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# Transcutaneous auricular vagus nerve stimulation enhanced working memory in older adults with age-related hearing loss

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**Age-related hearing loss (ARHL) is associated with an increased risk of dementia, highlighting the need for early interventions to support cognitive functioning. Despite promising evidence supporting transcutaneous auricular vagus nerve stimulation (taVNS) for mitigating cognitive impairment, its impact on working memory (WM) in older adults with ARHL is unexplored. This study is the first attempt to investigate taVNS effects on WM in the older adults with hearing impairment (HI) and with typical hearing (TH). WM capacity was assessed using n-back tasks, varying by WM domains (verbal and visuo-spatial) and complexity levels (1-back and 2-back). Participants underwent a two-session, within-subjects, randomized crossover, single-blind sham-controlled protocol, receiving 20 min of continuous stimulation in the active session, whereas only 30 s at the start and end in the sham session. The HI group performed significantly worse than the TH group on the 2-back tasks. Within the HI group, taVNS significantly enhanced performance across all WM domains and complexity levels compared to the sham condition. These findings suggest that taVNS enhances WM in hearing-impaired older adults, underscoring its potential as a clinical intervention for addressing WM challenges associated with ARHL.**

**Keywords** Age-related hearing loss, Cognitive intervention, Transcutaneous auricular vagus nerve stimulation, Working memory, N-back task

During the advanced stages of human aging, individuals typically encounter a range of physical and cognitive deteriorations. These changes include modifications in the structural and functional aspects of the auditory system. Consistent evidence from epidemiological studies strongly links sensory loss related to hearing with an elevated risk of developing dementia[1,2] with this link becoming more pronounced with age[3]. The deprivation hypothesis, proposed by Baltes and Lindenberger[3] has gained substantial support in explaining these connections[4–7]. It posits that prolonged periods of reduced auditory input over time due to untreated hearing impairment (HI) can lead to alterations in neural networks, subsequently affecting cognition and processing speed[8]. Overall, older adults with HI are now identified as preventative clinical populations in need of early cognitive interventions, given their demonstrated cognitive deficits relative to those with normal hearing[9,10].

Given the potential for sensory deprivation to impact cognition, recent evidence from a meta-analysis highlights that treating HI with cochlear implantation (CI) can induce significant improvements in certain cognitive functions in older adults[11]. Specifically, CI has been shown to enhance executive function and verbal memory—domains closely linked to auditory processing—particularly within the first six months post-implantation, with these gains generally maintained up to 12 months. However, improvements in non-verbal memory, which is less directly associated with auditory input, tend to emerge later and may require additional time or supplementary domain-targeted interventions to achieve meaningful benefits. In some cases, with early-onset or profound HI, where individuals have relied on lipreading, superior visuospatial abilities have been reported[12,13]. This variability in cognitive outcomes depending on the type and severity of hearing loss suggests that targeted interventions beyond hearing rehabilitation may be essential for optimizing cognitive outcomes in older adults with HI.

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Transcutaneous auricular vagus nerve stimulation (taVNS) has garnered recognition for modulating cognition by targeting the auricular branch of the vagus nerve. Research has covered various cognitive domains through taVNS, such as executive functions[14] and inhibitory controls[15]with notable improvements on memory functions[16–21]. A recent study highlighted its potential to improve working memory (WM), particularly in the visuo-spatial n-back task performance, within a cohort of healthy young adults aged 18 to 23 years[22]. Further, patients with mild cognitive impairment (MCI) exhibited notable improvements in verbal memory functions, including both immediate and delayed recalls, following a 24-week intervention of taVNS[23]. These studies highlight taVNS as a promising noninvasive approach for improving memory issues and potentially mitigating cognitive decline associated with aging.

Recent studies are increasingly focusing on the link between cognitive decline and age-related hearing loss (ARHL), especially utilizing WM tasks to explore this relationship[24–26]. Previously, a marked correlation was observed between hearing ability, as indexed by peripheral auditory thresholds, and WM functioning in a group of 156 individuals aged 70 and above[3]. This study highlighted early markers and intervention points for cognitive decline with a specific emphasis on hearing loss in older adults as a possible precursor to dementia. More recently, an EEG study identified this connection by examining the association between hearing loss and WM functions, finding significant correlations between auditory P300 latency and WM capacity in individuals with HI[27]. Subsequent studies have further supported the idea that impaired hearing can significantly contribute to the deterioration of WM capacity[28–30] suggesting that targeting cognitive function in older adults with ARHL early on could be a key intervention point to potentially slow further decline.

Extensive research on WM indicates that the specific domains and components of WM being targeted are considered critical when selecting WM tasks to examine individual differences in WM capacity[31–33]. For instance, in WM capacity across verbal and visuo-spatial domains, a study utilizing the digit and corsi span forward tests among patients in the early stages of Alzheimer's disease (AD) and healthy control subjects found a significant decline in the visuo-spatial WM domain among mild AD patients[34]. However, the differences between these patients and the control group in the digit span test were minimal. These findings highlight the significance of considering distinct WM domains of incoming information when evaluating WM capacity, particularly evident in cognitively impaired older adults[35–37].

