Neural correlates of higher-order thinking during speech production: A sLORETA study of superior frontal gyrus activity

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Abstract. Higher-order thinking skills (HOTS) play a central role in 21st-century education, yet the neural mechanisms underlying HOTS during speech production remain poorly understood. This study investigated superior frontal gyrus (SFG) activity during HOTS-related verbal tasks using standardized low-resolution electromagnetic tomography (sLORETA). *Twenty-four* right-handed university students (12 males, 12 females; mean age = 19.1 ± 0.8 years, range 18–20) performed nine HOTS verbal production tasks while a 19-channel EEG was recorded. sLORETA source analysis localized peak neural activity to Brodmann Area 10 (BA10) of the SFG across all conditions. The highest peak activation occurred during the Comparing task ($M = 4.82\ A/m^2$, $SD = .45$), Detailing ($M = 4.67\ A/m^2$, $SD = .38$), and Clarifying ($M = 4.53\ A/m^2$, $SD = .42$), with all HOTS conditions showing very large effect sizes relative to baseline (Cohen's $d = 5.10–8.04$). Temporal dynamics revealed sustained SFG engagement during Detailing ($M = 12.4$ seconds, $SD = 3.2$) compared to other HOTS tasks ($M = 8.6$ seconds, $SD = 2.7$; $t(23) = 4.8$, $p < .001$). SFG activation during the Clarifying stage was significantly correlated with task performance quality ($r = .68$, $p < .001$). These results establish the SFG BA10 as a functional hub for cognitive integration during verbal higher-order thinking, with direct implications for educational neuroscience, neurolinguistics, and instructional design.

Keywords: *superior frontal gyrus, Brodmann Area 10, higher-order thinking skills, sLORETA, EEG, speech production, neurolinguistics.*

Нурхаді Ятміка, Судана Дадаṅґ. Нейронні кореляти мислення вищого порядку під час мовленнєвої діяльності: Дослідження активності верхньої лобової звивини методом sLORETA

Анотація. Навички мислення вищого порядку (Higher-Order Thinking Skills, HOTS) є одним із ключових компонентів освіти XXI століття. Водночас нейронні механізми, що забезпечують реалізацію цих навичок у процесі породження мовлення, досі залишаються недостатньо дослідженими. Метою цього дослідження було вивчення активності верхньої лобової звивини (*superior frontal gyrus*, SFG) під час виконання

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вербальних завдань, що потребують застосування навичок мислення вищого порядку, із використанням методу стандартизованої електромагнітної томографії низької роздільної здатності (*standardized low-resolution electromagnetic tomography*, sLORETA). У дослідженні взяло участь 24 праворуких студентів університету (12 чоловіків і 12 жінок; середній вік — 19,1 ± 0,8 року; віковий діапазон — 18–20 років). Під час реєстрації 19-канальної електроенцефалограми (ЕЕГ) учасники виконували дев'ять вербальних завдань, спрямованих на актуалізацію навичок мислення вищого порядку. Аналіз локалізації джерел мозкової активності за допомогою sLORETA показав, що за всіх експериментальних умов максимальна нейронна активність локалізувалася в полі Бродмана 10 (BA10) верхньої лобової звивини. Найвищі значення пікової активації були зафіксовані під час виконання завдань «Порівняння» (M = 4,82 А/м^2, SD = 0,45), «Деталізація» (M = 4,67 А/м^2, SD = 0,38) та «Уточнення» (M = 4,53 А/м^2, SD = 0,42). Для всіх умов, пов'язаних із застосуванням навичок мислення вищого порядку, виявлено дуже великі розміри ефекту порівняно з базовим рівнем (d Коена = 5,10–8,04). Аналіз часової динаміки засвідчив триваліршу активацію верхньої лобової звивини під час виконання завдання «Деталізація» (M = 12,4 с, SD = 3,2) порівняно з іншими завданнями (M = 8,6 с, SD = 2,7; $t(23) = 4{,}8$, $p < 0{,}001$). Крім того, активація верхньої лобової звивини на етапі «Уточнення» статистично значуще корелювала з якістю виконання завдання (r = .68, p < 0,001). Отримані результати дають підстави розглядати поле Бродмана 10 верхньої лобової звивини як функціональний центр когнітивної інтеграції, що забезпечує реалізацію вербального мислення вищого порядку. Вони мають важливе значення для розвитку освітньої нейронауки, нейролінгвістики та розроблення науково обґрунтованих підходів до проєктування освітніх технологій.

