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Evidence for Memory-Guided Auditory Attention in Aging and Hearing Loss

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Previous studies have linked age-related hearing loss (ARHL) to cognitive decline, but the specific cognitive processes affected remain unclear. The sensory deprivation and cognitive load hypotheses suggest that ARHL makes auditory processing more cognitively demanding, straining overall cognitive resources and reducing the effective use of long-term memory. Memory and attention play a role in auditory perception, enabling listeners to organize complex sounds into meaningful objects that facilitate listening and behavior. One function of long-term memory is to guide attention, and auditory memory-guided attention engages hippocampal networks that are known to be vulnerable in age-related cognitive decline and hearing loss. Examining the interaction between auditory attention and memory may clarify the associations between ARHL and cognitive decline. We tested the preregistered hypothesis that older adults with greater ARHL would show weaker ability to use memory-guided auditory attention. Sixty-two adults aged 40–80 years participated in a memory-guided attention task in which they learned to associate background sounds with the spatial location of a probe-tone target. Contrary to predictions, results suggest preserved memory-guided attention in this age group, and this ability did not correlate with hearing thresholds. However, accuracy in verbally identifying background sounds was worse in those with greater ARHL, suggesting difficulty with recognizing acoustic scenes. Results indicate that mild-to-moderate hearing loss has little impact on middle-aged and older adults' ability to form long-term memory for auditory target–context associations under the conditions of this study.

Public Significance Statement
Hearing loss increases the risk of dementia in later life, but the mechanism remains unknown. To address this gap, we examined whether hearing loss in middle-aged and older adults predicted the use of memory to guide attention while listening to natural soundscapes. Participants with greater hearing loss had more difficulty recognizing soundscapes and were slower on the task, but they did not show impaired memory-guided attention.

Keywords: age-related hearing loss, aging, memory-guided attention, auditory, long-term memory

Supplemental materials: https://doi.org/10.1037/pag0001026.supp

Age-related hearing loss (ARHL), or presbycusis, is a common condition in the aging population that impairs the perception and identification of sound. It affects approximately one third of adults aged 65 years and older and exceeds half among adults aged above 70 years (Lin, Thorpe, et al., 2011). ARHL typically begins in middle age, progresses slowly, affects both ears symmetrically, and is most pronounced in the high-frequency hearing range (Gates & Mills, 2005). ARHL results from deterioration of inner and outer

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All data files and code used for analysis and figures are available on the Open Science Framework (https://osf.io/bysq5/). The preregistration of hypotheses and analysis plans is found at https://doi.org/10.17605/OSF.IO/YFMWJ. Preliminary results were previously presented as a poster at the annual meeting of the Association for Research in Otolaryngology in 2024. Feedback from this presentation informed refinements to the experimental paradigm. The authors declare no conflicts of interest.

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Mica Pec played a lead role in writing–original draft and an equal role in conceptualization, data curation, investigation, methodology, and project administration. Claude Alain played a lead role in resources and software and an equal role in conceptualization, project administration, supervision, validation, and writing–review and editing. Brandon T. Paul played a lead role in formal analysis, funding acquisition, project administration, supervision, and writing–review and editing and an equal role in conceptualization, data curation, resources, software, validation, and visualization.

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hair cells within the cochlea (Wu et al., 2020) or from degeneration of the synapses between hair cells and auditory nerve fibers (Wu et al., 2019). These hair cells and synaptic connections play a critical role in auditory transduction, and their decline disrupts perception of speech and other complex sounds. Degraded sound transmission due to ARHL can increase the demand for attentional and working memory resources during auditory processing (Rönnberg et al., 2021), but the downstream effects on memory-dependent listening are not fully understood.

ARHL and Cognitive Decline

Epidemiological and public health studies consistently show that cognition declines as ARHL worsens. For instance, results of the Baltimore Longitudinal Study of Aging (1990–1994) showed that greater hearing loss was associated with increased risk of cognitive decline and dementia (Lin, Metter, et al., 2011). Data from the 2014 Health Survey for England ($N > 10{,}000$) suggest that hearing loss is the strongest modifiable risk factor for dementia in adults aged 45–65 years (Livingston et al., 2017). Several competing hypotheses attempt to link hearing loss to dementia and cognitive impairment (Slade et al., 2020). For instance, the *social isolation hypothesis* suggests that hearing loss increases social withdrawal in older adults, thereby mediating the link between ARHL and cognitive decline (Rutherford et al., 2018), while the *common cause hypothesis* suggests that the association between hearing loss and cognition in older adults stems from a common neuro-degenerative mechanism (Eckert et al., 2012; Lockhart & DeCarli, 2014). The *cognitive load hypothesis* suggests that listeners with ARHL compensate for listening difficulty by exerting greater mental effort to understand and remember speech (Pichora-Fuller et al., 2016). The increasing listening demands associated with ARHL may increase cognitive load and deplete available neural resources (Powell et al., 2021). Finally, the *sensory deprivation hypothesis* posits that ARHL may trigger maladaptive changes in brain structure and function, leading to cognitive decline. Significant differences in cortical reorganization, such as reduced gray matter volume in the auditory cortex, are associated with ARHL (Wingfield & Peelle, 2015).

One influential framework linking hearing and cognition is the Ease of Language Understanding model, which focuses on the interaction between auditory processing and memory systems (Rönnberg et al., 2011). Hearing loss can disrupt the automatic matching of encoded auditory signals to stored representations in long-term memory. When this matching fails, listeners engage resource-demanding cognitive processes, such as short-term and working memory. In ARHL, a disproportionate amount of cognitive resources may be allocated to resolving degraded auditory input, thereby limiting the resources available for transferring auditory information into long-term memory. Consistent with the cognitive load and sensory deprivation hypotheses, these findings suggest a dose-dependent relationship in which greater hearing loss is associated with weaker cognitive processes (Danielsson et al., 2019). Using data from the UK Biobank, Rönnberg et al. (2014) found that ARHL was associated with declines in both auditory and visuospatial long-term memory. Merten et al. (2022) similarly reported reductions in auditory verbal long-term memory with ARHL. While these findings suggest a link between ARHL and memory, it is unclear whether ARHL interferes with memory retrieval and/or impedes listeners' ability to form new memories.

