

Age-Related Differences in Sentence Comprehension and Prefrontal Activation: A Functional Near-Infrared Spectroscopy (fNIRS) Study

Jiseong Kim, Eunsong Lee, Geum Chae Moon, Ji Yeon Lee, Yuri Cho, Seohui Lee, Jee Eun Sung

Department of Communication Disorders, Ewha Womans University, Seoul, Korea

Correspondence: Jee Eun Sung, Ph.D.
Department of Communication Disorders,
Ewha Womans University, 52 Ewhayeodae-gil,
Seodaemun-gu, Seoul 03760, Korea
Tel: +82-2-3277-2208
Fax: +82-2-3277-2122
E-mail: jeesung@ewha.ac.kr

Received: January 5, 2026

Revised: March 17, 2026

Accepted: March 17, 2026

This work was supported by the National Research Foundation of Korea (NRF) grants funded by the Korean government (MSIT) in 2026 (RS-2022-NR070151, RS-2024-00461617, NRF-2026S1A5A2A03006789). (Grant No. RS-2024-00461617, Project Title: Global Convergent Research on Healthcare Solutions to Overcome Hearing Loss and Dementia, 50%; Grant No. RS-2022-NR070151, Project Title: Development of language-hearing program and integrative neural network studies for early assessment and treatment of hearing loss-induced dementia, 25%; Grant No. NRF-2026S1A5A2A03006789, Project Title: Cross-linguistic and multicultural aspects of language processing in aging and neurogenic communication disorders: Evidence from Korean, Chinese, English, and Spanish, 25%).

Objectives: This study examined age-related differences in sentence comprehension by integrating behavioral performance and prefrontal cortical activation measured with functional near-infrared spectroscopy (fNIRS). Focusing on Korean sentence processing, which allows flexible word order through case marking, we investigated whether aging is associated with structure-specific syntactic deficits or with altered recruitment of prefrontal control resources that support sentence interpretation under increased processing demands. **Methods:** Younger (N = 11) and older (N = 10) Korean adults completed a picture-sentence matching task while fNIRS data were recorded. Sentence stimuli were systematically manipulated according to grammatical voice (active vs. passive) and word-order canonicity (canonical vs. noncanonical), yielding four sentence types. Behavioral measures included mean sentence comprehension scores and reaction times. Neural activity was indexed by changes in oxygenated hemoglobin (ΔHbO) within anatomically defined prefrontal subregions, including the frontopolar and orbitofrontal cortices. **Results:** Behaviorally, older adults demonstrated significantly lower comprehension scores and slower reaction times overall compared to younger adults. However, no significant Group $\times$ Sentence Type interactions were observed, indicating that age-related performance differences were not selectively tied to particular sentence structures. Hemodynamic analyses revealed a region- and condition-specific effect: younger adults showed greater task-evoked activation than older adults in the right orbitofrontal cortex during passive canonical sentence processing. No reliable age-related differences were observed in other prefrontal regions or sentence conditions. **Conclusion:** These findings suggest that age-related differences in sentence comprehension may reflect reduced efficiency in recruiting prefrontal control and regulatory mechanisms during sentence interpretation, rather than selective degradation of syntactic representations associated with specific grammatical structures.

Keywords: Aging, Sentence comprehension, Syntactic complexity, fNIRS, Prefrontal cortex

Aging affects sentence comprehension, particularly when syntactic structures become complex. Numerous studies have documented this decline across diverse linguistic contexts and experimental paradigms (Caplan et al., 2011; DeDe et al., 2004; Kemper & Kemtes, 1999). Working memory (WM) plays a central role in explaining these age-related difficulties. During sentence processing, WM temporarily holds linguistic information while syntactic

computations proceed and meaning is constructed (Just & Carpenter, 1992). The capacity of this system varies across individuals, and these differences predict comprehension success: people with greater WM capacity generally comprehend complex sentences more accurately (Waters & Caplan, 2003).

These cognitive declines are accompanied by structural and functional deterioration of the brain, which may underlie the

working memory and comprehension deficits described above, manifesting in diverse ways (Cabeza et al., 2018; Park & Reuter-Lorenz, 2009). Neuroimaging studies examining age-related changes in prefrontal activation during cognitive tasks have yielded contradictory findings. Some studies report that older adults exhibit increased prefrontal activation compared to younger adults, particularly at low to moderate levels of task difficulty. This pattern has been interpreted as neural compensation for declining cognitive resources (Cabeza, 2002; Reuter-Lorenz & Cappell, 2008). In this compensatory view, as sensory and cognitive systems deteriorate with aging, older adults may recruit additional resources to meet the demands of challenging tasks.

In contrast, other studies have reported reduced activation in task-sensitive brain regions in older adults relative to younger adults, suggesting limits in the effective recruitment of domain-specific neural systems with aging (Grady et al., 1994; Logan et al., 2002). This pattern of under-recruitment has been associated with insufficient neural resources to support task performance, particularly when cognitive complexity increases. This divergence underscores the importance of considering task demands and individual cognitive resources when interpreting age-related neural activation patterns. However, these competing accounts make distinct and testable predictions regarding the direction of age-related differences in prefrontal activation under increasing syntactic demands. Clarifying these predictions is essential for evaluating whether age-related changes reflect compensatory recruitment or reduced neural efficiency (Cabeza et al., 2002; Grady, 2012; Reuter-Lorenz & Cappell, 2008).

Research on the neural basis of sentence comprehension has primarily been conducted using functional magnetic resonance imaging (fMRI; Matchin et al., 2017; Meyer & Friederici, 2016; Rodd et al., 2010) and electroencephalography (EEG; Hald et al., 2006; Khachatryan et al., 2018; Weiss et al., 2005). However, both methods have distinct limitations. While fMRI provides high spatial resolution, it faces significant challenges during language- and auditory-based task performance due to equipment noise, constraints on bodily movement, and restrictions on acoustic stimulus presentation. Moreover, participation among older adults imposes a considerable burden. Although EEG offers excellent temporal resolution, its limited spatial resolution constrains the ability

to differentiate functional variations within subregions of the prefrontal cortex. In contrast, functional near-infrared spectroscopy (fNIRS) is quiet, non-invasive, and permits task performance in natural postures, thus demonstrating high ecological validity in language research (Cutini et al., 2012; Ferrari & Quaresima, 2012; Hoshi, 2011). Notably, the prefrontal cortex exhibits optical accessibility, enabling stable measurement of hemodynamic responses such as changes in oxyhemoglobin (ΔHbO) and deoxyhemoglobin (ΔHbR), which serve as indirect indices of local neural activity through neurovascular coupling (Ferrari & Quaresima, 2012; Herrmann et al., 2017; Sato et al., 2013; Shin et al., 2024).

The prefrontal cortex is thought to subserve domain-general cognitive control functions in sentence processing, such as monitoring information maintained in working memory, selecting among alternative semantic interpretations, and inhibiting or regulating responses in accordance with task demands (Hogeveen et al., 2022; Mansouri et al., 2017). These functions may be especially critical in the comprehension of Korean passive constructions and noncanonical word-order sentences, which frequently require re-analysis based on case-marking cues and verb information.

Within the prefrontal cortex, the frontopolar cortex (approximately Brodmann area 10) has been implicated in high-level cognitive control, including goal management, prospective memory, and the integration of multiple information sources during complex task performance (Hogeveen et al., 2022). The orbitofrontal cortex (OFC), corresponds broadly to ventral prefrontal regions, including Brodmann areas 11 and 12, and has been associated with cognitive control and the evaluation and updating of contextual information, which may support the regulation of competing interpretations under increased processing demands (Rolls, 2004).

By focusing on frontopolar and orbitofrontal regions accessible to fNIRS, the present study examines whether aging modulates the recruitment of prefrontal control and regulatory mechanisms that support sentence interpretation under increased syntactic processing demands.

Despite these methodological advantages, research using fNIRS to examine age-related changes in syntactic processing remains limited, particularly in languages with typologically distinct properties such as Korean. Korean offers unique opportunities to manipulate syntactic complexity due to its verb-final structure, rela-

tively flexible word order, and case-marking system, which differ substantially from English. However, studies that directly capture prefrontal activation differences between younger and older adults during Korean sentence comprehension remain scarce. Importantly, syntactic manipulations such as passive constructions and noncanonical word order are assumed to increase demands on prefrontal control processes, including working memory updating and the inhibition of initially preferred but incorrect interpretations. These processes place additional regulatory demands on prefrontal systems, providing a basis for linking syntactic complexity to prefrontal activation. The neural activity patterns underlying the cognitive load imposed by syntactic complexity, particularly their relationship to prefrontal functions for sentence comprehension, have not been sufficiently elucidated.

