Journal of Cognitive Enhancement
https://doi.org/10.1007/s41465-024-00295-0

ORIGINAL RESEARCH

Enhancing Multiple Object Analysis Skills Across Early and Late Adulthood Through Diverse Tasks

Chiara F. Tagliabue[1] · **Chiara Fornari**[1] · **Greta Varesio**[2] · **Veronica Mazza**[1]

Received: 24 November 2023 / Accepted: 8 April 2024

Abstract

Tasks on multiple targets involve, to some extent, at least two capacity-limited classes of mechanisms: attentional individuation and visuo-spatial working memory (vWM). It is also known that these mechanisms tend to decline with aging. In this study, we hypothesized that if both mechanisms underlie the analysis of multiple objects, then training one task involving multiple objects should benefit other tasks requiring multiple object processing, regardless of task contents or instructions. In addition, we predicted that older adults would benefit more from the training protocol. To test these hypotheses, we trained two groups of young and older participants, one with a delayed match-to-sample (DMTS) task and one with rapid enumeration. Training effects (compared to test/re-test effects of a passive control group) were assessed on both DMTS and rapid enumeration. Results indicated a training-related benefit within and across tasks, regardless of age. Older adults' gain from training was larger compared to the young counterpart. In addition, and irrespective of age, individual differences in baseline performance correlate with training outcomes, with compensatory activity likely occurring for low-performing individuals.

Keywords Enumeration · Working memory · Training · Aging · Attention · Individual differences

Statement of Relevance

Many daily activities, such as driving in traffic or shopping, involve processing multiple objects simultaneously. This multitasking activity relies on two keys, limited-capacity abilities: one for focusing attention on individual items and another for briefly remembering those items. Typically, both abilities decline with age. We hypothesized that if these abilities are fundamental for handling multiple objects, improving performance in one task involving multiple objects should benefit other tasks requiring similar skills, regardless of the specific task content. We trained one group of participants in a task requiring short-term item memory (delayed match-to-sample or DMTS), while another group engaged in rapid item counting. We also considered age differences by comparing younger and older adults. Although older individuals benefit more from training procedures, training per se positively impacted both types of tasks, regardless of participants' age. Furthermore, individuals with initially lower task performance showed significant improvements, suggesting that our brain compensates for weaker performance through increased effort during task practice.

✉ Veronica Mazza
veronica.mazza@unitn.it

1 Center for Mind/Brain Sciences (CIMeC), University of Trento, Rovereto, Italy

2 Department of Psychology, University of Torino, Turin, Italy

Introduction

The concurrent handling of multiple visual objects is a foundational process for creating a unified perception of the environment. As a result, this capability is a common feature in individuals of all age groups, as well as in various animal species (Cavanagh & Alvarez, 2005; Nieder, 2019; Xu et al., 2005). To investigate it thoroughly, research has developed several cognitive tasks involving the requirement to process multiple objects simultaneously. Popular paradigms encompass delayed match-to-sample (DMTS) judgments (Luck & Vogel, 1998), rapid visual enumeration (Trick & Pylyshyn, 1994), and multiple object tracking (Scholl, 2001). Despite some task-specific peculiarity (e.g., the presence of a cue in DMTS tasks, the inclusion of moving items in multiple-object tracking paradigms), it can be argued that all tasks requiring multiple object processing involve, to some extent, at least two classes of mechanisms: attentional individuation and working memory, both of which are capacity-limited (Xu, 2018).

Early individuation mechanisms provide a coarse representation of up to 3–4 objects, allowing the visual system to individuate each object as being separate from others.

Published online: 18 April 2024

Research has suggested that simultaneous indexing of relevant items is tightly related to attention, being indeed one of its key functions (see Cavanagh, 2011). Subsequent mechanisms, relying on the operation of visual working memory (vWM), maintain temporarily and efficiently up to 3–4 individual representations for further processing, ultimately leading to complete recognition and identification.

The proposed involvement of attentional individuation and vWM operations in analyzing multiple objects has empirically been supported by behavioral measures and neuroimaging data. Functional magnetic resonance imaging (fMRI) and electroencephalographic (EEG) studies on rapid enumeration and DMTS (e.g., Knops et al., 2014; LaBar et al., 1999; Tagliabue et al., 2020; Vogel & Machizawa, 2004) have indicated the existence of two distinct spatiotemporal patterns of neural activity (mainly in parietal and occipital extrastriata areas and with a latency of 180–300 ms and 350–600 ms, respectively) that correlate with the functional difference between individuation and late processing after individuation (Störmer et al., 2013; Zanto & Gazzaley, 2009). Crucially, the response of these two neural patterns increases with target numerosities and displays signs of capacity limits, reaching an asymptote at about 4 elements (Luria et al., 2016; Mazza & Caramazza, 2015). The two mechanisms are linked to one another (e.g., LaBar et al., 1999; Van Ede & Nobre, 2023; Zhou et al., 2022), with the former attentional mechanism preceding and likely influencing the functioning of the latter (Naveh-Benjamin & Cowan, 2023; Panichello & Bushman, 2021). For instance, previous studies (e.g., Piazza et al., 2011; Tagliabue et al., 2022a, 2022b) indicate that those individuals who are more efficient in selecting relevant items exhibit a larger vWM capacity.

Overall, the accumulating evidence so far points to the contribution of both mechanisms to the analysis of multiple objects in diverse experimental contexts. Thus, one should predict that training one task involving multiple objects should benefit other tasks requiring multiple object processing, regardless of the specific task contents or instructions. To test for this, in the current study, we trained two groups of participants, one with a DMTS task and one with a rapid enumeration task. Training effects (compared to test/re-test effects of a passive, control group) were then assessed on both DMTS and rapid enumeration. If the same underlying mechanisms (attention and working memory) are crucial to perform both DMTS and enumeration as shown in the previous literature, then training should impact, at least to some extent, both the trained and the untrained task, regardless of the task used during training. Namely, is it possible to improve performance in one task by practicing the other one? And do we get the same gain as in task repetition?

While searching for the interchangeable effects of multiple object training procedures, we additionally investigated whether training-induced effects are maintained across early and late adulthood by comparing younger and older adults. Indeed, it has been reported that several cognitive abilities, including attention and vWM, decline with aging, although some contrasting findings have been shown (for a recent review, see Naveh-Benjamin & Cowan, 2023). Thus, investigating the impact of training on older adults may be instrumental to understanding whether and how declining functions in aging could be (at least, temporarily) restored. In addition, accumulating evidence highlights a correlation between attention and vWM observed in older adults (Gazzaley et al., 2008; Naveh-Benjamin & Cowan, 2023), such that older individuals with a larger decline in attention tasks show a larger decline in WM functioning as well. Thus, one could predict that (1) the effects of training are boosted in older adults, as they have more room for improvement, and (2) given the correlation between attention and WM performance in older individuals, the improvement should be visible regardless of the specific task involved in the training phase, as predicted in young adults.

Finally, previous research has indicated that individual differences may have a key role in determining the success of a training procedure. In particular, it has been shown that variation in performance at baseline is linked to WM training outcome (Ophey et al., 2020). However, the specific direction of this relation can vary, ranging from magnification (wherein high-performing individuals experience greater benefit from training) to compensation (with low-performing experiencing larger training gains, see Lövdén et al., 2012). For these reasons, to better elucidate the impact of individual differences on training gains, here we investigated the link between individual accuracy at baseline in the two tasks and the subsequent training gains. In line with a meta-analysis in aging reporting a negative association between baseline performance and training gains (Traut et al., 2021), we predicted that at least in the case of older individuals, low performers at baseline should benefit more from training procedures.

Materials and Methods

Participants

The whole study was conducted online and participants were recruited through Prolific (https://www.prolific.co/). An a priori power analysis (PANGEA: https://jakewestfall.shinyapps.io/pangea/) estimated a sample size of 30 participants per group to detect a three-way interaction session * training * age; see "Statistical Analyses" for details) with 85% power (Cohen, 1988) and a medium effect size (Cohen's $d = 0.45$). To account for dropouts and technical issues, we set testing at 42 participants per group.