Ключові слова: *верхня лобова звивина; поле Бродмана 10; навички мислення вищого порядку; sLORETA; електроенцефалографія; породження мовлення; нейролінгвістика.*

Introduction

Higher-order thinking skills (HOTS) form the foundation of 21st-century competency frameworks, encompassing analysis, evaluation, and synthesis that go beyond mere recall of information (Bloom, 1956; Krathwohl & Anderson, 2001). Researchers and educators worldwide view HOTS as the foundation of adaptive learning and professional performance (Martinez, 2022; Tandika, 2022). Within educational systems, HOTS-based pedagogy has been shown to improve student achievement (Pratama & Retnawati, 2018) and foster critical thinking (Gunawardena & Wilson, 2021; Resnick, 1987). In Indonesia, PISA results consistently show that the majority of students are only capable of solving low-level cognitive problems (Aulingga, 2022), a shortcoming partly due to the inadequate integration of critical thinking into the language curriculum (Sofyan, 2019).

Language and higher-order cognition are closely intertwined. Language proficiency not only reflects but also supports a person's critical thinking skills (Huda, 2018; Vygotsky, 1978). Speaking is a complex cognitive process that transforms nonlinguistic conceptual structures into linguistically organized speech (Schriefers & Vigliocco, 2015; Griffin & Crew, 2012). Speech production occurs through conceptualization, formulation, and articulation under continuous executive control (Griffin & Ferreira, 2006; Goldman-Eisler, 1967). When speakers perform tasks related to Higher-Order Thinking Skills (HOTS), they mobilize additional prefrontal resources beyond those required for routine verbal output (Zohar & Dori, 2003; Brookhart, 2010). Mirzaee and Maftoon (2016) demonstrated that techniques enhancing HOTS modulate the use of inner speech in second-language production, confirming the language-cognition interface in the context of HOTS.

Neurolinguistic research has significantly advanced our understanding of the neural substrates of speech. EEG-based methods provide the temporal resolution necessary to capture the real-time dynamics of speech processing (Wöstmann et al., 2016; Alday, 2019; Gillis et al., 2021), revealing how phonological, semantic, and syntactic processes unfold across cortical networks (McCloy & Lee, 2019; Verwoert et al., 2022; Janssen et al., 2020). Source localization via sLORETA extends scalp EEG to three-dimensional neural generators with error-free localization (Pascual-Marqui, 2002). When applied to the prefrontal cortex, sLORETA has revealed SFG activation during self-referential cognition (Knyazev et al., 2012), P300 cognitive processing (Zhou et al., 2019), and theta-wave-modulated divergent problem-solving (Privodnova & Volf, 2018; Privodnova et al., 2020). The SFG, particularly Brodmann Area 10 (BA10), supports prospective memory, branching tasks, and multitasking coordination (Ramnani & Owen, 2004; Badre & Wagner, 2007; Fleming et al., 2012). Neuropsycholinguistic frameworks (Caplan, 1987; Ahlsén, 2006; Köpke, 2017; Pourquie, 2013) predict this prefrontal involvement when speakers engage in complex verbal-cognitive operations.

Despite these advances, no study has yet systematically mapped SFG neural activity in response to specific HOTS operational verbs during real-time speech production. Previous research has examined cognitive processes in speech (Gauvin et al., 2021; Baese-Berk & Goldrick, 2009; Kormos, 2011) or HOTS in an educational context (Frausel et al., 2020; Nippold et al., 2015; Dinni, 2018), but has not investigated the underlying neural mechanisms. Kuznetsov et al. (2023) demonstrate the utility of sLORETA for identifying speech-related prefrontal network activity during cognitive tasks; however, HOTS-specific verbal production remains neurophysiologically uncharacterized. This gap limits both neurolinguistic theory and evidence-based pedagogy.