Although research on Korean sentence processing in aging populations is limited, some behavioral studies have begun to address this gap. As a head-final language, Korean typically follows a canonical Subject–Object–Verb (SOV) order, which contrasts with the Subject–Verb–Object (SVO) order of English (Im, 2007; Nam, 1988; Nam et al., 2021). Moreover, because the verb remains clause-final, Korean permits considerable word-order flexibility through scrambling, which has led to its classification as a free word-order language (Sohn, 2006; Yoon, 2018). This flexibility allows scrambled structures such as object-subject-verb (OSV) alongside the canonical SOV order (Lee et al., 2015). Sung et al. (2017) leveraged these typological properties to examine how working-memory capacity affects sentence comprehension in older adults. They manipulated sentence complexity using two linguistic factors—voice (active vs. passive) and word order (canonical vs. noncanonical)—resulting in four sentence types that varied in syntactic difficulty. Results showed that older adults with higher working memory capacity achieved better comprehension of syntactically complex sentences, suggesting that working memory serves as cognitive reserve that mitigates age-related decline in linguistic processing.

In Korean active sentences, the nominative case marker “-ka” is typically interpreted as marking the agent of the action. For example, in “A-ka B-lul ccoth-ta (A가 B를 쫓다, *A chases B*),” the nominative noun phrase (NP) A-ka is straightforwardly understood as the actor who performs the chasing event. However, in

Korean passive constructions such as “A-ka B-eykey ccoth-ki-ta (A가 B에게 쫓기다, *A is chased by B*),” the NP marked with ‘-ka’ donates the theme (or patient), not the agent. This creates a mismatch between the syntactic marker and the thematic role expectation. Furthermore, the actual agent is marked by the dative case along with passive morphological inflections in the verbs. This reanalysis process associated with passivization is known to significantly increase processing demands (Sung, 2015; Sung et al., 2017).

Similarly, in noncanonical active sentences such as “B-lul A-ka ccoth-ta (B를 A가 쫓다),” the theme appears sentence-initially, preceding the agent. Although this structure is grammatically permissible in Korean due to case marking, the canonical “A-ka B-lul ccoth-ta (A가 B를 쫓다)” form is generally preferred in everyday usage. The structural flexibility of Korean allows both configurations to be interpreted correctly, but this flexibility allows multiple potential agent–theme interpretations during comprehension (Yoon, 2018). Korean speakers have been shown to rely on an initial agent-first parsing heuristic, preferentially interpreting the first noun phrase as the agent (Sung et al., 2017). In noncanonical structures, this heuristic must be suppressed, requiring readers to reassign thematic roles based on case-marking and verb-based cues rather than linear order (Hwang & Kaiser, 2014; Miyamoto, 2002).

These processing difficulties arise not from sentence length or lexical complexity, but from the need to inhibit incorrect structural interpretations that compete during comprehension. Older adults show particular vulnerability in these inhibitory processes; they experience greater difficulty suppressing misleading interpretations when confronted with noncanonical structures compared to younger adults (DeDe et al., 2004; Hasher & Zacks, 1988; Just & Carpenter, 1992; Kemper & Kemtes, 1999). These age-related vulnerabilities in syntactic processing have been observed across languages, suggesting that aging affects core components of syntactic parsing and the suppression of competing interpretations, thereby contributing to declines in sentence-comprehension performance.

Therefore, the present study investigated whether age-related difficulties in syntactic processing are closely related to changes in prefrontal function—either diminished efficiency or increased compensatory activation—during the comprehension of sentence-

es with varying syntactic complexity. By combining behavioral and fNIRS measures, the present study examined how syntactic conditions influence sentence-comprehension accuracy, reaction times, and prefrontal hemodynamics in younger and older Korean adults.

Based on these theoretical accounts, several predictions can be derived. First, at the behavioral level, we predicted a Group $\times$ Sentence Type interaction, such that older adults would show disproportionately reduced accuracy and increased reaction times relative to younger adults under conditions of greater syntactic complexity. Behaviorally, older adults were expected to experience greater difficulty than younger adults when processing syntactically complex sentences, particularly those involving passive constructions and noncanonical word order. Because these structures require reanalysis of thematic roles and suppression of initial parsing heuristics, older adults were predicted to show disproportionately lower comprehension accuracy and longer reaction times in these conditions. Importantly, the greatest difficulty was expected in conditions combining passive voice and noncanonical word order, which impose the highest syntactic processing demands. These behavioral predictions were operationalized as specific Group $\times$ Sentence Type interactions, with planned comparisons focusing on differences between canonical and noncanonical word orders as well as between active and passive constructions.

At the neural level, competing theoretical accounts make different predictions regarding prefrontal activation. These predictions can be directly tested by examining group differences in Δ HbO responses across syntactic conditions. Specifically, we examined age-related differences in Δ HbO responses across syntactic conditions and prefrontal regions to determine whether the observed activation pattern was more consistent with compensatory recruitment or under-recruitment. Under a compensatory recruitment account, increased task demands associated with syntactic complexity should elicit greater prefrontal activation in older adults relative to younger adults, reflecting the additional recruitment of cognitive resources. In contrast, an under-recruitment account predicts reduced activation in task-sensitive prefrontal regions in older adults, reflecting limitations in effectively engaging domain-relevant neural resources during complex sentence processing.

Specifically, we addressed the following research questions:

1. Do sentence-comprehension scores and reaction times differ depending on age groups and syntactic conditions?
2. Do Δ HbO responses differ between younger and older adults as a function of syntactic condition and prefrontal subregion?

METHODS

Participants

Twenty-one adults residing in South Korea participated in this study. Participants were divided into two age groups: Young adults ($N = 11$, $M = 27.36$, $SD = 6.10$) and Old adults ($N = 10$, $M = 68.73$, $SD = 8.19$). An independent sample t -test confirmed a significant age difference between the two groups, while no significant difference was observed in years of education. The current study was authorized by the Institutional Review Board (No. 2023-0337) and written consent was obtained from all participants.

Old adults were included if they scored at or above the 16th percentile, adjusted for age and education, on the Korean version of the Mini-Mental State Examination (K-MMSE; Kang, 2006), indicating normal cognitive function. Additionally, all participants scored within the normal range on both the Subjective Memory Complaints Questionnaire (SMCQ; Youn et al., 2009) and the Short-form Geriatric Depression Scale (SGDS-K; Cho et al., 1999). Group characteristics and test scores are summarized in Table 1.

Experimental Task

The experiment employed a sentence comprehension task adapted from previous work (Sung, 2015, 2017; Sung et al., 2017), in which similar manipulations have been shown to reliably mod-

Table 1. Demographic information and screening results

Variable	Young group ($N = 11$)	Older group ($N = 10$)	p -value
Sex (male: female)	5:6	5:5	-
Years of education	15.82 (1.07)	13.82 (3.40)	.088
K-MMSE	29.09 (1.22)	28.55 (2.01)	.452
SGDS-K	2.27 (2.19)	1.27 (1.48)	.226
SMCQ	1.55 (1.29)	2.36 (1.286)	.152

Values are presented as mean (standard deviation).

K-MMSE = Korean Mini-Mental State Examination (Kang, 2006); SGDS-K = Short version of the Geriatric Depression Scale (Cho et al., 1999); SMCQ = Subjective Memory Complaints Questionnaire (Youn et al., 2009).

ulate sentence comprehension performance. The task followed a picture-sentence matching paradigm, in which participants viewed pairs of pictograms depicting three abstract characters (the Yellow, the Blue, and the Black) and listened to corresponding Korean sentences. All stimuli were limited to two-argument structures and classified into four syntactic conditions based on two

Table 2. Representative sentence stimuli and their structural characteristics across conditions (A_C, A_NC, P_C, P_NC)

Condition	Example (English)	Example (Korean)	Gloss	Word count
A_C	The Yellow chases the Black.	노랑이가 검정이를 쫓다	Yellow-NOM Black-ACC chase-DECL	3
A_NC	The Yellow chases the Black.	검정이를 노랑이가 쫓다	Black-ACC Yellow-NOM chase-DECL	3
P_C	The Black is chased by the Yellow.	검정이가 노랑이에게 쫓기다	Black-NOM Yellow-DAT chase-PASS-DECL	3
P_NC	The Black is chased by the Yellow.	노랑이에게 검정이가 쫓기다	Yellow-DAT Black-NOM chase-PASS-DECL	3

Word count corresponds to eojeol units in Korean.