Evidence from older adults with ARHL suggests that performance differences emerge depending on the WM task types, such as those in the verbal and visuo-spatial domains[23–25]. Some studies employed verbal WM tasks[24,25] while others focused on the visuo-spatial domains of WM when studying older adults with ARHL[20]. The study, which examined the association between hearing ability and cognitive functions among older individuals with and without ARHL, focused on the verbal WM domain using the n-back task with letter presentation. It found that individuals with HI exhibited significantly slower reaction times and fewer correct responses on the 2-back task, although no substantial group differences were observed on the 0-back task[37]. Another group of researchers reported that individuals with HI exhibit WM deficits in the visuo-spatial domain, even in the absence of specific auditory challenges[23–25,38]. Despite the increasing research on WM deficits for older adults with ARHL, there have been no effort yet to apply the taVNS to improve WM functions for populations at risk of dementia due to ARHL. The current study aims to investigate the effects of taVNS on WM performance by systematically manipulating task complexity (1-back vs. 2-back) and WM domain (verbal vs. visuo-spatial). To the best of our knowledge, this represents the first attempt to examine these effects specifically in older adults with ARHL, a group in need of early cognitive intervention.

# Methods
## Participants
The study involved 56 participants aged over 60 years, consisting of 20 individuals with HI and 36 typical hearing (TH). All participants, who were native Korean speakers, met the following criteria: they obtained scores within normal ranges on the Korean version of the mini mental state examination (K-MMSE)[39] the Seoul verbal learning test (SVLT), the digit span tests, and the Korean geriatric depression scale (KGDS; < 8 out of 15)[40]. All cognitive assessments were administered as part of the standardized Seoul Neuropsychological Screening Battery-II (SNSB-II)[41]. None of the participants reported any visual impairments, learning difficulties, or a history of brain injuries.

All experiments were conducted in accordance with relevant guidelines and regulations. This research was approved by the Institutional Review Board on Human Subjects of Ewha Womans University (Approval No. 2022-0084), and all procedures were performed following ethical standards and institutional policies. Prior to participation, all individuals provided written informed consent.

An independent sample t-test was conducted, revealing no statistically significant differences in age, education years, or screening results of neuropsychological tests between the TH and HI groups (all *p-values* > 0.05). Detailed demographic information and descriptive statistics are provided in Table 1.

## Audiology measurements
Participants with sensorineural hearing loss were assessed using a standard pure-tone audiometry device (AS608 Basic; Interacoustics A/S, Middelfart, Denmark) at audiometric frequencies. A weighted 4-frequency average (W4FA) was calculated using the formula [(a + 2b + 2c + d)/6, where a, b, c, and d represent the thresholds at 0.5, 1.0, 2.0, and 4.0 kHz, respectively], following the clinical guidelines of The Korean Audiological Society[42]. Participants were classified as having HI if their average hearing threshold in the better ear exceeded 25 decibels hearing level (dB HL)[42,43]. Only individuals whose hearing threshold differences between the two ears were within 15 dB HL were included. No participants reported using hearing aids or cochlear implants at the time of testing. Audiological reports for each group are detailed in Table 2, with the corresponding audiograms presented in Fig. 1.

| | | TH Group $n = 36$ | HI Group $n = 20$ | Test statistics | *p*-value |
|---|---|---|---|---|---|
| Gender | Male | 23 (63.8%) | 14 (70%) | | |
| | Female | 13 (36.1%) | 6 (30%) | | |
| Age (years) | M(SD) | 64.03 (3.72) | 65.55 (3.66) | 1.481 | 0.146 |
| | Range | 60–72 | 60–72 | | |
| Education (years) | M(SD) | 14.56 (2.97) | 13.95 (3.18) | −0.698 | 0.490 |
| | Range | 9–23 | 9–23 | | |
| K-MMSE (max: 30) | M(SD) | 28.97 (1.36) | 28.75 (0.96) | −0.709 | 0.482 |
| | Range | 26–30 | 26–30 | | |
| SVLT-imme. (max: 36) | M(SD) | 21.28 (3.74) | 20.45 (3.84) | −0.780 | 0.440 |
| | Range | 15–31 | 15–30 | | |
| SVLT-delayed (max: 12) | M(SD) | 7.35 (2.03) | 6.86 (2.09) | 0.854 | 0.398 |
| | Range | 4–11 | 4–12 | | |
| Digit span-F (max: 14) | M(SD) | 10.44 (2.22) | 8.95 (2.85) | −2.024 | 0.051 |
| | Range | 6–14 | 5–14 | | |
| Digit span-B (max: 14) | M(SD) | 7.64 (2.76) | 6.20 (2.74) | −1.876 | 0.068 |
| | Range | 4–14 | 4–14 | | |
| Hearing threshold -left ear (dB HL) | M(SD) | 19 (5.97) | 33 (9.05) | 6.47 | < 0.001 |
| | Range | 10–41 | 24–58 | | |
| Hearing threshold -right ear (dB HL) | M(SD) | 19 (4.34) | 37 (10.59) | 7.19 | < 0.001 |
| | Range | 11–28 | 25–62 | | |
| Hearing threshold -better ear (dB HL) | M(SD) | 17 (3.83) | 33 (7.90) | 8.71 | < 0.001 |
| | Range | 10–24 | 25–41 | | |
| | M(SD) | 3.47 (0.73) | 3.25 (0.82) | | |

