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Multisensory training based on an APP for enhanced verbal working memory in older adults

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A R T I C L E I N F O

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Education level

A B S T R A C T

With the increasing aging population, contemporary society faces the imperative to develop approaches that efficiently delay the age-related decline in working memory capacity, which is a critical area within cognitive aging research. Nevertheless, there is insufficient evidence to support the efficacy of verbal working memory training across various sensory modalities (visual, auditory, and audiovisual) in enhancing the verbal working memory capacity of older adults. In this study, 60 healthy older adults (mean age = 67.07 ± 3.79 years, comprising 34 women and 26 men, mean education = 15.55 ± 2.53 years) were randomly assigned to one of four groups: visual verbal working memory (V-VWM) group, auditory verbal working memory (A-VWM) group, visual-auditory verbal working memory (VA-VWM) group, and a control group. The training duration spanned 12 days. We also investigated whether baseline level and education predicted the outcomes. Findings indicated that V-VWM training had a large effect on improving V-VWM task performance (*Cohen's d* = 1.765), A-VWM training showed a substantial effect on A-VWM task performance (*Cohen's d* = 1.904), and VA-VWM training demonstrated a significant effect on VA-VWM task performance (*Cohen's d* = 2.319) over pretest scores in older adults. Enhancements achieved through V-VWM training exhibited near transfer effects, improving performance in both A-VWM and VA-VWM tasks. In contrast, gains from A-VWM training were selectively transferred to the VA-VWM task. Furthermore, VA-VWM training led to improvements not only in V-VWM and A-VWM tasks but also extended to verbal operation span task with a significant 29.7 % increase. However, no significant transfer effects were observed for the DSF and DSB tasks across the three training groups. The maintenance effect of VA-VWM training persisted for two weeks across tasks involving VA-VWM, V-VWM, and A-VWM. The baseline of VWM span score influence the effect of V-VWM training and transfer effect of VA-VWM training. Education level did not predict the training effects of V-VWM, A-VWM, and VA-VWM. These findings highlight the nuanced effects of sensory-specific verbal working memory training in older adults, emphasizing the potential of tailored interventions to enhance specific aspects of cognitive function, while also highlighting the promising applications of mobile device training in enhancing cognitive skills among the elderly.

1. Introduction

Cognitive decline is a growing concern in an aging population, with working memory deficits representing a significant challenge to older individuals (Assecondi et al., 2022; Deary et al., 2009). Working memory is crucial for various daily tasks, including communication, problem-solving, and decision-making (Chai et al., 2018; Xing et al., 2019). Among the various components of working memory, verbal working memory (VWM) plays a pivotal role in language comprehension and expression. Aging is linked to a deterioration in VWM, which can lead to difficulties in comprehending spoken language, remembering instructions, or engaging in effective communication (Forsberg et al., 2020). Therefore, the pursuit of efficacious methods to ameliorate VWM potentially holds promise for augmenting language-related cognitive functions in the elderly.

Age-related alterations in working memory have been extensively

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studied, leading to the development of diverse interventions and cognitive training programs aimed at mitigating this decline. For example, executive function training can induce structural changes in the brain, resulting in augmented gray matter and cortical volume, and a general expansion of the frontal and parietal brain regions (Nguyen et al., 2019). Furthermore, VWM training not only improves the VWM of older adults but also enhances their language comprehension, visual-spatial working memory, information processing, and fluid intelligence (Brum et al., 2020; Carretti et al., 2013). However, VWM can be categorized into visual and auditory VWM based on differences in information input channels (Zhu et al., 2020). Most of studies concentrate on single-modality training, and it remains uncertain whether a multi-modality training approach can yield greater improvements in VWM for older adults. Additionally, vision and audition are critical sensory systems for human external information perception; however, aging is accompanied by sensory organ functional decline, resulting in diminished memory and processing capacities for visual and auditory information. It is imperative to conduct further investigation into the prospective advantages of VWM training across various sensory modalities (visual, auditory, and audiovisual) for enhancing VWM and additional cognitive capabilities in the elderly.

A meta-analysis has revealed that the effectiveness of working memory training in healthy older adults is contingent upon various factors, including the assessment measures, training type, duration, and baseline performance. Intriguingly, the maintenance effect of training has predominantly manifested within the realm of VWM (Teixeira-Santos et al., 2019). Individuals difference was one major factor of influencing the improvement effect, transfer effect and maintenance effect. Prior studies on individual differences have yielded a debate regarding who benefits the most from working memory training. According to the compensatory account, individuals with lower baseline levels tend to benefit more from working memory training (Karbach et al., 2017). In contrast, the magnification account posits that individuals with higher baseline cognitive abilities tend to benefit more from working memory training (Foster et al., 2017; Lövdén et al., 2012). Therefore, exploring the influence of baseline levels on the effectiveness and transfer effects of VWM training in older adults is of paramount importance in devising personalized and precision training regimens.

Furthermore, a higher level of education typically implies stronger cognitive reserve, potentially resulting in a higher baseline level of working memory. Recent studies have identified that transcranial direct current stimulation exerts a more conspicuous impact on enhancing working memory in older individuals with advanced educational attainment (Berryhill and Jones, 2012; Johnson et al., 2022). Therefore, it remains uncertain whether educational level and baseline performance can impact the enhancement of VWM in older adults.

To address the aforementioned concerns, this study seeks to explore the most effective techniques for augmenting the VWM of elderly individuals. This will be achieved through a comparative analysis of training interventions encompassing different sensory modalities, specifically visual, auditory, and audio-visual modalities. Additionally, we will assess how baseline performance and educational background influence the impact on improvement effect, maintenance effect and transfer effect. Previous research has already demonstrated that multi-sensory training holds the potential to enhance working memory to a greater extent when compared to isolated sensory domain-specific training (Pahor et al., 2021). Consequently, we posit that visual-audio training will yield superior enhancements as compared to unimodal approaches (i.e., visual or auditory training). Moreover, we hypothesize that individual differences in baseline VWM and levels of education may influence the benefits derived from multi-sensory training.

2. Experiment

2.1. Materials and methods

2.1.1. Participants

We enrolled 65 elderly participants through announcements and flyers distributed in the residential area of the school and the adjacent community centers, senior activity centers, and local healthcare facilities, targeting elderly individuals who expressed interest in participating in cognitive research studies. Among these participants, three elderly individuals withdrew from the study, while two others did not meet the experimental screening criteria due to scoring below 26 on the Montreal Cognitive Assessment (MoCA) (Freitas et al., 2011). The MoCA screenings were conducted by trained professionals from the institute for the development of aging and social research at our university, who have extensive experience in administering cognitive assessments to older adults. Ultimately, a total of 60 healthy older adults (mean age = 67.07 ± 3.79 years, comprising 34 women and 26 men, mean education = 15.55 ± 2.53 years) were included in the final sample. They were subsequently randomly allocated into four distinct groups: the visual verbal working memory (V-VWM) group, which consisted of 15 elderly participants (comprising 8 women and 7 men, with a mean age of 67.33 ± 3.39 years); the auditory verbal working memory (A-VWM) group, also comprised of 15 elderly participants (with 9 women and 6 men, and a mean age of 66.13 ± 4.81 years); the visual-auditory verbal working memory (VA-VWM) group, consisting of 15 elderly participants (comprising 8 women and 7 men, with a mean age of 68.67 ± 4.03 years); and the control group, consisting of 15 elderly participants (comprising 9 women and 6 men, with a mean age of 66.13 ± 2.29 years). Participants in the control group were on a waiting list and did not receive the training intervention. They were instructed to avoid starting any new cognitive exercises during the study to minimize external influences on cognitive performance changes.