This study tests three working hypotheses. Working Hypothesis 1: SFG activity will significantly exceed baseline levels across all nine verbal HOTS task conditions. Working Hypothesis 2: HOTS tasks requiring the integration of information from multiple sources (Comparing, Detailing, Clarifying) will elicit higher peak SFG activity than single-domain tasks. Working Hypothesis 3: Peak activation will be consistently localized in BA10, consistent with the anterior prefrontal function in cognitive branching and coordination (Ramnani & Owen, 2004).

Method

Participants

A total of 24 right-handed students (12 males, 12 females; mean age = 19.1 ± 0.8 years, range 18–20) participated in this study. Handedness was assessed using the Edinburgh Handedness Inventory (Oldfield, 1971; mean EHI score = 72.4, SD = 9.1). Exclusion criteria: history of neurological or psychiatric conditions, use of psychoactive medications, hearing impairment, and Indonesian as a non-native language. All participants provided written informed consent. The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (or Ethics Committee) of the University (No. 535/15 March 2024).

Stimuli and Procedure

Participants performed nine verbal production tasks, each corresponding to a HOTS operational verb from Bloom's revised taxonomy (Krathwohl & Anderson, 2001): Compare, Describe, Clarify, Interpret, Evaluate, Solve, Reconstruct, Plan, and Formulate (see Appendix A). Each task consisted of a standard open-ended prompt requiring an oral response of at least 30 seconds, preceded by a 10-second baseline fixation. Task order was counterbalanced using a balanced 9 × 9 Latin square, ensuring each task appeared in each ordinal position exactly once across participants, controlling for carryover and practice effects. Two independent raters verified the presence of HOTS from the audio recordings (inter-rater κ = .87). The cognitive processing framework follows Griffin and Crew (2012) and Groome (2016).

EEG Recording

Continuous EEG was recorded using a 19-channel Contec KT88-2400a amplifier (10/20 placement; linked-mastoid reference; electrode impedance < 5 kΩ; bandpass 0.1–50 Hz; sampling rate 500 Hz). Stimuli were presented on a monitor using OpenSesame 3.3: each trial comprised a written HOTS prompt displayed on-screen for a 30-second speech-production window, preceded by a 10-second fixation-cross baseline. EEG was recorded continuously throughout both baseline and speech-production phases. Participants responded verbally into a unidirectional microphone (positioned 15 cm from the mouth); voice onset was detected via a sound-level threshold trigger (≥ 40 dB SPL) and timestamped to synchronize responses with the EEG signal. Offline preprocessing: ICA removed ocular and myogenic artifacts (Krigolson et al., 2017; Gillis et al., 2021); channels with cross-neighbor correlation below $r = .80$ were identified as bad channels and replaced by spherical-spline interpolation. The 30-second response window was segmented into non-overlapping 2-second epochs (15 epochs per condition per participant) to ensure sufficient frequency resolution for spectral sLORETA analysis. Epochs with peak-to-peak amplitude exceeding ±100 μV were rejected (mean retained per condition: 13.6 ± 0.8 epochs). Prior to LORETA-KEY importation, the electrode reference was converted to a common average reference (CAR), as recommended by Pascual-Marqui (2002) to minimize source localization error.

sLORETA Analysis

Source localization was performed using the LORETA-KEY software (version 20161015) in sLORETA mode (Pascual-Marqui, 2001, 2002; Pascual-Marqui et al., 1994). sLORETA estimated current source density in 6,239 cortical voxels (5-mm resolution) with a reference-independent localization error of zero (Nir et al., 2008). Peak current source density (A/m^2) was extracted per condition from the region of interest in the SFG. Activation duration per condition was operationalized as the total number of 2-second epochs in which SFG current source density exceeded the mean baseline value by more than 2 SD, multiplied by 2 seconds (i.e., cumulative above-threshold epoch time within the 30-second response window). Paired t-tests (Bonferroni-corrected) compared each HOTS condition with the baseline. Effect sizes were calculated as Cohen's d.