**Table 1**. Participants' descriptive information and screening results of neuropsychological tests; TH, typical hearing; HI, hearing impairment; M(SD), mean(standard deviation); K-MMSE, Korean version of the mini-mental state examination; SVLT-imme., Seoul verbal learning test - immediate recall; SVLT-delayed, Seoul verbal learning test - delayed recall; digit span-F, digit span test forward; digit span-B, digit span test backward; dB HL, decibels hearing level.

| | | | Frequency in Hertz | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 500 | | 1000 | | 2000 | | 4000 | |
| Audiometry | Group | Measure | Left | Right | Left | Right | Left | Right | Left | Right |
| AS608 | TH group ($n = 36$) | Mean | 20 | 22 | 17 | 16 | 19 | 18 | 24 | 22 |
| | | Median | 20 | 25 | 15 | 15 | 20 | 18 | 22 | 20 |
| | | SD | 6.87 | 7.22 | 6.81 | 5.41 | 7.85 | 7.50 | 11.7 | 9.59 |
| | | Minimum | 10 | 5 | 10 | 5 | 5 | 5 | 5 | 10 |
| | | Maximum | 35 | 40 | 40 | 25 | 45 | 45 | 65 | 50 |
| | HI group ($n = 20$) | Mean | 26 | 28 | 28 | 30 | 40 | 39 | 50 | 53 |
| | | Median | 25 | 25 | 28 | 27 | 40 | 35 | 48 | 50 |
| | | SD | 9.45 | 9.53 | 9.63 | 11.5 | 14.2 | 17.8 | 17.5 | 21.2 |
| | | Minimum | 10 | 10 | 15 | 15 | 20 | 10 | 20 | 15 |
| | | Maximum | 55 | 50 | 55 | 55 | 70 | 80 | 85 | 100 |

**Table 2**. Audiological details for each group; TH, typical hearing; HI, hearing impairment; SD, standard deviation.

## Transcutaneous auricular vagus nerve stimulation (taVNS)

We administered stimulation using a commercial taVNS device (allearsTM TODOC, Seoul, South Korea) set at 25 Hz frequency, 200 µs pulse width, and a cycle of 30 s ON and 30 s OFF was repeated. The intensity of the stimulation was adjusted to 0.5 mA below each participant's pain threshold. The stimulation was calibrated to induce a tingling sensation, indicative of activating the afferent fibers of the auricular vagus nerve[44,45] and was targeted at the cymba concha of the ear, a site known for its strong activation of afferent vagal pathways[46]. The stimulation was applied to either the left or right ear, with counterbalancing across participants.

