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When body supports brain and autonomy: Embodied encoding reduces memory deficits in Alzheimer's disease

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Abstract:

Alzheimer's disease is characterized by early memory impairment, which progressively undermines patients' autonomy and independence in everyday life. Although pharmacological treatments are currently under development, their efficacy remains limited and must be complemented by non-pharmacological interventions targeting preserved cognitive and neural resources. The present study is grounded in a multimodal and embodied theoretical framework, positing that at early stages of the disease, patients may benefit from an enriched encoding context involving gestures associated with activities of daily living. Recruiting relatively preserved sensorimotor neural networks at this stage is hypothesized to support information retention and retrieval, while enhancing memory trace distinctiveness and resistance to interference. Using a within-subjects design, participants (patients with Alzheimer's disease and healthy older controls) learned sentences describing everyday actions across four encoding conditions, including a control condition. Three other experimental conditions were implemented: enactment of the action described by the sentence, sentence reading with interfering background music, and a combined gesture-music condition. Memory performance was subsequently assessed using a free recall task and a recognition task, from which a score of balanced accuracy, discrimination index, and response bias index were computed. Results revealed a robust effect of motor engagement, which markedly improved performance across all memory indices and attenuated the interfering impact of background music. These findings support the view that bodily involvement at encoding, through sensorimotor enrichment, constitutes a relevant lever for strengthening memory traces in the context of early-stage Alzheimer's disease.

Keywords: Embodied cognition, Alzheimer's disease, memory, musical interference, trace distinctiveness, enaction

Introduction

By 2050, the number of people living with dementia worldwide is expected to nearly triple, ranging from 131.5 million to 152.8 million, according to various reports (Alzheimer's Disease International, 2015, 2017; Nichols et al., 2022). Among individuals with dementia, nearly three-quarters are affected by Alzheimer's disease (AD; World Health Organization, 2018). From a pathophysiological perspective, AD is characterized by amyloid pathology and tauopathy, leading to the accumulation of senile plaques and neurofibrillary tangles. These alterations disrupt neuronal function, destabilize synaptic connectivity, and ultimately lead to neuronal death (Lohela et al., 2022; Roveta et al., 2024; Wang et al., 2025). Other studies have also pointed out that neurovascular vulnerabilities may trigger defensive inflammatory processes in response to peripheral infection. When dysregulated, these processes progressively induce hypersensitivity in glial cells of the central nervous system, rendering them toxic and contributing to neuronal degeneration (Holmes et al., 2009; Nefodova et al., 2024; Takeda et al., 2014; for a comprehensive review, see Xie et al., 2022). Functionally, AD is associated with impairments in language (Jiang et al., 2025; Taler & Phillips, 2008), executive functions (Amieva et al., 2004; Guarino et al., 2019; Silva et al., 2022), spatial orientation, and behavior (for a comprehensive overview, see Breijyeh & Karaman, 2020; Knopman et al., 2021). Among all of these impairments, memory related ones are the most frequently reported (Castellani et al., 2010; Knopman et al., 2021).

Despite significant advances in pharmacological treatments, the benefits remain largely confined to pathophysiological mechanisms (e.g., reduction of senile plaques). The few treatments that produce significant cognitive improvement often do so at the cost of considerable side effects and financial burden (Brück et al., 2023; Wimo et al., 2017), without yielding substantial gains in cognitive scores (Arroyo-Pacheco et al., 2025; Bregman et al., 2025; Dyck et al., 2023; Qiao et al., 2023). Given these therapeutic limitations, non-pharmacological approaches have emerged as essential complementary strategies to support patients' quality of life and cognitive functioning. Several interventions have already been proposed, including cognitive interventions ranging from games to targeted training (Buschert et al., 2010; Cotelli et al., 2006; Garrido-Pedrosa et al., 2017) or the use of compensatory tools such as planners or visualization techniques (Bourgeois et al., 2003; Sitzler et al., 2006; Tomaszewski Farias et al., 2018). Some of these approaches appear to be effective, but they often require a high level of engagement and substantial changes to patients' daily routines, precisely where the establishment of new learnings and routines is compromised by the progression of the disease. Moreover, these interventions primarily target compensation or recovery, without exploring residual cognitive and functional resources that could likely be mobilized as "mnemonic protections", that is, as buffers against forgetting.

Even though numerous neuronal and cognitive alterations are associated with the disease, the progression of Alzheimer's pathology is not uniform, and during its early stages, not all neural networks are equally affected. The development of senile plaques and neurofibrillary tangles tends to occur preferentially within the medial temporal lobe (Barnes et al., 2009; Jagust, 2018), affecting the hippocampus, rhinal cortices, and subsequently posterior regions. In contrast, cortical and subcortical regions associated with motor processes appear to be relatively preserved until the later stages of the disease. Behavioral findings suggest that non-declarative memory functions, such as procedural memory, remain intact and enable patients to continue playing an instrument, riding a bicycle, or performing well-established routines (Beaunieux et al., 2012; Chauvel et al., 2018; Knopman, 1991; Zanetti et al., 2001). These functions rely on neural networks that are only indirectly connected to the medial temporal lobe (the central hub of memory) and are particularly supported by motor-related regions such as the cerebellum, motor cortices, striatum, and prefrontal areas

(Doyon et al., 2009; Hong et al., 2019; Ullman, 2016). Several meta-analyses have provided evidence of preserved procedural performance in individuals with mild cognitive impairment (MCI) or early-stage Alzheimer's disease, as age-matched older adults (De Wit et al., 2021; Keith et al., 2023). More specifically, patients seem to retain the capacity to learn how to perform actions without recalling the learning episode itself (i.e., the preservation of implicit memory alongside the degradation of explicit memory). The resilience of procedural memory suggests that certain motor functions remain intact in these patients. Interestingly, motor activity is an integral component of learning.

Theories of embodied cognition and enaction suggest that knowledge is not stored in the brain as abstract codes, but is instead distributed across the central and peripheral nervous systems. Each piece of knowledge involves processing the environment, acting upon it, and interpreting the resulting sensory feedback (Finley, 2025; Iani, 2019; Wilson, 2002). These processes are then adaptively refined based on the observed consequences of the action and the feedback received. This constitutes an interaction between the body and the environment that enables the construction, consolidation, and modification of cognitive processes (Körner et al., 2015; Thompson & Varela, 2001; Varela et al., 2017). It also implies that knowledge is fundamentally composite and multisensory: it consists of multiple traces formed through neural activations resulting from environmental inputs during interaction with the world. A memory is essentially the reactivation of these past traces in the present moment (Briglia et al., 2018; Brouillet & Versace, 2019; Versace et al., 2014). From an applied perspective, this means that engaging the body during learning facilitates, and even enhances, the process by adding a sensorimotor trace. *Action* and *gesture* create additional anchors onto which the brain can attach new information, thereby making it more durable. Moreover, making a gesture that is logically associated with an encoded item enhances retention thanks to the congruent effect (Macedonia, 2014, 2025; Pine et al., 2013; Wu & Coulson, 2015). In the general population, several studies have shown that recalling "embodiable" material (e.g., concrete actions) is facilitated when it is enacted, as opposed to merely observed or seen (Faella et al., 2025; Novack & Goldin-Meadow, 2015; Post et al., 2013; for a meta-analysis of 145 studies, see Roberts et al., 2022).

This effect has been less frequently observed in clinical populations, mainly due to the limited number of studies conducted so far. Still, some findings are encouraging. For instance, Croze et al. (2022) showed that patients with mild to moderate Alzheimer's disease, Parkinson's disease, and healthy older adults all exhibited better memory for action images when they imitated the gesture rather than simply naming it. This suggests that embodied benefits do not require fully intact neural systems; residual motor and perceptual capacities, when mobilized, may already enhance performance. Beyond clinical samples, a large body of research indicates that the more multimodal a piece of knowledge is, the better it is learned and retained (Gasser & Davachi, 2022; Han et al., 2016; Li & Deng, 2023; Luan et al., 2021). Enriched encoding, such as combining auditory information with gestures or pictures, improves free recall days later and can even produce long-term benefits lasting several months (Andrä et al., 2020). Multimodal traces also appear more resistant to forgetting (Heikkilä et al., 2015; Li & Deng, 2023; Murray & Shams, 2023; Okray et al., 2023). These results converge on the idea that engaging motor systems creates richer, more robust memory representations.

Beyond global mnemonic benefits, the literature distinguishes between two key memory processes: recollection, which relies on the hippocampus and prefrontal regions for the access, control, and voluntary retrieval of information (Eichenbaum, 2017; Johnson et al., 2013; Yonelinas, 2002), and familiarity, which relies preferentially on parahippocampal regions (Diana et al., 2006; Skinner & Fernandes, 2007; Wixted et al., 2010). These processes differ in information distinctiveness and the

capacity for voluntary reinstatement. Recollection is cognitively costlier, requiring not only successful encoding but also voluntary access mechanisms, whereas familiarity relies on the mere existence of the information without the search cost: an evaluation of trace strength generating a “feeling of knowing” suffices. Recollection can thus be equated to the accessibility of specific episodic traces, and familiarity to the global availability of information in memory, without detailed episodic reconstruction. Crucially, clinical data suggest that while familiarity processes persist in early-stage Alzheimer’s disease, showing diminished yet functional performance, recollection-based performance is frequently degraded (Koen & Yonelinas, 2014; Schoemaker et al., 2014; Serra et al., 2010). Targeting both processes within a single protocol is therefore critical. Methodologically, this mitigates potential floor effects for recollection and ceiling effects for recognition, and more importantly, it allows us to test the specific consequences of sensorimotor and multimodal anchoring on memory. By combining free recall with a recognition task, we assess whether embodied, multimodal learning densifies memory traces and facilitates their integration and future retrieval, not merely through a feeling of knowing, but via conscious, voluntary access. Such performance patterns would support the hypothesis of partial compensation for memory deficits through modal enrichment.