Participants were rigorously screened to ascertain the absence of any prior neurological or psychiatric afflictions in their medical history, as well as to confirm that none of them were currently under prescription for neuroleptic, hypnotic, or anti-seizure medications. All participants underwent a hearing screening test to ensure accurate perception of auditory stimuli through headphones. Furthermore, given their exposure to English language education, a brief pre-experiment test was administered to confirm their proficiency in recognizing all 26 English letters. All participants signed an informed consent form, as required by the ethics committee (approval number: HR2023–02-011), before the experiment commenced. Remuneration was provided to each participant upon the experiment's completion.

2.1.2. Procedure

This experiment utilized a pretest-training-posttest design (Fig. 1). The pretest and posttest tasks encompassed a verbal operation span task, a visual letter n-back task, an auditory letter n-back task, an audio-visual dual n-back task and digit span backward and forward task, which are frequently used as quantitative measures of working memory in the Chinese elderly population (Ingvalson et al., 2015; Xin et al., 2014; Zhu et al., 2024; Zhidong et al., 2021). Previous studies have indicated that adaptive n-back training can improve working memory updating and daily living abilities in Chinese elderly individuals with mild cognitive impairment (Cheng et al., 2015; Liang, 2020). In the training stage, an adaptive working memory task was employed. This task adjusted its difficulty based on the individual's performance to maintain a challenging, engaging, and efficient training experience (Green et al., 2019). The training lasted for 12 working days, with the post-test task administered immediately upon training completion. Subsequently, two follow-up assessments occurred on the 7th and 15th days following the post-test.

Both the test and training tasks were administered using a working memory test application developed in our laboratory (Fig. 2). This

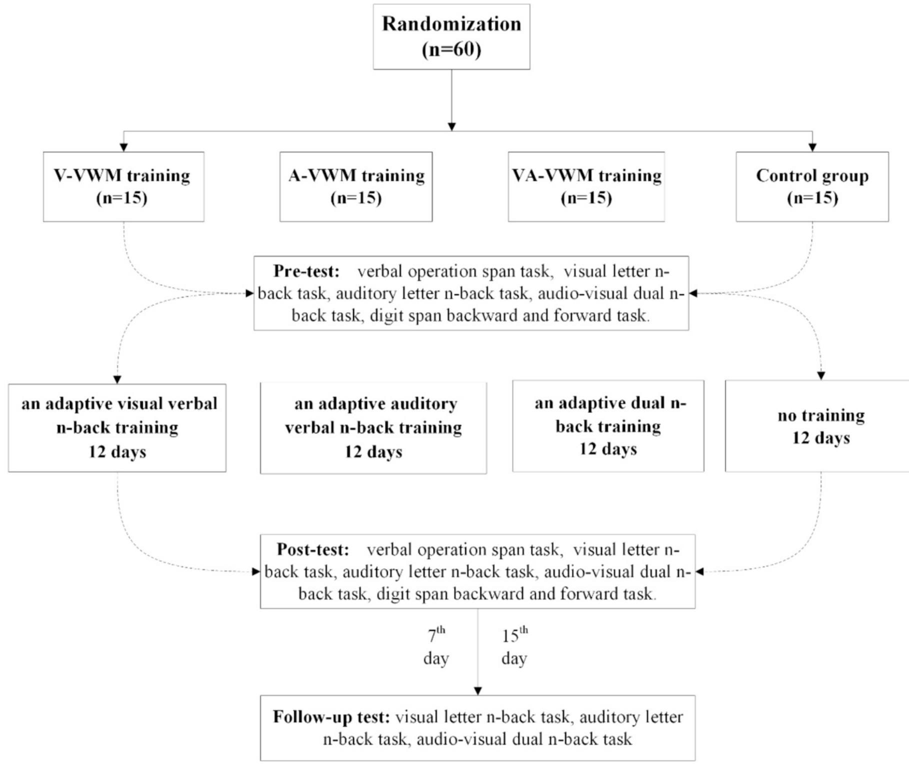

Fig. 1. Flowchart of the procedure.

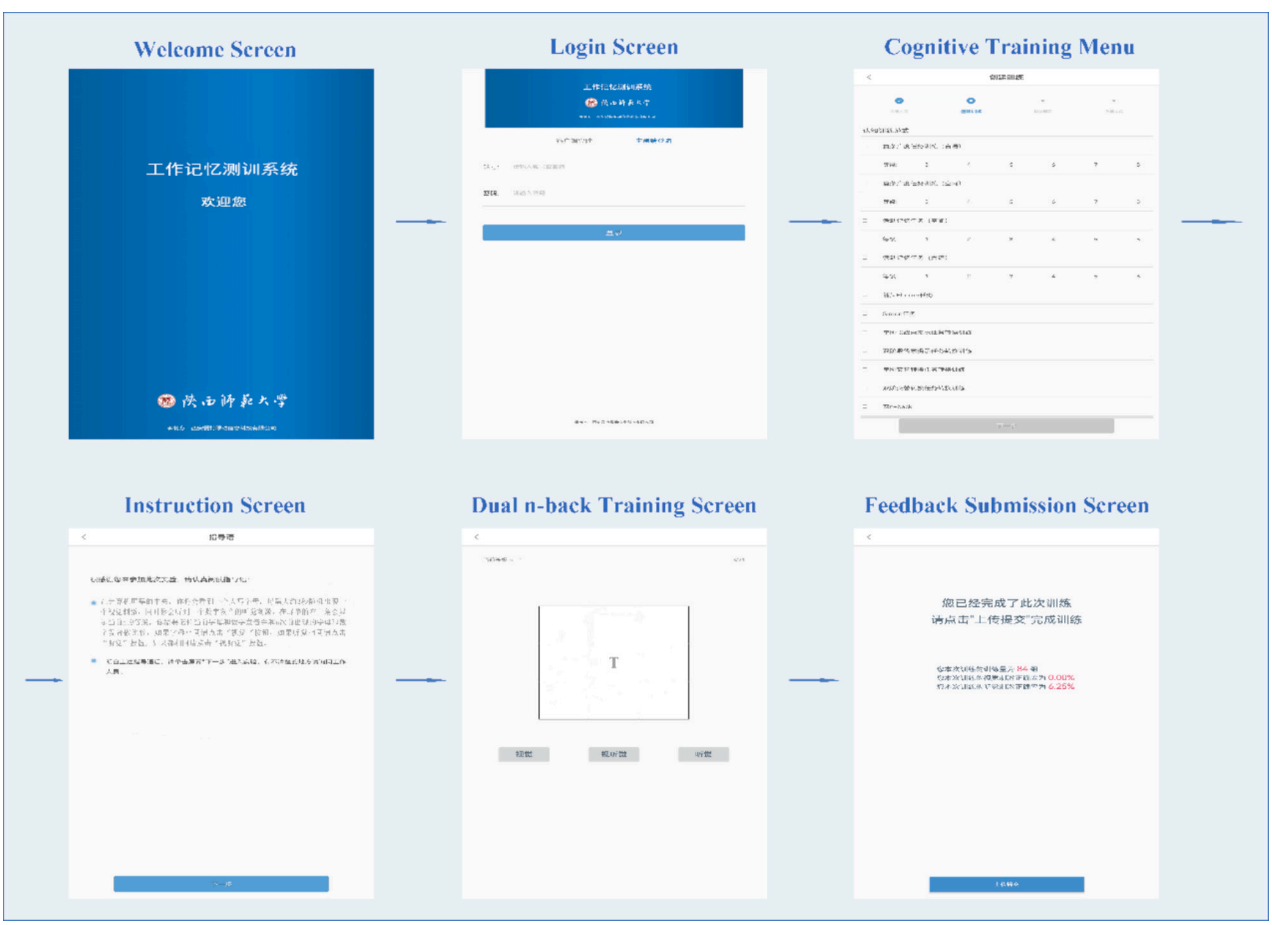

Fig. 2. Key screenshots for working memory training application.

application consists of three core modules: the primary test terminal used by the experimenter, the test terminal used by the experimental participants, and the cloud computing access module. Its functions encompass training and testing on various working memory tasks. The software development environment for this system is Android Studio 4.0, an officially released product by Google. The application is compatible with Android version 7.0 and higher, and it can operate on Android tablets of various sizes with a resolution of 1200 × 1920.