Selection criteria on Prolific were the following: age (young: from 20 to 30 years; old: from 65 to 75 years), handedness (right-handed), vision (normal or corrected-to-normal), health condition (no diagnosis of mild cognitive impairment or dementia and no ongoing mental illness), and fluency in English. Additionally, older participants completed a custom-made online version of SATURN (Self-Administered Tasks Uncovering Risk of Neurodegeneration; see Tagliabue et al., 2023a) to further exclude any potential cognitive impairment. A score of at least 26 on SATURN allowed older participants to be enrolled in the study.

For both age groups, outliers were identified as participants whose performance at baseline (in one or both tasks) exceeded three standard deviations at the easiest task condition (i.e., *k* at load 3 for younger and at load 2 for older in the DMTS task, and accuracy averaged across numerosity 1 and 2 for the enumeration task; see "Stimuli and Procedure" for further details). Within each age cohort, the three training groups did not differ in age ($ps > 0.454$), years of formal education ($ps > 0.310$), and familiarity with technology (FWT, measured through a custom-made questionnaire; $ps > 0.548$). Moreover, the three groups of older adults did not differ in SATURN score ($p = 0.627$). Notably, younger and older adults did not differ in years of formal education ($p_{Welch} = 0.874$) and familiarity with technology score ($p = 0.636$). The recruitment, exclusion, and allocation of participants are included in the CONSORT-like flow diagram (Fig. 1).

All participants were compensated for their participation (young adults in the passive group = £16; older adults in the passive group = £17.5; young adults in the training groups = £23.95; older adults in the training groups = £25.45). The additional reimbursement for older participants is due to the fact that they performed the SATURN test, which takes approximately 20 min.

The study was approved by the Ethics Committee of the University of Trento (Prot. 2022–041) and conducted in accordance with the 2013 Declaration of Helsinki. Participants' informed consent was acquired through the platform Psytoolkit (Stoet, 2010) before testing.

Training Structure

The whole study lasted 9 days. During the first and the last sessions (Sessions 1 and 7), all participants performed the DMTS and the enumeration task (task order was counterbalanced across participants and sessions). During the intermediate sessions (from Sessions 2 to 6), all the groups filled in

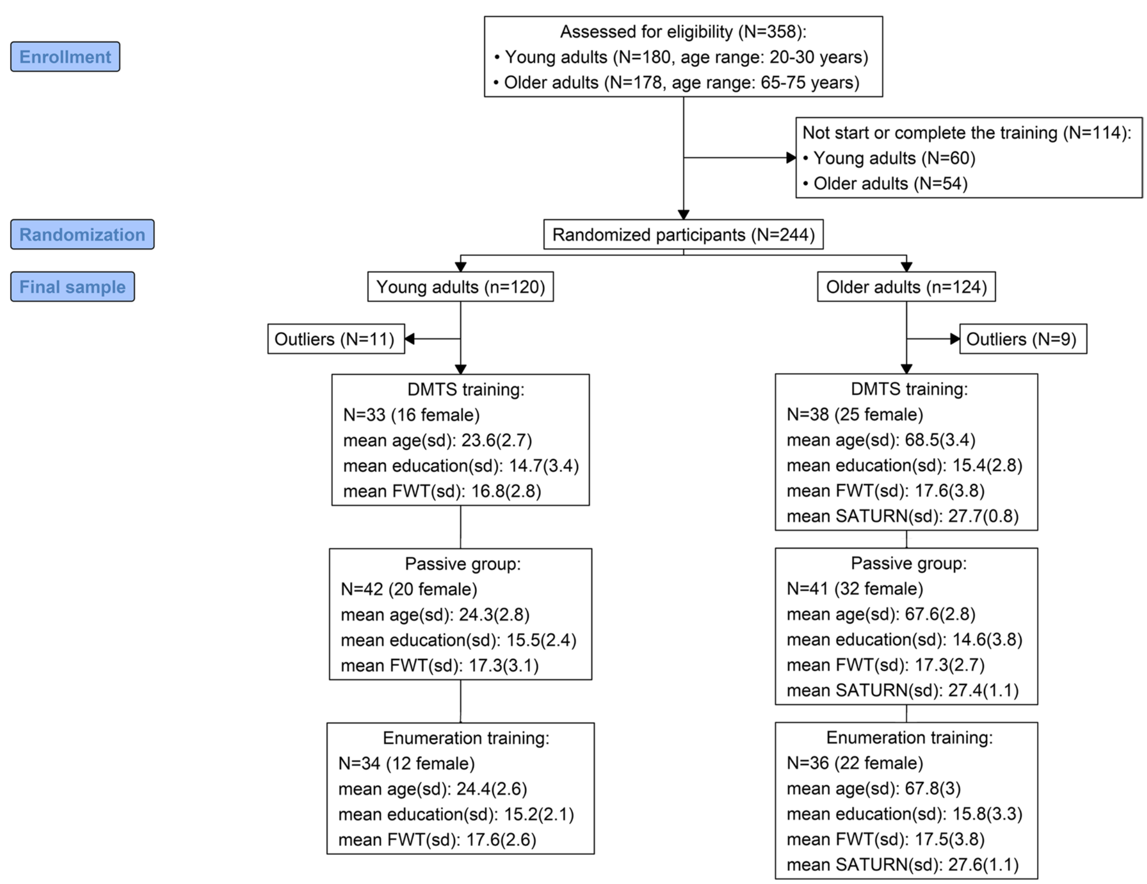

Fig. 1 CONSORT flow diagram for sample definition. Abbreviations: standard deviation (sd); familiarity with technology (FWT)

some questionnaires. Moreover, the two training groups performed an adaptive training version of either the DMTS or the enumeration task (see "Stimuli and Procedure"), according to group sorting. Participants had a 2-day break between Sessions 6 and 7 (Fig. 2A).

Stimuli and Procedure

The tasks were coded in PsychoPy (Peirce et al., 2019) and uploaded on the platform Pavlovia (https://pavlovia.org/). To ensure stable stimulus size across participants, at the beginning of each session, they had to sit in front of the monitor at arm's length distance (~70 cm) and complete a procedure that estimated the actual size of their monitor (see Li et al., 2020; https://gitlab.pavlovia.org/Wake/screenscale).

DMTS (Sessions 1 and 7)

Stimulus parameters and trial structure were similar to those used in previous studies (Tagliabue et al., 2022a, 2022b, 2023b). Stimuli were colored and light gray dots (0.6°) on a dark gray background. Specific colors were used for colored dots presented in the relevant (i.e., targets) and irrelevant hemifield. Since we increased the maximum difficulty reachable in the adaptive DMTS task with respect to the previous studies (Tagliabue et al., 2022a, 2022b, 2023b), we slightly changed the colors used as follows: eight unique colors for dots in the relevant hemifield (light blue [RGB: 28, 175, 255], yellow [RGB: 255, 255, 0], purple [RGB: 255, 47, 255], green [RGB: 0, 185, 0], red [RGB: 255, 0, 0], blue [RGB: 0, 0, 255], brown [RGB: 128, 64, 64], and orange [RGB: 244, 122, 0]) and eight unique colors for dots in the

