover, both participants with aphasia were able to communicate nonverbally (using symbols, numbers, and gestures) the rules they had inferred (**Figure 5**).

In **Experiment 2A**, we measured the healthy adults' brain responses while they performed the syllogistic deduction task; in the critical trials, participants were asked to solve more difficult syllogisms (e.g., i) If A is B, then A is also C. ii) A is not C. <u>Therefore</u>, A is not B), which followed Modus Tollens, and in the control condition, participants were given simpler, Modus Ponens, syllogisms (e.g., i) If A is B, then A is also C. ii) A is B. <u>Therefore</u>, A is C.). The response in the language brain areas to the deduction contrast not significantly different from the low-level fixation baseline (**Figure 2A**). Thus, the language areas in healthy adults are not engaged in formal syllogistic deduction.

Finally, in **Experiment 2B**, we asked whether another logical reasoning task can be performed without the language system by testing the same two individuals with global aphasia. We used a Matrix Reasoning task (Wechsler, 1999), which is used extensively as a test of deductive reasoning ability, and resembles Raven's Progressive Matrices; Raven & Raven, 2003). Despite their severe linguistic impairment, both participants performed significantly better than average when compared to normative data available for this task (**Figure 6**).

Overall, our results demonstrate that the left-lateralized fronto-temporal language system does not support—and is not needed for—logical reasoning (inductive or deductive), thus falsifying the variant of the LOT hypothesis whereby natural language is the medium of thought. These results add to the growing body of evidence against the idea that the language system supports thinking and reasoning, including mathematical reasoning (Varley et al., 2005; Fedorenko et al., 2011; Monti et al., 2012; Amalric & Dehaene, 2016), logical reasoning (Monti et al., 2009), understanding computer programs (Ivanova et al., 2020; Liu et al., 2020), social reasoning (Varley & Siegal, 2001; Apperly et al., 2006; Shain et al., 2023), physical reasoning (Kean et al., 2024), and causal reasoning (Pramod et al., 2024).

Beyond the dissociation between natural language and the LOT, our experiments reveal another intriguing dissociation. Whereas, as noted above, the inductive reasoning task engaged the Multiple Demand system, the deduction task did not elicit a response in this system (**Figure 2B**; see also Coetzee & Monti, 2018). Instead, deductive reasoning appears to engage a pair of left frontal brain areas that are distinct from both the language system and the Multiple Demand system (**Figure 2C**). These areas show some response to the induction task, albeit substantially weaker than to the deduction contrast. This finding suggests that inductive and deductive reasoning are at least partially dissociable: inductive reasoning draws primarily on the bilateral domain-general Multiple Demand system, which supports diverse goal-directed behaviors, whereas deductive reasoning recruits a specialized left-lateralized frontal system.

Methods (abbreviated)