The software is exclusively designed for research purposes and lacks any commercial intent or plans for commercialization. For this experiment, a Huawei tablet with a 10.4-in. screen was employed.

2.1.3. Pretest and posttest assessment

2.1.3.1. Verbal operation span task. The complex verbal operation span task required participants to remember a sequence of letters while also completing a distracting processing task. In each trial, a letter appeared at the screen's center for 1 s, followed by 4 s of a mathematical problem judgment task. Each to-be-remembered letter was preceded by 4 s of repeated, participant-paced, math problem decision tasks. Finally, a 4 × 4 alphabet was presented and participants were required to recall the letter sequence in the correct order (Fig. 3).

2.1.3.2. Verbal working memory tasks. The procedure of visual letter n-back task, auditory letter n-back task and audio-visual dual n-back task were the same as the training task (Fig. 4).

Digit span backward (DSB) and forward (DSF).

On each trial, a fixation cross was presented for 750 ms, followed by a sequence of digits (0–9) displayed one at a time at a rate of 1000 ms in the center of the screen. At the end of the sequence, participants were instructed to recall the digits in the same order they appeared (DSF) or in reverse order (DSB) and type their responses into the answer box. There were two trials for each string length (DSF: 3–9; DSB: 2–8). If participants performed correctly in at least one of the two trials at a specific span length, the string length was increased in the next trial. If participants performed incorrectly in both trials at a specific span length, the task was terminated.

2.1.4. Training tasks

2.1.4.1. Visual verbal working memory. The visual VWM training task in this study was the visual letter n-back task. In this training, participants were presented with a sequence of visual stimuli, consisting of English letters, displayed on a tablet screen for a duration of 500 ms, with a 2500 ms interval between consecutive stimuli. Their task was to remember whether the currently presented letter matched the one shown ‘n’ positions earlier in the sequence. The level of difficulty, denoted by ‘n’ adapted dynamically based on participants' performance. If participants responded with at least 90 % accuracy in this task, they would progress to the next level (e.g., from 2-back to 3-back), where they needed to match letters separated by a greater number of intervening items. However, if their accuracy dropped to 70 % or lower in either the visual or auditory tasks during a run, they would be moved down to a lower level (e.g., from 3-back to 2-back), with the lowest level being 1-back. When accuracy fell within the range of 70 % to 90 %, the ‘n-back’ level remained constant.

2.1.4.2. Auditory verbal working memory. The auditory VWM training task in this study was the auditory letter n-back task. The training procedure paralleled that of the visual VWM task, with the sole distinction being the auditory presentation of letters through headphones.

2.1.4.3. Visual-auditory verbal working memory. The visual-auditory VWM task employed in this study was a dual n-back paradigm. During each trial, participants were presented with two sets of stimuli concurrently: a visual set of English capital letters and an auditory set of Arabic digits. Each stimulus, both visual and auditory, was presented for a duration of 500 ms, followed by an interstimulus interval (ISI) of 2500 ms. After the ISI, the next pair of stimuli was presented (Fig. 4). Participants were instructed to remember the digits that were presented sequentially through the headphones and the letters displayed on the screen, and then to determine whether the digits presented matched the one presented n ($n = 1, 2, 3\ldots\ldots$) items before in the sequence, as well as whether the letters were the same as the one presented n ($n = 1, 2, 3\ldots\ldots$) items before in the sequence. Participants provided responses by touching the “visual” button at the screen's bottom for visual targets, the “auditory” button for auditory targets, and the “visual-auditory” button for both visual and auditory targets. During each training session, the task adapted based on performance. If a participant responded with at least 90 % correctly in both tasks, they advanced to the next level (e.g., from 2-back to 3-back). If a participant responded with 70 % accuracy or less in either of the tasks during a run, they were demoted to a lower level (e.g., from 3-back to 2-back), with the lowest level being 1-back. Otherwise (i.e., accuracy between 70 % and 90 %), the n-back level remained constant. After each block, participants received feedback on their visual and auditory n-back task performance and were informed of the n-back level for the subsequent run. Each training session comprised 20 blocks, each containing 20 + n trials. There were six visual and auditory targets as well as two visual-auditory targets per block. The initial training commenced with the 1-back task, and each subsequent training level was based on the level of the last block from the previous training. However, for each outcome session (pretest, post-test, follow-up 1, and follow-up 2), participants started from level 1.

2.1.5. Statistical analyses

Firstly, a one-way analysis of variance (ANOVA) was employed to assess significant variations in the pretest performance across four groups (V-VWM training group, A-VWM training group, VA-VWM training group, and control group) for the training tasks (visual letter n-back, auditory letter n-back, dual n-back task).

Secondly, to evaluate the improvement in the three training tasks

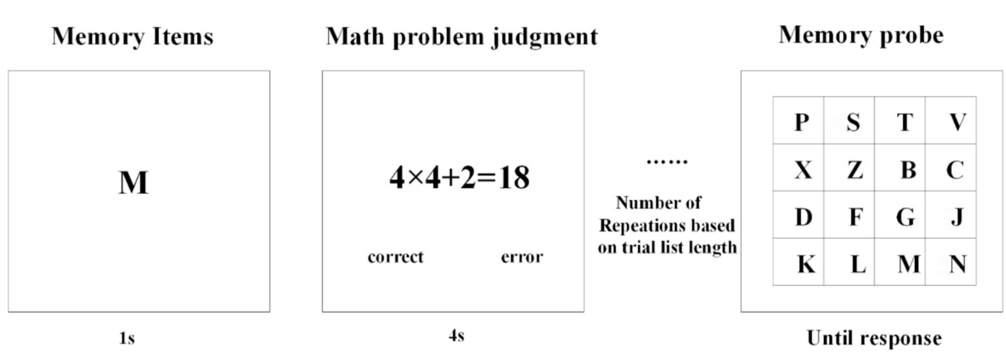

Fig. 3. The procedure of verbal operation span task.

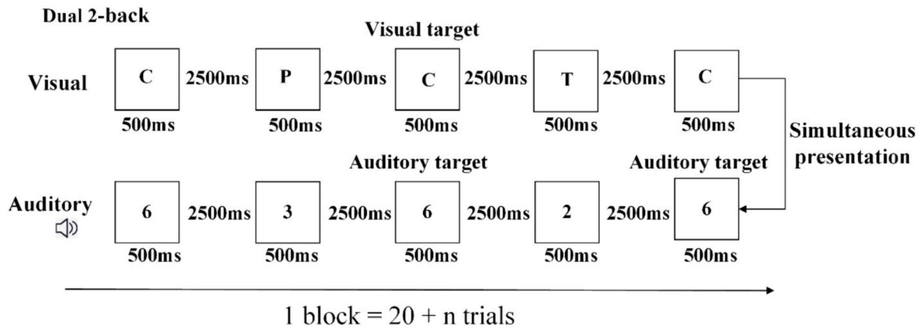

Fig. 4. The procedure of dual 2-back task.

while considering individual differences, we conducted three separate 4 × 2 mixed-design analysis of covariance (ANCOVA) tests on the mean "n" level achieved by participants. These tests included a between-subjects factor of group (V-VWM training group, A-VWM training group, VA-VWM training group, and control group) and a within-subject factor of time (pre-test, post-test). Additionally, we measured the baseline performance of visual / auditory / dual n-back, verbal operation span, DSB and DSF tasks. Subsequently, we standardized performance individually for each task based on the entire baseline sample and calculated the average for each person, resulting in a composite VWM span score. Therefore, we included baseline VWM span score and education as covariates in the analysis.