However, to date, very few therapeutic studies have applied this principle to Alzheimer’s disease. Yet disconnection models of the pathology indicate that memory impairment often stems from traces that have become blurred and insufficiently connected to the cortical networks that once supported their reactivation (Brier et al., 2014; Delbeuck et al., 2003; Mito et al., 2018; Vallet et al., 2013). When activation no longer reaches a sufficiently distinct pattern, memories become prone to overlap and competition. As highlighted by El Haj et al. (2020), patients are particularly vulnerable to intrusions, false recognitions, and interference effects (Budson et al., 2001; Choi et al., 2021; Chasles et al., 2024; Hanseeuw et al., 2010; Loewenstein et al., 2004; Turk et al., 2020). In this context, a trace enriched through bodily engagement would be more distributed, multimodal, and distinctive. It may offer a critical advantage. Yet, this possibility has rarely been explored in a population precisely characterized by its susceptibility to interference. This gap makes it relevant to examine whether embodied cognition, through the multimodal enrichment it provides, can protect memory from interference rather than merely attempting to compensate for already degraded capacities.

In this context, we propose to use music as an ecologically valid way to generate controlled auditory interference. Although some studies have reported beneficial effects of music on memory, these effects appear to be restricted to very specific situations: the retrieval of emotionally charged autobiographical memories (Belfi et al., 2016; El Haj et al., 2012; Kaiser & Berntsen, 2023; Stramba-Badiale et al., 2025), or learning tasks in which the music is explicitly congruent with the material to be remembered (for example, when the rhythmic structure of the music directly supports the encoding of the content, see Fritz et al., 2019; Moussard et al., 2012; Simmons-Stern et al., 2012). In most other situations, music seems to have rather negative or no effects. Several systematic reviews and meta-analyses conclude that background music has heterogeneous and generally small to no-effects on cognitive performance, with no clear advantage over noise or silence, which weakens the hypothesis that music induces a specific and robust memory state (Cournoyer Lemaire, 2019; Du et al., 2020; Mado Proverbio et al., 2015; Tan et al., 2014; see also Chee et al., 2024). More importantly, within Cognitive Load Theory, background music often constitutes an extraneous load that consumes working-memory resources and can divert processing away from the ongoing episodic task (Cheah et al., 2022; Paas & van Merriënboer, 2020; Silva et al., 2020; Sweller et al., 2019). For example, in their meta-analysis, Ghojzadeh and colleagues (2023) showed that using music can increase cognitive load and driving speed, thereby reducing the capacity to react in time when unexpected events require attention (see also Deng & Wu, 2020; Karageorghis et al., 2022; Li et al., 2019). In a more

episodic domain, Reaves and colleagues (2016) showed in older adults that face-name pair retrieval was impaired under music compared with silence. These results are corroborated by other studies of word recall (Deng et al., 2025; Echaide et al., 2019) and text comprehension (Lehmann & Seufert, 2017; Perham & Currie, 2014; Souza & Barbosa, 2023). Overall, when it is not specifically designed to support memory (i.e., through a semantic link with the to-be-learned material), background music tends to play a detrimental role in memorization.

Particularly for the present study, through its rhythmic structure, tempo, and dynamic fluctuations, music provides a background soundscape that can introduce variations and “surprises” likely to capture and divert attention (Parmentier, 2008, 2014; Vachon et al., 2017; Zeamer & Fox Tree, 2013), much like a conversation in the background, a television programme, or street noise when an effort of concentration or memorization is required. It thus offers an auditory noise similar to everyday sounds, capable of interfering with ongoing mnemonic processes. In addition, classical interference paradigms in patients with Alzheimer’s disease sometimes led to floor effects that partially obscure the conclusions that can be drawn (Ebert & Anderson, 2009; Lecouvey et al., 2019; Meyer et al., 2019). *Music* offers a methodological advantage in this respect: its various components (volume, complexity, tempo, presence or absence of voices; see Peretz, 2006; Peretz & Coltheart, 2003) can be adjusted to modulate the strength of interference and limit these floor effects. For example, Lin and colleagues (2023) and Woods and colleagues (2024) manipulated musical tempo either to specifically modulate performance in individuals with attentional difficulties or to show that a reduced tempo impaired performance more than a fast tempo. Finally, music is also a physiological activator that frequently elicits spontaneous movements such as foot tapping or head nodding (Burger et al., 2014; Patel & Iversen, 2014; Peckel et al., 2014; Vuilleumier & Trost, 2015). This task-irrelevant sensorimotor recruitment can draw on attentional and motor resources that would otherwise be available for encoding concrete action-related material, thereby further challenging episodic memory.

Building on these elements, the present study aims to assess whether body-based encoding can both enhance subsequent memory and mitigate the detrimental effects of auditory interference across different retrieval demands. Including both recall and recognition tasks in our design allows us to test whether embodied benefits and music-related costs generalize across these distinct forms of retrieval. We hypothesize that engaging the body at the time of learning will enhance mnemonic encoding for congruent, reenactable sentences depicting daily routines, leading to better performance at retrieval. Relative to a reading-only control condition, we expect action-based encoding to improve memory performance, whereas background music alone should impair it. When bodily involvement is combined with musical stimulation, we predict a compensatory pattern: performance in the dual (action + music) condition should be lower than in the pure action condition but higher than in the music-only condition. Accordingly, we expect the number of correctly retrieved items in both free recall and recognition to be higher in the action condition than in the control condition, lower in the music-only condition than in the control condition, and partially restored in the dual condition, with performance falling between the action and music-only conditions.

These hypotheses will be tested using short sentences describing everyday actions rather than isolated items, for two reasons. First, the present study is embedded in a broader project aiming to develop a therapeutic approach grounded in embodiment and trace strengthening as a way to support autonomy in individuals with cognitive impairment. Demonstrating that action sentences specifically designed to represent frequent, everyday activities (e.g., drinking a glass of water, stirring one’s coffee, taking a medication) can be learned and retained within this embodied framework

would open the way for interventions that target precisely those actions that are critical for independent living. Second, using brief sequences of action rather than single words could naturally recruit situated motor circuits, with an expected causal impact on the environment. As a result, they are likely to elicit broader and more complex sensorimotor activations at encoding than concrete objects alone. This could strengthen the robustness of the underlying memory traces in a way that is particularly relevant for everyday functioning.

Method

Participants

Participants were recruited between January 22, 2024 and May 16, 2025. In total, 40 individuals with AD (23 women, 17 men) and 38 control participants (29 women, 9 men) were included. Patients were recruited through three clinical centers: CHU Saint-Étienne (CHUSE), CHU Grenoble-Alpes (CHUGA), and HCL Charpenne. Controls were recruited via local mailing lists (MSH-Alpes, PLATIPUS) and personal networks.

AD diagnoses were established based on a comprehensive clinical evaluation including biomarkers and a neuropsychological assessment aligned with international recommendations (Dubois et al., 2014; McKhann et al., 2011). We also applied inclusion criteria on age and MMSE, with a lower age limit set at 60 years and MMSE above or equal to 21. Control participants reported no cognitive complaints, neurological or psychiatric disorders, and were taking no medications likely to affect cognition, were minimum 60 years old and MMSE above 26. Detailed descriptive statistics for the sample are presented in Table 1.

Exclusion criteria included participation in another cognitive study, uncorrected sensory deficits (hearing or vision), or psychiatric conditions likely to affect motor function, hearing, language comprehension, or oral communication. All participants were native French speakers and had sufficient visual acuity to read on-screen stimuli. This within-subject study in AD patients and matched controls was approved by an independent national ethics committee (ID: 2023-A01403-42; SI: 23.02307.000199). All data are openly available on OSF: [OSF LINK](#)

Materials and stimuli

The experiment was implemented with lab.js (Henninger et al., 2024). During the study, three- to four-word sentences were presented on a computer screen. All sentences described everyday actions embedded in patients' daily routines (e.g., "drink a glass of water", "stir one's coffee", "take a medication").

Two conditions incorporated music. Tracks were instrumental to limit verbal interference with reading and encoding, but were selected for a sufficiently regular beat to encourage entrainment without fully monopolizing attention. An internal, multi-rater evaluation within the team assessed arousal, valence, and urge to move. From 20 candidate tracks, we selected two (full ratings and audio files available on the OSF):

Artist: Di Crow; Song: 22 22; Type: Hip-Hop/Rap - Valence 3/5, Arousal 2.67/5, Moving 2.34/5

Artist: DJ KayDeKay; Song: Beat #27; Type: Hip-Hop/Rap - Valence 2.75/5, Arousal 2.5/5, Moving 2.5/5

Pre-testing of sentences

The selection of sentences for the main study followed a structured preparatory process to ensure ecological validity, motor feasibility, and linguistic congruency. Each sentence had to denote an action commonly performed by older adults, including those with cognitive impairment, in plausible daily contexts, while meeting three criteria: (1) high everyday frequency, (2) a short and easily

executable motor sequence, and (3) feasibility in a seated position (to standardize administration and include participants with reduced mobility).

Based on the above criteria, we first drafted 123 candidate action sentences and converted each into a short video depicting the corresponding action. All videos were filmed from a first-person perspective, showing only the actor's hands, against a neutral tabletop background. This setup approximated the participant's own point of view while reducing extraneous contextual information, visual variability and potential distractors. The actions covered typical domains of everyday life, including self-care, domestic activities and food-related tasks. Although these videos form the core experimental material in the broader project and will then be used in another study, in the present one they were used solely to get a lexical baseline for older adults' everyday language. Indeed, vocabulary varies systematically across age, and to minimize generational and regional lexical bias in sentence construction, we involved members of the target population in a pre-test phase.

Thirty-eight adults aged 24 to 79 years, none of whom took part in the main experiment, viewed the full set of videos and produced a brief three- to four-word label for each. They were instructed to use a simple verb-plus-complement structure (e.g., "mail a parcel"), allowing us to capture the spontaneous formulations used to describe each action. Particular attention was paid to (1) determiner choice (e.g., "turn the TV on" vs. "turn a TV on") and (2) lexical variants that might reflect generational or regional preferences (e.g., "lay the table" vs. "set the table"). After analyses, we selected the 100 highest-frequency sentences as experimental items in the main study. The resulting phrases provided short, ecologically and generational valid labels that served as the basis for the sentences presented at encoding in the main study.