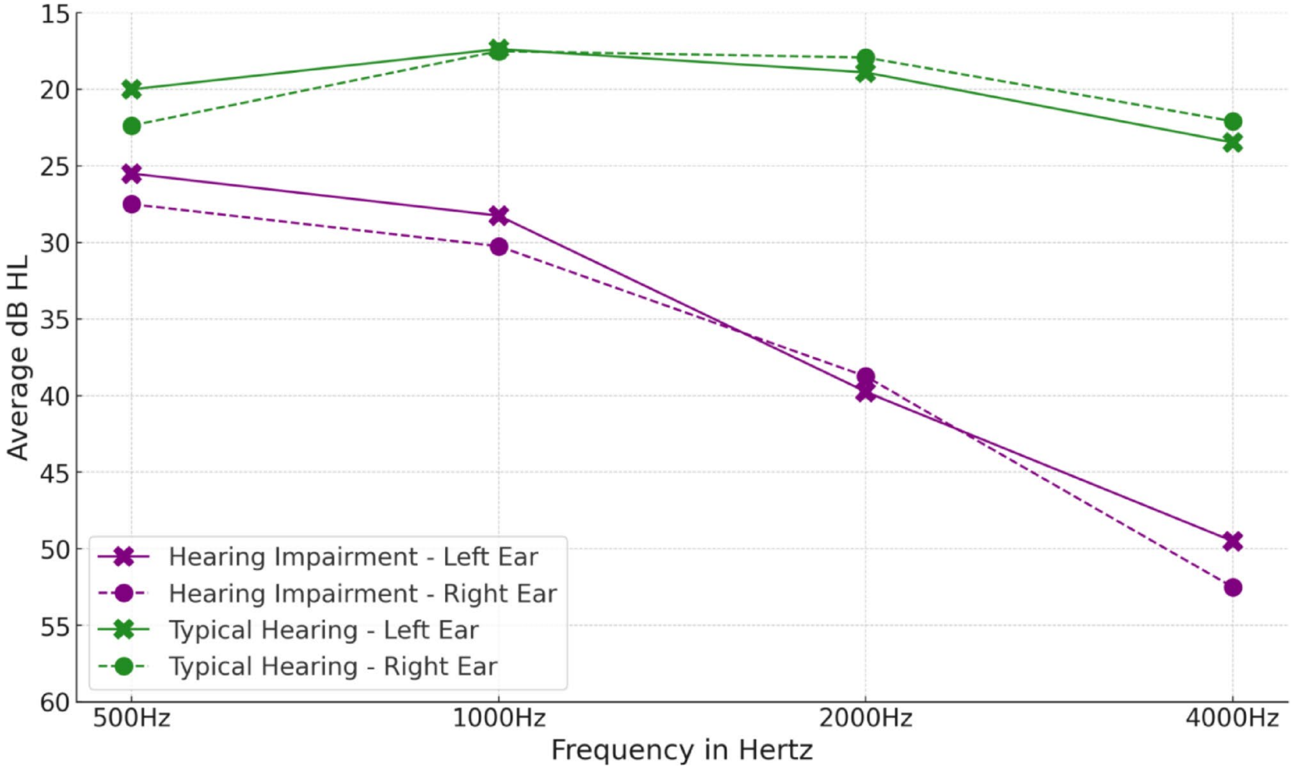


**Fig. 1**. Mean audiograms of air conduction hearing thresholds in the hearing impairment group (HI, N=20) and the typical hearing group (TH, N=36).

## N-back task

We conducted n-back tasks targeting two distinct WM domains: verbal vs. visuo-spatial. The verbal n-back task was based on the SemBack version[47] while the visuo-spatial n-back task was adapted from the study by Christensen and Wright[48]. To manipulate task complexity, we varied the 'n' values (1-back vs. 2-back). The number of task items was matched, with 22 target items out of 73 items in the 1-back condition and 22 targets out of 84 items in the 2-back condition. Each participant engaged in a preparatory block consisting of 10 practice items, including 2 targets, before beginning each n-back task. All task instructions for the n-back tasks were presented visually on the computer screen using written text prior to each task block.

In the verbal n-back task, each word in written form was presented on the screen, and participants were asked to press the spacebar if the current item belonged to the same semantic category as the item presented 1 or 2 back. The semantic categories included three distinct groups: fruits, animals, and clothes (Supplementary 1). The syllable length and structure in Korean were balanced across the three semantic categories.

The visuo-spatial task featured three-dimensional block cubes from Shepard and Metzler[49] arranged in various configurations across four blocks. Participants were asked to press the spacebar when the current item matched the shape of the block presented 1 or 2 back.

All the series of stimuli used in this study were presented visually using PsychoPy[50] on a 39.6 cm laptop screen (Samsung Galaxy Book Pro 39.6 cm Core™ i5), as illustrated in Fig. 2. Each trial began with the presentation of a fixation cross, which was displayed for 2750 ms, followed by a stimulus presented for 750 ms. Between each stimulus, the fixation cross was consistently displayed for 2750 ms, maintaining a regular interval throughout the experiment.

## Experimental protocol

The study employed a two-session, within-subject, randomized crossover, single-blind, sham-controlled design (as detailed in Fig. 3). The two sessions were divided into an active session and a sham session, based on the presence or absence of taVNS stimulation, and the order of stimulation counterbalanced. Participants received both active taVNS and sham stimulation, with each session spaced at least 7 days apart. To ensure consistency, the sessions were preferably conducted at the same time of day.

Prior to each session, participants were instructed to refrain from tobacco (2 h prior), caffeine (6 h prior), medications, alcohol, and intense physical activity (24 h prior). To mitigate potential expectation biases, no information was provided regarding the specific stimulation condition administered in each session or its expected effects.

The order of the verbal- and visuo-spatial n-back was balanced but consistent for individual participants across both sessions. Upon completing the tasks, stimulation ceased, and participants were given a questionnaire regarding any negative effects resulting from the stimulation.