Memory-Guided Attention as a Marker of Cognitive Deficits

Attention and memory play important roles in identifying acoustic signals and parsing complex scenes to guide listening. While many studies have examined attention and memory in isolation, fewer have focused on their interaction. Memory-guided attention is the process by which stored information in long-term memory biases attentional resources toward learned features of the environment, such as semantics or spatial locations (Backer et al., 2015; Zimmermann et al., 2016). For example, recognizing a "bird singing" relies on acoustic feature analysis and stored semantic knowledge, which directs attention to the sound's spatial location (e.g., "up in a tree"). As an example of memory-guided auditory attention, Zimmermann et al. (2017) showed that learned associations between environmental sounds (e.g., a bell) and spatial locations biased attentional orientation in auditory scenes. Participants responded faster to a target sound presented at previously learned locations than at novel locations, indicating that long-term memory can guide attention via contextual cues. Similar results have also been observed in vision (Patai et al., 2012; Stokes et al., 2012) and in voice familiarity, which can guide attention toward relevant speakers (Johnsrude et al., 2013).

Contextual cueing effects are thought to be driven by prior stimulus learning and engage the hippocampus, with repeated exposure to complex scenes reinforcing attentional selection and hippocampal activity (Goldfarb et al., 2016; Summerfield et al., 2006). Given that the hippocampus is pivotal for episodic memory and vulnerable to age-related neurodegeneration (Braak & Braak, 1991), disruption of memory-guided attention may be relevant in populations with ARHL (Billig et al., 2022). While memory-guided attention recruits networks involving the hippocampus (Zimmermann et al., 2017, 2019) and frontoparietal attention systems to orient preparatory attention (Stokes et al., 2012), tasks assessing memory-guided attention might reveal ARHL-related changes in brain networks.

The interaction between attention and memory-guided learning has been further demonstrated by Fischer et al. (2023), who showed that incidental exposure led to associative memory effects detectable in event-related potentials, but not in overt behavioral performance. This suggests a neural trace that reflects explicit attention to a target and its associated scene, thereby influencing behavior. When tonal targets are embedded in a sound environment without explicit instruction to attend or report them, participants fail to form reliable associations during the initial learning phase. Together, these findings suggest that attentional engagement at encoding is important for establishing memory-based representations that support behavior. The interactions between auditory attention and memory can reveal cognitive vulnerabilities in systems that support memory-guided attention, which may be relevant in adults with ARHL. In this context, the sensory deprivation or cognitive load hypotheses predict that neural reorganization following ARHL may affect memory and attentional networks known to decline with cognitive impairment, offering clarity on how ARHL increases the risk of cognitive decline (Lin, Metter, et al., 2011; Livingston et al., 2017). Consistent with this view, Zimmermann et al. (2019) reported weaker memory-guided auditory attention in asymptomatic *APOE4* carriers who are genetically predisposed to Alzheimer's disease, suggesting that disruption of memory-guided auditory attention may be a sensitive, early behavioral marker of cognitive vulnerability.

The Present Study

Here, we tested the preregistered hypothesis that ARHL is associated with deficits in memory-guided auditory attention. We employed a paradigm developed by Zimmermann et al. (2019) that required participants to learn associations between the spatial location of a target probe and a naturalistic acoustic background sound. Learned associations were then examined in a memory-guided auditory attention test phase by measuring differences in reaction time (RT) between learned target–context associations and novel, unlearned ones. We predicted that older adults with comparatively lower degrees of ARHL would show faster RTs to targets presented in previously learned locations than to targets presented in novel locations, reflecting intact memory-guided attentional facilitation. Older adults with greater ARHL would show slower RTs to learned targets, comparable to RTs for unlearned targets, indicating weaker memory-guided attention. Planned analyses controlled for numerical age within the sample.

Method

Transparency and Openness

The study design, hypotheses, and analytic approach were formally preregistered (https://osf.io/yfmwj/). De-identified data files and analysis code are available on the Open Science Framework (https://osf.io/bysq5/). Study materials are described in sufficient detail within this Method section to allow replication. Analyses were conducted in R (R Core Team, 2021), using the *lme4* (Bates et al., 2015), *glmmTMB* (McGillycuddy et al., 2025), *car* (Fox & Weisberg, 2019), and *DHARMa* (Hartig, 2024) packages. We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study.