Procedure

Each participant completed all four experimental encoding conditions in a within-subject design: *Reading* (control), *Action* (gesture), *Music*, and *Duo* (gesture + music). Each trial began with a fixation cross presented for 1000 ms, followed by a rectangle displaying one of the 15 sentences assigned to the current condition for 8000 ms. This duration was chosen to allow comfortable reading and, when required, execution of the gesture without time pressure. The order of conditions was counterbalanced across participants, and the temporal structure of trials (fixation plus sentence display) was identical in all conditions. A brief practice phase preceded the main task, and the experimenter systematically reiterated the instructions before each new condition. For the two musical conditions (*Music* and *Duo*), a short calibration phase was conducted at the beginning of the session to adjust sound volume to individual auditory sensitivity.

In the *Reading* condition, participants read each sentence aloud once and then waited for the next trial. In the *Action* condition, they read the sentence aloud while miming the designated action and then waited. In the *Music* condition, they read the sentence aloud while letting the background music guide their bodily rhythm, after which they waited for the next trial. No explicit motor instructions were given in the *Music* condition, allowing spontaneous rhythmic entrainment while avoiding imposed movements. In the *Duo* condition, they combined both forms of engagement, reading the sentence aloud while miming the action and allowing the background music to set the bodily rhythm, and then waiting for the next trial.

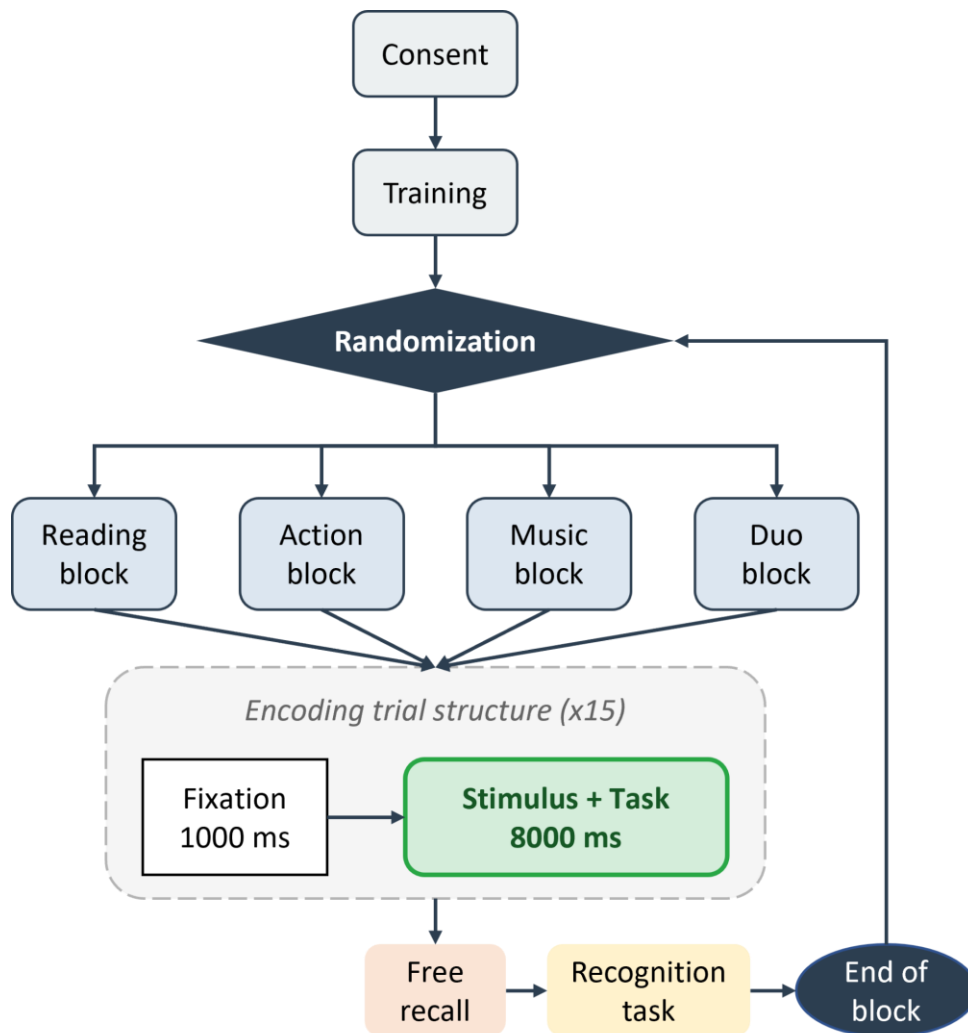
The overall design included these four encoding conditions and two subsequent memory tasks: free recall and recognition. After viewing the 15 sentences for a given condition, participants first carried out a free-recall task. Facing the experimenter, they were asked to recite all the sentences they could

remember from the condition they had just completed, following standard free-recall procedures described in the literature (Cutica et al., 2014; McDaniel et al., 1995; Sarazin et al., 2007). The experimenter recorded all recalled sentences, and a free-recall score was computed for each condition (these scores were later expressed as percentages in the Results section). No explicit time limit was imposed. This choice reflected the clinical context, in which the testing situation can be stressful and additional time pressure might disproportionately increase retrieval impairments. Participants were informed that they could stop whenever they felt they had recalled as many sentences as possible. When they first indicated that they wished to stop, the experimenter systematically invited them to try to recall one additional sentence, in order to ensure that task termination reflected an actual retrieval limit rather than discouragement. The free-recall phase ended immediately after this final attempt.

Immediately after the free-recall task for a given condition, the experimenter administered the corresponding recognition test. In the recognition task, participants were presented with both “signal” sentences that had been encoded in the current condition and “noise” sentences that had not been presented previously. For each condition, 15 sentences were studied at encoding and later re-presented as signal items, and 10 additional sentences served as noise items. Thus, each recognition block comprised 25 sentences (15 old, 10 new), yielding a total of 100 sentences across the four conditions. On each recognition trial, a single sentence was presented at the centre of the screen in the same format and position as during encoding. Participants judged whether the sentence had been part of the 15 sentences previously seen in that condition or whether it was new (see Figure 1), following standard recognition procedures described in prior work (Loizos et al., 2023; Roediger & McDermott, 1995; Yonelinas, 1994). Once all 25 items (15 signal and 10 noise) had been evaluated, the recognition block ended and participants were given a 5-minute break before starting the next encoding condition. The session concluded when all four conditions, each followed by its free-recall and recognition tasks, had been completed. A debriefing was then conducted with each participant, with particular attention paid to patients’ emotional state to ensure that the procedure did not cause lingering distress. See Fig. 1 for our experimental design.

Figure 1

Experimental design and procedural flow



Note. Participants completed four counterbalanced experimental blocks in a within-subjects design. Following a training phase, the order of blocks was randomized. Each of the 15 trials began with a fixation cross (1000 ms), followed by the stimulus presentation and task execution for 8000 ms. Memory assessment occurred immediately after encoding time, comprising an oral Free Recall task followed by a Recognition task containing the 15 target items interspersed with 10 distractors.

Statistical analyses

In this study, we assessed participants' performance, both patients and controls, using two memory tasks administered across four experimental conditions. Raw recall scores were obtained for each condition using a free recall task. These scores, which directly reflect the number of sentences recalled, were then used in the analysis as they offer a more direct interpretation. A recognition task was also conducted, yielding raw counts of hits, false alarms, misses, and correct rejections. From these measures, three indices were computed after applying standard corrections (e.g., adding 0.5 to extreme values, according to the log-linear adjustment method; see Hautus, 1995; Stanislaw & Todorov, 1999).

First, we calculated the balanced accuracy (*BAC*; Brodersen et al., 2010; also used by Delmas et al., 2024; Perquin et al., 2022), an index appropriate for imbalanced datasets in which the number of signal items (i.e., old sentences) differs from the number of noise items (i.e., new sentences). *BAC* reflects participants' ability to correctly classify both old and new sentences, and thus provides an index of overall memory precision. Second, we computed the discrimination index (d-prime, d' ; Snodgrass & Corwin, 1988; also used by Rivas-Fernández et al., 2024; Yonelinas, 1994). Widely employed in recognition memory research, this index captures the quality of memory by weighing hit rates against false alarm rates, thereby adjusting for confusions (i.e., incorrectly identifying a noise item as a signal). Finally, we derived a response bias index (*C*; Hautus, 1995; Stanislaw & Todorov, 1999), which quantifies participants' decision tendency under uncertainty. A liberal bias is reflected in a greater propensity to respond "old" (i.e., endorsing an item as previously seen), whereas a conservative bias corresponds to a greater tendency to respond "new" (i.e., rejecting an item as novel).

All statistical analyses were conducted in R (version 4.5.1; R Core Team, 2025). Planned contrasts were defined a priori and tested using Holm-adjusted p -values. All descriptive and analysis tables, together with the analysis scripts, are openly available on OSF: [OSF LINK](#)

For free recall scores, we used linear mixed-effects models implemented in the lme4 package (Bates et al., 2015) to predict recall scores as a function of engagement condition (reading, action, music, duo), pathology (AD vs. CTRL), and their interaction. The model included a random intercept for participants to account for within-subject variability due to repeated measures. Due to AD and CTRL differences, Education was initially included as a covariate after mean-centering and scaling. However, as it did not contribute significantly to the model, it was excluded from the final analyses [$F(1, 75) = 0.96, p = .33$]. Analysis of variance was performed using the Satterthwaite approximation with the lmerTest package (Kuznetsova et al., 2017). Finally, effects sizes are reported as partial eta squared (η^2_{p2}), as implemented in the effectsize package (Ben-Shachar et al., 2020), to facilitate comparability with prior literature.