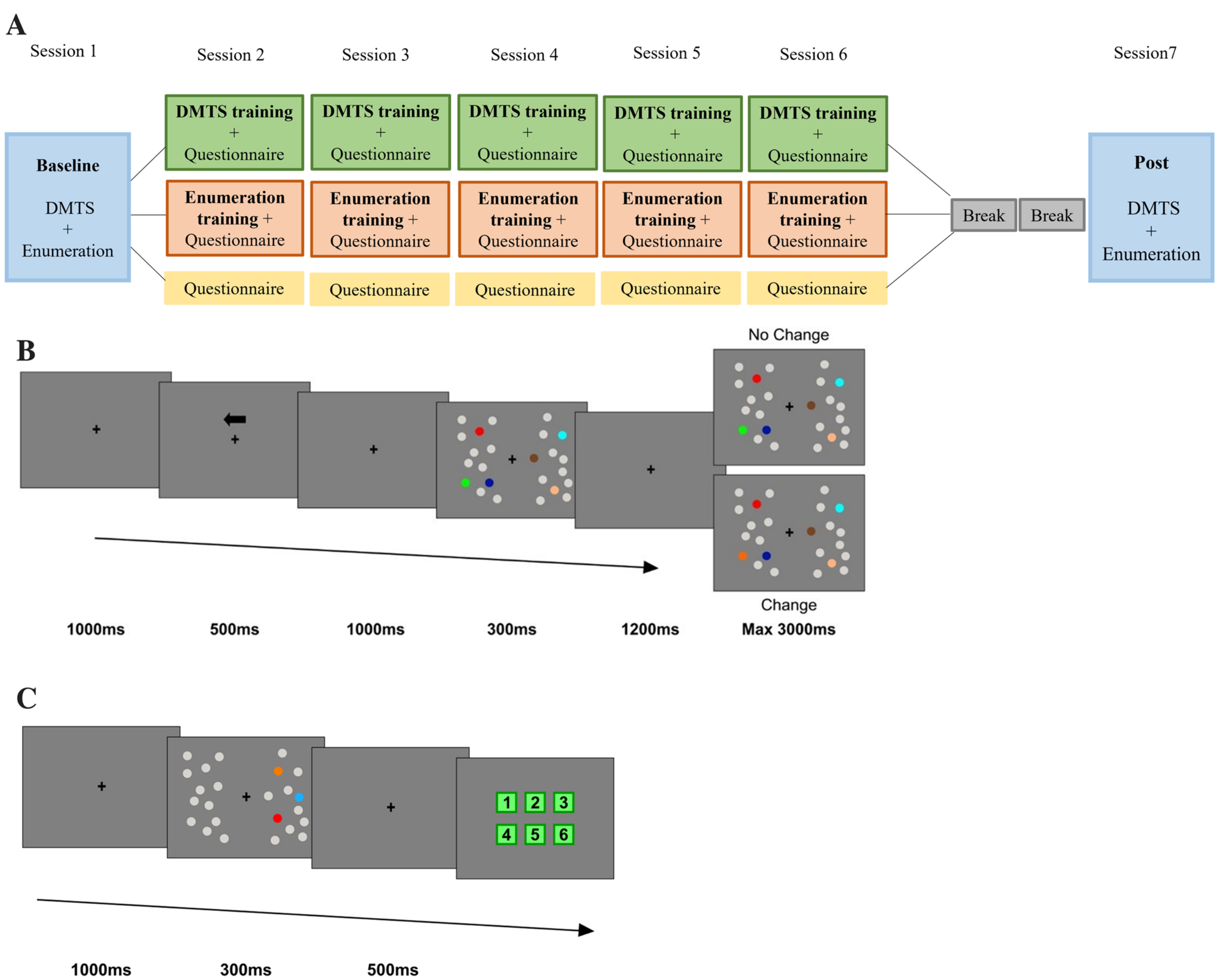

Fig. 2 **A** Training timeline for the three training groups: DMTS (top, green), enumeration (center, orange), and passive (bottom, yellow). **B** Temporal structure of a DMTS trial with a memory load of three elements in the left hemifield. **C** Temporal structure of an enumeration trial with three elements to enumerate

irrelevant hemifield (light blue [RGB: 81, 255, 255], salmon [RGB: 255, 128, 128], dark green [RGB: 0, 128, 0], violet [RGB: 128, 0, 255], light orange [RGB: 255, 175, 43], pink [RGB: 255, 155, 255], light yellow [RGB: 233, 218, 148], and light brown [RGB: 149, 92, 92]).

In each trial, to balance the overall perceived difficulty of the task between age groups (see Tagliabue et al., 2022a, 2022b), either 2, 3, 4 (for older adults) or 3, 4, 5 (for younger adults) colored dots were presented in each hemifield, together with gray dots. The total number of stimuli presented on screen was kept constant: 24, comprising 12 dots (colored + gray) per hemifield. The stimuli were randomly positioned inside an invisible 10 (columns) × 8 (rows) grid (16° width × 10° height), centered on the center of the screen.

A black fixation cross was present throughout the whole trial. After a 1-s inter-stimulus interval, a black arrow cue (100% valid), pointing with an equal probability toward left or right, appeared for 500 ms above fixation. The direction of the cue indicated the relevant hemifield to be attended to. After 1 s, a memory array was presented for 300 ms. Participants had to memorize the colored dots presented in the cued, relevant hemifield. After a 1200-ms delay period, a test array appeared: in half of the trials, the test array was identical to the memory array (i.e., no change trials), while in the other half of the trials it was different (i.e., change trials), meaning that one colored dot of the relevant hemifield changed its color. Participants judged whether the test array was identical or different from the memory array by pressing, with their right hand, the arrow keys on the keyboard: right arrow for "same," left arrow for "different." The test array stayed on screen until participant's response or for a maximum of 3 s (Fig. 2B). Participants performed 216 total trials, divided in 6 blocks of 36 trials each (12 trials per numerosity).

Enumeration (Sessions 1 and 7)

Stimulus parameters (size, color, spatial arrangement) were the same as in the DMTS task. Here, no arrow cue was presented to indicate the subsequent relevant hemifield. Following a 1-s inter-stimulus interval, an enumeration array appeared for 300 ms, with colored and gray dots presented in one hemifield, while the other hemifield included only gray dots. Thus, participants did not know in advance the hemifield where to-be-enumerated dots could be presented. The number of colored dots to be enumerated ranged from 1 to 6. After a delay of 500 ms, an answer grid with response buttons appeared (Fig. 2C). Participants responded through mouse clicks, without time limits. In total, there were 252 trials, divided into 7 blocks of 36 trials each (6 trials per numerosity).

Pseudo-Adaptive DMTS (Sessions 2 to 6)

Each training session was built as a staircase-like procedure: it started with the easiest memory load (i.e., one colored dot to remember) and increased in difficulty, by adding one colored dot per block, if accuracy was at least 90% at the end of the block. If accuracy was below 90%, the participant repeated the same difficulty level. There were 10 blocks of 20 trials, and the maximum reachable difficulty was a memory load of seven colored dots. Each training session lasted for approximately 20 min, without considering the completion of the questionnaires.

Pseudo-Adaptive Enumeration (Sessions 2 to 6)

Similar to the pseudo-adaptive DMTS, each training session started with the easiest difficulty level. The difficulty level was determined by the accuracy obtained with "target numerosities" within each block: each block included 24 trials and, of these 24 trials, 18 were defined "target numerosities" for a specific difficulty level (three target numerosities of six trials each), while the remaining trials were "non-target numerosities" (see Table 1). Participants completed 11 blocks and advanced to the next difficulty level if their accuracy reached at least 90% with target numerosities; otherwise, they remained at the same difficulty level. There were seven difficulty levels. Each training session lasted for approximately 20 min, without considering the completion of the questionnaires.

Statistical Analyses

Main Analysis

For the DMTS task, in both Session 1 and Session 7, we computed a vWM capacity estimate (k) for each memory load (Cowan, 2010; Rouder et al., 2011), using the following formula: $k = [(\text{hit rate} - \text{false alarm rate})/(1 - \text{false alarm rate})] * \text{load}$. Load is the number of to-be-remembered dots

Table 1 Difficulty levels of the adaptive enumeration task. In each block, 18 trials were "target numerosities" and 6 were "non-target numerosities"

Difficulty	Target numerosities	Non-target numerosities
1	1 2 3	4 5 6 7 8 9
2	2 3 4	1 5 6 7 8 9
3	3 4 5	1 2 6 7 8 9
4	4 5 6	1 2 3 7 8 9
5	5 6 7	1 2 3 4 8 9
6	6 7 8	1 2 3 4 5 9
7	7 8 9	1 2 3 4 5 6

(i.e., 2, 3, 4, 5), hits are correct responses in "change" trials (i.e., "different"), and false alarms are incorrect responses in "no change" trials (i.e., "different"). The higher the k value, the larger the individual vWM capacity. Following previous vWM studies where different memory loads were used for younger and older adults in vWM tasks (Iordan et al., 2020; Sander et al., 2011), only memory load conditions tested in both age groups were analyzed (i.e., 3, 4). k values were thus averaged across loads 3 and 4.

For the enumeration task, in both Session 1 and Session 7, we averaged the accuracy across numerosities 3 and 4, since the breaking point determining the subitizing range usually lies between these numerosities (e.g., Burr et al., 2010; Eayrs & Lavie, 2018) and it might represent a more sensible measure to investigate training-related effects.