Participants

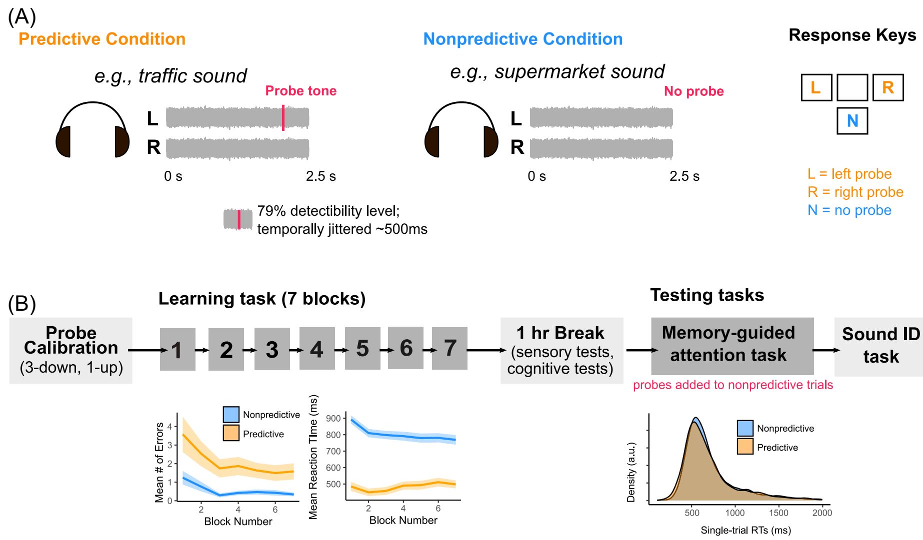
We planned to recruit 60 participants based on an a priori power analysis to detect a medium effect size (Cohen's $f^2 \sim 0.25$) for the interaction between memory conditions (within-subjects) and hearing sensitivity (between-subjects), assuming 80% power and a Type I error rate of 5%. Recruitment yielded 73 participants for the study. Participants who met our inclusion criteria were recruited by email invitation from the Baycrest Research Institute participant database and the Toronto Metropolitan Auditory Participant Pool at Toronto Metropolitan University. Inclusion criteria included the following: age between 40 and 80, pure-tone hearing thresholds below 80 decibels hearing level (dB HL) to exclude severe and profound cases of hearing loss that would prevent encoding of sound stimuli, no history of hearing-aid use, and a Montreal Cognitive Assessment (MoCA) score of 22 or higher. Three participants completed an earlier version of the task and were therefore omitted. Five participants scored less than 22 on the MoCA. They were removed from the analysis because research shows that a lower MoCA threshold offers higher specificity for mild cognitive impairment in general adult populations (Islam et al., 2023). Participants were predominantly native English speakers; five individuals in our sample had acquired English as a second language during early childhood (before age 6) and were included in the study. Two were omitted because they learned English during adulthood. One final participant was omitted due to a technical error during their data collection. The remaining 62 participants met our preregistered requirement for 60 participants and were aged 40–80 years ($M = 69.2$, $SD = 11.0$), with 38 self-reporting as women and 24 as men. Self-reported racial and ethnic identities were as follows: 55 identified as White, three as Black, five as East/Southeast Asian, one as Ashkenazi, and one as Jewish. All participants were non-hearing-aid users and did not report any history of neurological trauma or disorders. All participants provided written informed consent, and the study protocol was approved by the Research Ethics Board of the University of Toronto (Research Ethics Board No. 23-40) and Toronto Metropolitan University (Research Ethics Board No. 2023-439). The study was conducted at the Baycrest Academy for Research and Education in Toronto, Canada. Data were collected between 2023 and 2025. Participants received CAD 20 per hour for their voluntary participation.

To assess hearing ability, each participant underwent pulsed pure-tone audiometry, the "gold standard" measure of hearing loss, which determines the sound level (in dB HL) at which participants detect a pure tone 50% of the time. To calculate the degree of ARHL, thresholds were averaged from 2 to 8 kHz across both ears, herein referred to as the high-frequency pure-tone average (HF PTA). This approach reflects the typical high-frequency nature of ARHL and aligns with Statistics Canada methodology (Ramage-Morin et al., 2019). Twenty-five participants had HF PTA thresholds within the "normal" range (<25 dB HL), 17 had HF PTA values in the "mild" hearing loss range (>25 dB HL and <40 dB HL), and 20 had "moderate" hearing loss (HF PTA >40 dB HL and <70 dB HL). Therefore, participants had a mixture of normal hearing and high-frequency hearing loss, ranging from mild to moderate.

Stimuli and Materials

Forty acoustic scenes of natural sounds (e.g., rainfall) were sourced from https://www.freesound.org/. Sound files were shortened to 2.5 s, with a 100-ms rise and fall time, resampled to a standard digitization rate of 44,100 Hz, and normalized to the average root-mean-squared value across all sound files. Audio files were presented binaurally to participants through ER3-A insert earphones at an average sound pressure level of 65 dB, with some stimuli peaking at 77 dB sound pressure level, as measured with a Larson-Davis System 824 Sound Level Meter (Depew, New York). Participants were trained and tested using the same set of acoustic scenes. We selected the acoustic scenes used in a separate study by Zimmermann et al. (2019). These scenes were chosen for their everyday semantic relevance to increase participants' chances of forming associations between acoustic scenes and targets in long-term memory. In a pilot study (Zimmermann et al., 2019), the experimenters assessed audio clips on a five-step scale and included them if they had "most semantic relevance." The pure-tone target embedded in the acoustic scene had a frequency of 500 Hz and a duration of 200 ms. The target occurred at a random temporal position between 2 and 2.5 s after the start of the acoustic scene (Figure 1A).

Figure 1
Trial Structure and Sequence of Study Phases



Note. (A) Trial structure showing "predictive" trials in which participants heard an acoustic scene (e.g., traffic noise) and a probe tone was inserted into either the left or right channel. The probe tone was temporally jittered between 2 and 2.5 s and set to a 79% detectability level. Nonpredictive trials contained no probe tone. Participants responded by keypress to indicate the spatial location of the probe (left or right channel for predictive trials) or the absence of a probe (for nonpredictive trials). (B) Study procedure phases, in which participants first performed a calibration task to determine the signal-to-noise ratio corresponding to 79% probe detectability. Participants then completed seven training blocks, during which all 40 background sounds (20 nonpredictive, 20 predictive) were presented in random order within each block. The plots show changes in RTs and error rates across the training blocks. After a 1-hr break, participants completed sensory and cognitive tests. To end the study, participants completed the memory-guided attention task and the sound identification task. The distribution of raw RTs for predictive and nonpredictive trials is plotted below the attention task. RTs = reaction times; a.u. = arbitrary units. See the online article for the color version of this figure.

Design and Procedure

We used a mixed factorial design to assess HF PTA and spatial auditory memory across multiple listening blocks, with age as a covariate. The procedure comprised five main phases: (a) calibration, (b) training, (c) a memory retention interval, (d) a memory-guided attention task, and (e) a sound identification task. An outline of the procedure is shown in Figure 1B. The experimental conditions included predictive trials, in which acoustic scenes contained a target probe, and nonpredictive trials, in which acoustic scenes lacked a target probe. The analysis treated the task condition (predictive or nonpredictive) as a within-subject factor and included HF PTA as a continuous between-subject predictor. Before the study, participants completed an informed consent form and a demographic questionnaire, both administered via a secure online form.