For recognition scores, we used linear mixed-effects models implemented in the lme4 package (Bates et al., 2015). Separate mixed linear regressions were conducted to predict (1) memory accuracy (*BAC*), (2) discrimination (d'), and (3) response bias (*C*) as a function of engagement condition (reading, action, music, duo), pathology (AD vs. CTRL), and their interaction. Each model included a random intercept for participants to account for within-subject repeated measures. Due to AD and CTRL differences in Education, we add Education as a mean-centered and scaled covariate, but its presence in our model was not significant for *BAC* [$F(1, 75) = 0.18, p = .669$], for d' [$F(1, 75) = 0.18, p = .673$], and for *C* [$F(1, 75) = 0.28, p = .60$], so we finally excluded it for final analyses. Degrees of freedom for the linear mixed models were estimated using the Satterthwaite approximation via the lmerTest package (Kuznetsova et al., 2017). Finally, effects sizes are reported as partial eta squared

(η^2), as implemented in the effectsize package (Ben-Shachar et al., 2020), to facilitate comparability with prior literature.

Results

Free Recall

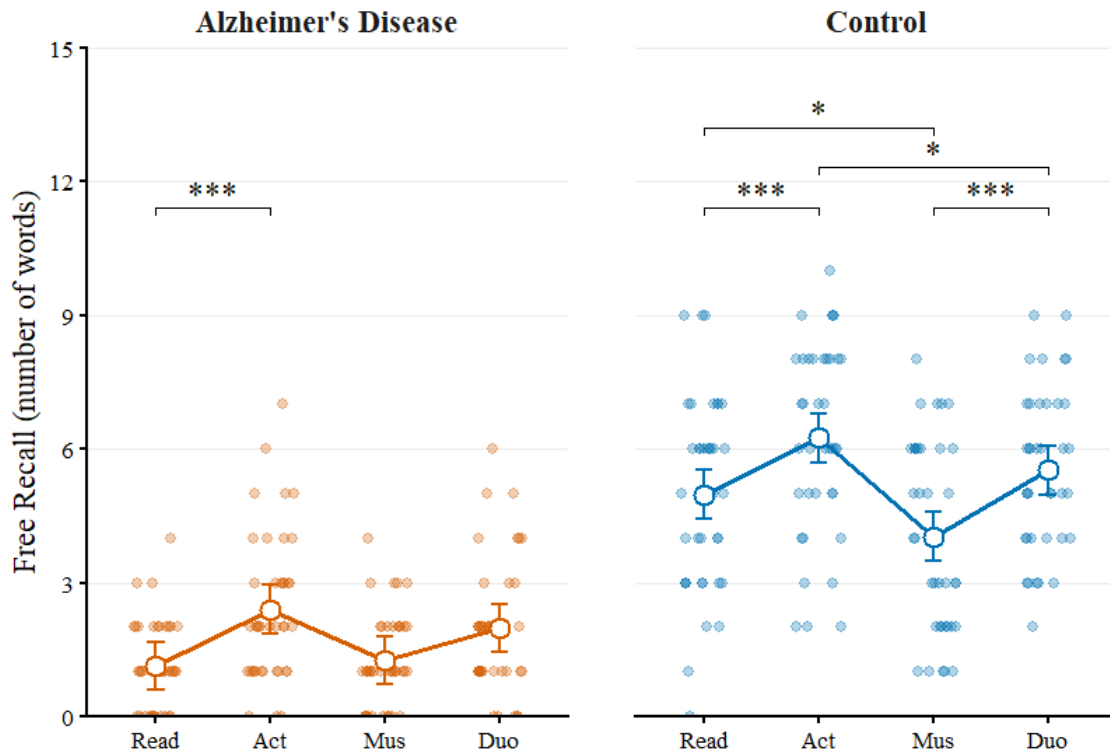
The analysis of group effects revealed a significant main effect of group, with patients with Alzheimer's disease performing worse than healthy controls, $F(1, 76) = 172.05$, $p < .001$, $\eta^2 = .69$, 95% CI [0.60, 1.00]. Across conditions, patients recalled on average 1.69 sentences ($SE = 0.19$, 95% CI [1.32, 2.06]), whereas controls recalled 5.19 sentences ($SE = 0.19$, 95% CI [4.81, 5.57]).

Regarding the effect of engagement condition, the analysis also revealed a significant main effect, $F(3, 228) = 20.27$, $p < .001$, $\eta^2 = .21$, 95% CI [0.13, 1.00], indicating that the ability to spontaneously recall up to 15 sentences varied as a function of the encoding modality. Specifically, the *Action* condition ($M_{Action} = 4.32$, $SE = 0.20$, 95% CI [3.93, 4.70]) yielded higher recall than the *Reading* condition ($M_{Reading} = 3.05$, $SE = 0.20$, 95% CI [2.66, 3.44]), with an estimated difference of 1.27, $SE = 0.23$, 95% CI [0.68, 1.86], $t(228) = 5.43$, $p < .001$. On the contrary, *Music* condition ($M_{Music} = 2.64$, $SE = 0.20$, 95% CI [2.25, 3.02]) did not differ significantly compared to the *Reading*, with an estimated difference of -0.41, $SE = 0.23$, 95% CI [-1.00, 0.18], $t(228) = -1.76$, $p = .08$. We observed a significant difference between *Duo* and *Action* conditions ($M_{Duo} = 3.75$, $SE = 0.20$, 95% CI [3.37, 4.14]), with an estimated difference of -0.57, $SE = 0.23$, 95% CI [-1.16, 0.02], $t(228) = -2.43$, $p = .032$. The difference is also significant between *Duo* and *Music* conditions: *Duo* yielded higher recall than *Music* (estimated difference = 1.11, $SE = 0.23$, 95% CI [0.52, 1.70], $t(228) = 4.76$, $p < .001$).

No significant interaction between group and condition was observed, $F(3, 228) = 2.32$, $p = .076$, $\eta^2 = .03$, 95% CI [0.00, 1.00]. While no global interaction emerged across all conditions, certain a priori planned pairwise comparisons revealed significant differences. For instance, both patients and controls performed better in the *Action* ($M_{AD*Action} = 2.40$, $SE = 0.27$, 95% CI [1.86, 2.94] and $M_{CTRL*Action} = 6.24$, $SE = 0.28$, 95% CI [5.68, 6.79]) than in the *Reading* condition ($M_{AD*Reading} = 1.13$, $SE = 0.27$, 95% CI [0.59, 1.66] and $M_{CTRL*Reading} = 4.97$, $SE = 0.28$, 95% CI [4.42, 5.53]), consistent with the absence of an interaction (estimated difference = 0.01, $SE = 0.47$, 95% CI [-0.91, 0.93], $t(228) = 0.03$, $p = .98$). However, a group-specific difference emerged between the *Music* and *Reading* conditions (estimated difference = 1.07, $SE = 0.47$, 95% CI [0.15, 1.99], $t(228) = 2.29$, $p = .023$). Specifically, controls performed worse in the *Music* than in the *Reading* condition (estimated difference = -0.95, $SE = 0.34$, 95% CI [-1.58, -0.31], $t(228) = -2.90$, $p = .008$), whereas no such difference appeared among patients (estimated difference = 0.13, $SE = 0.33$, 95% CI [-0.53, 0.77], $t(228) = 0.38$, $p = .70$). Finally, no group difference was observed between the *Duo* and *Action* conditions (estimated difference = 0.29, $SE = 0.47$, 95% CI [-0.64, 1.21], $t(228) = 0.61$, $p = .54$). Same results are observed between *Duo* versus *Music* conditions where we observed no different performance among our two groups (estimated difference = -0.78, $SE = 0.47$, 95% CI [-1.70, 0.15], $t(228) = -1.66$, $p = .099$). However, in more precise view, difference between those conditions is bigger for controls (estimated difference = 1.50, $SE = 0.34$, 95% CI [0.85, 2.14], $t(228) = 4.55$, $p < .001$) than for patients, where difference is not significant (estimated difference = 0.73, $SE = 0.33$, 95% CI [-0.08, 1.53], $t(228) = 2.21$, $p = .08$). Fig. 2 illustrates free recall for each participant across the experimental conditions.

Figure 2

Effect of engagement conditions on number of recalled sentences, as a function of group (Alzheimer's disease vs. Control)



Note. Each points represent individual number of recalled sentences by each participant, from 0 to 15, with orange for AD people and blue for control ones. White circles represent estimated marginal means (EMMs) and error bars represent 95% confidence intervals. Horizontal bars indicate significant planned contrasts adjusted with the Holm method: * $p < .05$, ** $p < .01$, *** $p < .001$.

Recognition Task

Balanced Accuracy (BAC)

The analysis of memory accuracy (BAC) revealed a significant effect of pathology, $F(1, 76) = 81.98, p < .001, \eta^2 = .52, 95\% \text{ CI } [0.39, 1.00]$. Patients showed lower specificity and sensitivity ($M_{AD} = 0.81, SE = 0.01, 95\% \text{ CI } [0.79, 0.83]$) compared to controls ($M_{CTRL} = 0.93, SE = 0.01, 95\% \text{ CI } [0.91, 0.95]$). Fig. 3 illustrates memory accuracy for each participant across the experimental conditions.