Thirdly, to evaluate the maintenance effect of VWM training (visual, auditory, and visual-auditory n-back), we conducted three separate 4 × 3 mixed ANCOVA analyses. These analyses included group (V-VWM training, A-VWM training, VA-VWM training, and control) as the between-subject factor and time (post-test, follow-up 1, follow-up 2) as the within-subject factor, with baseline VWM span score and education as covariates, focusing on the dependent variable ("n" level). It's noteworthy that not all participants participated in the follow-up test: V-VWM training group (only 8 participants), A-VWM training group (only 8 participants), VA-VWM training group (only 10 participants), and control group (only 9 participants).

Finally, the transfer effect of VWM training on the verbal operation span task, DSF and DSB task were calculated. For each transfer task, a one-way ANOVA was employed to examine significant differences in the pretest. Additionally, a 4 × 2 mixed-design ANCOVA was executed, with group (V-VWM training group, A-VWM training group, VA-VWM training group, and control group) as the between-subjects factor and time (pre-test, post-test) as the within-subject factor, baseline VWM span score and education as covariates.

3. Results

3.1. Enhancement of VWM tasks by multisensory training

3.1.1. Pre-test performance

One-way ANOVA results indicated no significant differences among the four groups during the pre-test phase for the visual letter n-back task (F (3,56) =1.062, $p = 0.372$, $\eta_p^2 = 0.054$), auditory letter n-back task (F (3,56) =1.081, $p = 0.365$, $\eta_p^2 = 0.055$), and audio-visual dual n-back task (F (3,56) = 0.992, $p = 0.403$, $\eta_p^2 = 0.051$).

3.1.2. Enhancement effect of visual letter n-back task

For the "n" level, the results of the 4 × 2 mixed-design ANCOVA revealed that the effect of the baseline VWM span score covariate was marginally significant, F (1,54) = 4.000, $p = 0.051$, $\eta_p^2 = 0.069$. The effect of education covariate was non-significant, F (1,54) = 1.163, p = 0.286, $\eta_p^2 = 0.021$. After controlling for these covariates, there was a significant main effect of group (F (3,54) = 5.008, $p < 0.01$, $\eta_p^2 = 0.218$) and a significant interaction effect of time and group (F (3,54) = 3.459, $p < 0.05$, $\eta_p^2 = 0.161$). Further simple effect analysis revealed a larger increase in performance in the post-test compared to pre-test among the V-VWM ($p < 0.01$, *Cohen's d* = 1.765) and VA-VWM training groups ($p < 0.01$, *Cohen's d* = 0.945). Conversely, no significant difference between pre-test and post-test was observed in the A-VWM ($p = 0.058$, *Cohen's d* = 0.567) and control groups ($p = 0.577$, *Cohen's d* = 0.148). Additionally, a significant difference was found between the post-test performance of the V-VWM ($p < 0.01$, *Cohen's d* = 1.449) group and the control group (VA-VWM and control group: $p < 0.01$, *Cohen's d* = 1.127). No significant difference between the post-test performance of A-VWM and control group was observed ($p = 0.085$, *Cohen's d* = 0.947) (Fig. 5a). These results indicated that V-VWM and VA-VWM training significantly improved V-VWM performance (Table 1). The marginal significance of the baseline VWM span score suggests it may have a minor influence on the improvement from V-VWM training.

3.1.3. Enhancement effect of auditory letter n-back task

For the "n" level, the results of the 4 × 2 mixed-design ANCOVA revealed that the effect of the baseline VWM span score and education covariate were not significant (baseline: F (1,54) = 1.654, $p = 0.204$, $\eta_p^2 = 0.030$; education: F (1,54) = 0.218, $p = 0.642$, $\eta_p^2 = 0.004$). After controlling for these covariates, there was a significant main effect of group (F (3,54) = 3.180, $p < 0.05$, $\eta_p^2 = 0.150$) and a significant interaction effect of time and group (F (3,54) = 6.712, $p < 0.01$, $\eta_p^2 = 0.272$). Further analysis of simple effects revealed a larger increase in performance in the post-test compared to pre-test among the V-VWM ($p < 0.05$, *Cohen's d* = 0.916), A-VWM ($p < 0.01$, *Cohen's d* = 1.904) and VA-VWM training groups ($p < 0.01$, *Cohen's d* = 1.587), while no significant difference was found in the control group ($p = 0.811$, *Cohen's d* = 0.016). There was a significant difference between the post-test performances of the V-VWM ($p < 0.05$, *Cohen's d* = 0.956) training group and the control group (A-VWM and control group: $p < 0.01$, *Cohen's d* = 1.749; VA-VWM and control group: $p < 0.01$, *Cohen's d* = 1.187) (Fig. 5Tb). These results indicated that V-VWM, A-VWM and VA-VWM training significantly enhanced A-VWM performance (Table 1).

3.1.4. Enhancement effect of audio-visual dual n-back task

For the "n" level, the results of the 4 × 2 mixed-design ANCOVA revealed that the effect of the baseline VWM span score (F (1,54) = 1.912, $p = 0.172$, $\eta_p^2 = 0.034$) and education covariate were not significant (F (1,54) = 0.897, $p = 0.348$, $\eta_p^2 = 0.016$). After controlling for these covariates, the main effect of group did not reach significance, F (3,54) = 2.301, $p = 0.088$, $\eta_p^2 = 0.113$. Notably, the interaction effect of time and group was significant, F (3,54) = 9.190, $p < 0.01$, $\eta_p^2 = 0.338$. Further analysis of simple effects revealed a larger increase in performance in the post-test compared to pre-test in the V-VWM ($p < 0.01$, *Cohen's d* = 1.771), A-VWM ($p < 0.01$, *Cohen's d* = 0.828) and VA-VWM ($p < 0.01$, *Cohen's d* = 2.319) training group, while no significant difference was observed in the control group ($p = 0.131$, *Cohen's d* = 0.484). Additionally, a significant difference was found between the VA-VWM training group and the control group in post-test performance (p

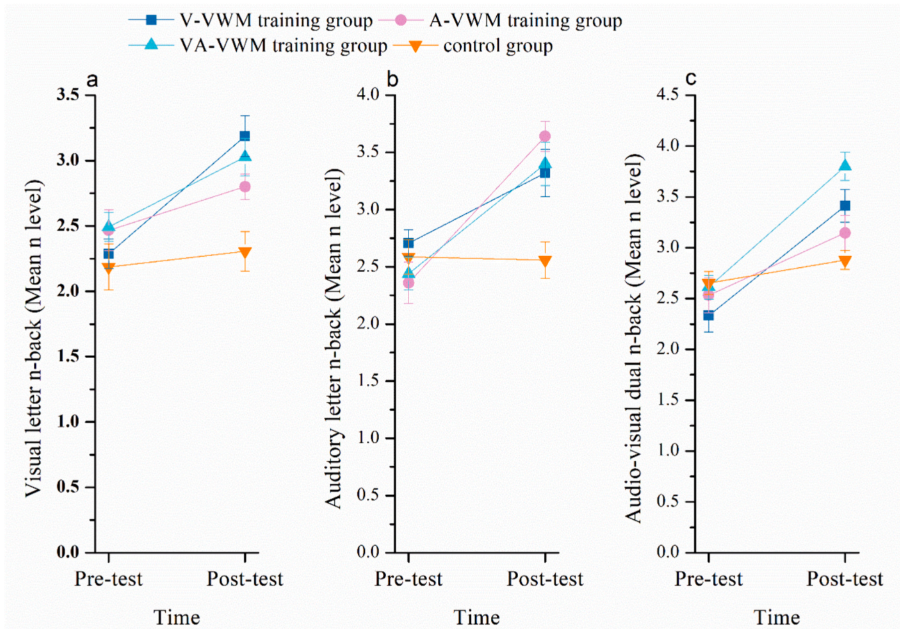

Fig. 5. Performance of pre-test and post-test on the visual n-back (a), auditory n-back (b) and audio-visual dual n-back for four groups (c).