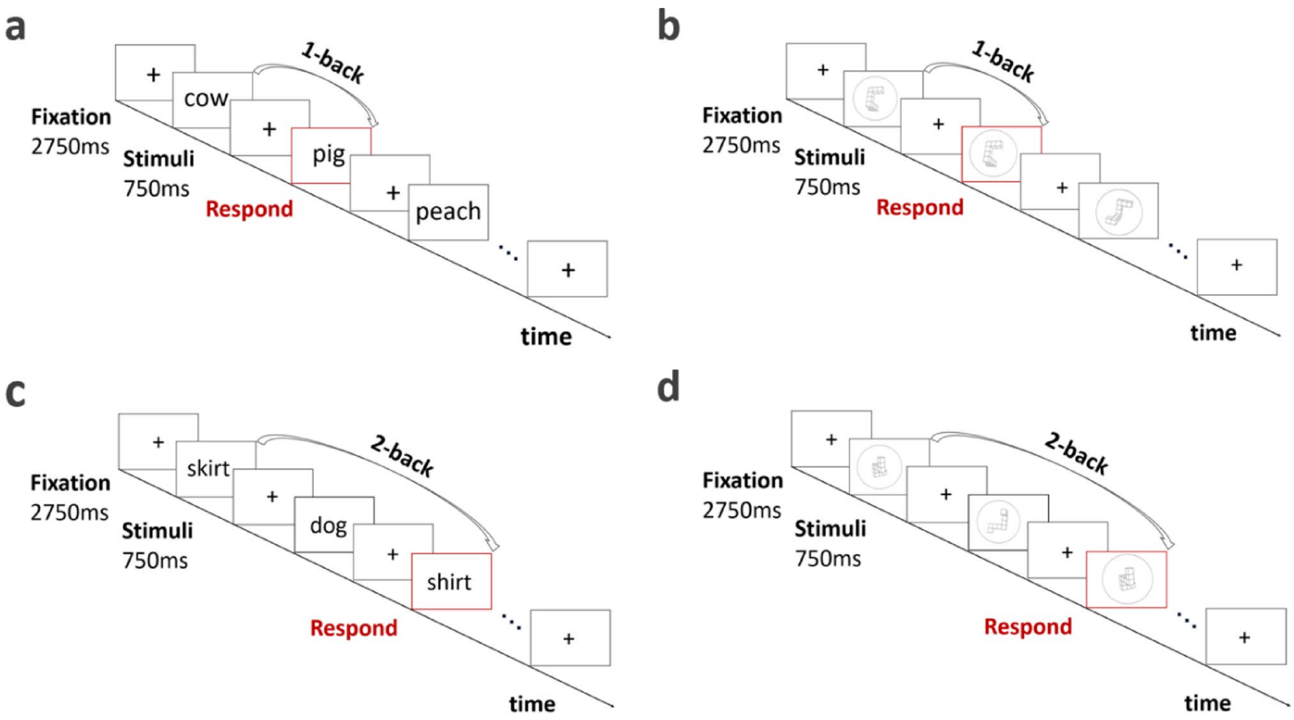


**Fig. 2**. Experimental procedures of n-back tasks. **a**. verbal 1-back; **b**. visuo-spatial 1-back; **c**. verbal 2-back; **d**. visuo-spatial 2-back.

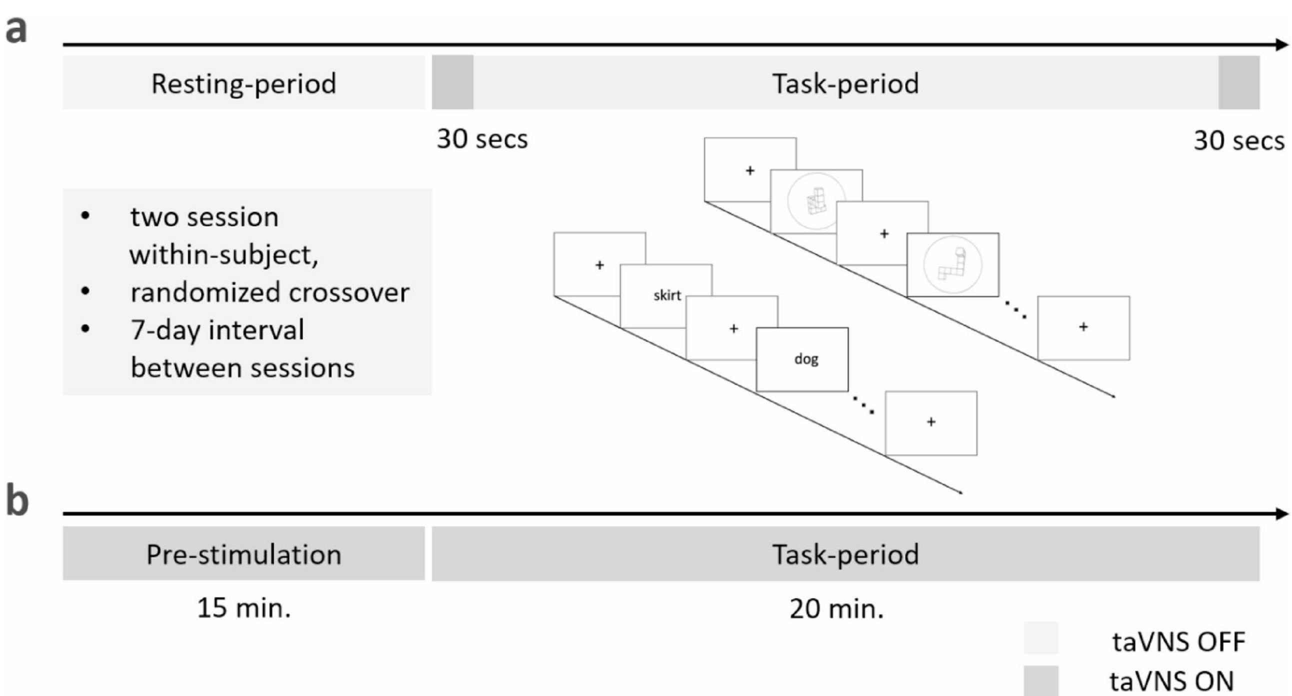


**Fig. 3**. Experimental protocol for each session depending on stimulation condition. In the sham session (**a**), stimulation was administered for 30 seconds at the beginning and end of the session. During the active session (**b**), participants underwent a 15-minute pre-stimulation phase, and then received stimulation until they completed the n-back tasks (20 min), totaling approximately 35 minutes of stimulation.