Phase 1: Calibration

All participants completed a calibration task to determine the sound level required to detect a 500 Hz, 200 ms pure-tone target across four audio scenes with a 79% detection rate. We did not include the acoustic scenes from this phase in other parts of the experiment. On each trial, we presented each acoustic scene twice in succession for 2,500 ms, with a 500-ms interval between the first and second repetition. The pure-tone target occurred randomly in either the first or second presentation of the audio scenes. Participants used a two-alternative forced-choice method, indicating by pressing a key which of the two acoustic scenes contained the probe tone. Participants had a 2000-ms response window after the second stimulus, followed by a visual feedback box. Each participant's 79% detectability signal-to-noise ratio threshold was estimated using a three-down, one-up algorithm (Levitt, 1971).

Phase 2: Training

Participants learned to associate 40 acoustic scenes with the presence or absence of a probe tone across seven training blocks. We divided the training blocks into two trial types, predictive and nonpredictive, each consisting of 20 trials. For each trial type, 10 trials were presented to the left ear and 10 to the right ear, with the ear of presentation randomly determined per trial. At the end of each trial, participants reported whether the probe tone was in the left or right ear by pressing the corresponding key (e.g., the left key indicated the left probe location). Twenty nonpredictive trials did not contain a probe tone. Participants pressed the "down" button after the trial ended if they did not hear a probe tone. We instructed participants to respond as quickly as possible once the screen displayed "Respond Now." Participants had a 2000-ms response window, followed by a 500-ms visual feedback box. Each participant listened to the same 40 trials across seven training blocks, for a total of 280 trials.

Phase 3: Memory Retention Interval

During a 1-hr retention interval, participants completed a series of additional tasks. The first task was a pure-tone audiometry test to assess hearing thresholds using pulsed pure tones, measured in half-octave steps from 125 Hz to 8 kHz in each ear. The procedure followed the Hughson–Westlake method (Lentz et al., 2017). Next, participants' visual acuity was evaluated using the Freiburg Vision Test (Bach, 1996). Corrective lenses (e.g., eyeglasses or contact lenses) were permitted during testing. Finally, cognitive function was assessed using the MoCA, a 30-point screening tool, with scores below 22 indicating mild cognitive impairment (Islam et al., 2023). The assessment examined multiple cognitive domains, including short-term memory, visuospatial abilities, executive functioning, attention, working memory, language, and orientation to time and place.

Phase 4: Testing

To assess memory for target locations, participants completed an RT task using the same acoustic scenes heard during training. On each trial, the environmental sounds were presented twice. The first acoustic scene lacked a probe and served as a memory cue to prompt participants to recall the probe's location. The second acoustic scene contained a probe presented on either the left or right side. Participants responded to the probe location as quickly as possible by pressing the corresponding key. RTs for the button press were recorded. A 500-ms interval separated the end of one trial and the start of the next. On predictive trials, the target probe was embedded within the acoustic scene at a random temporal position between 2.0 and 2.5 s and was presented in the same spatial location as during training. Nonpredictive trials from the training phase, which did not include a probe tone, were presented with a target tone randomly assigned to either the left or right ear. Participants heard all 40 acoustic scenes four times across four blocks, following Zimmermann et al. (2019).

Phase 5: Sound Identification Task

During the sound identification task, participants listened to all 40 acoustic scenes presented during the experiment's training and testing phases. They heard the scenes without probe tones and were asked to identify each scene by typing their responses into a textbox. Participants had unlimited time to respond and describe the sound they heard. An independent rater, unfamiliar with the task and participants, manually scored participants' responses, determining whether the typed responses matched the acoustic scene and grading them as correct or incorrect.

Statistical Analysis

We used R (R Core Team, 2021) to fit generalized linear mixed-effects models with the *lme4* (Bates et al., 2015) and *glmmTMB* (McGillycuddy et al., 2025) libraries. All analyses were conducted on unaggregated (single-trial) observations unless otherwise noted. We also used the *car* package for model interpretation (Fox & Weisberg, 2019) and the *DHARMa* package to assess model performance and diagnostics (Hartig, 2024). Diagnostics for all models indicated no aberrations and no under- or overdispersion of residuals. Given the correlation between age and HF PTA ($r = .6$), variance inflation factors were computed to check for multicollinearity. However, all values were below 1.47 (factors above 5 indicate potentially problematic collinearity). The α criterion for Type I error was set at 5%. Following recommendations by Lorah (2018), effect sizes for significant generalized linear mixed-model terms are reported as the normalized difference of pseudo-R^2 values of the full models and pseudo-R^2 values of reduced models lacking the fixed-effect term of interest: $(R^2_{\text{full}} - R^2_{\text{reduced}})/(1 - R^2_{\text{full}})$. This yields a standard effect size referred to as an f^2 value (Aiken & West, 1991), interpreted using conventions of small = .02, medium = .15, and large = .35.

Training

Training trial performance was scored as "correct" if participants accurately reported the location or absence of the probe tone and "incorrect" otherwise. Many participants committed zero errors, and because there was no variance in these sets of observations, statistical analysis of unaggregated data could not be completed. We analyzed RTs across the seven training blocks and measured target-onset responses during the response screen that followed each trial. This analysis focused on RTs from trials in which a probe was present. RTs below 100 ms and longer than 2000 ms were omitted from analysis. We modeled RTs using the inverse Gaussian and gamma families of probability distributions, with either the identity or the inverse link functions. Our final model used a Gaussian family with a log link, which produced the lowest Akaike information criterion value (Lo & Andrews, 2015). RTs were analyzed for trials with correct performance.

As a reminder, RTs were recorded as participants' keypresses relative to the onset of a text prompt that appeared after the end of the sound presentation. During predictive trials, participants were preparing to register their response on the prompt screen once the target and its location were perceived. During nonpredictive trials, no target tone was present, and RTs after the screen prompt likely reflected different cognitive operations. For instance, participants may have been reviewing the auditory signal in auditory working memory to determine whether a target occurred, or they may have been anticipating the tone at the time the text prompt appeared. Supporting this view, RTs for nonpredictive trials were approximately 350 to 400 ms longer than predictive trials (Figure 1B). Therefore, RTs during training blocks were analyzed separately for predictive and nonpredictive trials, and the α criterion was set to 2.5% to account for the use of two models. The model structure assigned RTs as the outcome variable and included HF PTA, block number, and the interaction between these terms as fixed effects. Age was included as a covariate. Each participant and stimulus were treated as a random intercept, and the model also included correlated by-participant random slopes across blocks.