Table 1
Pre- and post-test performance and significant changes across different training groups.

Training groups	Tasks	Pre (Mean ± SD)	post (Mean ± SD)	gain	Percentage change	Significant Increase
V-VWM training	V-VWM	2.3(0.4)	3.2(0.6)	0.9	39.1 %	Yes
	A-VWM	2.7(0.4)	3.3(0.8)	0.6	22.2 %	Yes
	VA-VWM	2.3(0.6)	3.4(0.6)	1.1	47.8 %	Yes
	operation span	30.1(9.2)	33.5(8.1)	3.4	11.3 %	No
	DSB	5.2(1.6)	5.3(1.8)	0.1	1.9 %	No
	DSF	6.5(1.4)	6.1(1.5)	−0.4	−6.1 %	No
A-VWM training	V-VWM	2.5(0.6)	2.8(0.4)	0.3	12.0 %	No
	A-VWM	2.4(0.7)	3.6(0.5)	1.2	50.0 %	Yes
	VA-VWM	2.5(0.7)	3.1(0.7)	0.6	24.0 %	Yes
	operation span	27.4(7.6)	29.7(8.8)	2.3	8.4 %	No
	DSB	6.0(1.4)	5.7(1.3)	−0.3	−5.0 %	No
	DSF	6.5(1.5)	7.2(1.5)	−0.7	−10.8 %	No
VA-VWM	V-VWM	2.5(0.4)	3.0(0.6)	0.5	20.0 %	Yes
	A-VWM	2.4(0.5)	3.4(0.7)	1.0	41.7 %	Yes
	VA-VWM	2.6(0.5)	3.8(0.5)	1.2	46.2 %	Yes
	operation span	29.6(8.1)	38.4(6.7)	8.8	29.7 %	Yes
	DSB	5.9(1.2)	5.3(1.2)	−0.6	−10.2 %	No
	DSF	5.9(1.4)	6.5(1.3)	−0.4	−6.8 %	No
Control	V-VWM	2.2(0.7)	2.3(0.6)	0.1	4.5 %	No
	A-VWM	2.6(0.6)	2.6(0.6)	−0.01	0 %	No
	VA-VWM	2.7(0.4)	2.9(0.4)	0.2	7.4 %	No
	operation span	29.1(7.6)	29.4(5.8)	0.3	1.0 %	No
	DSB	5.0(1.9)	4.8(1.4)	−0.2	−4.0 %	No
	DSF	6.4(1.8)	6.7(1.7)	0.3	4.7 %	No

Notes: V-VWM refers to visual-verbal working memory; A-VWM refers to Auditory verbal working memory; VA-VWM refers to visual-auditory verbal working memory; DSB refers to digit span backwards; DSF refers to digit span forwards.

< 0.01, *Cohen's d* = 1.923). Conversely, no significant difference was observed between the V-VWM training group ($p = 0.08$, *Cohen's d* = 0.947) and the control group (A-VWM and control group: $p = 0.09$, *Cohen's d* = 0.339) in post-test performance (Fig. 5c). These results indicated that V-VWM, A-VWM and VA-VWM training significantly enhanced VA-VWM performance (Table 1).

3.2. Maintenance effect of VWM training

In the visual letter n-back task, the results of 4 × 3 mixed ANCOVA showed that both the effect of the baseline VWM span score (F (1,29) = 1.403, $p = 0.246$, $\eta_p^2 = 0.046$) and education covariate were not significant (F (1,29) = 3.770, $p = 0.062$, $\eta_p^2 = 0.115$). In addition, the main effect of time (F (2, 58) = 0.259, $p = 0.773$, $\eta_p^2 = 0.010$) and the interaction effect between time and group (F (6, 58) = 1.295, $p = 0.274$, $\eta_p^2 = 0.118$) were not significant. The main effect of group was significant (F (3, 29) = 12.944, $p < 0.01$, $\eta_p^2 = 0.572$). Post-hoc tests with Bonferroni correction revealed significant differences in performance between the A-VWM group and control group ($p < 0.05$), the V-VWM (VA-VWM) group and control group ($ps < 0.01$) at both the posttest and the follow-up test time points (Fig. 6a). The findings indicate that the improvements observed in the visual letter n-back task were maintained during the one-week and two-week follow-up assessments following VA-VWM training interventions.

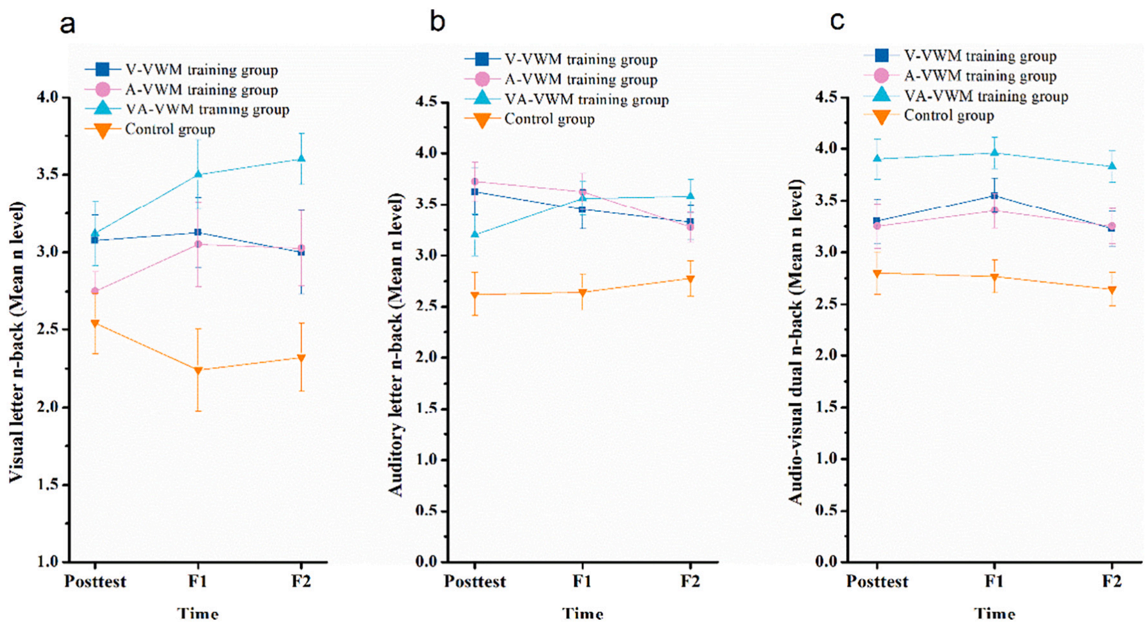

Fig. 6. Maintenance effect of visual letter n-back (a), auditory letter n-back (b) and audio-visual dual n-back (c) in different groups.

In the auditory letter n-back task, the results of 4 × 3 mixed ANCOVA indicated that the effect of the baseline VWM span score (F (1,29) = 0.451, p = 0.507, η_p^2 = 0.015) and education covariate were not significant (F (1,29) = 0.003, p = 0.959, η_p^2 = 0.000). In addition, the main effect of time was not significant, F (2, 58) = 0.485, p = 0.618, η_p^2 = 0.016. The main effect of group (F (3, 29) = 5.978, $p < 0.01$, η_p^2 = 0.382) and interaction effect between time and group (F (6, 58) = 2.810, $p < 0.05$, η_p^2 = 0.225) were significant. Subsequent simple effect analyses indicated no significant difference between the posttest and follow-up test ($ps > 0.05$) in the four groups. A significant difference was observed among the V-VWM, A-VWM, and VA-VWM groups compared to the control group at the first follow-up test time point (V-VWM group: $p < 0.05$; A-VWM and VA-VWM group: $ps < 0.01$). At the second follow-up test, only the VA-VWM group showed a significant difference compared to the control group ($p < 0.01$), while neither the A-VWM nor the V-VWM group exhibited significant differences (A-VWM group: p = 0.461; V-VWM group: p = 0.336) (Fig. 6b). The results indicate that the VA-VWM group maintained significant performance improvements in auditory letter n-back task over the two-week period.