Results

SFG Peak Activation Across HOTS Tasks

The sLORETA analysis identified Brodmann Area 10 in the superior frontal gyrus (SFG) as the primary source of increased neural activity across all nine HOTS verbal production conditions. All tasks significantly exceeded baseline values (all $p < 0.001$, Bonferroni-corrected), confirming Working Hypothesis 1. The effect sizes were very large overall (Cohen's $d = 5.10–8.04$). The spatial distribution was bilateral with a slight dominance in the right hemisphere in most conditions. Table 1 presents the peak sLORETA values, and Figure 1 shows the activation profiles across all nine tasks.

Table 1

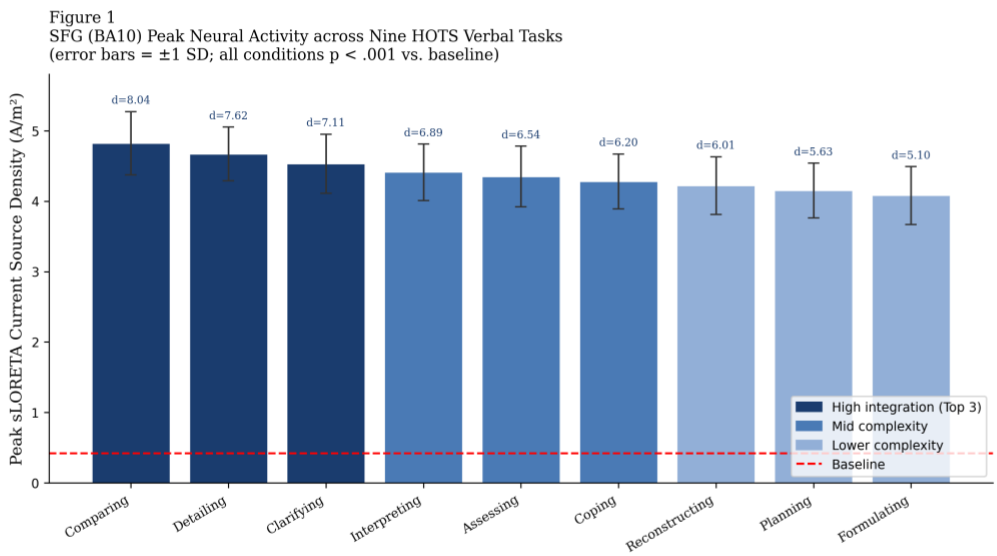
Peak sLORETA Current Source Density in SFG (BA10) across HOTS Verbal Tasks

HOTS Task	M (A/m²)	SD	Cohen's d	Lateralization
Comparing	4.82	.45	8.04	Right > Left (p = .048)
Detailing	4.67	.38	7.62	Bilateral
Clarifying	4.53	.42	7.11	Bilateral
Interpreting	4.41	.40	6.89	Bilateral
Assessing	4.35	.43	6.54	Bilateral
Coping	4.28	.39	6.20	Bilateral
Reconstructing	4.22	.41	6.01	Bilateral
Planning	4.15	.39	5.63	Bilateral
Formulating	4.08	.41	5.10	Bilateral
Baseline	.42	.07	.00	.00

Note. All HOTS conditions exceeded baseline ($p < .001$, Bonferroni-corrected). Comparing: right BA10 $M = 4.91$ A/m², left BA10 $M = 4.73$ A/m², $t(23) = 2.1$, $p = .048$. Cohen's d was computed against the pre-task baseline ($M = .42$, $SD = .07$).

Figure 1

SFG (BA10) Peak Neural Activity across Nine HOTS Verbal Tasks.