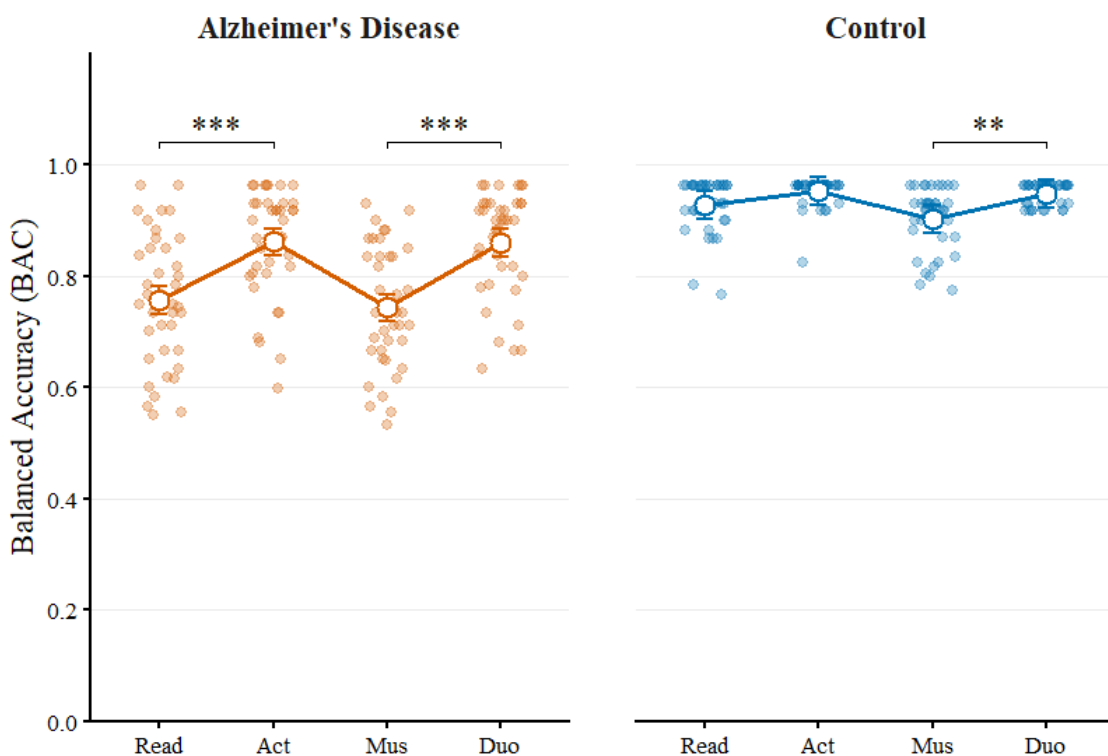
A main effect of engagement condition was also observed, $F(3, 228) = 44.09, p < .001, \eta^2 = .37, 95\% \text{ CI } [0.29, 1.00]$, indicating that memory accuracy varied across the four encoding modalities. No significant difference emerged between the *Music* ($M_{Music} = 0.82, SE = 0.01, 95\% \text{ CI } [0.81, 0.84]$) and *Reading* conditions ($M_{Reading} = 0.84, SE = 0.01, 95\% \text{ CI } [0.82, 0.86]$; estimated difference = $-0.02, SE = 0.01, 95\% \text{ CI } [-0.04, 0.00], t(228) = -2.08, p = .078$). By contrast, the *Action* condition yielded higher accuracy than *Reading* ($M_{Action} = 0.91, SE = 0.01, 95\% \text{ CI } [0.89, 0.92]$; estimated difference = $0.06, SE = 0.01, 95\% \text{ CI } [0.04, 0.09], t(228) = 7.08, p < .001$). Finally, no significant difference was found between

the two gesture-based conditions, *Action* and *Duo* ($M_{Duo} = 0.90$, $SE = 0.01$, 95% CI [0.89, 0.92]; estimated difference = -0.002, $SE = 0.01$, 95% CI [-0.03, 0.02], $t(228) = -0.25$, $p = .804$). Conversely, *Duo* leads to a better accuracy than *Music* condition, with estimated difference = 0.08, $SE = 0.01$, 95% CI [0.06, 0.10], $t(228) = 8.91$, $p < .001$.

Finally, the interaction between group and engagement condition was significant, $F(3, 228) = 11.67$, $p < .001$, $\eta^2 = .13$, 95% CI [0.07, 1.00], suggesting that the effect of condition on memory accuracy differed by group. Results showed that patients benefited more than controls from the *Action* condition relative to *Reading* (estimated difference = 0.08, $SE = 0.02$, 95% CI [0.04, 0.12], $t(228) = 4.36$, $p < .001$). Specifically, patients exhibited a clear improvement in accuracy between *Action* and *Reading* (estimated difference = 0.10, $SE = 0.01$, 95% CI [0.07, 0.14], $t(228) = 8.20$, $p < .001$), whereas this effect was not reliable in controls (estimated difference = 0.02, $SE = 0.01$, 95% CI [-0.01, 0.06], $t(228) = 1.90$, $p = .176$). In both groups, the *Music* condition did not significantly impair accuracy compared to *Reading* (estimated difference = 0.01, $SE = 0.02$, 95% CI [-0.03, 0.05], $t(228) = 0.55$, $p = .583$). Likewise, *Action* and *Duo* did not differ significantly (estimated difference = 0.003, $SE = 0.02$, 95% CI [-0.03, 0.04], $t(228) = 0.16$, $p = .877$). Finally, for *Duo* vs. *Music* conditions (estimated difference = 0.07, $SE = 0.02$, 95% CI [0.04, 0.11], $t(228) = 3.97$, $p < .001$), results indicated that patients improved their accuracy performance in *Duo* compared to *Music* (estimated difference = 0.12, $SE = 0.01$, 95% CI [0.09, 0.15], $t(228) = 9.23$, $p < .001$), whereas controls, although a modest benefit was observed, show a more reasonable improvement (estimated difference = 0.05, $SE = 0.01$, 95% CI [0.01, 0.08], $t(228) = 3.45$, $p = .003$).

Figure 3

Effect of engagement condition on estimated mean memory accuracy as a function of group (Alzheimer's disease vs. Control)



Note. Each point represents an individual participant. Solid lines and open circles depict estimated

marginal means (EMMs) derived from linear mixed-effects models, with error bars indicating 95% confidence intervals. Black bars show statistically significant planned contrasts, adjusted for multiple comparisons using the Holm procedure, * $p < .05$, ** $p < .01$, *** $p < .001$. BAC reflects the mean of sensitivity and specificity, and thus reflects memory accuracy.

Discrimination index (d')

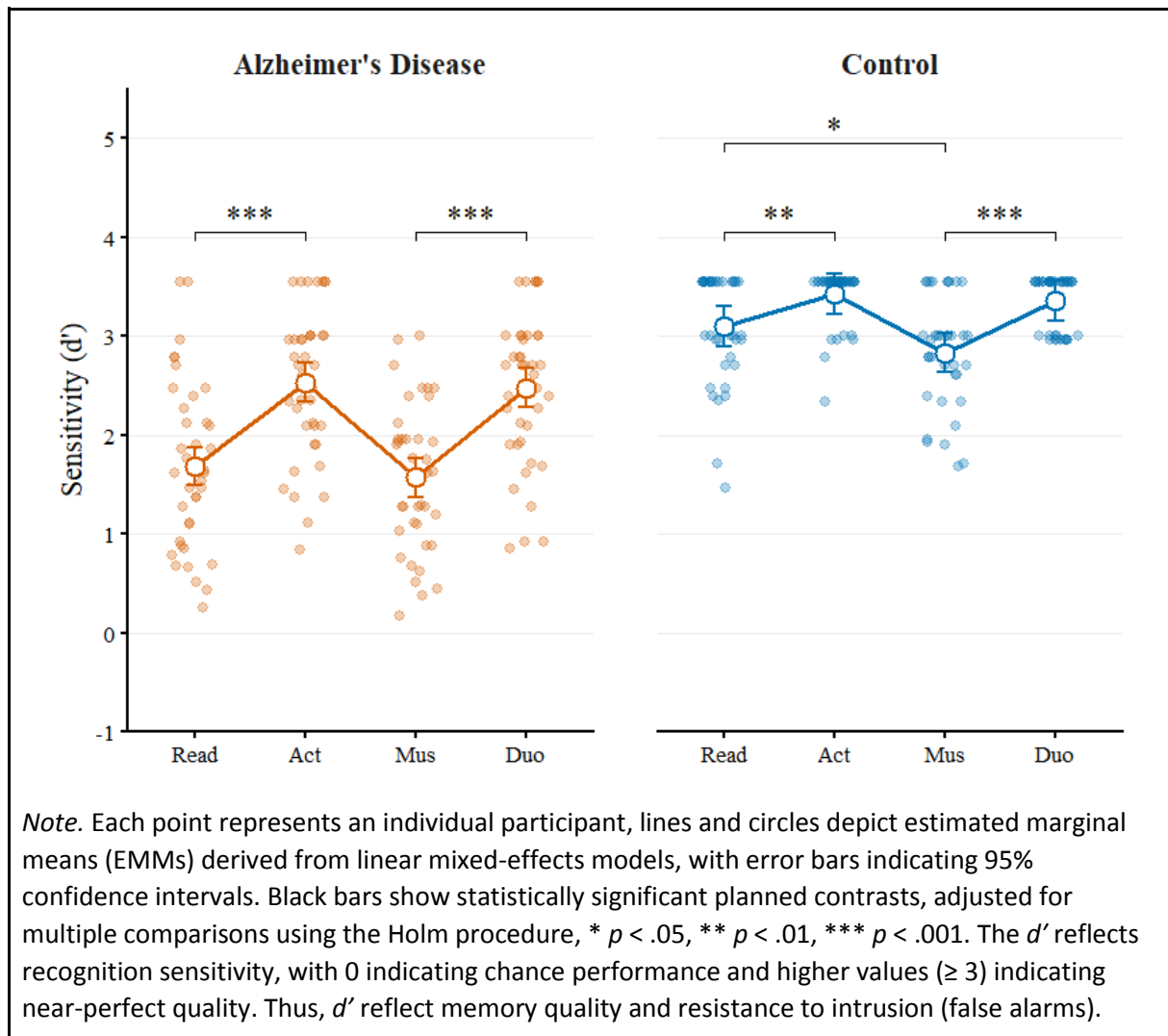
The analysis of memory quality, as indexed by d' , revealed a significant main effect of group, $F(1, 76) = 100.80$, $p < .001$, $\eta^2 = .57$, 95% CI [0.45, 1.00], indicating lower recognition performance in Alzheimer's patients compared to controls ($M_{AD} = 2.06$, $SE = 0.08$, 95% CI [1.91, 2.22]; $M_{CTRL} = 3.18$, $SE = 0.08$, 95% CI [3.02, 3.34]). Fig. 4 illustrates memory quality (d') for each participant across the experimental conditions.