In all analyses, the regions of interest were identified functionaly in individual participants to ensure the highest sensitivity and functional resolution—the ability to differentiate nearby functional areas (Saxe et al., 2006; Nieto-Castanon & Fedorenko, 2012). To define the ***language areas***, we used a localizer that was introduced in Fedorenko et al. (2010) and used in many subsequent studies (e.g., Blank et al., 2016; Fedorenko et al., 2020; Hu, Small et al., 2022; Chen et al., 2023; Tuckute et al., 2024; Shain, Kean et al., 2024; the task is available for download from https://www.evlab.mit.edu/resources). Participants silently read sentences and lists of unconnected, pronounceable nonwords in a blocked design. The Sentences > Nonwords contrast targets cognitive processes related to high-level language comprehension, including understanding word meanings and combinatorial linguistic processing. To define the ***Multiple Demand (MD) areas***, we used a spatial working memory task that was introduced in Fedorenko et al. (2011) and used in many subsequent studies as a localizer for the MD system (Blank et al., 2014; Shashidhara et al., 2019, 2020, 2021, 2024; Diachek, Blank, Siegelman et al., 2020; Malik-Moraleda, Ayyash et al., 2022). Participants had to keep track of spatial locations presented in a sequence within a 3x4 grid (8 locations in the Hard condition, 4 locations in the Easy condition). The Hard > Easy contrast targets cognitive processes broadly related to performing demanding tasks—what is often referred to by an umbrella term 'executive function processes'. For both the language and the Multiple Demand systems, we used an approach where group-level parcels (or masks)—derived from a large group of independent participants performing the same task—are intersected with individual activation maps, and within each parcel, the most responsive voxels (top 10%) in each participant are selected as that participant's functional region of interest (fROI) (see Fedorenko et al., 2010 for details). Importantly, to estimate the responses of these fROIs to the contrast that is used to define the fROIs, we use a split-half approach where one run is used to define the areas, and the other run to estimate their responses, so as to avoid non-independence (e.g., Kriegeskorte, 2011). Because we did not observe a strong response during the deduction task in either the language or the MD areas, we performed a group-constrained subject-specific (GSS) analysis (Fedorenko et al., 2010; Julian et al., 2012) on our data to see whether any areas of consistent activation emerge. Indeed, two such areas emerged in the left frontal lobe, and we used those parcels to define individual deduction-responsive fROIs. Similar to the language and the MD system localizers, we used a split-half approach using half of the data to define the individual fROIs, and the other half—to estimate their responses to the deduction task conditions.

(Extended Methods and Results available upon request.)

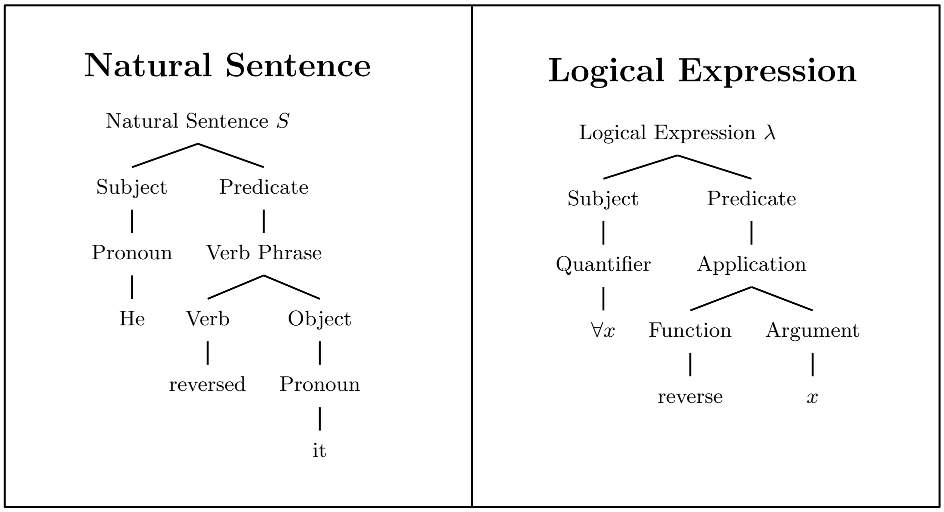

Figure 1. Structured parses of a sentence in natural language and a function in formal logic.