In the audio-visual dual n-back task, the results of 4 × 3 mixed ANCOVA showed that the effect of the baseline VWM span score (F (1,29) = 0.799, p = 0.379, η_p^2 = 0.027) and education covariate were not significant (F (1,29) = 0.849, p = 0.364, η_p^2 = 0.028). The main effect of time (F (2, 58) = 0.003, p = 0.953, η_p^2 = 0.000) and the interaction of time and group were not significant (F (6, 58) = 1.192, p = 0.323, η_p^2 = 0.110). The main effect of group was significant, F (3, 29) = 8.682, $p < 0.01$, η_p^2 = 0.473. Post-hoc tests with Bonferroni correction revealed significant differences in performance between the VA-VWM group and control group ($p < 0.01$) at both the posttest and the follow-up test time points. In contrast, no significant differences were observed between the V-VWM (A-VWM) group and control group, with p-values of 0.146 and 0.216, respectively (Fig. 6c). The results indicate that the VA-VWM group maintained significant performance improvements in audio-visual dual n-back task over the two-week period.

3.3. Transfer effects

3.3.1. Performance of verbal operation span task

3.3.1.1. Pre-test. For the verbal operation span score, one-way ANOVA showed that there was no significant difference among four groups in the pre-test phase (F (3,56) = 0.316, p = 0.814, η_p^2 = 0.017).

3.3.1.2. Enhancement effect. The results of the 4 × 2 mixed-design ANCOVA revealed that the effect of the baseline VWM span score covariate was significant, F (1,54) = 14.327, $p < 0.01$, η_p^2 = 0.210. The effect of education covariate was not significant, F (1,54) = 0.535, p = 0.468, η_p^2 = 0.010. After controlling covariate, the main effect of time and group was not significant (time: F (1,54) = 3.397, p = 0.071, η_p^2 = 0.059; group: F (3,54) = 2.233, p = 0.095, η_p^2 = 0.110). The interaction effect between time and group was found to be significant, F (3,54) = 3.759, $p < 0.05$, η_p^2 = 0.173. Subsequent simple effect analyses revealed a significant difference between pre-test and post-test scores in the VA-VWM training group ($p < 0.01$, *Cohen's d* = 1.145), while no significant differences were observed between pre-test and post-test scores in the other groups (V-VWM group: p = 0.07, *Cohen's d* = 0.379; A-VWM group: p = 0.197, *Cohen's d* = 0.270; control group: p = 0.913, *Cohen's d* = 0.043). Moreover, a significant difference was observed between the VA-VWM training group and the control group ($p < 0.01$, *Cohen's d* = 1.387) in post-test performance (A-VWM training and control group: $p < 0.01$, *Cohen's d* = 0.038) (Fig. 7). These results indicated that VA-VWM training improved the performance of verbal operation span task, and the baseline VWM span score significantly influenced the overall improvement.

3.3.2. DSB and DSF performance

3.3.2.1. Pre-test. The one-way ANOVA showed that the pre-test performance of digit span backward task and forward task did not exist significant difference among four groups (DSB: F (3,56) = 1.510, p = 0.222, η_p^2 = 0.075; DSF: F (3,56) = 0.606, p = 0.614, η_p^2 = 0.031).

3.3.2.2. Enhancement effect. The results of 4 × 2 mixed-design ANCOVA revealed the absence of any statistically significant effect of the baseline VWM span score and education covariate in either DSB (baseline: p = 0.277; education: p = 0.802) or DSF tasks (baseline: p = 0.305; education: p = 0.167). In addition, there was no significant main effects of time for both DSB (F (1,54) = 0.832, p = 0.366, η_p^2 = 0.015) and DSF tasks (F (1,54) = 2.984, p = 0.09, η_p^2 = 0.052). Similarly, there was no significant interaction effect between time and group observed in either

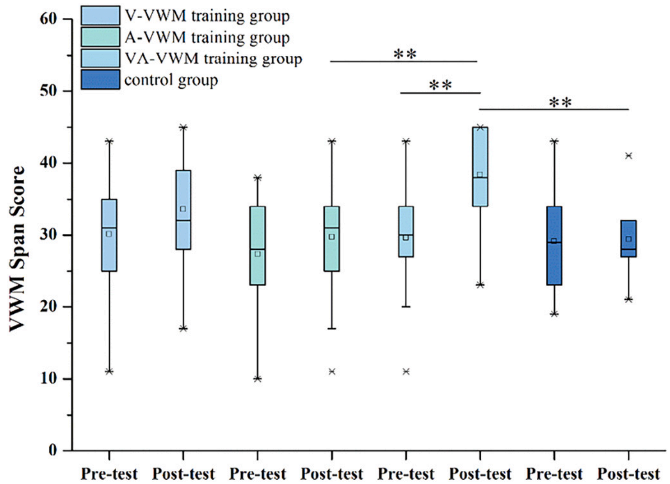

Fig. 7. Performance on the verbal operation span task at pre-training and post-training, separately for V-VWM training group, A-VWM training group, VA-VWM training group and control group. ** indicate significant differences at $p < 0.01$.

DSB (F (3,54) = 0.748, p = 0.528, η_p^2 = 0.040) or DSF tasks (F (3,54) = 1.346, p = 0.269, η_p^2 = 0.070) (Fig. 8). These results indicated that VWM training did not improve the DSB and DSF.

4. Discussion

The primary objective of this study was to examine the efficacy of multisensory training facilitated through a mobile application (APP) in augmenting verbal working memory among healthy older adults. Our results reveal that V-VWM training significantly improves V-VWM, with a discernible near-transfer effect extending to A-VWM and VA-VWM. In contrast, A-VWM training enhances auditory verbal working memory and selectively transfers to the VA-VWM task. Remarkably, VA-VWM training not only enhances VA-VWM but also demonstrates positive effects on both V-VWM, A-VWM domains and verbal operation span task. Overall, these findings indicate a nuanced influence of multisensory training modalities on various facets of verbal working memory in the aging population, underscoring the significance of personalized approaches that take into account the specific sensory components implicated in working memory processes.

We observed that the baseline level of VWM span score might have a minor influence on the improvement from V-VWM training, while did not reveal a significant impact of baseline level on A-VWM and VA-VWM training effects. One possible explanation for this discrepancy lies in the composite VWM span score utilized as the baseline measure, which predominantly comprises tasks associated with visual-verbal working memory. This alignment between the baseline measure and the training content implies a potential advantage for individuals with higher baseline scores in visual-verbal tasks in terms of their response to V-VWM training. Another possible explanation is that different channels of VWM may engage distinct brain regions and processing mechanisms (Buchsbaum and D'Esposito, 2019; Crottaz-Herbette et al., 2004), leading to differential effects of baseline level across them. Moreover, the baseline level of VWM span score also influences the transfer to verbal operation span task. Previous studies have suggested that individual differences in baseline scores impact the transfer effect of working memory (Zhu et al., 2017; Zinke et al., 2014). These modality-specific responses underscore the need for tailored interventions that account for the unique cognitive demands associated with different working memory tasks. In essence, understanding and leveraging task-specific nuances have the potential to optimize cognitive training programs based on individual differences and task characteristics.