A main effect of engagement condition was also observed, $F(3, 228) = 55.85$, $p < .001$, $\eta^2 = .42$, 95% CI [0.34, 1.00], showing that memory performance varied across the four encoding modalities. Recognition was lower in the *Music* condition ($M_{Music} = 2.20$, $SE = 0.07$, 95% CI [2.06, 2.34]) than in *Reading* ($M_{Reading} = 2.39$, $SE = 0.07$, 95% CI [2.25, 2.53]; estimated difference = -0.19, $SE = 0.07$, 95% CI [-0.38, -0.01], $t(228) = -2.63$, $p = .018$). *Action* condition ($M_{Action} = 2.98$, $SE = 0.07$, 95% CI [2.84, 3.12]), showed higher d' relative to *Reading* (estimated difference = 0.59, $SE = 0.07$, 95% CI [0.40, 0.77], $t(228) = 8.05$, $p < .001$) but *Action* did not differ significantly from the *Duo* condition ($M_{Duo} = 2.92$, $SE = 0.07$, 95% CI [2.78, 3.06]; estimated difference = -0.06, $SE = 0.07$, 95% CI [-0.25, 0.12], $t(228) = -0.86$, $p = .393$). When comparing *Duo* and *Music* condition, however, we saw that the former is clearly above the latter (estimated difference = 0.72, $SE = 0.07$, 95% CI [0.53, 0.90], $t(228) = 9.83$, $p < .001$).

Finally, the interaction between group and engagement condition was significant, $F(3, 228) = 6.83$, $p < .001$, $\eta^2 = .08$, 95% CI [0.03, 1.00], suggesting that the effect of condition differed between groups. Specifically, between *Action* and *Reading*, patients (estimated difference = 0.85, $SE = 0.10$, 95% CI [0.59, 1.11], $t(228) = 8.35$, $p < .001$) benefited more than controls (estimated difference = 0.33, $SE = 0.10$, 95% CI [0.06, 0.59], $t(228) = 3.11$, $p = 0.006$) with estimated difference = 0.53, $SE = 0.15$, 95% CI [0.24, 0.81], $t(228) = 3.60$, $p < .001$). No significant group differences were observed for the comparison of *Music* versus *Reading* (estimated difference = 0.16, $SE = 0.15$, 95% CI [-0.13, 0.44], $t(228) = 1.06$, $p = .29$). No significant difference is found between *Action* versus *Duo* (estimated difference = 0.01, $SE = 0.15$, 95% CI [-0.28, 0.30], $t(228) = 0.09$, $p = .93$). A significant difference is found between *Duo* and *Music* conditions (estimated difference = 0.38, $SE = 0.15$, 95% CI [0.10, 0.67], $t(228) = 2.62$, $p = .009$), supported by a larger difference in AD people (estimated difference = 0.91, $SE = 0.10$, 95% CI [0.65, 1.16], $t(228) = 8.92$, $p < .001$) than observed difference in controls (estimated difference = 0.53, $SE = 0.10$, 95% CI [0.26, 0.79], $t(228) = 5.03$, $p < .001$).

Figure 4

Effect of engagement condition on estimated mean discrimination index (d') as a function of group (Alzheimer's disease vs. Control).



Note. Each point represents an individual participant, lines and circles depict estimated marginal means (EMMs) derived from linear mixed-effects models, with error bars indicating 95% confidence intervals. Black bars show statistically significant planned contrasts, adjusted for multiple comparisons using the Holm procedure, * $p < .05$, ** $p < .01$, *** $p < .001$. The d' reflects recognition sensitivity, with 0 indicating chance performance and higher values (≥ 3) indicating near-perfect quality. Thus, d' reflect memory quality and resistance to intrusion (false alarms).

Response bias (C)

The analysis of response profiles, as indexed by the response bias C , revealed a significant effect of pathology, $F(1, 76) = 5.86, p = .018, \eta^2 = .07, 95\% \text{ CI } [0.01, 1.00]$, indicating that patients and controls differed in their decision strategies. Specifically, patients adopted a more conservative response strategy ($M_{AD} = 0.11, SE = 0.05, 95\% \text{ CI } [0.02, 0.21]$) compared to controls ($M_{CTRL} = -0.06, SE = 0.05, 95\% \text{ CI } [-0.15, 0.04]$). Fig. 5 illustrates response strategy (C) for each participant across the experimental conditions.

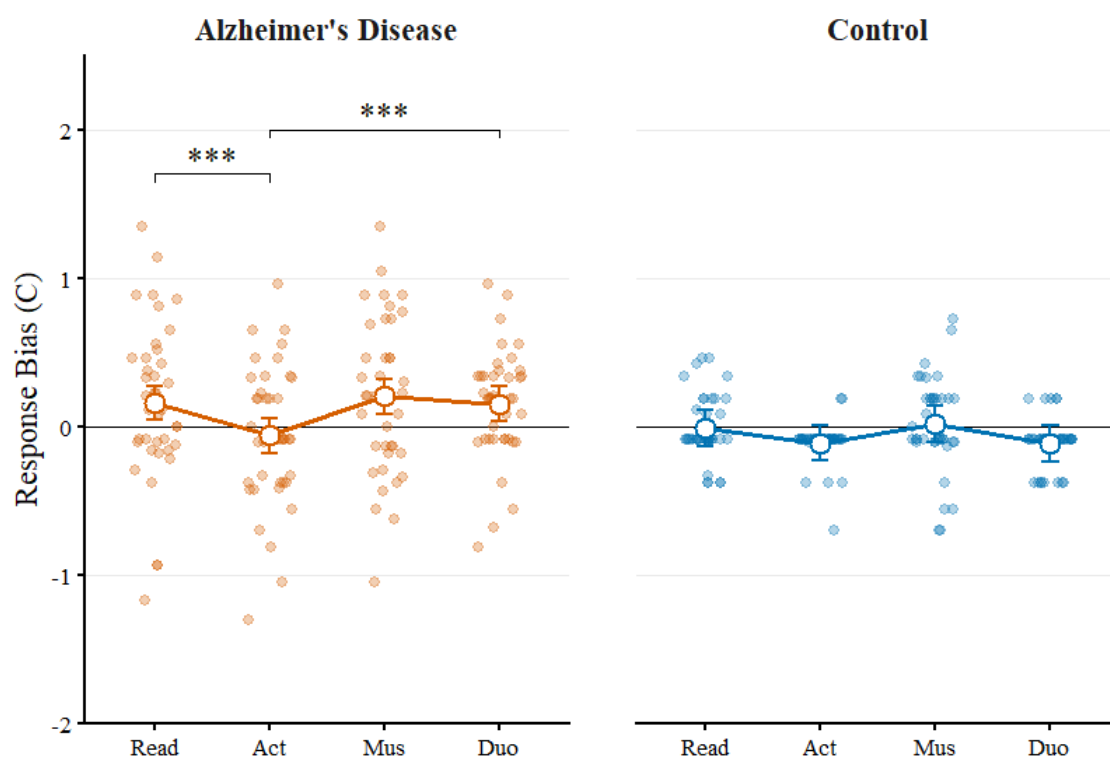
The analysis also revealed a main effect of engagement condition, $F(3, 228) = 9.09, p < .001, \eta^2 = .11, 95\% \text{ CI } [0.05, 1.00]$, showing that participants' response tendencies varied depending on the encoding modality. For instance, responses were more liberal in the *Action* condition ($M_{Action} = -0.09, SE = 0.04, 95\% \text{ CI } [-0.17, -0.00]$) than in *Reading* ($M_{Reading} = 0.08, SE = 0.04, 95\% \text{ CI } [-0.01, 0.16]$); estimated difference = $-0.16, SE = 0.04, 95\% \text{ CI } [-0.26, -0.06], t(228) = -4.04, p < .001$. The difference between *Music* and *Reading* was not significant ($M_{Music} = 0.11, SE = 0.04, 95\% \text{ CI } [0.02, 0.19]$); estimated difference = $0.03, SE = 0.04, 95\% \text{ CI } [-0.07, 0.14], t(228) = 0.84, p = .403$. By contrast, the *Duo* condition ($M_{Duo} = 0.02, SE = 0.04, 95\% \text{ CI } [-0.06, 0.10]$) was more conservative than *Action* (estimated difference = $0.11, SE = 0.04, 95\% \text{ CI } [0.01, 0.21], t(228) = 2.68, p = .024$). The *Duo* and *Music* conditions did not differ significantly, even if descriptively, responses in *Duo* tended to be

more liberal than in *Music* (estimated difference = -0.09, $SE = 0.04$, 95% CI [-0.19, 0.01] $t(228) = -2.20$, $p = .058$).

Finally, the analysis of the interaction indicated that overall response bias did not differ significantly between patients and controls across conditions, $F(3, 228) = 2.49$, $p = .061$, $\eta^2 = .03$, 95% CI [0.00, 1.00]. For example, no group difference was observed for the *Action* versus *Reading* comparison (estimated difference = -0.12, $SE = 0.08$, 95% CI [-0.28, 0.04], $t(228) = -1.49$, $p = .137$). However, a closer look revealed that patients became more liberal in the *Action* than in the *Reading* condition (estimated difference = -0.22, $SE = 0.06$, 95% CI [-0.36, -0.08], $t(228) = -3.96$, $p < .001$), whereas controls did not show a significant shift (estimated difference = -0.10, $SE = 0.06$, 95% CI [-0.25, 0.04], $t(228) = -1.78$, $p = .231$). Consistent with the overall analyses, no group differences were found between *Music* and *Reading* (estimated difference = 0.02, $SE = 0.08$, 95% CI [-0.14, 0.18], $t(228) = 0.22$, $p = .824$). In contrast, a significant group difference emerged for the *Action* versus *Duo* comparison (estimated difference = 0.22, $SE = 0.08$, 95% CI [0.06, 0.37], $t(228) = 2.70$, $p = .008$). Specifically, while controls remained liberal across both conditions (estimated difference = -0.00, $SE = 0.06$, 95% CI [-0.14, 0.14], $t(228) = -0.02$, $p = 1$), patients shifted back to a conservative bias in the *Duo* condition compared to *Action* (estimated difference = 0.22, $SE = 0.06$, 95% CI [0.08, 0.36], $t(228) = 3.85$, $p < .001$). Ultimately, the two groups did not differ significantly in their response profiles between the *Duo* and *Music* conditions, indicating neither a more liberal nor a more conservative response bias in either controls or patients (estimated difference = 0.08, $SE = 0.08$, 95% CI [-0.08, 0.24], $t(228) = 0.98$, $p = .326$).