English translations are identical across canonical and noncanonical conditions because differences arise from word order rather than propositional meaning.

NOM=nominative case marker; ACC=accusative case marker; DAT=dative case marker; PASS=passive marker; DECL=declarative sentence ending; A_C=active-canonical; A_NC=active-noncanonical; P_C=passive-canonical; P_NC=passive-noncanonical.

variables: voice (active vs. passive) and word order canonicity (canonical vs. noncanonical), resulting in four conditions: active-canonical (A_C), active-noncanonical (A_NC), passive-canonical (P_C), and passive-noncanonical (P_NC). Sentence length (word count) was controlled across conditions, with word counts based on eojeol units in Korean. Representative examples of each sentence type are provided in Table 2.

A block-design functional near-infrared spectroscopy (fNIRS) paradigm was used to examine cerebral hemodynamic responses to these syntactic structures. Each block began with a 60-second rest period, followed by six trials from a single syntactic condition. Each of the four syntactic conditions (A_C, A_NC, P_C, P_NC) was presented in a single block, resulting in a total of 24 trials (6 trials per condition). The sequence of blocks was pseudo-randomized across participants to minimize order effects. In each trial, participants listened to a sentence presented only once, then selected the matching picture from two options displayed on a laptop screen. Responses were made using designated keyboard keys, and only the first response was recorded (correct = 1, incorrect = 0). The position of the correct response (left/right) was counterbalanced across trials, and foil images were also counterbalanced to minimize response bias. Before the main task, participants completed four practice trials to become familiar with the

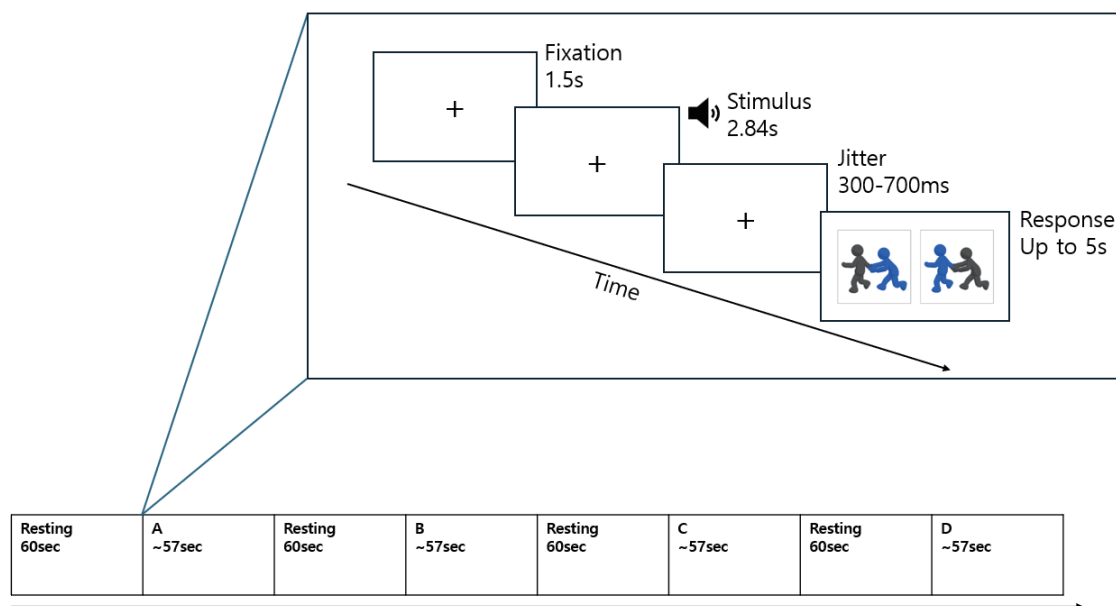


Figure 1. Experimental task procedure of the fNIRS block design.

procedure (see Figure 1 for task structure).

All visual and auditory stimuli were presented using PsychoPy version 2024.1.5 (Open Science Tools, Nottingham, UK) on a Samsung laptop with a 13.3 × 10.8 inch screen. Stimuli were controlled for lexical properties and plausibility across conditions. In addition, auditory stimuli were matched for duration as closely as possible to ensure comparability across sentence types. Participants wore the fNIRS device throughout the experiment, including during rest and task blocks.

fNIRS Device and Data Acquisition

Cerebral hemodynamic activity was measured using the NIR-SIT Lite system (OBELAB Inc., Seoul, South Korea), a portable fNIRS device with a sampling rate of 8.138 Hz (Choi et al., 2016). The device consists of five laser sources and seven photodetectors, yielding 21 channels: 15 long-separation channels (source-detector distance: 3 cm) and 6 short-separation channels (0.8 cm). Near-infrared light at 780 and 850 nm was emitted by the sources, and the detectors captured signal changes reflecting changes in hemoglobin concentration (ΔHb). To reduce the influence of superficial blood flow, only 15 long-separation channels were included in the analysis, while short-separation channels were used to regress out extracerebral signals.

Prior to device placement, participants' foreheads were fully exposed by securing their hair with pins or bands. The center mark of the device was aligned with the midpoint between the eyebrows, and the headband was fastened with a Velcro strap, to ensure a secure yet comfortable fit and prevent discomfort or headaches.

Signal Preprocessing

Raw light intensity signals were first screened for quality. Channels with a signal-to-noise ratio below 20 dB (Lin et al., 2023) were excluded. Participants for whom more than 30 percent of channels failed to meet this criterion were removed from subsequent analyses (three younger and two older participants). The remaining signals were converted to optical density and corrected for motion artifacts using Temporal Derivative Distribution Repair (TDDR; Fishburn et al., 2019). Short-separation channel data (8 mm) were regressed out of long-separation signals (30 mm) to remove superficial hemodynamics (Gagnon et al., 2012; Wyser et al., 2020). The

optical density time series were then filtered using a fourth-order Butterworth bandpass filter (0.01–0.5 Hz) and transformed into hemoglobin concentration changes via the Modified Beer–Lambert Law, applying Moaveni's extinction coefficients (Zhao et al., 2017). Additional noise correction was performed using Correlation-Based Signal Improvement (CBSI; Cui et al., 2010; Ehliis et al., 2024).

The final 15 seconds of the rest period preceding each block were defined as the baseline, and changes in oxygenated hemoglobin (ΔHbO) during sentence processing were computed relative to this baseline.

Channel Selection and Anatomical Grouping

To examine the effects of syntactic condition on cortical activation, the prefrontal cortex (PFC) was divided into four anatomical subregions: right frontopolar PFC (right FP), right orbitofrontal cortex (right OFC), left frontopolar PFC (left FP), and left orbitofrontal cortex (left OFC). Channel assignments to each subregion were determined based on estimated anatomical locations derived from Montreal Neurological Institute (MNI) coordinates and the standard layout of the NIR-SIT Lite system.

Of the 15 long-separation channels, three were excluded from the ROI analysis: Channel 8, located near the midline and corresponding to a central region, and Channels 1 and 15, located at the lateral edges of the montage, whose measurement fields did not sufficiently overlap with any of the four target subregions. The remaining 12 channels were assigned to ROIs according to the spatial correspondence between each channel's estimated measurement field and the target subregions. Channels whose measurement fields fell predominantly within a single subregion were assigned exclusively to that subregion: Channels 2, 3, 5, and 6 to the right FP; Channel 7 to the right OFC; and Channels 9, 11, 12, and 14 to the left FP. Three channels—Channel 4 in the right hemisphere and Channels 10 and 13 in the left hemisphere—were located at the boundary between the frontopolar and orbitofrontal subregions, with measurement fields overlapping the two adjacent regions to approximately equal extents (about 50% each). Rather than assigning these boundary channels arbitrarily to a single region, each was included in both adjacent ROIs with a weight of .5. Accordingly, ROI-level ΔHbO values were computed as weighted

averages of the constituent channels: right FP (Channels 2, 3, 5, 6; Channel 4, $w = .5$), right OFC (Channel 7; Channel 4, $w = .5$), left FP (Channels 9, 11, 12, 14; Channels 10 and 13, $w = .5$ each), and left OFC (Channels 10 and 13, $w = .5$ each). A complete visualization of the channel-to-region mapping is provided in Figure 2.