To investigate improvements between Sessions 1 and 7 (in mean k and accuracy for the DMTS and enumeration task, respectively), we performed separate mixed analysis of variance (ANOVA) on training gains (i.e., S7-S1 scores, see Jaeggi et al., 2011) for each task, with age (2 levels: young, old) and training (3 levels: passive, DMTS, enumeration) as between-subject factors. For follow-up analyses to investigate significant main and interaction effects, we conducted FDR corrected (p_{fdr}) t-tests (https://www.sdmproject.com/utilities/?show=FDR). In case of significant Mauchly's or Levene's tests, corrected Greenhouse–Geisser or Welch p values are reported, respectively. The effect size was computed using partial eta squared (η_p^2) and Cohen's d indexes for ANOVAs and t-tests, respectively.

Post HocAnalysis of Individual Differences

Correlation Between Tasks at Baseline To assess the link between the DMTS and enumeration tasks, we performed Pearson correlations between the performance in the two tasks (mean k across loads 3 and 4, mean accuracy across numerosities 3 and 4) during Session 1, separately for the two age groups (and regardless of training).

Baseline Performance and Training Gains (S7-S1) In cognitive training procedures, individual differences at baseline could represent a critical factor in determining the training outcomes. Therefore, following previous studies with comparable sample size (Arciniega et al., 2018; Tagliabue et al., 2022a, 2022b), we conducted a post hoc analysis based on a median-split division of accuracy performance values obtained in Session 1. Namely, participants in each age group were classified as high and low performers, on the basis of the ranked mean k values computed for load 3 and load 4 for DMTS, and mean accuracy values for numerosities 3 and 4 for enumeration. This procedure led to four groups of participants (young high performers, young low performers, old high performers, and old low performers) in each task. The data were analyzed as in the main analysis, with the additional factor of performance (2 levels: low, high) as a between-subject factor. To avoid redundancies with the main analysis, here we conducted follow-up analyses only for significant effects involving performance as a factor.

Further post hoc correlational analyses limited to the active training groups were performed, to further test the impact of individual differences at baseline on training outcomes using a more continuous dimension on performance accuracy at baseline.

Baseline Performance and Training Phase (DMT and Enumeration, Sessions 2 to 6) Here, we further evaluated the impact of individual differences at baseline on the learning pattern during the training phase. Specifically, we asked whether the learning trend differs between low versus high performers. Following our previous study (Tagliabue et al., 2022a, 2022b), an index was obtained by multiplying the difficulty level reached in each block by its relative accuracy, averaged across blocks to obtain one value per session [average*(difficulty level reached*accuracy in each block)]. Separately for the DMTS and enumeration training groups, these values were analyzed by means of a mixed ANOVA, with age (2 levels: old and young) and performance (2 levels: low and high) as between-subject factors and session (5 levels: S2, S3, S4, S5, S6) as within-subject factor. Post hoc analyses involving a significant effect of session were conducted by means of polynomial contrasts, which investigate the presence of specific training patterns (e.g., linear, quadratic).

All the statistical analyses were performed with JASP (v. 0.18.1.0) (JASP Team, 2023) and plots were computed with RStudio (RStudio Team, 2020), using ggplot2 library (Wickham, 2016).

Results

Control Analysis

In order to control for performance differences at baseline (Session 1), we computed an ANOVA separately for each age group, with training (3 levels: DMTS, enumeration, passive) as between subject factor. In both older and young adults, and in both DMTS and enumeration tasks, no significant effects were found in Session 1, ps > 0.05. This suggests that the training groups were comparable at baseline.

Main Analysis

DMTS—Session 1 vs Session 7 A summary of the basic descriptive statistics is reported in Table 2.

The ANOVA showed significant main effects of training ($F_{(2, 218)} = 7.839$, $p < 0.001$, $n_p^2 = 0.067$) and age ($F_{(1,218)} = 6.835$, $p = 0.010$, $n_p^2 = 0.030$). Specifically, older adults gained more than young adults ($t_{(222)} = 2.704$, $p = 0.007$, $d = 0.361$). Pairwise comparisons across trainings showed that the DMTS and enumeration groups improved more than the passive group (passive vs DMTS: $t_{(152)} = -3.637$, $p_{fdr} < 0.001$, $d = 0.588$; passive vs enumeration: $t_{(151)} = -2.277$, $p_{fdr} = 0.036$, $d = 0.369$), while no difference emerged between DMTS and enumeration individuals ($p_{Welch} = 0.058$). Post hoc one-sample *t*-tests versus zero (i.e., no improvement) indicated significant vWM enhancement in the DMTS ($t_{(70)} = 6.184$, $p < 0.001$, $d = 0.734$) and enumeration groups ($t_{(69)} = 5.929$, $p < 0.001$, $d = 0.709$), but not in the passive group ($p = 0.213$).

In sum, the results on *k* values showed that older people improved more than younger adults regardless of training, although older participants could not reach the performance level of the younger counterparts. Moreover, we found similar training-related effects in both age groups, with DMTS and enumeration training enhancing vWM capacity to the same extent (Fig. 3).

Enumeration—Session 1 vs Session 7 A summary of the basic descriptive statistics is reported in Table 3.

The ANOVA indicated significant effects of training ($F_{(2, 218)} = 6.037$, $p = 0.003$, $n_p^2 = 0.052$) and age ($F_{(1,218)} = 6.499$, $p = 0.011$, $n_p^2 = 0.029$). Specifically, older adults gained more than young ($t_{(222)} = 2.694$, $p = 0.008$, $d = 0.360$). The improvement of the DMTS and enumeration groups was larger than that of the passive group (passive vs DMTS: $t_{(152)} = -2.517$, $p_{fdr} = 0.020$, $d = 0.407$; passive vs enumeration: $t_{(151)} = -3.321$, $p_{fdr} = 0.003$, $d = 0.539$), while no difference in training gain magnitude emerged between the DMTS and enumeration groups ($p_{fdr} = 0.491$). One-sample *t*-tests against zero showed a significant improvement for the DMTS ($t_{(70)} = 5.151$, $p < 0.001$, $d = 0.611$) and enumeration groups ($t_{(69)} = 6.525$, $p < 0.001$, $d = 0.780$), while no significant improvement was evident in the passive group ($p = 0.052$).

To summarize, similar to the DMTS, in the enumeration task larger improvement was evident in older compared to younger adults regardless of training (enumeration versus DMTS), even though younger adults outperformed their older counterparts in both sessions. Finally, training had comparable effects across age groups, with both DMTS and enumeration enhancing the performance in the enumeration task (Fig. 4).

Post HocAnalysis of Individual Differences

Correlation Between Tasks at Baseline In both young and older adults, a significant positive correlation emerged between the performance in the DMTS and enumeration

Table 2 Summary of mean and standard deviation (sd) for the WM capacity in the DMTS task during Session 1 and Session 7 for each age (young and old) and training group (DMTS, passive, enumeration)

	Session 1						Session 7					
Group	*Young*			*Old*			*Young*			*Old*		
Training	DMTS	Passive	Enum	DMTS	Passive	Enum	DMTS	Passive	Enum	DMTS	Passive	Enum
N	33	42	34	38	41	36	33	42	34	38	41	36
Mean (sd)	2.326 (0.65)	2.318 (0.6)	2.387 (0.55)	1.935 (0.65)	1.872 (0.46)	2.002 (0.53)	2.588 (0.55)	2.3 (0.95)	2.594 (0.56)	2.438 (0.44)	2.043 (0.55)	2.285 (0.51)