### Statistical analysis

Statistical analysis was conducted using Python package (v1.2.0). The dependent variables included accuracy (%) and response time (ms). Accuracy (%) was determined by considering trials where participants correctly responded in the n-back tasks. The number of correct responses were divided by the total number of responses (44) per condition, multiplied by 100 to calculate the percentage of correctly responded trials. Response time (RT)—the duration from the presentation of stimuli on the screen to the moment the button was pressed—was measured in milliseconds (ms). Only trials where participants responded correctly to the n-back tasks were included into the RT analyses.

For each dependent variable, two-separate four-way mixed-design analyses of variance (ANOVAs) were conducted with group (TH vs. HI), stimulation condition (Sham vs. Active), WM domain (Verbal vs. Visuo-spatial), and task complexity (1-back vs. 2-back) as independent variables.

## Results

Table 3 displays the descriptive statistics of the verbal and visuo-spatial n-back performance for each group, detailing the accuracy (%) and RT (ms).

### Accuracy

Our analysis revealed significant main effects of group ($F_{(1,54)} = 18.5$, $p < 0.001$; TH group > HI group), WM domain ($F_{(1,54)} = 17.2385$, $p < 0.001$; verbal > visuo-spatial), and task complexity ($F_{(1,54)} = 206.1979$, $p < 0.001$; 1-back > 2-back), while stimulation condition did not reach significance ($F_{(1,54)} = 2.6406$, $p = 0.110$). Specifically, the accuracy for the HI group was significantly worse compared to the TH counterparts. Furthermore, the accuracy was significantly lower for visuo-spatial than the verbal WM domain, and for the 2-back compared to the 1-back task.

Next, a significant two-way interaction between group (TH vs. HI) and stimulation condition (Active vs. Sham) was observed ($F_{(1,54)} = 6.1515$, $p = 0.016$). This was attributed to the fact that, unlike the TH group (91.28% for active vs. 91.95% for sham), the HI group (87.21% for active vs. 83.63% for sham) showed a significantly improved performance in the active condition compared to the sham condition, see Fig. 4a.

Additionally, a significant two-way interaction was observed between group and task complexity ($F_{(1,54)} = 17.2221$, $p < 0.001$). This interaction stemmed from the HI group displaying significantly lower accuracy compared to the TH group, specifically during the 2-back task (85.03% for TH vs. 73.29% for HI), see Fig. 4b.

### Response time

In the RT analyses, no significant main effects were observed for group ($F_{(1,54)} = 0.0170$, $p = 0.897$) or stimulation condition ($F_{(1,54)} = 0.7978$, $p = 0.376$). However, significant main effects were found for WM domain ($F_{(1,54)} = 17.8593$, $p < 0.001$; verbal > visuo-spatial) and task complexity ($F_{(1,54)} = 135.6700$, $p < 0.001$; 1-back < 2-back), indicating that RTs were significantly longer in the 2-back than the 1-back task, and for verbal compared to visuo-spatial WM domain.

Furthermore, a significant two-way interaction was identified between WM domain and task complexity ($F_{(1,54)} = 8.3440$, $p = 0.006$). The two-way interaction was attributed to significant differences in the 1-back condition between the verbal and visuo-spatial WM domain (843.36 ms for verbal vs. 745.88 ms for visuo-spatial) compared to those differences in the 2-back (999.95 ms for verbal vs. 916.51 ms for visuo-spatial) (Fig. 5). No other interactions were significant (all *p values* > 0.05).

## Discussion

Our findings are in line with previous research on MCI—recognized as an early stage of dementia—where taVNS showed promising improvements in verbal memory functions[21]. Given the limited research on the efficacy of taVNS in aging populations, our exploration serves as an important step in highlighting the clinical potential of taVNS, stressing the need for further exploration into its potential to support cognitive function in ARHL as a high-risk group who may be progressing towards dementia.

| WM domain | | | Verbal | | Visuo-spatial | |
|---|---|---|---|---|---|---|
| Task complexity | | | 1-back (*SD*) | 2-back (*SD*) | 1-back (*SD*) | 2-back (*SD*) |
| Accuracy (%) | TH group (*n* = 36) | Active | 98.10 (3.61) | 86.86 (12.29) | 98.10 (3.91) | 82.07 (13.24) |
| | | Sham | 98.73 (3.48) | 88.38 (10.52) | 97.85 (2.93) | 82.82 (10.50) |
| | HI group (*n* = 20) | Active | 98.86 (2.43) | 80 (13.81) | 97.95 (3.65) | 72.04 (15.23) |
| | | Sham | 98.40 (2.97) | 75 (20.95) | 95 (6.57) | 67.72 (14.07) |
| RT (ms) | TH group (*n* = 36) | Active | 843.96 (110.91) | 1020.68 (154.95) | 774.31 (187.70) | 931.35 (171.56) |
| | | Sham | 849.38 (128.33) | 1032.44 (160.61) | 768.41 (173.57) | 918.49 (172.77) |
| | HI group (*n* = 20) | Active | 846.02 (110.06) | 976.36 (180.03) | 708.94 (183.25) | 900.08 (161.81) |
| | | Sham | 828.78 (106.83) | 927.75 (159.38) | 691.10 (135.66) | 902.69 (157.64) |

**Table 3**. Descriptive statistics of the verbal and visuo-spatial n-back performance for each group; TH, typical hearing; HI, hearing impairment; RT, response time; SD, standard deviation.