Statistical Analyses

Behavioral data

To evaluate group differences in sentence-comprehension performance, two dependent measures were analyzed separately: mean scores and reaction times (RT). For each measure, a two-way mixed analysis of variance (ANOVA) was conducted with Group (Young, Old) as a between-subjects factor and Sentence Type (A_C, A_NC, P_C, P_NC) as a within-subjects factor. Assumptions of normality and sphericity were assessed prior to analysis, and when sphericity was violated, Greenhouse–Geisser corrections were applied. Partial eta squared (η_p^2) was reported as a measure of effect size for all ANOVA tests. All behavioral analyses were performed using IBM SPSS Statistics (version 29.0), with the significance level set at $\alpha = .05$ (two-tailed).

Hemodynamic data

To examine age-related differences in task-evoked cortical activation, ΔHbO values were averaged within four anatomically de-

fined regions of interest (ROIs) in the prefrontal cortex: the right frontopolar prefrontal cortex (right FP), the right orbitofrontal cortex (right OFC), the left frontopolar prefrontal cortex (left FP), and left orbitofrontal cortex (left OFC), based on long-separation channel groupings in the NIRSIT Lite montage. Given the small sample size and the need to minimize reliance on parametric assumptions, two-sample permutation tests (10,000 iterations) were performed to compare the Young and Old groups for each syntactic condition. Null distributions of the mean differences were generated by randomly permuting group labels. Multiple comparisons across ROI-condition combinations were corrected using the Benjamini–Hochberg false discovery rate (FDR) procedure with a significance threshold of $\alpha = .05$. All hemodynamic analyses were performed in Python (Google Colab), using the pandas, NumPy,

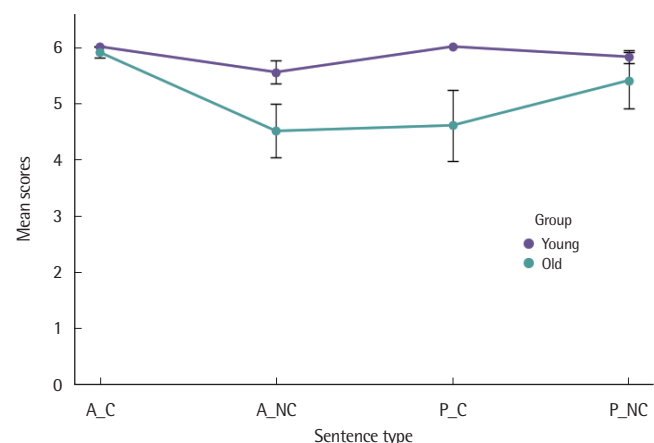


Figure 3. Group differences in sentence comprehension scores across sentence types.

Error bars represent ± 1 standard error of the mean (SE).

Sentence types included active-canonical (A_C), active-noncanonical (A_NC), passive-canonical (P_C), and passive-noncanonical (P_NC).

Young = younger adults; Old = older adults.

Table 3. Descriptive statistics of sentence comprehension scores by sentence type and group

Sentence type	Young	Old
A_C	6.00 (.000)	5.90 (.316)
A_NC	5.55 (.688)	4.50 (1.509)
P_C	6.00 (.000)	4.60 (2.011)
P_NC	5.82 (.405)	5.40 (1.578)

Values are presented as the mean (SD).

Sentence types included active-canonical (A_C), active-noncanonical (A_NC), passive-canonical (P_C), and passive-noncanonical (P_NC).

SD = standard deviation; Young = younger adults; Old = older adults.

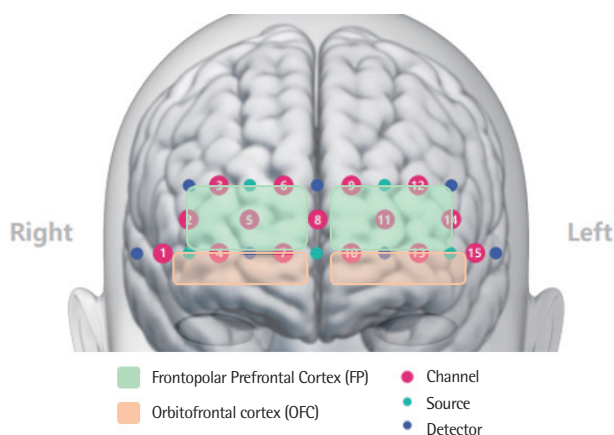


Figure 2. Anatomical grouping of fNIRS channels based on estimated cortical location.

The layout includes source (green), detector (blue), and channel (pink) positions projected onto the forehead, along with estimated anatomical locations corresponding to subregions of the prefrontal cortex. Image and coordinate data adapted from “[NIRSIT LITE] Channel Information”, OBELAB Inc.

and statsmodels libraries, with custom permutation procedures implemented in NumPy.

RESULTS

Behavioral Performance

A two-way mixed ANOVA was conducted to examine the effects of Sentence Type (A_C, A_NC, P_C, P_NC) and Group (Young, Old) on sentence comprehension scores. Descriptive sta-

Table 4. Descriptive statistics of sentence comprehension reaction time by sentence type and group

Sentence type	Young	Old
A_C	1,062.9 (158.9)	2,399.9 (629.6)
A_NC	1,242.3 (252.3)	2,520.3 (760.8)
P_C	1,253.2 (282.9)	2,833.7 (759.2)
P_NC	1,295.7 (287.2)	2,687.5 (571.8)

Values are presented as the mean (SD) in milliseconds (ms).

Sentence types included active-canonical (A_C), active-noncanonical (A_NC), passive-canonical (P_C), and passive-noncanonical (P_NC).

SD=Standard deviation.

Table 5. ROI-wise permutation *p*-values and FDR-corrected *q*-values for group comparisons (Young vs. Old) on mean ΔHbO for each condition

Condition	ROI	Permutation <i>p</i> -value	FDR-corrected <i>q</i> -value
A_C	Rt_OFC	.083	.184
A_C	Rt_FP	.191	.306
A_C	Lt_OFC	.035	.184
A_C	Lt_FP	.028	.184
A_NC	Rt_OFC	.175	.306
A_NC	Rt_FP	.572	.572
A_NC	Lt_OFC	.409	.504
A_NC	Lt_FP	.507	.541
P_C	Rt_OFC	.002*	.024*
P_C	Rt_FP	.092	.184
P_C	Lt_OFC	.320	.427
P_C	Lt_FP	.312	.427
P_NC	Rt_OFC	.078	.184
P_NC	Rt_FP	.078	.184
P_NC	Lt_OFC	.070	.184
P_NC	Lt_FP	.488	.541

p-values were corrected using the Benjamini–Hochberg FDR procedure.

Asterisks (*) indicate statistically significant differences at $q < .05$.

Sentence types included active-canonical (A_C), active-noncanonical (A_NC), passive-canonical (P_C), and passive-noncanonical (P_NC).

Regions of interest (ROIs) included the right orbitofrontal cortex (Rt-OFC), right frontopolar prefrontal cortex (Rt-FP), left orbitofrontal cortex (Lt-OFC), and left frontopolar prefrontal cortex (Lt-FP).

tistics for comprehension scores across groups and sentence types are presented in Table 3 and Figure 3. The analysis revealed a significant main effect of Group, $F_{(1, 19)} = 5.23$, $p < .05$, $\eta^2 = .22$, indicating that overall mean scores differed between the two groups. There was also a significant main effect of Sentence type, $F_{(3, 57)} = 4.25$, $p < .05$, $\eta^2 = .18$, demonstrating that mean scores varied across the four sentence conditions. In contrast, the Group $\times$ Sentence Type interaction was not significant, $F_{(3, 57)} = 2.31$, $p = .086$, $\eta^2 = .11$, suggesting that the pattern of sentence-type effects was comparable across groups.