Testing

We assessed implicit spatial memory for probe locations using a generalized linear mixed model. RTs were modeled with a Gaussian distribution and log link function, as was done for the training blocks. RTs below 100 ms and above 2000 ms were omitted from analysis. The model structure assigned RTs as the outcome variable and included HF PTA, trial conditions (predictive vs. nonpredictive), and the interaction between these terms as fixed effects. Age was included as a covariate. Each participant and stimulus were treated as a random intercept, and the model also included correlated by-participant random slopes across conditions.

The sound-naming task was analyzed using a logistic mixed-effects model. Correct sound labels were scored as "1" and incorrect labels as "0." Participant age and HF PTA were included as predictor variables and were *z*-scored prior to modeling to facilitate model convergence. Random intercepts were specified for each participant and stimulus. Age and HF PTA slope coefficients, along with their standard errors, are reported as odds ratios. One participant's data were improperly logged during this task, and 61 individuals were analyzed.

Deviations From Preregistration Plan

We met our target sample size and successfully tested the study's primary hypothesis, which was that hearing loss correlates with smaller RT differences between nonpredictive and predictive conditions during the testing phase. However, there were two notable deviations from our preregistration plan for secondary hypotheses. First, the original study design included an explicit memory testing phase in which, after the memory retention break, participants listened to each of the 40 stimuli from the training phase and reported whether they recalled the sound clip had a probe on the left or right side or no probe. We found that several participants confused this task with the training-phase instructions, even after providing written and verbal instructions. Several participants consistently reported that each clip had no probe and scored 0% on recall of predictive trials. This indicated that participants were selecting the "no probe" key, believing they were listening for a probe, rather than recalling whether a probe was present. We therefore could not determine whether performance reflected memory processes or misinterpretation of task instructions, and so this analysis was abandoned. In addition, we planned to include a selective attention task in our study, but a coding error precluded the collection of these data. These tasks constituted secondary hypotheses, and this did not affect the test of our primary hypothesis.

There were a few other minor changes to the preregistration analysis plan that had minimal effects on the test of the primary hypothesis. First, we conducted an unplanned, exploratory analysis on the training data that was not specified in the preregistration. Second, during the testing phase, the probe side (left or right) was not included in the general linear model because we did not anticipate main effects or interactions for this variable, but we ran a follow-up model to explore this possibility. Third, we specified in our preregistration that RTs during the testing phase greater than 2,500 ms were to be excluded. RTs above 2000 ms (360 observations, 4% of total observations) produced outlier values that prevented models from converging, so they were omitted. Crucially, this did not change the statistical significance of outcomes for the testing model, but coefficients for models that fail to converge should not be interpreted. Last, we *z*-scored the age and HF PTA variables during the sound-naming task because the model would not otherwise converge, and the possibility of data transformation was not specified in the preregistration. This did not affect the test of the primary hypothesis.

Results

Training Phase

A general linear mixed model for RTs on predictive training trials revealed no significant main effects or interactions (Figure 1B; Supplemental Table S1). A model for nonpredictive trials showed a main effect of trial block ($\beta = -0.031$, $SE = 0.010$), $\chi^2(1) = 10.23$, $p = .001$, $f^2 = .02$ (Supplemental Table S2), indicating that RTs decreased across training blocks in this condition, with a small effect size. Figure 1B shows that RTs decreased sharply after one block and continued to decline throughout the training blocks. Neither HF PTA nor age correlated with RTs in either the predictive or nonpredictive trial models. The decrease in RTs for nonpredictive trials suggests that participants were learning associations between certain stimuli and the absence of a probe. However, other factors, such as learning the timing of the text prompt relative to the offset of nonpredictive trials, could also modulate RTs across blocks.

Trial errors were analyzed using a linear mixed model on aggregated data because some participants committed zero errors, precluding analysis of unaggregated data. This model found only a main effect of trial type, with errors for predictive trials higher than for nonpredictive trials, with a small-to-medium effect size ($\beta = 2.56$, $SE = 0.98$), $\chi^2(1) = 6.83$, $p = .009$, $f^2 = .05$ (Supplemental Table S3). Figure 1B shows that the mean number of errors declined sharply after two training blocks and averaged under two errors for the remaining blocks, indicating above 95% accuracy. Unplanned analyses tested for potential gender effects and nonlinear associations between predictor variables and RTs during training, but no significant effects were found (ps > .05).

Testing Phase

RTs During the Memory-Guided Attention Task

The average RT for nonpredictive trials was ~710 ms, and for predictive trials, it was ~694 ms, suggesting a memory-guided attention effect size of 16 ms. General linear modeling (Table 1) found a main effect of condition ($p = .021$, $f^2 = .01$), indicating faster RTs on predictive than on nonpredictive trials (Figure 2A). This result confirmed the presence of memory-guided attention, as RTs were faster for predictive trials in which acoustic scenes were paired with a probe during the training phase and slower for nonpredictive trials that did not contain any probes during training, although the effect size was small. In addition, a main effect of HF PTA indicated that poorer hearing sensitivity was associated with slower RTs across predictive and nonpredictive trials, with a small-to-medium effect size ($p = .006$, $f^2 = .06$; Figure 2B). However, there was no interaction between HF