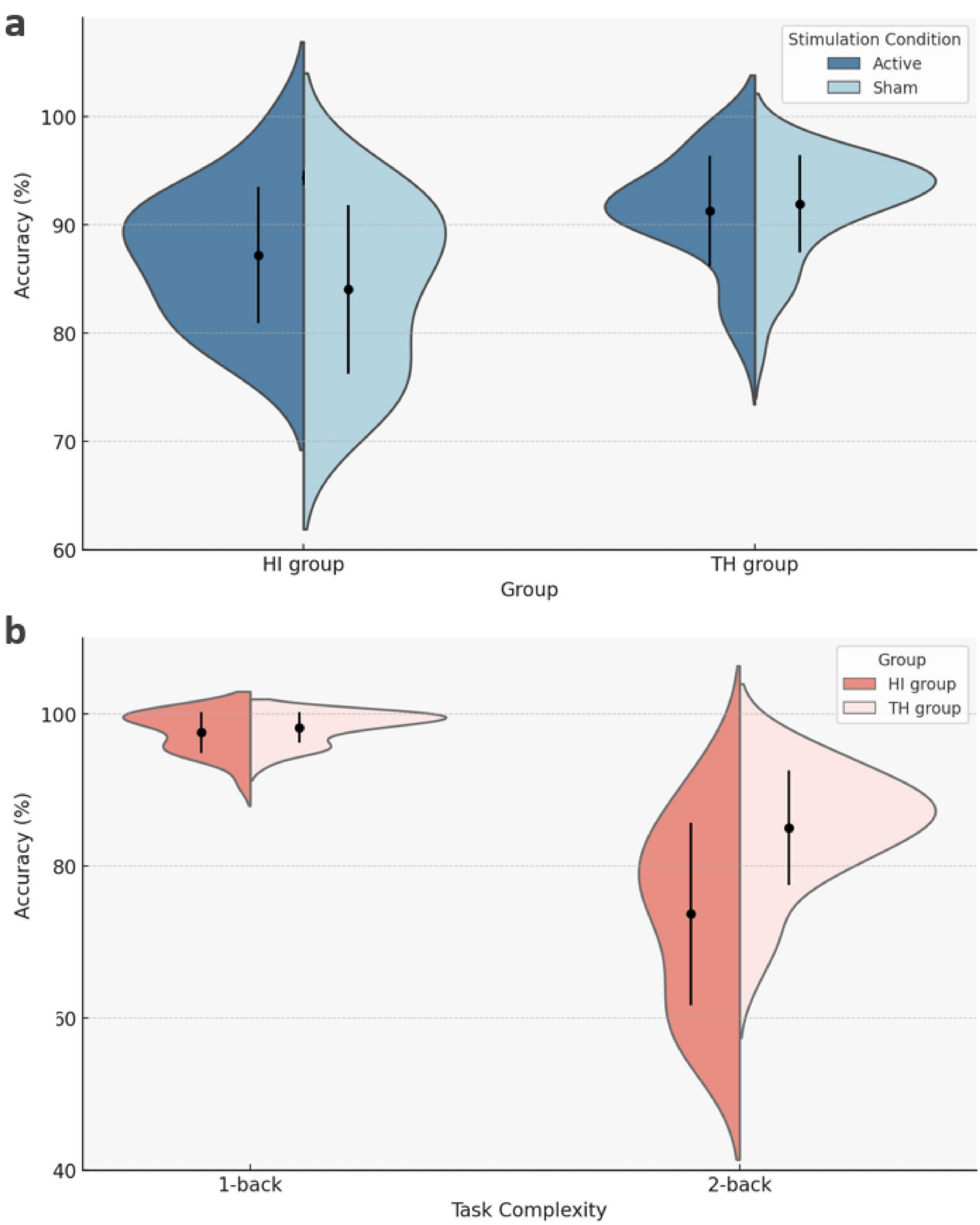


**Fig. 4**. Accuracy (in percent) by (**a**) group × stimulation condition and (**b**) task complexity × group. Error bars indicate group mean ± standard deviations (SD). HI group: participants with hearing impairment (N=20); TH group: participants with typical hearing (N=36).