A two-way mixed ANOVA was conducted to examine the effects of Sentence Type (A_C, A_NC, P_C, P_NC) and Group (Young, Old) on reaction time (RT) during sentence comprehension. Mean RTs for each group and sentence type are summarized in Table 4 and Figure 4. The main effect of Group was significant, $F_{(1, 19)} = 527.01$, $p < .05$, $\eta^2 = .97$, indicating that overall RT differed between the two groups. In contrast, the main effect of Sentence Type was not significant, $F_{(3, 57)} = 2.71$, $p > .05$ (Greenhouse–Geisser corrected), $\eta^2 = .12$, suggesting that RT did not vary reliably across the four sentence conditions. The Group $\times$ Sentence Type interaction was also not significant, $F_{(3, 57)} = .61$, $p > .05$, $\eta^2 = .03$, indicating that the pattern of RT across sentence types was comparable between the groups.

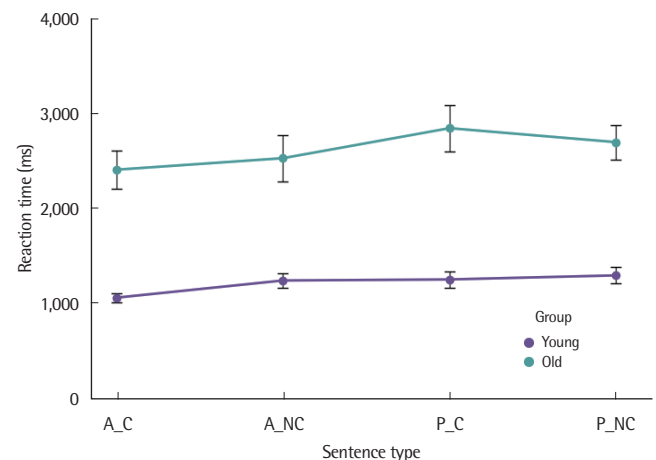


Figure 4. Group differences in sentence comprehension response times across sentence types.

Error bars represent ± 1 standard error of the mean (SE).

Sentence types included active-canonical (A_C), active-noncanonical (A_NC), passive-canonical (P_C), and passive-noncanonical (P_NC).

Young = younger adults; Old = older adults.

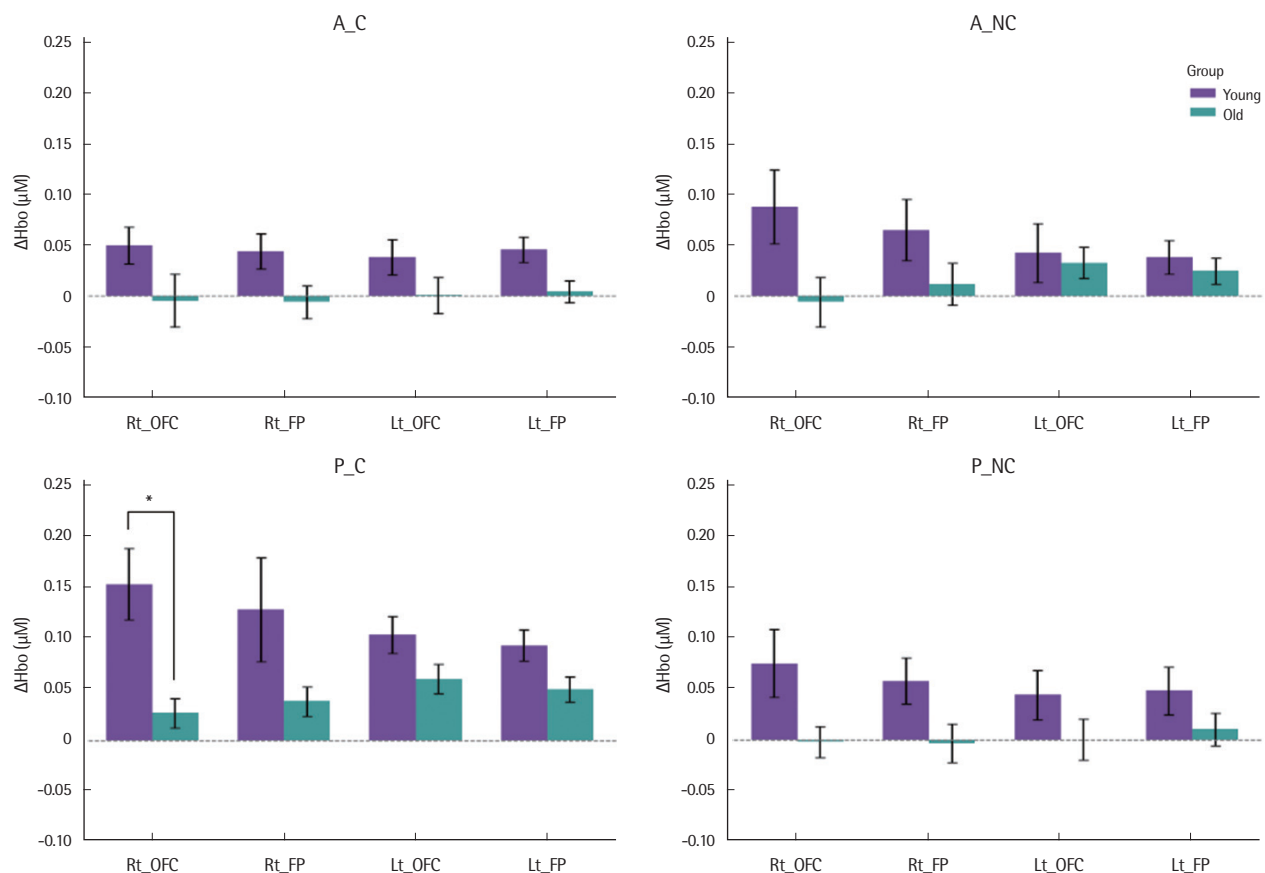


Figure 5. Group differences in ΔHbO by ROI across sentence conditions.

Mean ΔHbO with standard error for Young and Old groups.

Asterisks (*) indicate significant group differences after FDR correction ($q < .05$).

Sentence types included active-canonical (A_C), active-noncanonical (A_NC), passive-canonical (P_C), and passive-noncanonical (P_NC).

Regions of interest (ROIs) included left frontopolar prefrontal cortex (Lt_FP), right frontopolar prefrontal cortex (Rt_FP), left orbitofrontal cortex (Lt_OFC), and right orbitofrontal cortex (Rt_OFC).

Hemodynamic Responses

To examine age-related differences in task-evoked cortical activation, permutation tests ($N = 10,000$) were conducted for each syntactic condition and ROI, with the FDR correction applied. The right OFC showed significantly higher activation in younger adults in the P_C condition ($p = .002$, FDR-corrected $q = .024$). No other ROI showed significant differences after FDR correction ($q > .05$). All ROI-wise results are summarized in Table 5 and Figure 5.

DISCUSSION

The current study examined age-related differences in sentence comprehension using both behavioral measures and fNIRS-de-

rived hemodynamic responses, focusing on sentences that varied systematically in syntactic structure. By manipulating voice and word order, the study sought to determine whether aging selectively affects particular syntactic configurations or more general aspects of linguistic processing efficiency. However, it is important to note that the present design primarily captures prefrontal contributions to sentence processing and does not directly assess neural systems traditionally associated with core syntactic computation.

The results demonstrated age-related differences in behavioral performance, alongside highly selective neural effects. While older adults showed lower mean scores and slower response times overall, the pattern of sentence-type effects was comparable across age groups. At the neural level, significant age-related differences were

confined to the right orbitofrontal cortex during passive canonical sentence processing. This finding indicates a condition-specific difference in prefrontal engagement rather than a generalized pattern of neural change. Importantly, because this effect was observed in a single condition and a single region, it should be interpreted with caution and not taken as evidence for broader neural mechanisms underlying syntactic processing.

The implications of these findings for models of sentence processing and cognitive aging are discussed in detail in the following sections.

The behavioral results demonstrated age-related differences in sentence comprehension scores, with younger adults showing higher overall performance than older adults. However, this difference was not uniform across all sentence types, and some conditions showed comparable performance between groups. This main effect of group is in line with a substantial body of literature documenting age-related declines in sentence comprehension, particularly in tasks that impose demands on syntactic processing and working memory resources (Caplan et al., 2011; DeDe et al., 2004; Kemper & Herman, 2006; Kemper & Kemtes, 1999). In addition, the significant main effect of sentence type indicates that comprehension scores varied as a function of syntactic structure, confirming that the experimental manipulation effectively modulated processing difficulty.