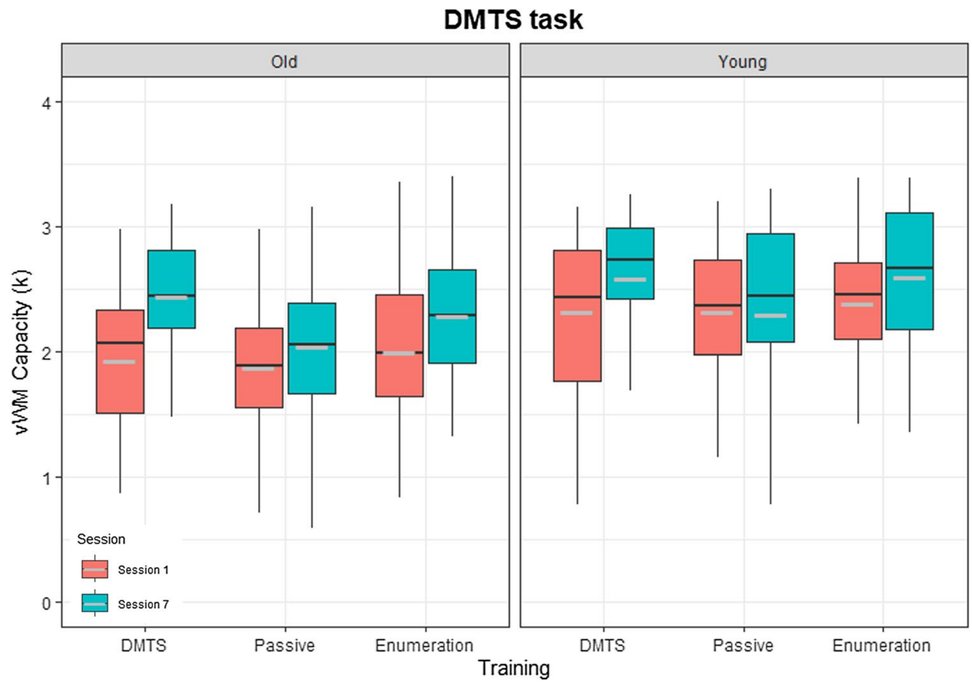

Fig. 3 Box and whisker plot of the vWM capacity (k) in the DMTS task across Session 1 and Session 7 for old and young adults. The horizontal bar inside the box represents the median (in black) and the mean (in gray). The lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the largest value no further than 1.5 * IQR from the hinge (where IQR is the interquartile range or distance between the first and third quartiles). The lower whisker extends from the hinge to the smallest value at most 1.5 * IQR of the hinge

tasks during Session 1 (younger: $r_{(109)} = 0.288$, $p = 0.002$, $R^2 = 0.083$; older: $r_{(115)} = 0.324$, $p < 0.001$, $R^2 = 0.105$). The results thus indicate that the higher the accuracy in the enumeration task, the larger the vWM capacity.

Baseline Performance and Training Gains (S7-S1) Participants were divided into low and high performers according to a median split on the mean value computed on load 3 and load 4 for k value (old, 1.925; young, 2.446) and on the mean accuracy across numerosities 3 and 4 (old, 0.714; young, 0.893) in Session 1, separately for each group. Notably, within the DMTS and enumeration tasks, both older and young low and high performers did not differ in age and years of education (ps > 0.05).

DMTS Based on the DMTS performance, participants were divided as follows: 113 high performers (58 old: 18 in the passive group, 22 in the DMTS, and 18 in the enumeration training groups; 55 young: 20 in the passive group, 16 in the DMTS, and 19 in the enumeration training groups) and 111 low performers (57 old: 23 in the passive group, 16 in the DMTS, and 18 in the enumeration training groups; 54 young: 22 in the passive group, 17 in the DMTS, and 15 in the enumeration training groups). A chi-square test checked whether the frequencies in each group were statistically different from each other. No significant differences were found (all ps > 0.46).

The ANOVA indicated significant effects of training ($F_{(2, 212)} = 9.869$, $p < 0.001$, $n_p^2 = 0.085$), age ($F_{(1, 212)} = 8.439$, $p = 0.004$, $n_p^2 = 0.038$), and performance ($F_{(1, 212)} = 15.734$, $p < 0.001$, $n_p^2 = 0.069$) and of the training × performance interaction ($F_{(2, 212)} = 5.387$, $p = 0.005$, $n_p^2 = 0.048$). In low performers, those included in the DMTS training group improved more than those included in the passive ($t_{(76)} = -3.746$, $p_{fdr} = 0.003$, $d = 0.859$) and enumeration training groups ($t_{(64)} = 2.81$, $p_{fdr} = 0.011$, $d = 692$), while no differences were found between the enumeration training group and the passive group. In high performers, no significant differences emerged (ps > 0.05).

The correlational analyses limited to the active training groups and separately for age were in line with the results of the median-split ANOVA. Indeed, in older adults, significant negative correlations (Session 1 and training gains) were found for the DMTS training, $r_{(38)} = -0.729$, $p < 0.001$, and for the enumeration training, $r_{(36)} = -0.335$, $p = 0.046$, with lower performers resulting in larger improvements. The same results emerged in young adults (DMTS training, $r_{(33)} = -0.581$, $p < 0.001$; enumeration training, $r_{(34)} = -0.369$, $p = 0.032$).

In sum, irrespective of age, low performers were overall facilitated by training, with a slight larger benefit for task repetition (DMTS training) over enumeration training (Fig. 5).

Enumeration On the basis of the enumeration performance at baseline, participants were divided as follows: 123 high performers (61 old: 18 in the passive, 18 in the DMTS, and 25 in the enumeration training groups; 62 young: 28 in the passive, 17 in the DMTS, and 17 in the enumeration training groups) and 101 low performers (54 old: 23 in the passive, 20 in the DMTS, and 11 in the enumeration training groups; 47 young: 14 in the passive, 16 in the DMTS, and 17 in the enumeration training groups). A chi-square test checked whether the

Table 3 Summary of mean and standard deviation for the correct response proportion in the enumeration task during Session 1 and Session 7 for each age (young and old) and training group (DMTS, passive, enumeration)

	Session 1						Session 7					
Group	*Young*			*Old*			*Young*			*Old*		
Training	DMTS	Passive	Enum	DMTS	Passive	Enum	DMTS	Passive	Enum	DMTS	Passive	Enum
N	33	42	34	38	41	36	33	42	34	38	41	36
Mean (sd)	0.855 (0.11)	0.879 (0.11)	0.868 (0.13)	0.695 (0.14)	0.672 (0.15)	0.743 (0.12)	0.899 (0.09)	0.871 (0.12)	0.945 (0.05)	0.781 (0.12)	0.726 (0.13)	0.823 (0.09)

frequencies in each group were statistically different from each other. No significant differences were found (all ps > 0.26).

The ANOVA indicated significant effects of training ($F_{(2, 212)} = 7.549$, $p < 0.001$, $n_p^2 = 0.066$), age ($F_{(1, 212)} = 7.063$, $p = 0.008$, $n_p^2 = 0.032$), and performance ($F_{(1, 212)} = 32.025$, $p < 0.001$, $n_p^2 = 0.131$). Low performers improved more than high performers ($t_{(166)} = -5.491$, $p_{\text{Welch}} < 0.001$, $d = 0.752$).

The correlational analyses limited to the active training groups and separately for age were in line with the results of the ANOVA. In older adults, lower performers had larger improvements, in the enumeration training, $r_{(36)} = -0.609$, $p < 0.001$, and in the DMTS training, $r_{(38)} = -0.604$, $p < 0.001$. The same pattern was present in young adults (enumeration training: $r_{(34)} = -0.907$, $p < 0.001$; DMTS training: $r_{(33)} = -0.631$, $p < 0.001$).

In sum, irrespective of age, low performers had larger gains than high performers (Fig. 6).

Baseline Performance and Training Phase (DMTS and Enumeration, Sessions 2 to 6)

The performance trend across the intermediate sessions for the DMTS and enumeration training is depicted in Fig. 7A, B, respectively.

DMTS Training The ANOVA indicated significant effects of session ($F_{(3.4, 227.5)} = 3.827$, $p = 0.008$, $n_p^2 = 0.054$), age ($F_{(1,67)} = 13.909$, $p < 0.001$, $n_p^2 = 0.172$), and performance ($F_{(1,67)} = 43.851$, $p < 0.001$, $n_p^2 = 0.396$) and of the interactions session × age ($F_{(3.4, 227.5)} = 5.494$, $p < 0.001$, $n_p^2 = 0.076$) and session × age × performance ($F_{(3.4, 22.7.5)} = 2.929$, $p = 0.029$, $n_p^2 = 0.042$). Both in older and in younger adults, high performers outperform low performers. Older participants' performance followed a significant linear trend ($p < 0.001$), irrespective of the level of initial performance (low vs high). In young adults, no significant trend emerged.

Enumeration Training There were effects of session ($F_{(3.4, 225.1)} = 15.185$, $p < 0.001$, $n_p^2 = 0.187$) and age ($F_{(1,66)} = 115.4$, $p < 0.001$, $n_p^2 = 0.636$), with young adults outperforming older adults, and performance ($F_{(1,66)} = 51.5$, $p < 0.001$, $n_p^2 = 0.438$), with high performers outperforming low performers. The polynomial contrast on session indicated a significant quadratic trend ($p = 0.048$), with performance increasing until reaching an asymptote approximately at Session 4.

Discussion

In the current study, we trained groups of young and older individuals in two tasks that required simultaneous attention and memory maintenance of multiple relevant objects.