Figure 5

Effect of engagement condition on response bias (C) as a function of group (Alzheimer's disease vs. Control).



Note. Each point represents an individual participant, lines and circles depict estimated marginal

means (EMMs) derived from linear mixed-effects models, with error bars indicating 95% confidence intervals. Black bars show statistically significant planned contrasts, adjusted for multiple comparisons using the Holm procedure, * $p < .05$, ** $p < .01$, *** $p < .001$. Positive values (above 0) indicate a more conservative response tendency, whereas negative values (below 0) indicate a more liberal bias.

Discussion

This study examined whether engaging the body during encoding could strengthen memory for everyday-action sentences and mitigate the detrimental effects of background music, particularly in individuals with Alzheimer's disease and during two specific memory tasks. We contrasted four encoding conditions (*Reading*, *Action*, *Music*, and *Duo*, both *Action* and *Music*) in a within-subject design and assessed memory with both free recall and recognition. Free recall places substantial demands on recollection processes and is therefore mainly impaired in Alzheimer's disease (AD). Combining free recall with recognition allowed us to see if an embodied, trace-enrichment framework could be useful to support memory with recollection processes despite hippocampal alterations, and not only familiarity-based ones. We derived several indices to characterize recognition performance: Balanced accuracy (*BAC*) was used to assess whether the conditions modify the ability to classify items correctly as old or new, providing a measure of mnemonic precision. The sensitivity index d' captured the robustness or vulnerability of memory under each condition, thus indexing mnemonic quality. Finally, the response criterion C reflected participants' tendency toward conservative or liberal responding, and therefore their susceptibility to doubt or decision bias.

Given the neurocognitive impairments affecting memory in patients with Alzheimer's disease (impairments that extend broadly to networks involving medial temporal regions, thalamus, and prefrontal regions, Aggleton & Brown, 2006; Yonelinas et al., 2024), we expected that patients would perform worse than controls, consistent with the literature (Epelbaum et al., 2018; Sarazin et al., 2010). All of our results are in line with this. In the free recall task, patients recalled one-third as many sentences as controls. As established above, the free recall task is more difficult than the recognition task because it requires mobilizing more resources to retrieve the content. One might therefore expect recognition to narrow the gap between patients and controls. Yet, across all measured indices, patients remain below controls: they are *almost* 15 % less accurate (*BAC* index) and show *almost* 54% lower memory quality (d' index). However, patients tend to adopt a more conservative criterion than controls. This profile is rather surprising because, by contrast, patients have generally tended to be more liberal (Beth et al., 2009; Malone et al., 2019). This pattern may reflect that the awareness of their difficulties, at the onset of the pathology, led them to greater caution.

Mobilizing the body creates an alternative route and more distinctive traces

In AD, the degradation of the medial temporal lobe (MTL) makes the binding of multiples information inefficient, leading to weak traces that are easily lost. Our findings provide compelling evidence for the enactment effect, as a trace protector, demonstrating that physically performing the action described in a sentence leads to superior retention compared to standard verbal reading. Regardless of pathology, we observe a higher free recall rate in the *Action* condition than in the *Reading* condition (nearly 41% of enhancement). This difference is similarly reflected in recognition indices, where balanced accuracy and d' (memory quality) increased by almost 7% and 24% respectively with body engagement.

Crucially, this benefit is particularly critical for patients with Alzheimer's disease. Specifically, patients seem to benefit more from *Action* relative to *Reading* than controls do. They recall about 2 times more sentences when comparing their performance between *Reading* and *Action* (an increase of almost 50%), whereas controls only increase their scores by nearly 10%. From a methodological standpoint, this asymmetry is explained in part by a recall of around 5 sentences for controls, a performance close to the classically reported memory span (Cowan, 2001; Miller, 1956; Oberauer,

2019). A similar kind of ceiling is also observed in *BAC* scores (only 3 percentage point in more in *Action* than in *Reading*, where the minimum is near 92%). However, the existence of a ceiling in controls does not diminish the clinical significance of the gain in patients. The fact that patients, who typically perform at floor levels (1 sentence in *Reading*), can be boosted significantly by enactment confirms our hypothesis: by recruiting the body, one engages areas that are partially preserved in the early stage of the disease (e.g., frontal networks), thereby partially “compensating” for initial hippocampal impairments (Chauvel et al., 2018; Iani, 2019; Zanetti et al., 2001). From an embodied and multi-trace perspective, as the memory formed is not an abstract code but a distributed multimodal pattern, when the purely verbal pathway fails, the enactment condition offers an alternative and amplified access route via the sensorimotor pathway. These sensorimotor activations serve as a robust and powerful entry point, effectively driving the *re-instantiation* of the episode by grounding the retrieval in preserved bodily experience, without requiring a fully intact hippocampal binding.

Beyond spontaneous free recall, enactment also fundamentally modified the precision and the quality of the memory trace, as evidenced by the profound improvement, both in *BAC* and in the sensitivity index (d'). A core deficit in Alzheimer’s disease is the failure of pattern separation (i.e., the ability to distinguish between similar events, Ally et al., 2013; Stark et al., 2013), which typically leads to high false alarm rates. Enactment appears to counteract this deficit by increasing the distinctiveness of the encoded event (Brunel et al., 2010; Hornstein & Mulligan, 2004; Vallet, 2015; Zimmer, 2001). Unlike a read sentence, which relies on abstract semantic traces susceptible to interference, an enacted sentence is grounded in specific sensorimotor details. This grounding allows patients to easily segregate traces at retrieval, facilitating the correct endorsement of signals while ignoring noise (Huff et al., 2015; Purkart et al., 2022). Furthermore, the absence of such specific motor information for new items allows patients to confidently reject them via the distinctiveness heuristic (i.e., the metacognitive inference that if an event had occurred, they would recall the accompanying *Action*; Budson et al., 2002, 2005; Gallo et al., 2008; Schacter & Wiseman, 2006). This strategy reduces false alarms and consequently boosts sensitivity performance, effectively compensating for the reliance on vague, gist-based memory.

Music as extraneous load: impact on trace quality and retrieval

Contrary to the hypothesis sometimes advanced of a mnemonic benefit of music, our results support the idea that, outside a specific emotional or autobiographical context, music acts primarily as a disruptor. The analysis of the d' supports this conclusion, revealing significantly lower performance in the *Music* condition compared to the *Reading* condition. Although this decline is not substantial (i.e., an 8% drop relative to the *Reading* condition), it indicates that *Music* is not neutral and that it reduces the quality of the memory trace. These observations align with Cognitive Load Theory (Cheah et al., 2022; Paas & van Merriënboer, 2020; Silva et al., 2020; Sweller et al., 2019). As a task-irrelevant stimulus, music imposes an extraneous load that competes with the attentional resources required for encoding. The acoustic and rhythmic variations of the soundtrack monopolize a portion of these resources, reducing their allocation to the processing of target sentences. Consequently, this competition reduces item distinctiveness, increasing confusion (false alarms) and causing a drop in d' . In controls, background music appears to act as a distractor during encoding, reducing the richness of the memory trace and leading to poorer memory performance.

In AD, since cognitive resources are already limited, one might expect a more disruptive effect, and, whereas action enhances trace distinctiveness, music should add a lot of “noise” to it. However, the

analysis of free recall and d' reveals a paradoxical interaction between group and condition: while controls effectively experience the expected interference effect (a significant drop in the *Music* condition) as discussed above, patients maintain stable performance between *Reading* and *Music*. Several mechanisms may explain this apparent resilience in patients, who, despite being cognitively more vulnerable, appear less impacted by the distractor. First, a strong floor effect seems to exist in this population. With approximately 1 to 2 sentences recalled, patients operate at a performance level close to the minimal threshold, leaving little margin to observe further degradation induced by music. Conversely, controls, with a mean recall of 5 sentences, possess a sufficient performance range for the cognitive cost of interference to manifest. Second, a complementary clinical interpretation relies on hippocampal binding capacities and integration processes based on Act-In (Versace et al., 2014, 2018). Integration processes allowing binding of multiple components into a unified same trace need congruency between component. Unlike action, which is logically integrated into the memory trace because it is related to encoded information (action sentences), music constitutes irrelevant contextual information: this distractor status imposes an extraneous load that increases processing costs. The interference observed in controls could thus reflect the cost of a challenged binding process: their intact hippocampus attempts to integrate the musical context into the episode, diverting resources away from sentence encoding. However, in patients, binding processes are already impaired and costly, and the encoding task further imposes a maximal subjective load that may saturate their processing capacities (as evidenced by the floor effect). In this state of saturation, peripheral stimuli (here, music) would be excluded early from processing to reduce costs and thus simply be ignored (Brockhoff et al., 2022; see also work on similar perceptual load, Lavie, 2005; Raveh & Lavie, 2015). Paradoxically, this would “protect” patients from the interference experienced by controls. Third, and finally, the absence of interference may be explained by the impairment of attentional alerting and orienting mechanisms characteristic of the pathology (Baddeley et al., 2001; Perry & Hodges, 1999; Siéroff et al., 2020). Unlike energetic or structurally complex music capable of triggering exogenous attentional capture, our musical stimuli were instrumental and regular. This methodological choice, initially designed to limit floor effects, likely rendered the distractor insufficiently salient to divert the attention of patients whose threshold of reactivity to irrelevant stimuli is high, or who exhibit rigid focal attention in dual-task situations (see Festa et al., 2010; Park et al., 2007).