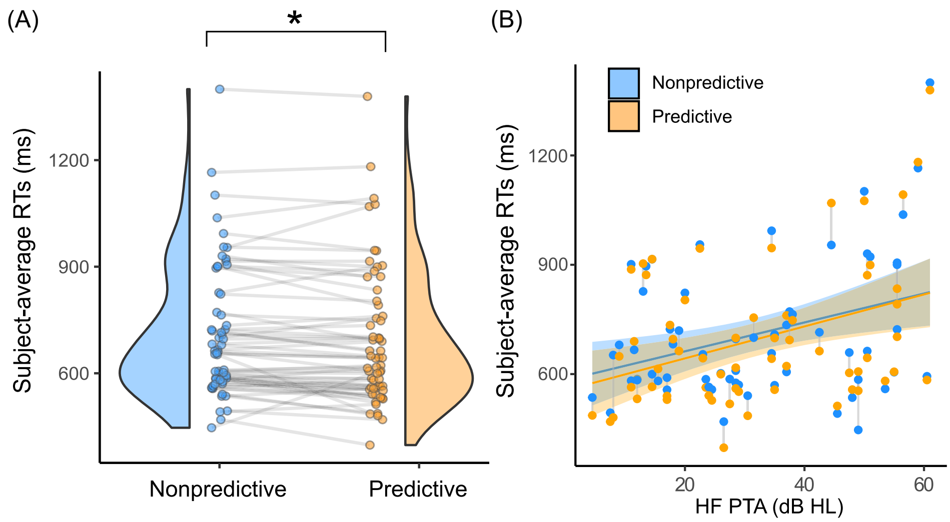
Table 1
Statistical Values for the Memory-Guided Attention Task Model

Model term	Coefficient estimate	*SE*	$\chi^2(1)$	*p*
HF PTA	0.006	0.002	7.55	**.006**
Condition	−0.042	0.018	5.37	**.021**
Age	−0.003	0.003	0.61	.436
HF PTA × Condition	0.0003	0.0004	0.33	.565

Note. Significant values appear in bold. "Condition" refers to predictive versus nonpredictive trials. χ^2 indicates values on the likelihood ratio test, with 1 degree of freedom in parentheses. *SE* = standard error; HF PTA = high-frequency pure-tone average.

Figure 2

RT Performance During the Memory Testing Phase



Note. (A) Raincloud plot showing participant-average RTs as a function of nonpredictive (blue/dark gray) and predictive (orange/light gray) trials. Each participant is represented as a dot, with dots connected across trial types by a gray line. Kernel density estimates of the data distributions flank the participant-average data points. (B) Participant-average RTs during the testing phase as a function of HF PTA measured in dB HL. Individual data points are represented as dots and are connected within each participant by a gray line. Colors indicate trial type (predictive = orange; nonpredictive = blue). Solid lines indicate model predictions for each condition, with a 95% confidence interval. HF PTA = high-frequency pure-tone average; RTs = reaction times; dB HL = decibels hearing level. See the online article for the color version of this figure.
* $p < .05$.

PTA and predictive versus nonpredictive trials ($p = .565$). The full model table is provided in Table 1. Therefore, the model results do not support our hypothesis that memory-guided auditory attention declines in those with worse hearing sensitivity. We also ran a follow-up, unplanned analysis to test if the target spatial location (left vs. right) influenced RTs, but no main effects or interactions with probe location were found ($ps > .05$). Follow-up, unplanned analyses tested for gender effects and nonlinear associations between predictor variables and RTs during the testing phase, but no statistically significant outcomes were found ($ps > .05$).

Performance on the Sound Identification Task

Overall performance on the sound identification task was 76.0% ($SD = 12.2\%$), with individual participants' scores ranging from 42.5% to 97.5%. Performance for each stimulus (Figure 3A) ranged from 55.56% (*bees and insects*) to 91.8% (*supermarket* and *lightning*). Participant performance was analyzed at the single-trial level using a logistic mixed-effects model, with age and HF PTA as predictors (Figure 3B). Participants with poorer hearing sensitivity showed lower performance on the identification task ($p < .001$, $f^2 = .03$; Table 2). Age was not a significant predictor ($p = .16$). Gender and nonlinear effects of other predictor variables were not statistically significant in additional unplanned analyses ($ps > .05$).

Discussion

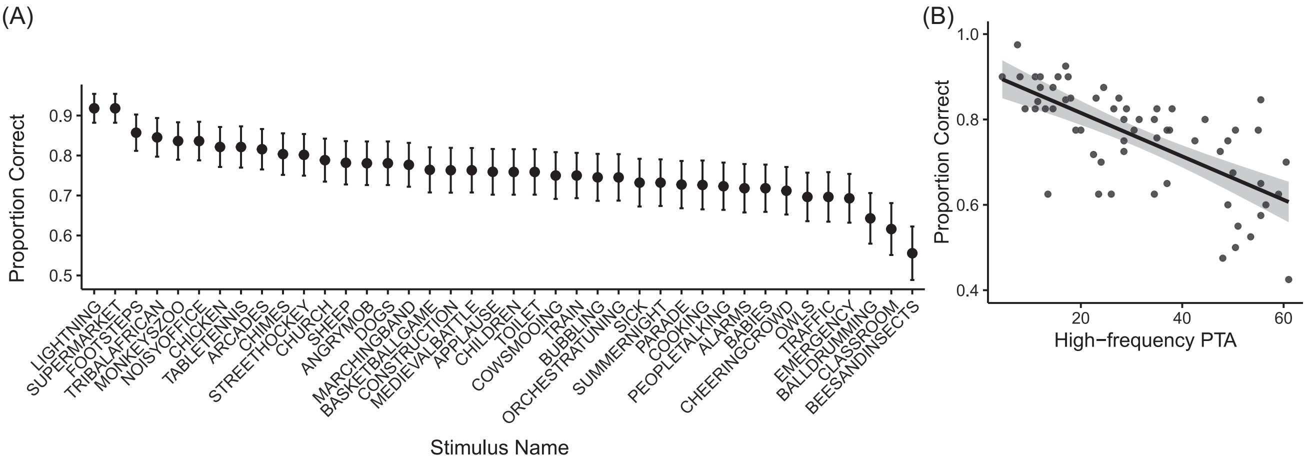
In this study, we examined how ARHL relates to behavioral performance on a memory-guided attention task. This work extended Zimmermann et al. (2019), who proposed that memory-guided auditory conditions may serve as sensitive markers of early cognitive impairment in middle-aged individuals at genetic risk for Alzheimer's disease. Memory-guided attention reflects the ability to use stored auditory scene representations to anticipate upcoming targets. Prior research indicates that intact performance is characterized by faster RTs for probes appearing at learned sound locations (Fischer et al., 2023, 2025; Zimmermann et al., 2017, 2019). We therefore tested whether these associations were attenuated in individuals with greater degrees of ARHL, given evidence that hearing loss is associated with declines in long-term memory. In addition, we examined whether any association between ARHL and memory-guided attention would be independent of performance on a sound-identification task, allowing us to distinguish higher level memory-attention mechanisms from deficits in semantic labeling. However, we did not find that hearing sensitivity was associated with memory-guided attention performance; furthermore, sound identification declined with poorer hearing sensitivity.