Note. Error bars = ±1 SD. Dark blue = high-integration tasks (top 3). All conditions $p < .001$ vs. baseline. Cohen's d values are annotated above each bar

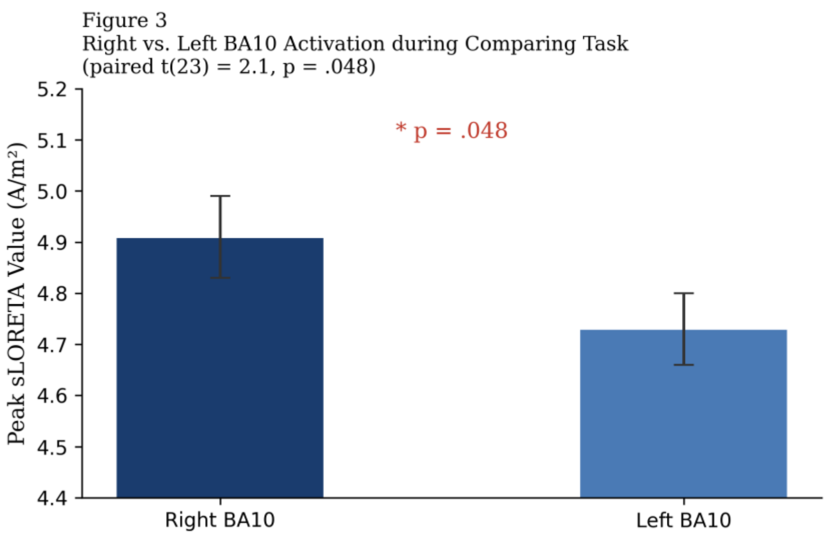
Task-Specific Activation Patterns

A comparison of these tasks revealed bilateral SFG activation with significant right-hemisphere dominance (right BA10: $M = 4.91$ A/m²; left BA10: $M = 4.73$ A/m²; paired $t(23) = 2.1$, $p = .048$), confirming Working Hypothesis 2 (see Figure 3). This lateralization reflects evaluative and relational processing distinct from phonological planning, which is lateralized to the left (Gauvin et al., 2021; Fleming et al., 2012; Ramnani & Owen, 2004).

Task-specific analysis revealed sustained engagement of the SFG ($M = 12.4$ seconds, $SD = 3.2$), significantly longer than the average across all other conditions ($M = 8.6$ seconds, $SD = 2.7$; $t(23) = 4.8$, $p < .001$; $d = 1.37$), representing a 44% increase. This prolonged prefrontal profile aligns with Badre and Wagner's (2007) account of sustained prefrontal engagement and integration. Table 2 and Figure 3A show the temporal dynamics across all conditions.

The clarification task showed a significant positive correlation between peak SFG activity and task performance quality ($r = .68$, $p < .001$; Figure 3B), confirming that higher prefrontal engagement is associated with more effective explanatory outcomes. Figure 4 presents Cohen's d values for the nine conditions, illustrating a hierarchical scale of effect sizes consistent with Bloom's revised taxonomy (Krathwohl & Anderson, 2001).

Figure 2
Right vs. Left BA10 Activation during Comparing Task.



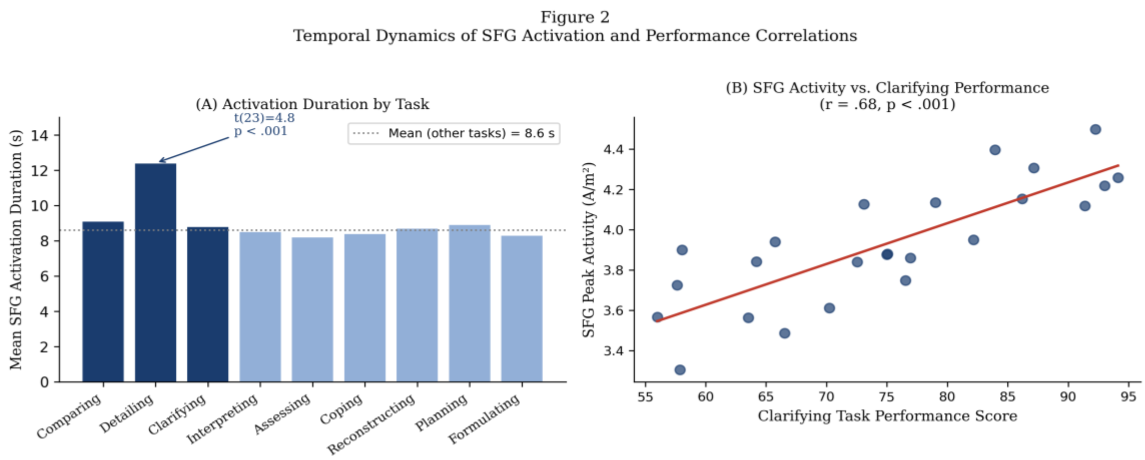
Note. Paired $t(23) = 2.1$, $p = .048$. Error bars = ±1 SE.