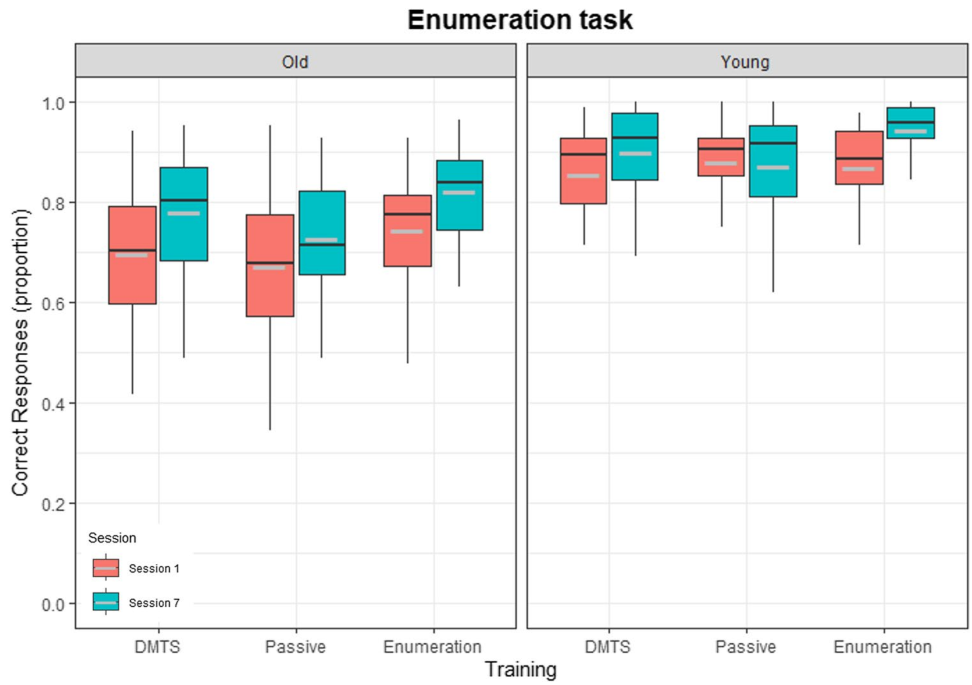

Fig. 4 Box and whisker plot of the proportion of correct responses in the enumeration task across Session 1 and Session 7 for old and young adults. The horizontal bar inside the box represents the median (in black) and the mean (in gray). The lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the largest value no further than 1.5 * IQR from the hinge (where IQR is the interquartile range or distance between the first and third quartiles). The lower whisker extends from the hinge to the smallest value at most 1.5 * IQR of the hinge

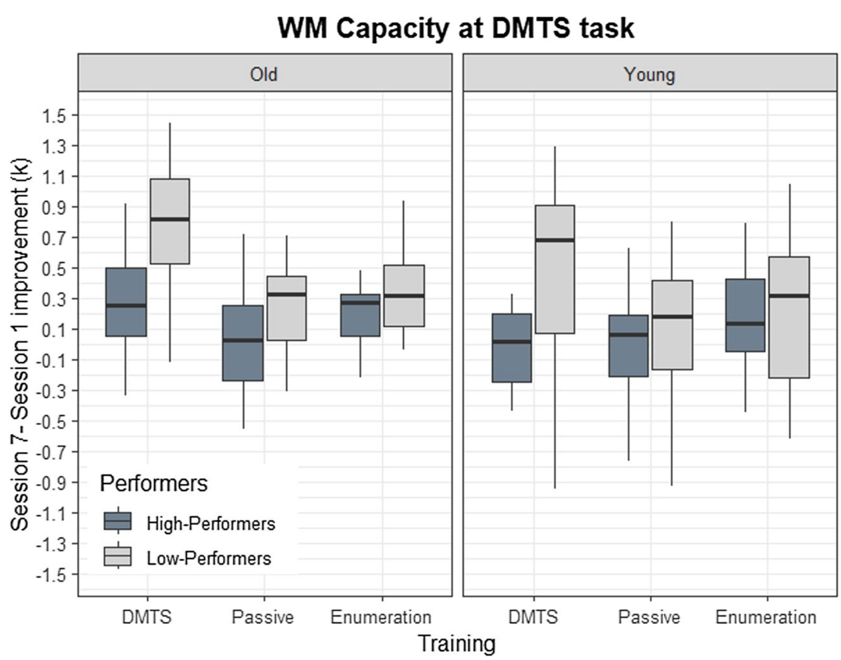

Fig. 5 Box and whisker plot of the median proportion of *k* values (difference between Session 7 and Session 1) in the DMTS task for old and younger adults. The lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the largest value no further than 1.5 * IQR from the hinge (where IQR is the interquartile range or distance between the first and third quartiles). The lower whisker extends from the hinge to the smallest value at most 1.5 * IQR of the hinge

Subsequently, we assessed the degree to which any acquired improvement from one task could be effectively applied to the other in a mutually interchangeable manner. The results of the main analyses provided a positive answer.

Indeed, in the DMTS task and for both age groups, there were training-related improvements, with DMTS and enumeration training enhancing vWM capacity to the same extent. The same pattern was replicated in the enumeration task, where both DMTS and enumeration training enhanced enumeration accuracy for the subitizing values, for both older and young individuals. While behavioral data alone do not allow for interpretations regarding the specific weight of each mechanism (attention individuation versus vWM) in the execution of enumeration or DMTS tasks, previous neurophysiological research on rapid enumeration tasks has indicated that attentive individuation has a primary role compared to vWM

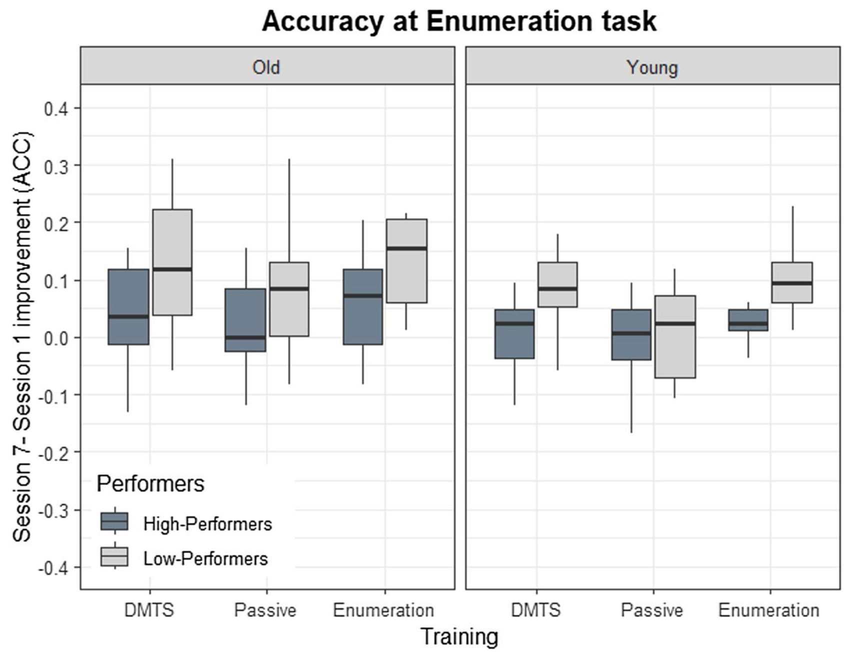

Fig. 6 Box and whisker plot of the median proportion of accuracy (difference between Session 7 and Session 1) in the enumeration task for old and younger adults. The lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the largest value no further than 1.5 * IQR from the hinge (where IQR is the interquartile range or distance between the first and third quartiles). The lower whisker extends from the hinge to the smallest value at most 1.5 * IQR of the hinge