Auditory Associative Learning

In the training phase of the study, participants demonstrated evidence of associative learning across blocks. Error rates declined sharply after two blocks, as did RTs for neutral trials. The reduction in RT for nonpredictive trials likely reflects increasing familiarity with the task structure, including expectancy and temporal anticipation. Participants may have learned that nonpredictive trials lacked a probe, allowing more efficient response preparation, or they may have become more sensitive to the timing of the response prompt relative to sound offset. In predictive trials, which elicited shorter RTs than

Figure 3

Performance on the Sound Identification Task



Note. (A) Proportion of correctly identified stimulus sounds for each stimulus, with standard error bars. (B) Scatterplot of performance on the sound-naming task as a function of high-frequency PTA. Individual dots represent participant-average performance. A least-squares line is shown, shaded with 95% confidence intervals. PTA = pure-tone average.

nonpredictive trials, participants likely prepared button presses for the response screen upon perceiving the probe tone. This asymmetry in RTs suggests that training may not solely indicate strengthening of target–context associations but may instead reflect strategic adjustments or learning of task structure. Interestingly, error rates were roughly twice as high in predictive trials, potentially reflecting the conditional nature of response requirements for predictive trials (target presence and its spatial location). In nonpredictive trials, only the presence of the target was queried.

This pattern of findings for the training phase is consistent with prior work. The literature on measuring memory-guided attention suggests that attention to the task during the learning phase is necessary to form associations between a target and an acoustic scene (Fischer et al., 2023). Zimmermann et al. (2017) suggested the initial learning phase in memory-guided attention often relies on deliberate knowledge of target locations and contextual cues, as participants were asked to respond to the pure-tone targets themselves. Zimmermann et al. (2019) also showed that improvement in RTs across training blocks was not moderated by genetic risk for Alzheimer's disease. Consistent with this view, Zimmermann et al. reported early learning effects in healthy young adults, with RTs decreasing by approximately 64 ms between the first two training blocks and total training-related gains of 96–100 ms across experiments. Improvements in RTs across training blocks were also shown not to be moderated by genetic risk for Alzheimer's disease (Zimmermann et al., 2019). In line with these findings, neither age nor hearing sensitivity correlated with performance during the training blocks in the present sample, suggesting that basic associative learning and task acquisition remain intact in middle-aged and older adults. These results indicate that any patterns observed during the testing phase are unlikely to be attributable to deficits in initial learning.

Table 2

Statistical Values for the Sound Identification Task Model

Model term	*OR*	*SE*	$\chi^2(1)$	*p*
HF PTA	0.67	0.05	21.72	**<.001**
Age	0.89	0.07	2.02	.155

Note. Significant values appear in bold. χ^2 indicates values on the likelihood ratio test, with 1 degree of freedom in parentheses. *SE* = standard error; HF PTA = high-frequency pure-tone average.

Memory-Guided Attention

In the testing phase, participants responded significantly faster to memory-oriented predictive trials than to nonpredictive trials, consistent with retrieval of learned context-to-target associations that guided attention to target spatial locations. Importantly, the magnitude of this memory-guided attention effect did not correlate with age or hearing sensitivity. Although individuals with poorer hearing exhibited slower overall RTs, the relative benefit for predictive trials was preserved. This dissociation suggests that while aging may lower overall response speed, it does not diminish the ability to use learned auditory memories to guide attention. To our knowledge, these findings provide the first behavioral evidence that memory-guided auditory attention is present in middle-aged and older adults across a range of hearing sensitivities.

Prior studies in younger adults have shown reliable memory-guided attention effects when participants undergo incidental training followed by a surprise test assessing implicit recall of target–sound clip pairings. In these paradigms, participants are not explicitly instructed to form target–context associations, yet memory-cued predictive trials are consistently faster than nonpredictive trials, with RT benefits of approximately 13–17 ms (Fischer et al., 2023, 2025). In contrast, studies in which participants receive clearer task instructions and repeated exposure to target–context acoustic scenes report larger behavioral benefits, with RT improvements of approximately 60 ms under structured target onsets and larger benefits approaching 100 ms when associative learning was reinforced in longer blocks (Zimmermann et al., 2017). In older adults and non-gene-related carriers of Alzheimer's disease, an RT benefit of approximately 56 ms has been reported for memory-cued trials relative to nonpredictive trials (Zimmermann et al., 2019). However, these effects are reduced in *APOE4* carriers, who show a minimal RT benefit of approximately 10–15 ms. In the present study, these effects were sustained in older adults, with participants showing preserved memory-guided attentional facilitation and a 16 ms RT benefit. Although this implicit retrieval effect was smaller than that observed in younger adults under similar training conditions, the present sample showed a slightly larger benefit than reported in *APOE4* carriers, implying preserved memory-guided attention in middle-aged and older adults.

Models of auditory aging often emphasize sensory deprivation and increased reliance on effortful working memory processes, predicting downstream disruptions in long-term memory representations (Rönnberg et al., 2011, 2014). However, much of this evidence derives from speech-based paradigms that impose semantic and cognitive demands different from those posed by nonspeech stimuli (Lorenzi et al., 2023). The present findings using nonspeech acoustic scenes suggest that ARHL does not necessarily impair the formation or retrieval of associative auditory memories. Instead, ARHL may primarily affect general processing speed while leaving memory-guided attentional mechanisms for nonspeech sounds relatively intact. This pattern is consistent with findings from visual memory-guided attention paradigms, in which older adults often demonstrate preserved implicit facilitation of visual target detection despite reductions in explicit contextual recall (Kuo et al., 2014; Salvato et al., 2016). Across modalities, implicit retrieval of learned associations appears more resilient to aging than conscious recollection. While the present study did not find correlations with age, the overall patterns suggest that aging may impact explicit memory and processing speed, leaving memory-guided attentional mechanisms relatively stable. Alternatively, the small effect size for the RT benefit in the present study (16 ms) may have hindered detection of an interaction between hearing sensitivity and memory-guided attention conditions. Design factors such as the number of stimuli, salience of probes, and semantic diversity of background sounds could have contributed to this effect size and may require adjustment. Adjustments to the study design are also required to accurately measure explicit recall of previously learned acoustic scenes in older adults.