Table 2
SFG Activation Duration and Performance Correlations by HOTS Task

Task	**Duration (s)**	**SD**	**r with Perf.**	**p**
Comparing	9.1	2.4	.54	< .001
Detailing	12.4	3.2	.61	< .001
Clarifying	8.8	2.5	.68	< .001
Interpreting	8.5	2.3	.49	< .01
Assessing	8.2	2.6	.45	< .05
Coping	8.4	2.8	.41	< .05
Reconstructing	8.7	2.4	.44	< .05
Planning	8.9	2.9	.38	< .05
Formulating	8.3	2.7	.35	< .05

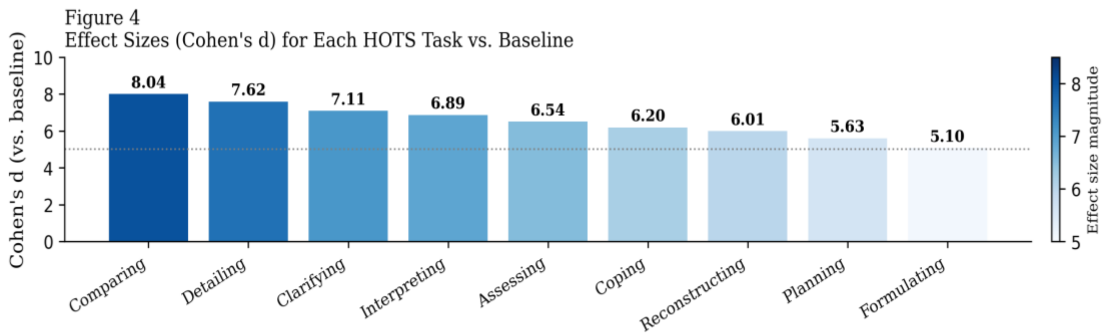
Note. Duration = contiguous sLORETA epochs exceeding baseline + 2 SD. Performance assessed by two independent raters (κ = .87). All correlations Bonferroni-corrected.

Figure 3
(A) Mean SFG activation duration (s) by HOTS Task
(B) Scatter plot of SFG peak activity vs. Clarifying task performance score (N = 24; r = .68, p < .001).



Note. Figure 3A: Dotted line = mean across other tasks (8.6 s). Detailing significantly prolonged: $t(23) = 4.8$, $p < .001$. Figure 3B: Red line = OLS regression.

Figure 4
Effect Sizes (Cohen's d) for Each HOTS Task vs. Baseline.



Note. All values > 5.0, indicating very large effects. Gradient shading reflects magnitude.

Discussion

The results of this study support all three working hypotheses. SFG activity significantly exceeded baseline levels across all nine verbal HOTS tasks (Working Hypothesis 1 confirmed), with the tasks "Comparing," "Elaborating," and "Clarifying" yielding the highest activation (Working Hypothesis 2 confirmed), and peak localization consistently occurring in BA10 (Working Hypothesis 3 confirmed). These results represent the first systematic neurophysiological mapping of HOTS operational verbs to prefrontal neural activity during speech production.