Our investigation did not reveal a significant influence of older adults' education levels on the enhancement effect of training, a finding inconsistent with previous studies (Berryhill and Jones, 2012; Johnson et al., 2022). This discrepancy may stem from the notably high educational background of our participants, with an average of 15.55 ± 2.53 years of education. The elevated education levels in our sample may have minimized the impact of educational variations on the efficacy of working memory enhancement. As a result, the generalizability of our findings to populations with diverse educational backgrounds might be limited.

In our investigation, the maintenance effects of verbal working

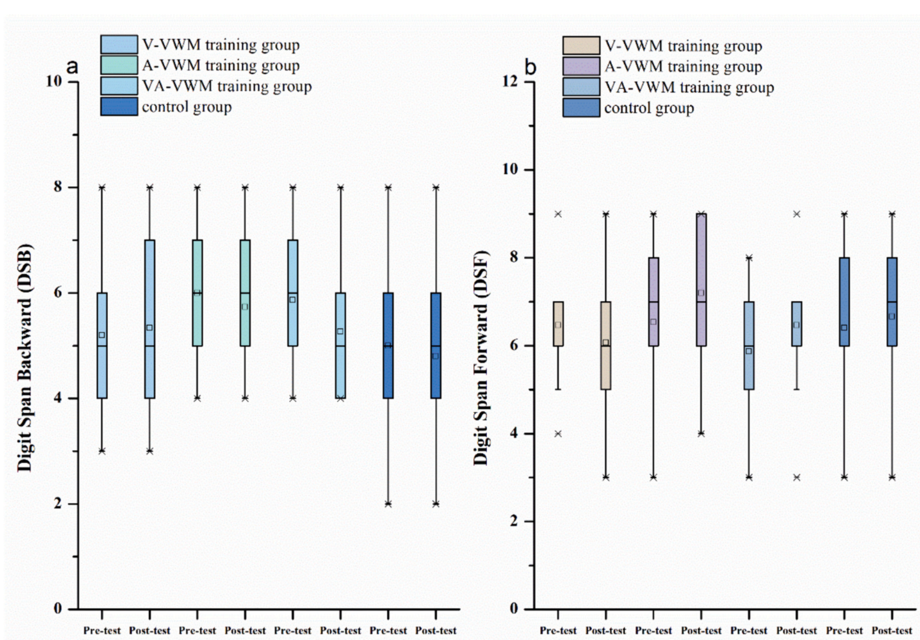

Fig. 8. Performance on the DSB (a) and DSF (b) task at pre-training and post-training, separately for V-VWM training group, A-VWM training group, VA-VWM training group and control group.

memory training were evident, with distinct temporal patterns observed for the visual (V-VWM) and auditory (A-VWM) modalities. Notably, although the improvement effect of V-VWM persisted for two weeks following the training, a declining trend was observed after the first week. Similarly, the enhancement effect induced by A-VWM training demonstrated lasted only for one week. This nuanced temporal distinction sheds light on the differential dynamics of working memory improvements across sensory modalities. Remarkably, the VA-VWM training method not only sustained the improvement effect of VA-VWM for two weeks but also maintained the enhancement effects of both V-VWM and A-VWM for the same duration. This suggests that the incorporation of multisensory components in training may confer an advantage in the maintenance of both the trained and untrained tasks. The synergistic effects of combining visual and auditory stimuli might contribute to a more robust and enduring impact on working memory functions.

We noted that the benefits of training in the VA-VWM group uniquely extended to the verbal operation span task, reflecting an augmentation in the breadth of verbal operations. Conversely, both the V-VWM and A-VWM training groups did not demonstrate significant transfer effects to verbal operation span tasks, implying a more constrained influence on the breadth of verbal operations for these groups. Previous studies have suggested that dual n-back training can induce both task-specific and task-general near transfer (Soveri et al., 2017). In our study, the complex verbal operation span task encompassed two subtasks: memory and math problem decision tasks, while the dual n-back task involved both visual and auditory tasks. The ease of transferring to other cognitive skills appears to be facilitated when training and transfer tasks exhibit overlap through shared cognitive processes and structural similarity in tasks (De Simoni and von Bastian, 2018; Holmes et al., 2019; Zhao et al., 2022). Notably, it is essential to highlight that none of the three training groups demonstrated significant transfer effects to the DSF and DSB tasks. The question of whether working memory training can transfer to DSF and DSB tasks has consistently yielded inconsistent results in older adults (Booth et al., 2023; Heinzel et al., 2014; McAvinue et al., 2013).

Our findings indicated that mobile terminal training have the potential to improve verbal working memory of older adults. Regarding working memory training, there remains limited research on training via mobile devices. Previous studies focused on enhancing training flexibility predominantly employed non-laboratory training on home computers through webpages, with inconsistent effectiveness (Oh et al., 2017). One significant challenge is the inability to ensure the prescribed training volume, a concern that may be mitigated on mobile devices due to higher training flexibility, convenience, and enhanced enjoyment. Furthermore, the working memory training application we developed not only includes working memory tasks but also incorporates additional cognitive tasks such as risk decision-making and attentional tasks. This application can be installed on both tablets and smartphones. Thus, the use of such training applications for improving cognitive skills in older adults holds promising prospects.

It is imperative to evaluate the study's contribution within the context of several constraints. Firstly, it is important to note that not all older adult participants were included in the follow-up sessions for various reasons. This limitation prompts a call for future studies to delve deeper into the long-term maintenance effects of multisensory training specifically tailored for older adults. Understanding how these effects evolve over extended periods could provide valuable insights into the sustainability and generalizability of multisensory interventions in cognitive training programs. Secondly, the older participants in this study possessed relatively elevated levels of education to ensure their proficiency in conducting training operations on a tablet. Subsequent studies can explore the impact of education on training outcomes across varying educational levels among older adults. Thirdly, a potential limitation of this study is that while participants demonstrated basic English literacy by recognizing all 26 letters, the depth of their English proficiency and its impact on verbal working memory engagement during the task remains undetermined. Future studies may opt for stimuli universally recognized by participants or ensure language proficiency to mitigate this potential confounding factor. Fourthly, the sample size in this study was relatively small, primarily due to the challenges associated with recruiting older adult participants for a prolonged 12-day training period. Future research should aim to recruit a larger number of participants to enhance the statistical power and reliability of the findings, and to further explore the effects of multisensory training in older adults. Finally, we employed the passive control group rather than the active control group in this study. A prior study demonstrated that the active-control task exhibited a certain level of face validity as a cognitive training intervention (Green et al., 2019). Future research can investigate the augmentative impact of multisensory training in older adults compared to the active control group.

5. Conclusion

This study examined the impact of multisensory training utilizing a mobile application on the improvement, maintenance, and transfer effects of verbal working memory training in healthy older adults. Results revealed that V-VWM training enhances visual verbal working memory in older adults, with the improvement effect persisting for two weeks. Similarly, A-VWM training improves auditory verbal working memory in older adults, with the improvement effect persisting for one week. Moreover, VA-VWM training not only improves visual-auditory verbal working memory but also enhances V-VWM, A-VWM and verbal operation span tasks. However, no evidence of transfer to the DSF and DSB tasks was observed. The maintenance effect of VA-VWM training persisted for two weeks across VA-VWM, V-VWM, and A-VWM tasks. The baseline VWM span score influences the training effect of V-VWM and affects the improvement of VA-VWM training transfer to the verbal operation span task. The education level did not serve as a predictor for the training effects of V-VWM, A-VWM, and VA-VWM. In summary, these results suggest that multisensory training may confer advantages in enhancement, maintenance, and transfer effects. Mobile terminal training for enhancing cognitive skills in older adults shows promising potential.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Assecondi, S., Hu, R., Kroeker, J., Eskes, G., Shapiro, K., 2022. Older adults with lower working memory capacity benefit from transcranial direct current stimulation when combined with working memory training: a preliminary study. Front. Aging Neurosci. 14, 1009262.