These interference effects, however, warrant a nuanced interpretation. Contrary to our initial hypothesis predicting marked interference, we observed only a marginal decline or, in some instances, a null effect. From a methodological standpoint, the potential for physiological arousal, attentional and cognitive load induced by the music was not objectively quantified during the task. While we relied on a subjective inter-rater questionnaire before the study, it would have been preferable to measure this with objective methods such as dual-task paradigms or pupillometry (Beatty, 1982; van der Wel & van Steenbergen, 2018; Zekveld et al., 2010). Admittedly, for feasibility reasons, we would not have placed sensors on participants during the study; however, it is unfortunate that no physiological data were collected from them, which would have allowed us to include these measures as additional variables in the statistical analysis. The effects of music on encoding are complex and seem to depend on very fine musical construction, both rhythmic structure and harmony (Jäncke, 2019; Schulkind, 2009). Thus, the selected tracks might simply have been too low in arousal or acoustic variations to trigger an orienting response, compared to fast or loud ones (Kämpfe et al., 2011; Thompson et al., 2012). This argues for the need to carefully design an effective musical environment, considering working memory load framework and its interactions with clinical issues.

Enaction prevents interference and improves metacognition

We initially hypothesized a partial compensation mechanism in the *Duo* condition, whereby enactment would strengthen encoding while background music would still exert a disruptive influence, yielding performance intermediate between *Action* and *Music* (i.e., better than *Music* alone, yet poorer than *Action* alone). Part of our data aligns with this prediction. In controls, free recall performance in *Duo* was significantly higher than in *Music*, while remaining lower than in *Action*, a pattern consistent with partial compensation of musical interference. In patients, however, the particularly demanding context of free recall may constrain the expression of these effects. Specifically, the absence of reliable differences between *Duo* and *Music*, and between *Duo* and *Action*, does not necessarily imply that enactment was ineffective in *Duo*. Rather, it may reflect reduced measurement sensitivity due to pronounced floor effects in free recall, with performance compressed around one to two recalled sentences across conditions. Under such compression, the descriptively higher *Duo* mean relative to *Music* (approximately 1.97 vs. 1.25) and its proximity to *Action* (approximately 2.40) may simply be too small to yield statistically detectable contrasts. Besides, in the action-only encoding context, enactment appears able to improve performance. Taken together, these observations suggest that the limiting factor in patients is more consistent with floor-related insensitivity (and thus limited discriminability among conditions) than with a true absence of enactment-related support.

Nevertheless, in the recognition task, the effect of action appeared to be fully expressed and even to extend beyond a partial compensation of musical interference, resulting in a complete compensation. Specifically, *BAC* and *d'* scores in the *Duo* condition reached levels comparable to those observed in the *Action* condition. Statistical analysis confirmed, here, that no significant difference between the *Duo* and *Action* conditions exist, whereas a marked difference was maintained compared to the *Music* condition (e.g., *Duo* increase *BAC* by 9.5% and *d'* by 32.59% compared to *Music*). Even if a gap was occasionally more pronounced in patients, likely due to the ceiling-like effects previously noted in controls, collectively, these data refute the intermediate hypothesis in recognition paradigm. Instead, the *Duo* condition appears to completely neutralize musical interference. Thus, the results converge toward the same conclusion, suggesting that enactive support may compensate for background music interference when task demands are moderate. This underscores the potent role of enactment in reinforcing the memory trace and establishing a robust, alternative route for information access.

We extended our analysis to participant response profiles by quantifying “risk-taking” behaviors during the recognition task, specifically examining response bias (*C*) to determine the extent to which decision criteria shifted between liberal and conservative poles across conditions. The analysis of the response bias (*C*) offers a view into the participants' decision-making strategies and metacognitive states. While previous literature has often described a tendency toward a liberal bias in Alzheimer's disease, attributed to source monitoring deficits (Beth et al., 2009; Malone et al., 2019), our patients exhibited a consistently conservative response strategy in three of the four experimental conditions. This conservatism likely reflects a compensatory caution born from an awareness of their own memory unreliability. However, the *Action* condition triggered a striking shift: patients abandoned this conservative profile to adopt a liberal criterion, effectively harmonizing their response profile with that of healthy controls. Crucially, this shift was not a regression toward a pathological liberal “yes-bias” (which would increase false alarms without aiding discrimination). Instead, viewed alongside the concomitant improvement in sensitivity (*d'*) and accuracy (*BAC*), this relaxation of the decision criterion appears to be an adaptive metacognitive response. We posit that this shift reflects a restoration of confidence in memory performance. According to the metacognitive framework

(Busey et al., 2000; Ferrigno et al., 2017; Rhodes & Castel, 2008), the vividness and richness of the sensorimotor trace generated by enactment serve as a strong diagnostic cue during retrieval. This enriched signal acts as a validation of the memory's robustness, inducing a higher feeling of knowing. Consequently, patients perceive themselves as capable of retrieving the content, leading to a reduction in doubt and a greater willingness to endorse items, as a marker of normalized cognitive functioning in this specific, embodied context. We must, however, apply a slight nuance regarding the *Duo* condition, where a conservative bias appeared to re-emerge more strongly in patients than in controls. This suggests that while the music was successfully filtered at an attentional level, it may still have been perceived as "noise". Aware of the potential disturbance caused by the auditory environment, patients likely adopted caution: knowing they might have been distracted, they reverted to a more prudent assessment of their own capacities.

Clinical implications

The engagement of the body during learning seems to fulfil two distinct clinical objectives. First, enactment significantly reinforced the quality of the memory trace. This benefit was evidenced by the improvement in sensitivity (d') as well as the depth of encoding and retrieval capacity, demonstrated by the increases in Free Recall and Balanced Accuracy (*BAC*). Second, and perhaps equally important, enactment seemed to restore the patients' confidence in their own knowledge and their agency. It became evident that in the *Action* condition, patients' response profiles realigned with those of healthy controls: they regained the ability to accurately monitor what they knew versus what they did not, exhibiting a willingness to take adaptive risks.

In this study, we used every day action sentences that are closely tied to instrumental activities of daily living, and two memory tasks that probed complementary aspects of functioning. Free recall is a stringent test of self-initiated retrieval and is highly sensitive to Alzheimer's disease, whereas recognition, quantified here with signal-detection indices (balanced accuracy, d' , and decision criterion C), provides a more graded readout of discrimination and decision strategies. The fact that enactment improved both free recall and recognition, particularly in patients, opens avenues for engaging the body during encoding because it could strengthen the memory for actions that matter for autonomy, and not only enhance performance on decontextualized laboratory items. The pattern of results indicates that gesture-based encoding could be used as a simple, low-cost remediation tool. Asking patients to enact the actions they need to remember, for example, steps of a routine or instructions related to daily care, is easily implementable at home or in institutional settings and does not require specialized equipment. Our data further argue for caution regarding background music in learning contexts: in its current form, music did not provide any memory benefit and even slightly degraded the quality of recognition, suggesting that non-relevant musical stimulation should be limited when new information has to be encoded. Music might be better conceived as a targeted ingredient in other frameworks (e.g., autobiographical, congruent, or emotion-eliciting music), rather than as a generic cognitive enhancer.

Limits

Several limitations should be acknowledged when interpreting these findings. First, the sample was recruited within a single country and only comprised individuals with clinically and biologically confirmed Alzheimer's disease. As such, the results may not generalize to other dementia or advanced stages of the disease. Second, the experimental paradigm targeted a very specific material

and timescale: short sentences describing every day actions, learned in a single session and tested immediately with one free-recall and one recognition phase per condition. This increases internal validity, but limits the extent to which one can extrapolate to long-term retention of action routines in daily life. Third, the musical manipulation was deliberately restrictive: participants heard a small set of non-personalized instrumental tracks, with no systematic variation of tempo, arousal, harmonic complexity, or emotional and autobiographical relevance, and we did not collect physiological or behavioral markers of entrainment or attentional load. Consequently, the present data do not allow strong inferences about music in general, nor about the mechanisms through which different kinds of music might modulate encoding. Finally, despite the use of mixed-effects models and signal-detection indices, the pattern of results is constrained by potential floor effects in free recall among patients and ceiling effects in recognition among controls, which may have reduced our sensitivity to some interactions and to subtle differences between *Action* and *Duo*.

Conclusion

This study provides compelling evidence that engaging the body during encoding creates a resilient memory trace that withstands cognitive interference, even in the context of Alzheimer's disease. By shifting reliance from degraded hippocampal binding to preserved sensorimotor cortical networks, enactment not only amplified memory performance, but also neutralized the detrimental effects of background music. Crucially, this benefit extended beyond mere retention: enactment modified the patients' decision-making profiles, shifting them from a cautious, conservative criterion to a more confident, adaptive strategy similar to that of healthy controls. This suggests that embodied learning enhances both the availability of the memory trace and the subjective awareness of its quality. From a clinical perspective, these findings advocate for a pragmatic shift in cognitive rehabilitation. While background music should be used with caution given its potential as an extraneous load, gesture-based encoding emerges as a potent, low-cost intervention. By grounding abstract information in physical action, clinicians and caregivers can leverage the enactment effect to support autonomy and restore a sense of agency in individuals with Alzheimer's disease. Future research should now explore how these short-term benefits can be consolidated into long-term routines and whether personalized musical contexts could transform the auditory environment from a distractor into a mnemonic scaffold.

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Table 1*Descriptive statistics for Alzheimer's disease (N = 40, AD) and control (N = 38, CTRL) groups*

	MMSE		Age		Education	
	AD	CTRL	AD	CTRL	AD	CTRL
Mean (SD)	25.02 (1.94)	28.29 (1.27)	72.65 (6.25)	70.32 (5.41)	11.78 (4.23)	14.84 (3.00)
[Min ; Max]	[22 ; 29]	[26 ; 30]	[61 ; 87]	[60 ; 84]	[5 ; 20]	[9 ; 20]
Test	W = 1374		t(75.4) = -1.77		W = 1096	
p-value	< .001		= 0.081		< .001	

Note. Years of education were computed according to the French system, counting from age 3 up to the age at which the highest degree was obtained. Although a significant difference in MMSE was observed, we reasonably decided not to include it as a covariate in subsequent analyses, as a precise diagnosis was established between AD and CTRL, rendering MMSE redundant. In contrast, education differed significantly between the AD and CTRL groups and was therefore included as a mean-centered and scaled covariate.