However, the absence of a significant Group $\times$ Sentence Type interaction should be interpreted with caution. Notably, the effect size for the interaction ($\eta^2 = .11$) suggests a non-negligible magnitude despite the lack of statistical significance. This pattern indicates that the absence of a significant interaction may reflect limited statistical power rather than the absence of meaningful group differences. Given the relatively small effective sample size following data-quality exclusion and the trend-level significance ($p = .086$), the present study may have been underpowered to detect interaction effects. In addition, ceiling-level performance in some conditions among younger adults may have reduced variability and sensitivity to group-by-condition differences. Therefore, the absence of a significant interaction does not provide strong evidence against structure-specific syntactic difficulty in aging. Rather, the present findings may reflect limitations in statistical power and task sensitivity.

Reaction time analyses revealed a significant main effect of group, but no main effect of sentence type and no group $\times$ sentence type interaction. Older adults responded more slowly overall, a finding that is well established in the aging literature and commonly attributed to generalized slowing of cognitive and motor processes (Myerson et al., 2003; Salthouse, 1996; Waters & Caplan, 2001). However, the absence of sentence-type effects on reaction time should be interpreted with caution: given the moderate effect size ($\eta^2 = .12$), this null result may reflect limited statistical power with the present sample size rather than a true absence of condition-specific differences in syntactic processing. Notably, older adults slowed uniformly across sentence types rather than selectively under greater syntactic demands—a pattern more consistent with general age-related slowing than with syntax-specific processing costs, although this interpretation remains tentative given the power considerations noted above.

Importantly, older adults did not slow their responses selectively in response to increased syntactic demands to maintain accuracy; instead, they exhibited uniformly slower response times across sentence types. However, this pattern may reflect generalized processing slowing rather than a definitive absence of sensitivity to syntactic complexity.

Although both behavioral and neural measures revealed age-related differences, the present study did not directly examine the relationship between individual differences in behavioral performance and prefrontal activation. In addition, because the observed neural effect was limited to a single condition and region, the current findings do not allow for strong conclusions regarding brain-behavior correspondence. Future studies should incorporate individual-level analyses to more directly examine these relationships.

The hemodynamic findings revealed a highly selective, region- and condition-specific pattern of age-related differences in cortical activation. Specifically, younger adults showed greater task-evoked activation than older adults in the right orbitofrontal cortex during passive canonical sentence processing. Importantly, no significant group differences were observed in the remaining prefrontal ROIs after FDR correction. These null findings should not be interpreted as evidence for the absence of functional differences, but rather should be considered in light of the limited sample

size, restricted number of trials, and potential constraints in signal sensitivity. Given that this effect was limited to a single region and condition, it should be interpreted as preliminary and requires replication. Furthermore, effect sizes and brain–behavior relationships were not examined in the present study, limiting conclusions about the functional significance of this activation difference. Accordingly, the present finding should be understood as a condition-specific observation rather than evidence of a generalizable neural mechanism underlying syntactic processing. The observation that greater neural activation in younger adults does not indicate processing difficulty *per se*, but rather reflects the engagement of neural resources supporting successful sentence comprehension, is consistent with neurocognitive frameworks emphasizing efficient resource utilization and compensatory mechanisms in aging (Cabeza et al., 2018; Pelle et al., 2010; Reuter-Lorenz & Cappell, 2008; Rypma et al., 2006; Wingfield & Grossman, 2006).

In the present study, younger adults demonstrated near-ceiling mean scores in the passive canonical condition, which may have constrained variability and contributed to the observed neural differences. By comparison, passive sentences have been consistently reported as particularly challenging for older adults. However, in the absence of direct measures of working memory or executive control, the interpretation that reduced activation reflects diminished recruitment of these processes remains indirect. Thus, any functional interpretation of this neural difference should be considered tentative. From this perspective, the reduced neural activation observed in older adults during passive canonical sentence processing may reflect limitations in the recruitment of auxiliary neural resources, rather than a degradation of syntactic representations themselves.

The orbitofrontal cortex is not traditionally considered a core language-processing region, but has been consistently implicated in higher-order evaluative and regulatory functions, including outcome monitoring, expectation updating, and decision-related control (Badre & D’Esposito, 2009; Kringelbach & Rolls, 2004). Accordingly, its involvement in the present study should be interpreted in relation to domain-general processes rather than core syntactic computation. In addition, the right-hemisphere localization of this effect warrants further investigation, as right prefrontal regions have been associated with broader contextual and inte-

grative processes during language comprehension.

Accordingly, the reduced right orbitofrontal cortex activation observed in older adults is tentatively interpreted as reflecting limitations in the recruitment of auxiliary regulatory processes required during sentence comprehension (Cabeza et al., 2018; Caplan et al., 2011; Just & Carpenter, 1992).

Taken together, the present study examined age-related differences in sentence comprehension by integrating behavioral measures with fNIRS-derived hemodynamic responses to sentences varying in syntactic structure. Behaviorally, older adults demonstrated lower overall scores and slower response times compared to younger adults, while preserving a sentence-type difficulty pattern that was comparable across age groups. However, this pattern should not be taken as definitive evidence against structure-specific syntactic impairment, given the methodological constraints noted above.

At the neural level, age-related differences were confined to reduced engagement of the right orbitofrontal cortex during passive canonical sentence processing. Because the present study did not include classical language regions (e.g., left inferior frontal or temporoparietal areas), it cannot directly adjudicate between structure-specific syntactic accounts and domain-general processing accounts. These findings therefore provide limited but suggestive evidence regarding age-related differences in prefrontal engagement during sentence comprehension. Together, these results underscore the importance of considering both behavioral performance and neural resource allocation in characterizing sentence comprehension in healthy aging, while also highlighting the need for cautious interpretation of neural findings derived from restricted cortical coverage.

Further methodological advances could also be achieved by integrating fNIRS with complementary neuroimaging modalities that offer higher spatial resolution or greater depth sensitivity, thereby enabling the examination of temporo-parietal and subcortical regions implicated in language processing. Future studies should also include independent measures of working memory and executive function to more directly test the proposed mechanisms underlying age-related differences in sentence comprehension.

In addition, although the syntactic manipulation was based on

prior literature, the relative difficulty of the four sentence types was not independently validated within the present sample. The block design may also have obscured trial-level variability in sentence processing, thereby limiting sensitivity to item-level or trial-level effects. Furthermore, averaging ΔHbO across relatively broad prefrontal ROIs may have reduced anatomical specificity and limited the ability to detect more fine-grained functional differences within prefrontal subregions.

Importantly, the relatively small sample size and participant exclusion based on data quality may have limited statistical power, particularly for detecting interaction effects and stabilizing effect estimates. Therefore, the absence of significant effects should not be interpreted as evidence for the absence of true differences. Instead, the observed patterns should be considered in light of effect sizes (e.g., η^2 values observed in the present analyses) and theoretical expectations. In addition, effect sizes for the hemodynamic group contrasts were not reported, which limits the evaluation of the practical significance of the observed neural differences.

In addition, alternative explanations should be considered when interpreting the hemodynamic findings. For example, age-related differences in vascular responsiveness, baseline shifts, or hemodynamic changes independent of neural activity may have contributed to the observed group differences in ΔHbO . Future studies with larger samples, improved experimental designs, and multimodal approaches are required to confirm the robustness and generalizability of the present findings.