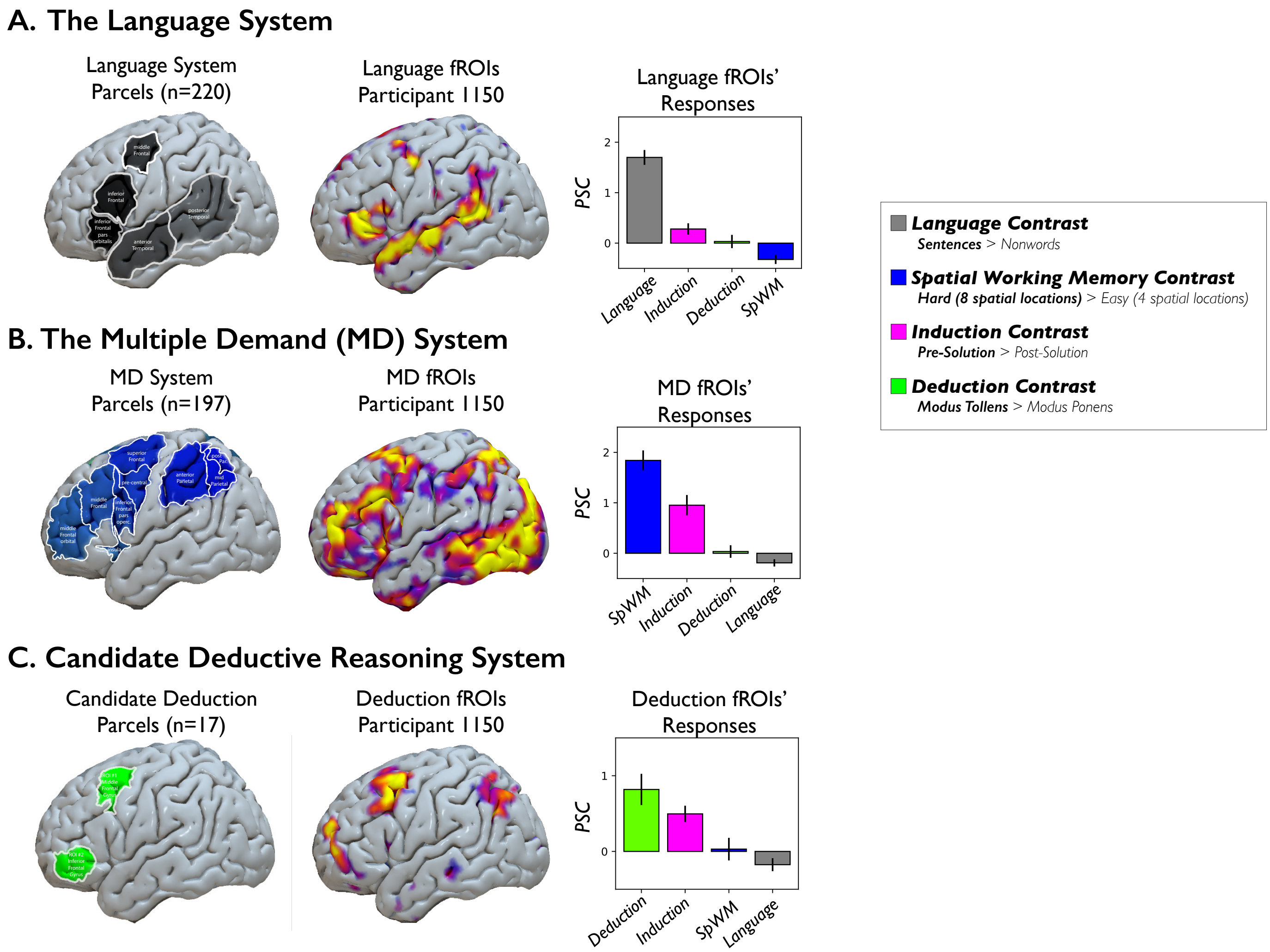

Figure 2. The language brain areas do not respond during inductive, nor deductive reasoning. The brain areas of interest (the parcels are shown in the first column, and a sample participant's whole-brain activation maps for the localizer contrasts are shown in the second column; **(A)** the language system, **(B)** the Multiple Demand (MD) system, and **(C)** the deduction system) and their response (third column) to the language localizer contrast (Sentences>Nonwords, in gray), to the MD localizer contrast (Hard>Easy, in blue), to the rule induction task contrast (Pre-Solution>Post-Solution, in pink), and to the syllogistic deduction task contrast (Modus Tollens>Modus Ponens, in green). In all cases, we average the response profiles across the fROIs within each system (5 fROIs in the language system, 20 fROIs in the MD system, and 2 fROIs in the deductive reasoning system, because the profiles of the individual fROIs are similar). In the language system, we observe a strong and selective response to the Sentences>Nonwords contrast, with little or no response to the inductive and deductive reasoning contrasts. In the MD system, we observe a strong response to the Hard>Easy contrast in the spatial working memory task, as well as a strong response to the inductive reasoning contrast. Finally, in the candidate deduction system, we observe a strong and selective response to the Modus Tollens>Modus Ponens contrast, with a weaker response to the inductive reasoning contrast.