The previous investigations into the impact of taVNS on WM have been limited to specific domains—namely verbal WM[21] or visuo-spatial WM[22]. Our research extends this scope, demonstrating taVNS's efficacy across a wider array of WM domains. The current finding suggests that taVNS enhanced WM performance, particularly in terms of accuracy across the WM domains within the HI group. This indicates that taVNS may exert a similar

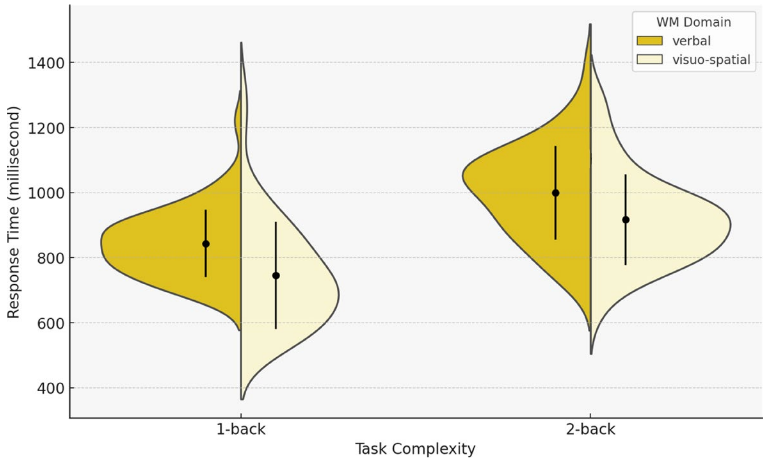


**Fig. 5**. Response time (in millisecond) by task complexities× working memory domains. Error bars indicate group mean ± standard deviations (SD).

impact on both verbal and visuo-spatial domains in individuals with ARHL. Further research is necessary to extend these WM enhancement effects after taVNS to a broader range of populations at risk.

Another standout in our data is that the significant interaction between group performance and task complexity unveils a clear performance disparity between the HI group and the TH group, especially on the cognitively more challenging 2-back tasks. This distinction is critical as it corroborates the link between ARHL and cognitive decline, aligning with previous studies that have observed differences in n-back task performance among older adults with various cognitive impairments, including MCI[51,52] and AD[53]. Further, patients with amnestic MCI (aMCI) showed comparable performance to that of healthy controls in the 1- and 2-back tasks. However, they exhibited inferior discrimination ability in the 3-back task compared to healthy controls[54]. Our research highlights the importance of supporting cognitive function in individuals with HI, who are at elevated risk of cognitive decline[1,2] rather than solely focusing on addressing hearing loss itself. It pinpoints the cognitive domains affected by ARHL, providing a foundation for developing evidence-based interventions and strategies to support cognitive health targeting WM enhancements.

While the impact of taVNS on the accuracy of WM tasks is evident, RT appears to be relatively unaffected. Our study did not find significant changes in RTs following the application of taVNS. The primary advantage of taVNS, as evidenced in our study, is its significant contribution to boosting decision-making accuracy in WM tasks among older adults with hearing loss. The enhancement in task performance is likely associated with the heightened selective attention induced by taVNS[22]. However, the effects of stimulation did not extend to accelerating processing speed sufficiently to be reflected in reduced RT. This observation aligns with prior research on taVNS/tVNS effects in verbal word order[53] and visuo-spatial[22] memory tasks in healthy individuals, where the improvements were noted in task performance without a reduction in RT. However, a study investigating the effect of taVNS on epilepsy patients demonstrated significant decreases in RT due to taVNS[55]. Highlighting the need for further investigation into the effects of taVNS on processing speed in WM tasks across diverse clinical populations, including ARHL.

The suggested directions for future research are as follows: The average hearing loss in the HI group was classified as mild, with levels around 33 dB HL. Notably, the finding that taVNS effectively elicited WM enhancement even at this mild level of hearing loss is particularly significant. It is important to conduct further research to examine the effects of taVNS across a broader spectrum of hearing loss severities, which would be essential to comprehensively understand its efficacy in populations with more severe levels of hearing loss. Secondly, given that our study concentrated on the immediate effects following a single session of taVNS, this presents a clear rationale for initiating intervention studies involving multiple sessions. Such studies should feature extended intervention periods of taVNS treatment to comprehensively evaluate the long-term therapeutic impacts of taVNS.

## Conclusion
The current study provides compelling evidence that individuals with ARHL experience significant memory difficulties in WM tasks compared to those with normal hearing, even when these tasks do not involve auditory challenges. Remarkably, applying taVNS to the HI group led to significant improvements in their WM performance. This finding highlights the potential of taVNS to help slow the trajectory of cognitive decline, particularly by targeting the decrease in WM capacity linked to hearing loss.

## Data availability
The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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## Author contributions

J.S. conceptualized the study, conducted formal analysis, designed the methodology, and visualized the results. She also wrote the original draft of the manuscript. S.N. and J.P. were responsible for data curation, investigation, and writing—review & editing. S.B.J. and J.E.S. contributed to the study's conceptualization, funding acquisition, and supervision, and they also participated in writing—review & editing. All authors reviewed and approved the final manuscript.

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## Declarations

## Conflict of interest

The authors state that they have no known competing financial interests or personal relationships that could appear to have influenced the work presented in this paper.

## Generative AI and AI-assisted technologies

During the preparation of this work the author(s) used [ChatGPT 4.0] to [improve readability and check for grammar corrections]. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

## Ethics approval and consent to participate

This research was approved by the Institutional Review Board on Human Subjects of Ewha Womans University (No. 2022-0084). Prior to participation, all individuals provided written informed consent.

## Additional information

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