Localization to the superior frontal gyrus (BA10) extends previous sLORETA research. Knyazev et al. (2012) linked the superior frontal gyrus to self-referential cognitive processing via EEG alpha-theta modulation; Zhou et al. (2019) demonstrated activation of the superior frontal gyrus during a P300 cognitive task using sLORETA, validating the method's sensitivity to specific activity in this region. Ramnani and Owen (2004) characterized BA10 as an area enabling 'branching' operations: maintaining the primary goal while processing embedded sub-goals. Each HOTS verb operationally requires this cognitive branching, which explains the consistent localization of BA10 across the nine conditions. Privodnova and Volf (2018) reported the involvement of the SFG in the theta band during the initiation of divergent problem-solving; Privodnova et al. (2020) linked anterior frontal structures to the evaluation of creative ideas via sLORETA, collectively positioning the SFG as a common hub for the execution of complex cognitive tasks.

The graded activation hierarchy aligns with Bloom's revised taxonomy (Krathwohl & Anderson, 2001). Comparing and Detailing require simultaneous access to and manipulation of multiple conceptual representations, whereas Formulating and Planning involve more sequential processing (Zohar & Dori, 2003). The 44% longer SFG engagement during Detailing (12.4 s vs. 8.6 s; $p < .001$) confirms Badre and Wagner's (2007) account of sustained prefrontal retrieval and integration. Right-hemisphere dominance during Comparing ($p = .048$) reflects evaluative, relational processing, consistent with Fleming et al.'s (2012) report of right prefrontal metacognitive monitoring. Goldman-Eisler (1967) noted that rightward asymmetries during speech signal elevated integration demands, corroborating the present lateralization data.

The correlation between SFG-Clarifying performance ($r = 0.68$, $p < 0.001$) confirms that prefrontal cortex engagement can predict effective explanatory output, consistent with Vygotsky's (1978) thesis that language functions as a regulator of thought and with neuropsycholinguistic frameworks (Köpke, 2017; Villiard & Nespoulous, 1989; Pourquie, 2013; Radjabovich, 2022). Kuznetsov et al. (2023), in a comparable sLORETA study, demonstrated that the lateral frontoparietal network regulates controlled verbal thinking during divergent problem-solving. This study complements those findings: the superior frontal gyrus (BA10) functions as a real-time execution center for higher-order thinking skills (HOTS) during open speech. Together, these lines of research point to a picture of prefrontal verbal cognition in which both controlled inner speech and open speech driven by HOTS recruit anterior prefrontal structures.
Methodologically, Nir et al. (2008) validated sLORETA to identify well-defined cortical generators. Convergent localization to BA10 across nine independent conditions aligns with fMRI evidence from branching paradigms (Ramnani & Owen, 2004; Badre & Wagner, 2007), providing cross-method validation. The EEG approach captures dynamic neural activity in real-time during speech, an advantage over hemodynamic methods (Wöstmann et al., 2016; Alday, 2019). Limitations include a small sample size ($N = 24$) and the restriction to young adult Indonesian students; future research should employ a larger sample, whole-brain connectivity analysis, and a longitudinal design.

Conclusions

This study provides the first direct neurophysiological evidence linking specific HOTS operational verbs to superior frontal gyrus activity during speech production. sLORETA analysis localized peak activation to BA10 across all nine HOTS conditions; Comparing, Detailing, and Clarifying elicited the strongest and most sustained engagement (Cohen's $d = 5.10–8.04$). SFG BA10 serves as a functional hub for cognitive integration during higher-order verbal thinking. Incorporating HOTS operational verbs, particularly comparing, detailing, and clarifying, into language pedagogy targets the prefrontal circuits underlying critical cognition, providing a neurobiologically grounded basis for 21st-century curriculum design (Martinez, 2022; Merzenich et al., 1996).

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CRediT Statement

Jatmika Nurhadi: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Writing – Original Draft, Writing – Reviewing & Editing, Visualization; **Dadang Sudana:** Validation, Writing – Reviewing & Editing, Supervision.

Disclosure Statement

The authors reported no potential conflicts of interest.

Generative AI Statement

Artificial intelligence-based language tools (DeepL and Grammarly) were used to assist with the translation, drafting, and editing of the manuscript. All EEG data collection, sLORETA analysis, statistical calculations, and scientific interpretation were performed entirely by the research team. The text drafted with the assistance of AI has been reviewed, verified, and approved by all authors.

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