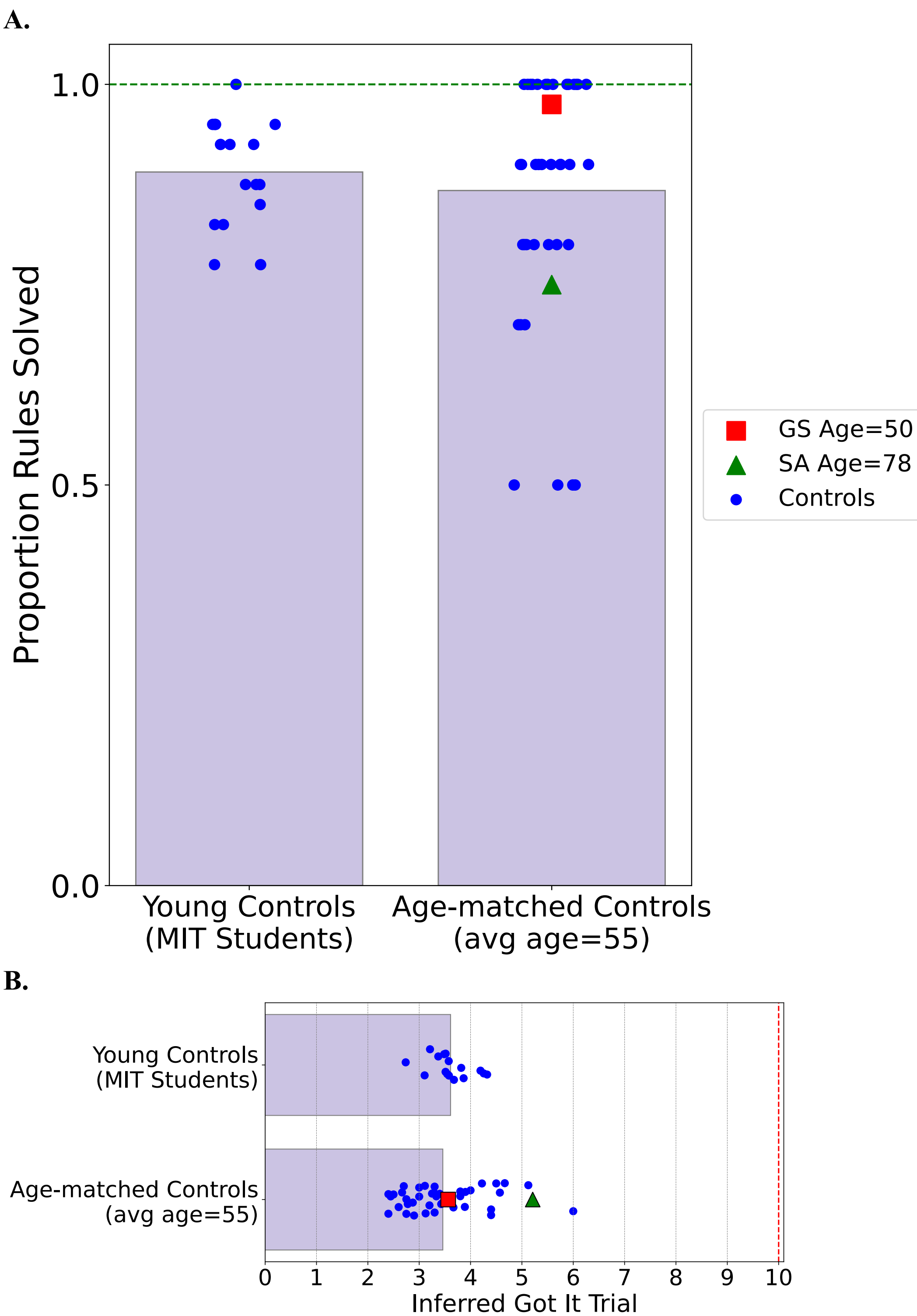

Figure 2. Individuals with profound aphasia perform well on the rule induction task. (A) The proportion of rules solved by the neurotypical young participants in the fMRI study (MIT students) and age-matched controls (40 participants with an average age of 55 years) in the behavioral study, with the proportion of rules solved by the two participants with global aphasia shown in special symbols (GS was 50 years old at testing, shown as a red square, and SA was 78 years old at testing, shown as a green triangle). **(B)** The average trial at which participants solved the rule (operationalized as the point at which participants made no more errors on subsequent trials) for the neurotypical young participants in the fMRI study and the age-matched controls, with the average solution trial for the two participants with aphasia shown in special symbols (GS, red square; SA, green triangle).

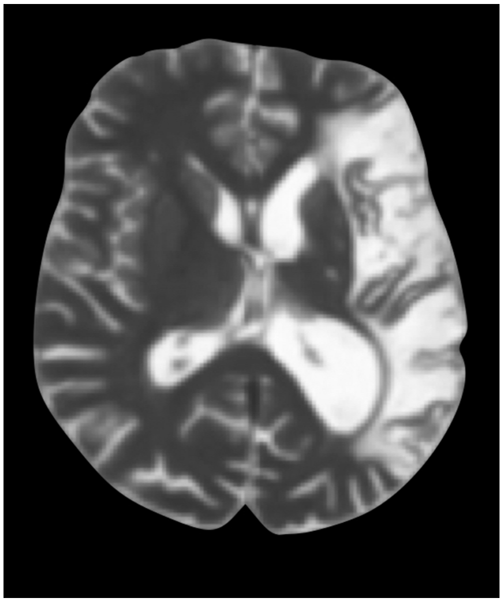

Figure 4. Structural MRI scan from S.A., which shows extensive Perisylvian damage in the left hemisphere, encompassing both frontal and temporo-parietal areas.

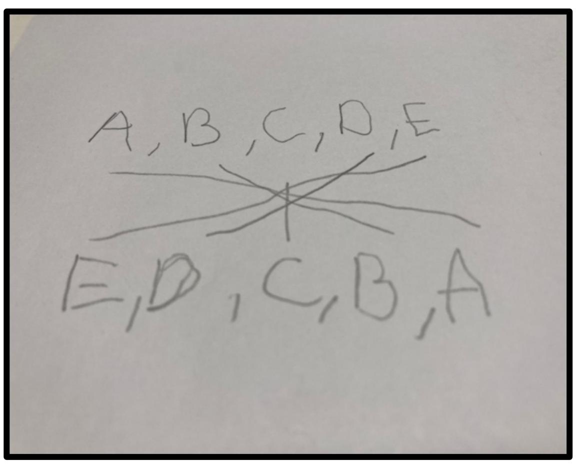

Figure 5. Rule representation for a sample rule produced by G.S.