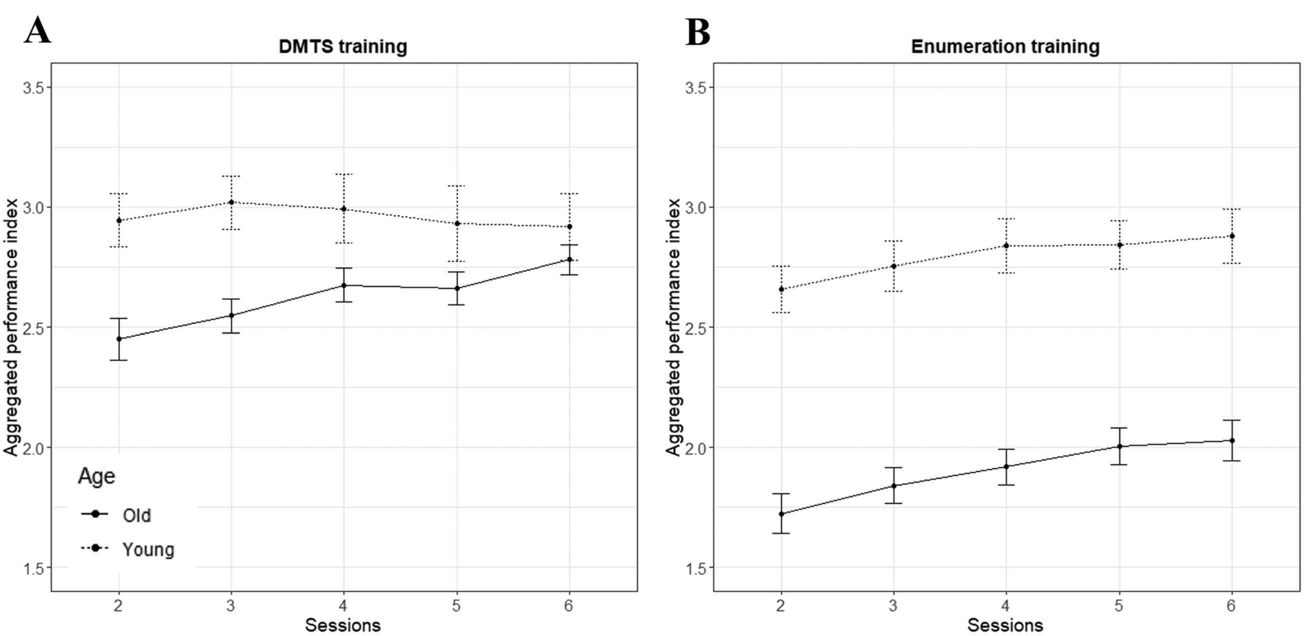

Fig. 7 The aggregate performance index per each intermediate session in (**A**) the DMTS and (**B**) enumeration training groups, for both old (solid lines) and young (dashed lines) adults. Vertical bars represent standard errors

(see Mazza & Caramazza, 2015, for a review). Likewise, it was previously shown (Tagliabue et al., 2020) that practicing a DMTS task over 4 days improved the efficiency not only of the memory buffer where items are retained in vWM (as reflected by practice-related modulations of an EEG marker of item maintenance; Luria et al., 2016), but also of the previous processing stage of item individuation. Based on these data, we speculate that for both tasks, the enhancement of attentive individuation may have a beneficial cascade effect also on the subsequent item retention. Future research will directly address this issue by coupling neurophysiological measures to the training tasks used here and teasing apart the role of the attention and vWM components in the training gains on both DMTS and enumeration tasks.

The second aspect investigated in the present study was related to age-related effects in the amount of benefit from training and in transfer effects. In line with the predictions mentioned in the "Introduction," the results indicated that, although the overall performance in both vWM and rapid enumeration remains deficient in old age with respect to young adulthood, the improvement within and across tasks was larger in older than young individuals. In addition, as for the young individuals, older adults benefit both from trained and from untrained tasks. Thus, the multiple object training tasks used here had an interchangeable effect that overcomes aging.

A limit of the present study pertains to the number of tasks used to assess training effects. It would be interesting to have a broader battery of tasks tapping attentional, vWM and the processing of multiple objects to address the questions raised in the present study. The limitation is due to the need to maintain the length of the online experimental sessions reasonable. Nevertheless, this implies that the current findings only offer a limited evaluation of the "transfer" effects of the training tasks used. Future research should expand the investigation of the advantages of training multiple object processing through different tasks.

The results additionally indicated an impact of individual differences, which was the third aspect considered in the present study. First, in both age groups, we replicated the positive relationship between accuracy within the critical subitizing range (numerosities 3 and 4) and vWM capacity measured in the DMTS task (Piazza et al., 2011). Notably, both subitizing and vWM capacity limits lie at around 3–4 items (Burr et al., 2010; Cowan, 2001; Eayrs & Lavie, 2018; Tagliabue et al., 2022a), again suggesting that attentive individuation might represent a first bottleneck filter through which relevant items are selected for subsequent processing (e.g., mapping onto a symbolic value for rapid enumeration and maintenance in the memory buffer for probe comparison during DMTS).

Second, training gains varied as a function of performance at baseline. Specifically, and replicating previous studies (e.g., Tagliabue et al., 2022b), low (but not high) performers showed substantial improvement, with a slightly larger effect of vWM training. This was shown either with a discrete separation of low and high performers (i.e., in the median-split analysis) or with the more continuous approach of correlations and irrespective of age. Previous studies on individual differences and training outcomes (Lövdén et al., 2012) have indicated that training procedures can lead to either magnification (wherein high-performing individuals experience greater benefit from training) or compensation (with low-performing experiencing larger training gains). In line with the latter view, the findings of the present study provided support to the compensation view. The additional analysis of the training sessions elucidated that there were no effects of individual differences on the learning pattern across training sessions. Indeed, here we only found an age-related linear trend effect for older adults in vWM training and a quadratic trend for the enumeration training in all participants (likely due to an asymptote at Session 4). The current study investigated individual variation in baseline performance; however, future research should explore the effect of other factors that may crucially affect the trajectory of an individual's improvement during training.

To conclude, the current data provide evidence that training either attentional individuation or vWM positively influences the ability to analyze multiple relevant objects. While older adults benefit more than young by training, the nature of the improvement does not seem to be influenced by aging. In contrast, individual variation in baseline performance was found to be linked to training outcomes, with compensatory activity likely occurring for low-performing individuals.

Author Contribution C.T.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, supervision, visualization, writing—original draft, writing—review and editing.

C. F.: formal analysis, investigation, writing—review and editing.

G.V.: formal analysis, investigation, writing—review and editing.

V.M.: conceptualization, funding acquisition, methodology, project administration, resources, supervision, writing—original draft, writing—review and editing.

Funding Open access funding provided by Università degli Studi di Trento within the CRUI-CARE Agreement. This work was supported by Fondazione Cassia di Risparmio di Trento e Rovereto (CARITRO).

Data Availability Data are available upon request to the corresponding author.

Declarations

Conflict of Interest The authors declare no competing interests.

References

Arciniega, H., Gözenman, F., Jones, K. T., Stephens, J. A., & Berryhill, M. E. (2018). Frontoparietal tDCS benefits visual working memory in older adults with low working memory capacity. *Frontiers in Aging Neuroscience, 10*, 57. https://doi.org/10.3389/fnagi.2018.00057

Burr, D. C., Turi, M., & Anobile, G. (2010). Subitizing but not estimation of numerosity requires attentional resources. *Journal of Vision, 10*(6), 20–20. https://doi.org/10.1167/10.6.20

Cavanagh, P. (2011). Visual cognition. *Vision Research, 51*(13), 1538–1551. https://doi.org/10.1016/j.visres.2011.01.015

Cavanagh, P., & Alvarez, G. A. (2005). Tracking multiple targets with multifocal attention. *Trends in Cognitive Sciences, 9*(7), 349–354. https://doi.org/10.1016/j.tics.2005.05.009

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Routledge. https://doi.org/10.4324/9780203771587

Cowan, N. (2001). The magical number 4 in short-term memory: a reconsideration of mental storage capacity. *The Behavioral and Brain Sciences, 24*(1), 87–114. Discussion 114–185. https://doi.org/10.1017/S0140525X01003922

Cowan, N. (2010). The magical mystery four: How is working memory capacity limited, and why? *Current Directions in Psychological Science, 19*(1), 51–57. https://doi.org/10.1177/0963721409359277

Eayrs, J., & Lavie, N. (2018). Establishing individual differences in perceptual capacity. *Journal of Experimental Psychology: Human Perception and Performance, 44*(8), 1240–1257. https://doi.org/10.1037/xhp0000530

Gazzaley, A., Clapp, W., Kelley, J., McEvoy, K., Knight, R. T., & D'Esposito, M. (2008). Age-related top-down suppression deficit in the early stages of cortical visual memory processing. *Proceedings of the National Academy of Sciences, 105*(35), 13122–13126. https://doi.org/10.1073/pnas.0806074105

Iordan, A. D., Cooke, K. A., Moored, K. D., Katz, B., Buschkuehl, M., Jaeggi, S. M., Polk, T. A., Peltier, S. J., Jonides, J., & Reuter-Lorenz, P. A. (2020). Neural correlates of working memory training: Evidence for plasticity in older adults. *NeuroImage, 217*, 116887. https://doi.org/10.1016/j.neuroimage.2020.116887

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Shah, P. (2011). Short- and long-term benefits of cognitive training. *Proceedings of the National Academy of Sciences, 108*(25), 10081–10086. https://doi.org/10.1073/pnas.1103228108

JASP Team (2023). JASP (Version 0.18.1.0) [Computer software].