Hearing Sensitivity, Identification of Acoustic Scenes, and Memory-Guided Attention

We reasoned that an effective claim for a decline in memory-guided attention with hearing loss would account for differences in semantic understanding of the sounds, which was the rationale for the sound identification task. However, despite predictions, lower hearing sensitivity was strongly associated with poorer performance on the sound-naming task, consistent with an age-related decline in auditory processing. Age-related elevations in hearing thresholds result from the accumulation of lifelong damage to structures of the inner ear that are responsible for sound transduction and feature encoding (Huang & Tang, 2010). The subsequent reductions in audibility and sound clarity make speech and other sounds less intelligible and potentially less capable of activating semantic meaning. This would explain the lower ability to identify soundscapes.

Our findings align with prior research on the perception of natural or ecological sounds in individuals with hearing loss. Miller-Viacava et al. (2024) used a three-interval "odd-one-out" paradigm to test listeners' discrimination of different acoustic biomes. Compared with younger, typically hearing participants, older participants with mild-to-severe hearing loss had lower discrimination scores, but this association was only partially explained by reduced audibility. Other suprathreshold sound-encoding deficits related to hearing loss likely contributed to the discrimination deficits. This is relevant to the present study because the sound levels for acoustic scenes were fixed at an average of 65 dB sound pressure level. A consequence of a fixed sound level is that acoustic scenes may have been perceived as less audible by those with reduced hearing sensitivity, as was suggested by Miller-Viacava et al. While this may have partly accounted for the reduced RT across all trials in the testing phase and the lower performance on the semantic naming task, suprathreshold encoding deficits associated with cochlear cellular loss are likely an additional contributing factor. Interestingly, this issue appeared to have little bearing on memory-guided attention performance in middle-aged and older adults.

Previous research suggests that the decision-making process of recalling a contextual scene is influenced by noise (e.g., environmental distractors, general difficulty of memory task) and variability in a participant's memory strength (Kuo et al., 2015). In visual tasks, strong perceptual cues of stimuli may reduce interference and improve recall of target locations (Kuo et al., 2012, 2014; Ward et al., 2013). In auditory research, perceptual cues involving spatial expectations and temporal regularities in a moving sound source influence conscious target detection (Rimmele et al., 2011), and auditory objects defined by spectrotemporal acoustic features (e.g., tone frequency, duration, pitch) improve explicit recall (Backer et al., 2015). These studies suggest that memory-guided attention can be influenced by relevant or salient perceptual features. In our study, participants with poorer hearing sensitivity and lower performance on the identification task may have relied on specific spectral or temporal perceptual features to associate the scene with the target's spatial location, rather than on overall semantic representation. In addition, semantic processing of acoustic scenes, involving the integration of meaning and context of learned associations, may build cognitive representations that contribute to memory formation alongside perceptual cues, a strategy that may have been used by those in our study with better hearing sensitivity.

Limitations

This study has several limitations. First, participants had mild-to-moderate sloping high-frequency hearing loss, which represents the majority of ARHL cases in this age group (Haile et al., 2021). However, more severe cases of hearing loss, which are less prevalent than mild hearing losses in older adults, may lead to deficits in memory performance. Future research may extend this paradigm to include these individuals, as well as hearing-aid users. Furthermore, we did not collect information on the onset or duration of hearing loss in the study participants. Early- or sudden-onset hearing loss could affect memory or attention differently from gradual hearing loss over years. Third, participants above the age of 80 were excluded, and we cannot rule out that mild-to-moderate hearing loss in this age group may produce more apparent memory-guided attention deficits. Fourth, our results provide evidence for memory-guided attention in middle-aged and older adults with varying levels of hearing sensitivity, but we did not compare this cohort to younger adults and cannot infer whether there were differences between these age groups. Fifth, we were unable to measure participants' explicit recall of acoustic scenes containing probes because of a potential misunderstanding of the task instructions. We cannot draw conclusions about explicit versus implicit memory processes, and it is possible that participants with poorer hearing sensitivity had lower explicit memory recall for target–probe associations. Last, there may be other factors associated with variability in memory-guided attention performance, such as education level and physical activity level. We did not measure these variables, but they may be important covariates to consider in future research.

Implications and Conclusions

The main contribution of this study is the evidence of associative learning and memory-guided attention functioning in natural acoustic scenes among middle-aged and older adults with varying high-frequency hearing thresholds. This implies that memory-guided auditory attention is a measurable function in older adults and can be included in studies investigating how this ability changes over the lifespan, given that a descriptive comparison to previous literature suggests a smaller effect in older adults compared to younger adults (Zimmermann et al., 2017). Measurement of auditory memory-guided attention in older adults also permits the identification of neural correlates and comparison with visual memory-guided attention ability to understand domain-general versus domain-specific cognitive processes (Stokes et al., 2012).

Inconsistent with our preregistered hypothesis, we did not find that memory-guided auditory attention was associated with age-related mild-to-moderate hearing loss. Therefore, the study does not, at present, resolve competing hypotheses linking hearing loss to cognitive decline, such as the *sensory deprivation* or *cognitive load* hypotheses (Slade et al., 2020). If an association between hearing loss and memory-guided attention exists, it may be smaller than the medium effect size our study was powered to detect. The effect size for memory-guided auditory attention might also be larger in severe-to-profound cases of ARHL. Furthermore, had we identified a relationship between hearing sensitivity and memory-guided attention in this study, the result may have been difficult to interpret, given that participants with poorer hearing sensitivity had more difficulty labeling the acoustic scenes. This also means that participants could learn spatial targets in a natural soundscape despite difficulty forming semantic representations and implies that target–context learning can arise through dependence on spectrotemporal acoustic cues.

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