Berryhill, M.E., Jones, K.T., 2012. tDCS selectively improves working memory in older adults with more education. Neurosci. Lett. 521 (2), 148–151.

Booth, S.J., Brown, L.J.E., Taylor, J.R., Pobric, G., 2023. Experimental investigation of training schedule on home-based working memory training in healthy older adults. Front. Psychol. 14, 1165275.

Brum, P.S., Borella, E., Carretti, B., Sanches Yassuda, M., 2020. Verbal working memory training in older adults: an investigation of dose response. Aging Ment. Health 24 (1), 81–91.
Buchsbaum, B.R., D'Esposito, M., 2019. A sensorimotor view of verbal working memory. Cortex 112, 134–148.
Carretti, B., Borella, E., Zavagnin, M., de Beni, R., 2013. Gains in language comprehension relating to working memory training in healthy older adults. Int. J. Geriatr. Psychiatry 28 (5), 539–546.
Chai, W.J., Abd Hamid, A.I., Abdullah, J.M., 2018. Working memory from the psychological and neurosciences perspectives: a review. Front. Psychol. 9, 401.
Cheng, C.P., Chan, S.S., Mak, A.D., Chan, W.C., Cheng, S.T., Shi, L., Lam, L.C.W., 2015. Would transcranial direct current stimulation (tDCS) enhance the effects of working memory training in older adults with mild neurocognitive disorder due to Alzheimer's disease: study protocol for a randomized controlled trial. Trials 16, 1–7.
Crottaz-Herbette, S., Anagnoson, R.T., Menon, V., 2004. Modality effects in verbal working memory: differential prefrontal and parietal responses to auditory and visual stimuli. Neuroimage 21 (1), 340–351.
De Simoni, C., von Bastian, C.C., 2018. Working memory updating and binding training: Bayesian evidence supporting the absence of transfer. J. Exp. Psychol. Gen. 147 (6), 829–858.
Deary, I.J., Corley, J., Gow, A.J., Harris, S.E., Houlihan, L.M., Marioni, R.E., Starr, J.M., 2009. Age-associated cognitive decline: normal (non-pathological) cognitive aging. Br. Med. Bull. 92 (1), 135–152.
Forsberg, A., Johnson, W., Logie, R.H., 2020. Cognitive aging and verbal labeling in continuous visual memory. Mem. Cognit. 48 (7), 1196–1213.
Foster, J.L., Harrison, T.L., Hicks, K.L., Draheim, C., Redick, T.S., Engle, R.W., 2017. Do the effects of working memory training depend on baseline ability level? J. Exp. Psychol. Learn. Mem. Cogn. 43 (11), 1677.
Freitas, S., Simões, M.R., Alves, L., Santana, I., 2011. Montreal cognitive assessment (MoCA): normative study for the Portuguese population. J. Clin. Exp. Neuropsychol. 33, 989–996.
Green, S.C., Bavelier, D., Kramer, A.F., Vinogradov, S., Ansorge, U., Ball, K.K., et al., 2019. Improving methodological standards in behavioral interventions for cognitive enhancement. Journal of Cognitive Enhancement 3, 2–29.
Heinzel, S., Schulte, S., Onken, J., Duong, Q.L., Riemer, T.G., Heinz, A., et al., 2014. Working memory training improvements and gains in non-trained cognitive tasks in young and older adults. Aging Neuropsychology & Cognition 21, 146–173.
Holmes, J., Woolgar, F., Hampshire, A., Gathercole, S.E., 2019. Are working memory training effects paradigm-specific? *Frontiers in psychology*, *10*. Article 1103.
Ingvalson, E.M., Dhar, S., Wong, P., Liu, H., 2015. Working memory training to improve speech perception in noise across languages. J. Acoust. Soc. Am. 137 (6), 3477–3486.
Johnson, E.L., Arciniega, H., Jones, K.T., Kilgore-Gomez, A., Berryhill, M.E., 2022. Individual predictors and electrophysiological signatures of working memory enhancement in aging. Neuroimage 250, 118939.
Karbach, J., Könen, T., Spengler, M., 2017. Who benefits the most? Individual differences in the transfer of executive control training across the lifespan. J. Cogn. Enhanc. 1, 394–405.
Liang, W.J., 2020. *Updating Training Can Improve the Daily Living Abilities of the Elderly with Mild Cognitive Impairment* [Master's Thesis, Northwest Normal University].
Lövdén, M., Brehmer, Y., Li, S.C., Lindenberger, U., 2012. Training-induced compensation versus magnification of individual differences in memory performance. Front. Hum. Neurosci. 6, 141.
McAvinue, L.P., Golemme, M., Castorina, M., Tatti, E., Pigni, F.M., Salomone, S., et al., 2013. An evaluation of a working memory training scheme in older adults. Front. Aging Neurosci. 5, 20.
Nguyen, L., Murphy, K., Andrews, G., 2019. Cognitive and neural plasticity in old age: a systematic review of evidence from executive functions cognitive training. Ageing Res. Rev. 53, 100912.
Oh, H., Park, J., Seo, W., 2017. Development of an evidence-based intervention program for patients with mild cognitive impairment after stroke: a home-based, online cognitive rehabilitation program. Topics in Geriatric Rehabilitation 33 (2), 140–151.
Pahor, A., Collins, C., Smith-Peirce, R.N., Moon, A., Stavropoulos, T., Silva, I., Peng, E., Jaeggi, S.M., Seitz, A.R., 2021. Multisensory facilitation of working memory training. J. Cogn. Enhanc. 5 (3), 386–395.
Soveri, A., Karlsson, E.P.A., Waris, O., Grönholm-Nyman, P., Laine, M., 2017. Pattern of near transfer effects following working memory training with a dual n-back task. Experimental Psychology, 64 (4), 240–252.
Teixeira-Santos, A.C., Moreira, C.S., Magalhães, R., Magalhães, C., Pereira, D.R., Leite, J., Sampaio, A., 2019. Reviewing working memory training gains in healthy older adults: a meta-analytic review of transfer for cognitive outcomes. Neurosci. Biobehav. Rev. 103, 163–177.
Xin, Z., Lai, Z.R., Li, F., Maes, J.H., 2014. Near-and far-transfer effects of working memory updating training in elderly adults. Appl. Cogn. Psychol. 28 (3), 403–408.
Xing, Q., Lu, Z., Hu, J., 2019. The effect of working memory updating ability on spatial insight problem solving: evidence from behavior and eye movement studies. Front. Psychol. 10, 927.
Zhao, X., Yang, T., Wang, T., Sun, J., 2022. The influence of task structural similarity on transfer effect of working memory training. Journal of Psychological Science 45 (6), 1337–1343.
Zhidong, C., Wang, X., Yin, J., Song, D., Chen, Z., 2021. Effects of physical exercise on working memory in older adults: a systematic and meta-analytic review. Eur. Rev. Aging Phys. Act. 18, 1–15.
Zhu, Z., Duan, Y., Wang, S., 2017. The baseline fluid intelligence modulated the transfer effect from working memory to fluid intelligence. Acta Psychol. Sin. 49 (8), 1022.
Zhu, R., Luo, Y., Wang, Z., You, X., 2020. Modality effects in verbal working memory updating: transcranial direct current stimulation over human inferior frontal gyrus and posterior parietal cortex. Brain Cogn. 145, 105630.
Zhu, D., Zhu, B., Zhao, J., Zhang, C., He, J., Song, D., Han, T., 2024. Investigation on the effectiveness of augmented reality memory training game for Chinese older adults: a randomized controlled trial. Games for Health 13 (1), 5–12.
Zinke, K., Zeintl, M., Rose, N.S., Putzmann, J., Pydde, A., Kliegel, M., 2014. Working memory training and transfer in older adults: effects of age, baseline performance, and training gains. Dev. Psychol. 50 (1), 304.