REFERENCES

- Badre, D., & D'Esposito, M. (2009). Is the rostro-caudal axis of the frontal lobe hierarchical? *Nature Reviews Neuroscience*, 10(9), 659-669.
- Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: the HAROLD model. *Psychology & Aging*, 17(1), 85-100.
- Cabeza, R., Albert, M., Belleville, S., Craik, F. I., Duarte, A., Grady, C. L., & Rajah, M. N. (2018). Maintenance, reserve and compensation: the cognitive neuroscience of healthy ageing. *Nature Reviews Neuroscience*, 19(11), 701-710.
- Cabeza, R., Anderson, N. D., Locantore, J. K., & McIntosh, A. R. (2002). Aging gracefully: compensatory brain activity in high-performing older adults. *NeuroImage*, 17(3), 1394-1402.
- Caplan, D., DeDe, G., Waters, G., Michaud, J., & Tripodis, Y. (2011). Effects of age, speed of processing, and working memory on comprehension of sentences with relative clauses. *Psychology & Aging*, 26(2), 439-450.
- Cho, M. J., Bae, J. N., Suh, G. H., Hahm, B. J., Kim, J. K., Lee, D. W., & Kang, M. H. (1999). Validation of Geriatric Depression Scale, Korean version (GDS) in the assessment of DSM-III-R major depression. *Journal of Korean Neuropsychiatric Association*, 38(1), 48-63.
- Choi, J. K., Kim, J. M., Hwang, G., Yang, J., Choi, M. G., & Bae, H. M. (2016). Time-divided spread-spectrum code-based multichannel fNIRS IC for portable functional brain imaging. *IEEE Journal of Solid-State Circuits*, 51(2), 484-495.
- Cui, X., Bray, S., & Reiss, A. L. (2010). Functional near-infrared spectroscopy signal improvement based on negative correlation between oxygenated and deoxygenated hemoglobin dynamics. *NeuroImage*, 49(4), 3039-3046.
- Cutini, S., Moro, S. B., & Bisconti, S. (2012). Functional near-infrared optical imaging in cognitive neuroscience: an introductory review. *Journal of Near Infrared Spectroscopy*, 20(1), 75-92.
- DeDe, G., Caplan, D., Kemtes, K., & Waters, G. S. (2004). The relationship between age, verbal working memory, and language comprehension. *Psychology & Aging*, 19(4), 601-616.
- Ehlis, A. C., Zarantonello, L., Haeussinger, F. B., Rohe, T., Rosenbaum, D., Fallgatter, A. J., & Maier, M. J. (2024). The DLPFC is centrally involved in resolving Stroop conflicts, suppressing distracting sensory input within the auditory and visual system. *Frontiers in Psychology*, 15, 1427455.
- Ferrari, M., & Quaresima, V. (2012). A brief review on the history of human functional near-infrared spectroscopy (fNIRS) development and fields of application. *NeuroImage*, 63(2), 921-935.
- Fishburn, F. A., Ludlum, R. S., Vaidya, C. J., & Medvedev, A. V. (2019). Temporal derivative distribution repair (TDDR): a motion correction method for fNIRS. *NeuroImage*, 184, 171-179.
- Gagnon, L., Cooper, R. J., Yücel, M. A., Perdue, K. L., Greve, D. N., & Boas, D. A. (2012). Short separation channel location impacts the performance of short-channel regression in NIRS. *NeuroImage*, 59(3), 2518-2528.
- Grady, C. (2012). The cognitive neuroscience of ageing. *Nature Reviews Neuroscience*, 13(7), 491-505.
- Grady, C. L., Maisog, J. M., Horwitz, B., Ungerleider, L. G., Mentis, M. J., Salerno, J. A., & Haxby, J. V. (1994). Age-related changes in cortical blood flow activation during visual processing. *Journal of Neuroscience*, 14(3), 1450-1462.
- Hald, L. A., Bastiaansen, M. C., & Hagoort, P. (2006). EEG theta and gamma

- responses to semantic violations in online sentence processing. *Brain & Language*, 96(1), 90-105.
- Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: a review and a new view. *Psychology of Learning and Motivation*, 22, 193-225.
- Herrmann, M. J., Horst, A. K., Löble, S., Möll, M. T., Katzorke, A., & Polak, T. (2017). Relevance of dorsolateral and frontotemporal cortex on phonemic verbal fluency: a fNIRS study. *Neuroscience*, 367, 169-177.
- Hogeveen, J., Medalla, M., Ainsworth, M., Galeazzi, J. M., Hanlon, C. A., Mansouri, F. A., & Costa, V. D. (2022). What does the frontopolar cortex contribute to goal-directed cognition and action? *Journal of Neuroscience*, 42(45), 8508-8513.
- Hoshi, Y. (2011). Towards the next generation of near-infrared spectroscopy. *Philosophical Transactions of the Royal Society A*, 369(1955), 4425-4439.
- Hwang, H., & Kaiser, E. (2014). The role of the verb in grammatical function assignment in English and Korean. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 40(5), 1363-1377.
- Im, H. P. (2007). Language typological approach to word order of Korean. *Humanities Journal*, 22, 53-120.
- Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: individual differences in working memory. *Psychological Review*, 99(1), 122-149.
- Kang, Y. (2006). A normative study of the Korean-Mini Mental State Examination in the elderly. *Korean Journal of Psychology*, 25(2), 1-12.
- Kemper, S., & Herman, R. E. (2006). Age differences in memory-load interference effects in syntactic processing. *Journals of Gerontology: Series B*, 61(6), P327-P332.
- Kemper, S., & Kemtes, K. (1999). Limitations on syntactic processing. In S. Kemper & R. Kliegl (Eds.), *Constraints on language: Aging, grammar, and memory* (pp. 79-105). Kluwer Academic.
- Khachatryan, E., Brouwer, H., Staljanse, W., Carrette, E., Meurs, A., Boon, P., & Van Hulle, M. M. (2018). A new insight into sentence comprehension: the impact of word associations in sentence processing as shown by invasive EEG recording. *Neuropsychologia*, 108, 103-116.
- Kringelbach, M. L., & Rolls, E. T. (2004). The functional neuroanatomy of the human orbitofrontal cortex: evidence from neuroimaging and neuropsychology. *Progress in Neurobiology*, 72(5), 341-372.
- Lee, Y., Kwon, Y., & Gordon, P. C. (2015). Thematic roles, markedness alignment and processing complexity. *Journal of Psycholinguistic Research*, 44(3), 317-336.
- Lin, J., Lu, J., Shu, Z., Yu, N., & Han, J. (2023). An EEG-fNIRS neurovascular coupling analysis method to investigate cognitive-motor interference. *Computers in Biology & Medicine*, 160, 106968.
- Logan, J. M., Sanders, A. L., Snyder, A. Z., Morris, J. C., & Buckner, R. L. (2002). Under-recruitment and nonselective recruitment in aging. *Neuron*, 33(5), 827-840.
- Mansouri, F. A., Koechlin, E., Rosa, M. G., & Buckley, M. J. (2017). Managing competing goals—a key role for the frontopolar cortex. *Nature Reviews Neuroscience*, 18(11), 645-657.
- Matchin, W., Hammerly, C., & Lau, E. (2017). The role of the IFG and pSTS in syntactic prediction. *Cortex*, 88, 106-123.
- Meyer, L., & Friederici, A. D. (2016). Neural systems underlying the processing of complex sentences. In G. Hickok & S. L. Small (Eds.), *Neurobiology of Language* (pp. 597-606). Academic Press.
- Miyamoto, E. T. (2002). Case markers as clause boundary inducers in Japanese. *Journal of Psycholinguistic Research*, 31(4), 307-347.
- Myerson, J., Hale, S., Zheng, Y., Jenkins, L., & Widaman, K. F. (2003). The difference engine: a model of diversity in speeded cognition. *Psychonomic Bulletin & Review*, 10(2), 262-288.
- Nam, M. H. (1988). *Study on word order in Korean* (Master's thesis, Seoul National University).
- Nam, Y., Chung, H., & Kim, Y. (2021). An eye-tracking study on word order preference and the effect of phrasal length in Korean. *Communication Sciences & Disorders*, 26(4), 964-974.
- Park, D. C., & Reuter-Lorenz, P. (2009). The adaptive brain: aging and neurocognitive scaffolding. *Annual Review of Psychology*, 60(1), 173-196.
- Peelle, J. E., Troiani, V., Wingfield, A., & Grossman, M. (2010). Neural processing during older adults' comprehension of spoken sentences. *Cerebral Cortex*, 20(4), 773-782.
- Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive aging and the compensation hypothesis. *Current Directions in Psychological Science*, 17(3), 177-182.
- Rodd, J. M., Longe, O. A., Randall, B., & Tyler, L. K. (2010). Functional organisation of the fronto-temporal language system. *Neuropsychologia*, 48(5), 1324-1335.
- Rolls, E. T. (2004). The functions of the orbitofrontal cortex. *Brain & Cognition*, 55(1), 11-29.
- Rypma, B., Berger, J. S., Prabhakaran, V., Bly, B. M., Kimberg, D. Y., Biswal, B. B., & D'Esposito, M. (2006). Neural correlates of cognitive efficiency. *Neuroimage*, 33(3), 969-979.

- Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, 103(3), 403-428.
- Sato, H., Yahata, N., Funane, T., Takizawa, R., Katura, T., Atsumori, H., ..., & Kasai, K. (2013). A NIRS-fMRI investigation of prefrontal cortex activity during a working memory task. *NeuroImage*, 83, 158-173.
- Shin, J. H., Kang, M. J., & Lee, S. A. (2024). Wearable functional near-infrared spectroscopy for measuring dissociable activation dynamics of prefrontal cortex subregions during working memory. *Human Brain Mapping*, 45(2), e26619.
- Sohn, H. M. (2006). *The Korean language*. Cambridge University Press.
- Sung, J. E. (2015). Effects of syntactic structure on sentence comprehension ability as a function of word-order canonicity in Korean-speaking elderly adults. *Communication Sciences & Disorders*, 20(1), 24-33.
- Sung, J. E. (2017). Age-related decline in case-marker processing and its relation to working memory capacity. *Journals of Gerontology: Series B*, 72(5), 813-820.
- Sung, J. E., Yoo, J. K., Lee, S. E., & Eom, B. (2017). Effects of age, working memory, and word order on passive-sentence comprehension. *International Psychogeriatrics*, 29(6), 939-948.
- Waters, G. S., & Caplan, D. (2001). Age, working memory, and on-line syntactic processing in sentence comprehension. *Psychology & Aging*, 16(1), 128-144.
- Waters, G. S., & Caplan, D. (2003). The reliability and stability of verbal working memory measures. *Behavior Research Methods, Instruments, & Computers*, 35(4), 550-564.
- Weiss, S., Mueller, H. M., Schack, B., King, J. W., Kutas, M., & Rappelsberger, P. (2005). Increased neuronal communication accompanying sentence comprehension. *International Journal of Psychophysiology*, 57(2), 129-141.
- Wingfield, A., & Grossman, M. (2006). Language and the aging brain: patterns of neural compensation revealed by functional brain imaging. *Journal of Neurophysiology*, 96(6), 2830-2839.
- Wyser, D., Mattile, M., Wolf, M., Lamercy, O., Scholkmann, F., & Gassert, R. (2020). Short-channel regression in functional near-infrared spectroscopy. *Neurophotonics*, 7(3), 035011.
- Yoon, J. H. S. (2018). Korean syntax. *Oxford Research Encyclopedia of Linguistics*, 1-48.
- Youn, J. C., Kim, K. W., Lee, D. Y., Jhoo, J. H., Lee, S. B., Park, J. H., ..., & Woo, J. I. (2009). Development of the subjective memory complaints questionnaire. *Dementia and Geriatric Cognitive Disorders*, 27(4), 310-317.
- Zhao, Y., Qiu, L., Sun, Y., Huang, C., & Li, T. (2017). Optimal hemoglobin extinction coefficient data set for near-infrared spectroscopy. *Biomedical Optics Express*, 8(11), 5151-5159.

국문초록

노년층 문장이해능력과 관련된 전전두엽 피질활성화 fNIRS 연구

김지성 · 이은송 · 문금채 · 이지연 · 조유리 · 이서희 · 성지은

이화여자대학교 언어병리학과

배경 및 목적: 본 연구는 행동적 수행력과 근적외선분광법(fNIRS)으로 측정한 전전두피질 활성화를 결합하여 문장 이해에서 나타나는 노화 관련 차이를 살펴보는 것을 목적으로 하였다. 격조사를 통해 어순이 비교적 자유로운 한국어의 특성에 주목하여, 노화가 특정 통사 구조에 국한된 결함과 관련되는지, 혹은 처리 부담이 증가할 때 문장 해석을 지원하는 전전두엽 통제 자원의 동원 양상 변화와 관련되는지를 살펴보았다. **방법:** 청년층(11명)과 노년층(10명)을 대상으로 그림-문장 짝짓기 과제를 실시하며 fNIRS 자료를 수집하였다. 문장 자극은 문법적 태(능동/피동)와 어순 규범성(규범/비규범)에 따라 4가지 유형으로 구성하였다. 행동 측정치(정반응률, 반응시간)는 전체 21명을 대상으로 분석하였으며, 신호 품질 기준에 따라 일부 참가자를 제외한 후 fNIRS 분석은 16명(청년 8명, 노년 8명)을 대상으로 실시하였다. 신경학적 지표로는 전두극피질 및 안와전두피질을 포함한 전전두엽 하위 영역의 산화헤모글로빈(ΔHbO) 변화량을 분석하였다. **결과:** 노년층은 청년층보다 전반적으로 유의하게 낮은 정반응률과 느린 반응시간을 보였다. 집단×문장유형 상호작용은 유의하지 않았으나 효과크기가 작지 않았다. 혈액학적으로는 청년층이 노년층보다 우측 안와전두피질에서 피동 규범 어순 문장 처리 시 유의하게 더 높은 과제 유발 활성화를 보였으며, 다른 전전두엽 영역 및 문장 조건에서는 유의한 집단 간 차이가 없었다. **논의 및 결론:** 이러한 결과는 노화가 문장 이해 과정에서 전전두엽 자원의 동원 양상을 변화시킨다는 가설을 부분적으로 지지하며, 이는 통사 표상 자체의 손상보다는 통제 과정을 동원하는 효율성의 저하를 반영하는 것으로 해석된다. 본 결과의 일반화 및 임상적 함의를 확인하기 위해서는 더 큰 표본을 통한 반복 검증이 필요하다.

핵심어: 노화, 문장 이해, 통사적 복잡성, 근적외선분광법(fNIRS), 전전두피질

이 논문은 2026년도 정부(과학기술정보통신부)의 재원으로 한국연구재단의 지원을 받아 수행된 연구임.

(RS-2024-00461617, 과제명: 난청 및 치매 극복을 위한 글로벌 융복합 헬스케어 솔루션 연구, 기여율 50%; RS-2022-NR070151, 과제명: 난청 유발 치매극복을 위한 언어청각 평가-중재 프로그램 개발 및 신경네트워크 융합연구, 기여율 25%; NRF-2026S1A5A2A03006789, 과제명: 언어유형과 문화적 특성에 따른 노년층 및 신경언어장애 유형별 언어처리 비교연구: 한국어, 중국어, 영어, 스페인어를 중심으로, 기여율 25%).

참고문헌

- 강연옥 (2006). K-MMSE (Korean-mini mental state examination)의 노인 기준 연구. *한국심리학회지: 일반*, 25(2), 1-12.
- 남미혜 (1988). *국어 어순 연구: 어순 재배치 현상을 중심으로*(석사학위논문, 서울대학교).
- 남윤주, 정혜녕, 김영주 (2021). 한국어 어순 선호와 성분 길이 효과에 대한 시선추적연구. *Communication Sciences & Disorders*, 26(4), 964-974.
- 성지은 (2015). 한국어 어순 규범성과 문장유형이 노년층 문장이해능력에 미치는 영향 및 작업기억용량과의 관계. *Communication Sciences & Disorders*, 20(1), 24-33.
- 임홍빈 (2007). 어순에 관한 언어 유형적 접근과 한국어의 기본 어순. *서강인문논총*, 22, 53-120
- 조맹제, 배재남, 서국희, 함봉진, 김장규, 이동우, 강민희 (1999). DSM-III-R 주요우울증에 대한 한국어판 Geriatric Depression Scale (GDS)의 진단적 타당성 연구. *신경정신의학*, 38(1), 48-63.

ORCID

김지성(제1저자, 대학원생 <https://orcid.org/0000-0002-1819-3467>); 이은송(공동저자, 대학원생 <https://orcid.org/0009-0005-6079-6922>); 문금채(공동저자, 대학원생 <https://orcid.org/0009-0001-3566-9965>); 이지연(공동저자, 대학원생 <https://orcid.org/0009-0009-5087-1107>); 조유리(공동저자, 대학원생 <https://orcid.org/0009-0009-5059-6977>); 이서희(공동저자, 대학원생 <https://orcid.org/0009-0005-0266-9650>); 성지은(교신저자, 교수 <https://orcid.org/0000-0002-1734-0058>)