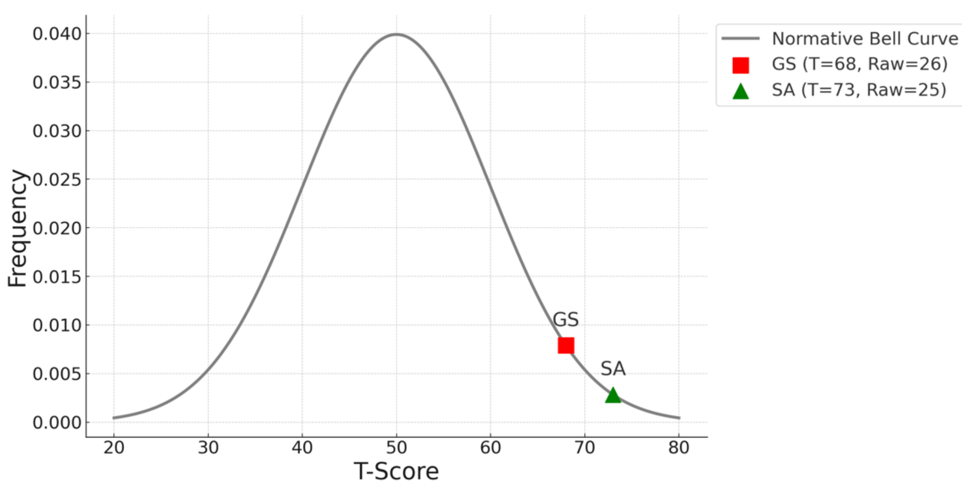

Figure 6. Individuals with profound aphasia perform well on a deductive reasoning task (the Matrix Reasoning Task from Wechsler's Abbreviated Scale of Intelligence (WASI-II). GS raw score = 26/30, SA raw score = 25/30.

	GS	SA
Age	50	78
Time post-onset	2.5 years	33 years
Etiology	Left hemisphere stroke	Left subdural empyema and meningitis
Previous occupation and educational background	Graduate degree; worked in cybersecurity	Left school at 15; police sergeant
Cognitive assessments		
- Forward digit span (Wechsler Adult Intelligence Scale)	- 3 items	- 2 items
- Pyramid & Palm Trees (3-picture version)	- 50/52	- 49/52
- WASI Matrices	- 26/30	- 25/30
Grammatical processing		
Comprehension spoken reversible sentences:		
- Total (chance = 40/80)	- 22/80	- 30/80
- Active (20/40)	- 20/40	- 16/40
- Passive (20/40)	- 2/40	- 14/40
Comprehension written reversible sentences:		
- Total (chance = 40/80)	- 38/80	- 46/80
- Active (20/40)	- 32/40*	- 34/40*
- Passive (20/40)	- 6/40	- 12/40
Auditory grammaticality judgment:		
- Total (chance = 32/64)	- 36/64	- 48/64*
Written grammaticality judgment:		
- Total (chance = 32/64)	- 44/64*	- 29/64
Lexical processing		
ADA spoken-word picture matching (total):	- 60/66	- 51/66
ADA written-word picture matching (total):	- 63/66	- 53/66
PALPA Picture Name (spoken or written):		
- High-frequency set	- 19/20	- 1/20
- Mid-frequency set	- 15/20	- 0/20**
- Low-frequency set	- 13/20	- 0/20**
ADA Synonym Judge (combined written and auditory presentation):		
- Total	- 137/160	- 135/160
- High imageability errors	- 2	- 4
- Low imageability errors	- 10	- 12
- High frequency errors	- 4	- 6
- Low frequency errors	- 7	- 3

Supplemental Table 1. Demographic and language assessment information for the two participants with aphasia. Cognitive assessments include the WAIS digit span (Wechsler, 1981), Pyramid and Palm Trees test, assigning meaning to words and pictures (Howard and Patterson, 1992) and WASI matrices (Wechsler, 1999). Grammatical processing assessments from Linebarger et al. (1983), include spoken and written reversible sentences and grammaticality judgments, with repetition penalties for spoken/auditory tasks. Lexical processing includes the picture matching and synonym judge tasks from the ADA comprehension battery (Franklin et al. 1992) and picture naming task from the PALPA test battery (Kay et al. 1992). * indicates performance above chance under a binomial test at $p = 0.05$. ** a cut-off was applied for SA's PALPA test: with 1/20 on the high frequency set, the mid- and low-frequency sets were automatically scored 0/20 without further testing.

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