Knops, A., Piazza, M., Sengupta, R., Eger, E., & Melcher, D. (2014). A shared, flexible neural map architecture reflects capacity limits in both visual short-term memory and enumeration. *Journal of Neuroscience, 34*(30), 9857–9866. https://doi.org/10.1523/JNEUROSCI.2758-13.2014

LaBar, K. S., Gitelman, D. R., Parrish, T. B., & Mesulam, M. M. (1999). Neuroanatomic overlap of working memory and spatial attention networks: A functional MRI comparison within subjects. *NeuroImage, 10*(6), 695–704. https://doi.org/10.1006/nimg.1999.0503

Li, Q., Joo, S. J., Yeatman, J. D., & Reinecke, K. (2020). Controlling for participants' viewing distance in large-scale, psychophysical online experiments using a virtual chinrest. *Scientific Reports, 10*(1), 904. https://doi.org/10.1038/s41598-019-57204-1

Lövdén, M., Brehmer, Y., Li, S.-C., & Lindenberger, U. (2012). Training-induced compensation versus magnification of individual differences in memory performance. *Frontiers in Human Neuroscience, 6*, 141. https://doi.org/10.3389/fnhum.2012.00141

Luck, S. J., & Vogel, E. K. (1998). Response from luck and vogel. *Trends in Cognitive Sciences, 2*(3), 78–79. https://doi.org/10.1016/S1364-6613(98)01143-7

Luria, R., Balaban, H., Awh, E., & Vogel, E. K. (2016). The contralateral delay activity as a neural measure of visual working memory. *Neuroscience & Biobehavioral Reviews, 62*, 100–108. https://doi.org/10.1016/j.neubiorev.2016.01.003

Mazza, V., & Caramazza, A. (2015). Multiple object individuation and subitizing in enumeration: a view from electrophysiology. *Frontiers in human neuroscience, 9*, 162. https://doi.org/10.3389/fnhum.2015.00162

Naveh-Benjamin, M., & Cowan, N. (2023). The roles of attention, executive function and knowledge in cognitive ageing of working memory. *Nature Reviews Psychology, 2*(3), 151–165. https://doi.org/10.1038/s44159-023-00149-0

Nieder, A. (2019). *A brain for numbers: The biology of the number instinct*. MIT press.

Ophey, A., Roheger, M., Folkerts, A. K., Skoetz, N., & Kalbe, E. (2020). A systematic review on predictors of working memory training responsiveness in healthy older adults: Methodological challenges and future directions. *Frontiers in Aging Neuroscience, 12*, 575804.

Panichello, M. F., & Buschman, T. J. (2021). Shared mechanisms underlie the control of working memory and attention. *Nature, 592*(7855), 601–605. https://doi.org/10.1038/s41586-021-03390-w

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods, 51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Piazza, M., Fumarola, A., Chinello, A., & Melcher, D. (2011). Subitizing reflects visuo-spatial object individuation capacity. *Cognition, 121*(1), 147–153. https://doi.org/10.1016/j.cognition.2011.05.007

Rouder, J. N., Morey, R. D., Morey, C. C., & Cowan, N. (2011). How to measure working memory capacity in the change detection paradigm. *Psychonomic Bulletin & Review, 18*(2), 324–330. https://doi.org/10.3758/s13423-011-0055-3

RStudio Team (2020). *RStudio: Integrated development for R. RStudio*. PBC. http://www.rstudio.com/

Sander, M. C., Werkle-Bergner, M., & Lindenberger, U. (2011). Contralateral delay activity reveals life-span age differences in top-down modulation of working memory contents. *Cerebral Cortex, 21*(12), 2809–2819. https://doi.org/10.1093/cercor/bhr076

Scholl, B. J. (2001). Objects and attention: The state of the art. *Cognition, 80*(1–2), 1–46. https://doi.org/10.1016/S0010-0277(00)00152-9

Stoet, G. (2010). PsyToolkit: A software package for programming psychological experiments using Linux. *Behavior Research Methods, 42*(4), 1096–1104. https://doi.org/10.3758/BRM.42.4.1096

Störmer, V. S., Li, S. C., Heekeren, H. R., & Lindenberger, U. (2013). Normative shifts of cortical mechanisms of encoding contribute to adult age differences in visual–spatial working memory. *NeuroImage, 73*, 167–175. https://doi.org/10.1016/j.neuroimage.2013.02.004

Tagliabue, C. F., Varesio, G., & Mazza, V. (2022a). Inter-and intra-hemispheric age-related remodeling in visuo-spatial working memory. *Frontiers in Aging Neuroscience, 13*, 807907.

Tagliabue, C. F., Varesio, G., Assecondi, S., Vescovi, M., & Mazza, V. (2022b). Training attentive individuation leads to visuo-spatial working memory improvement in low-performing older adults: An online study. *Attention, Perception, & Psychophysics, 84*, 2507–2518.

Tagliabue, C. F., Assecondi, S., Cristoforetti, G., & Mazza, V. (2020). Learning by task repetition enhances object individuation and memorization in the elderly. *Scientific Reports, 10*, 19957. https://doi.org/10.1038/s41598-020-75297-x

Tagliabue, C. F., Bissig, D., Kaye, J., Mazza, V., & Assecondi, S. (2023a). Feasibility of remote unsupervised cognitive screening with SATURN in older adults. *Journal of Applied Gerontology*, 07334648231166894. https://doi.org/10.1177/07334648231166894

Tagliabue, C. F., Varesio, G., Assecondi, S., Vescovi, M., & Mazza, V. (2023b). Age-related effects on online and offline learning in visuo-spatial working memory. *Aging, Neuropsychology, and Cognition, 30*(3), 486–503. https://doi.org/10.1080/13825585.2022.2054926

Traut, H. J., Guild, R. M., & Munakata, Y. (2021). Why does cognitive training yield inconsistent benefits? A meta-analysis of individual differences in baseline cognitive abilities and training outcomes. *Frontiers in Psychology, 12*, 662139.

Trick, L. M., & Pylyshyn, Z. W. (1994). Why are small and large numbers enumerated differently? A limited-capacity preattentive stage in vision. *Psychological Review, 101*, 80. https://doi.org/10.1037/0033-295X.101.1.80

Van Ede, F., & Nobre, A. C. (2023). Turning attention inside out: How working memory serves behavior. *Annual Review of Psychology, 74*, 137–165. https://doi.org/10.1146/annurev-psych-021422-041757

Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature, 428*(6984), 748. https://doi.org/10.1038/nature02447

Wickham, H. (2016). *Ggplot2: Elegant graphics for data analysis* (2nd ed.) [PDF]. Springer-Verlag New York. https://ggplot2.tidyverse.org.

Xu, F., Spelke, E. S., & Goddard, S. (2005). Number sense in human infants. *Developmental Science, 8*(1), 88–101. https://doi.org/10.1111/j.1467-7687.2005.00395.x

Xu, Y. (2018). Sensory cortex is nonessential in working memory storage. *Trends in Cognitive Sciences, 22*(3), 192–193. https://doi.org/10.1016/j.tics.2017.12.008

Zanto, T. P., & Gazzaley, A. (2009). Neural suppression of irrelevant information underlies optimal working memory performance. *Journal of Neuroscience, 29*(10), 3059–3066. https://doi.org/10.1523/JNEUROSCI.4621-08.2009

Zhou, Y., Curtis, C. E., Sreenivasan, K. K., & Fougnie, D. (2022). Common neural mechanisms control attention and working memory. *Journal of Neuroscience, 42*(37), 7110–7120. https://doi.org/10.1523/JNEUROSCI.0443-22.2022