Proceedings of the Annual Meeting of the Cognitive Science Society

## Title

A blocked learning curriculum reduces age-related deficits in memory

## Permalink

https://escholarship.org/uc/item/1hc22723

## Journal

Proceedings of the Annual Meeting of the Cognitive Science Society, 46(0)

## Authors

Ren, Xiangjuan
Petzka, Marit
Schuck, Nicolas

## Publication Date

2024

# A blocked learning curriculum reduces age-related deficits in memory

**Xiangjuan Ren (xiangjuan.ren@uni-hamburg.de)**
Institute of Psychology, Universität Hamburg, Von-Melle-Park 5, 20146, Hamburg, Germany
**Marit Petzka (marit.petzka@uni-hamburg.de)**
Institute of Psychology, Universität Hamburg, Von-Melle-Park 5, 20146, Hamburg, Germany
**Nicolas W. Schuck (nicolas.schuck@uni-hamburg.de)**
Institute of Psychology, Universität Hamburg, Von-Melle-Park 5, 20146, Hamburg, Germany

## Abstract

Age-related memory decline is a multifaceted and heterogeneous process. Previous studies on working memory and episodic memory have demonstrated that older participants' memory for item-context bindings (e.g. the location in which an object appeared) drops dramatically, while memory for individual items is relatively preserved. Here, we extend this research in two ways: first, we study memory for ordered object sequences with spatial context, rather than single objects. Second, we investigate how blocked versus interleaved learning curricula affect independent (or marginal) sequence memory (i.e., which objects appeared, and which spatial locations were seen) versus joint sequence memory (which objects appeared where) for older versus younger adults. Across two behavioral experiments with 108 younger (18-35 years) and 100 older (over 65 years) adults, we found better memory for object sequences than position sequences and worst performance for joint object-position sequence reports in both age-groups. Notably, age *differences* in memory performance followed the same pattern, being least pronounced for sequential object memory and most for joint object-position sequences. Changing the learning curriculum such that either object or spatial location sequences repeated across times, rather than occurring in an interleaved fashion, improved memory performance in both age groups, but had a stronger effect on older than younger adults, suggesting that blocked learning curricula can help older adults with reallocation of limited cognitive resources.

**Keywords:** aging; item-context binding; ordered sequences; learning curriculum; cognitive resources.

## Introduction

Aging is accompanied by changes in multiple cognitive functions, including working memory and long-term episodic memory (Nyberg et al., 2012). But not all aspects of memory change uniformly with age. Previous studies reported that while older adults have relatively intact memory for individual items (e.g., object, color, shape), their joint memory of item-context bindings (e.g., object + location) is often impaired. Peterson and Naveh-Benjamin (2016), for instance, demonstrated in a working memory task that recognition of the item-context binding is impaired in older relative to younger adults, while their memory for intra-item binding (e.g., color + shape) remains intact. Similar age-related binding deficits are also prevalent in episodic memory tasks (Dai et al., 2018; Muffato et al., 2019; Tran et al., 2021). For example, Tran et al. (2021) found that older adults showed a significant impairment on object position change trials, but not object identity change trials compared to younger adults in an object-in-context recognition task. Taken together, these findings suggest that the way humans process information changes with age.

While the above studies mostly focused on the integration of "what" (i.e., objects) occurred "where" (i.e., spatial position), real live experiences also comprise "when" (i.e., temporal order) something occurs. To what extent ordered memory ("when") performance varies with the other two marginal dimensions ("what" or "where") or with the joint stimuli ("what" bound to "where") in a sequence across aging is still unknown.

To address this question, we designed a new Sequential Memory Task (SMT) to probe human memory for sequences of objects appearing in different positions. During the task, human participants were required to remember a sequence of five different object images that occurred at different positions on a circle (e.g., a cat appearing in the 12 o'clock position followed by a hat appearing at 9 o'clock *etc*). This allowed us, in a first experiment, to detect how aging affects memory for independent memory of object sequences and position sequences (i.e., marginal memory) and joint object-position sequence memory (i.e., joint memory). Using this task, we observed that ordered memory was reduced as a function of age (Experiment 1). In a follow-up experiment, we then set out to test to which extent the learning curriculum can counteract these age-related memory deficits (Experiment 2).

The learning curriculum, which specifies how learning material is presented has been shown to impact the learning success (Beukers et al., 2023; Flesch et al., 2018; Hayes & Wedell, 2023). For example, Flesch et al. (2018) demonstrated in a rule-switching classification task that humans, but not machines, benefit from training regimes that block one rule at a time, which improved human performance on a later test involving randomly interleaved rules, compared to a interleaved training. Interestingly, aging studies also suggest that blocking trials by categorical or spatial types facilitate both younger and older adults' memory performance in different ways (Dai et al., 2018). In Experiment 2 we therefore blocked objects or spatial location sequences to test for a potential facilitation of memory performance.

In L. K. Samuelson, S. L. Frank, M. Toneva, A. Mackey, & E. Hazeltine (Eds.), *Proceedings of the 46th Annual Conference of the Cognitive Science Society.*

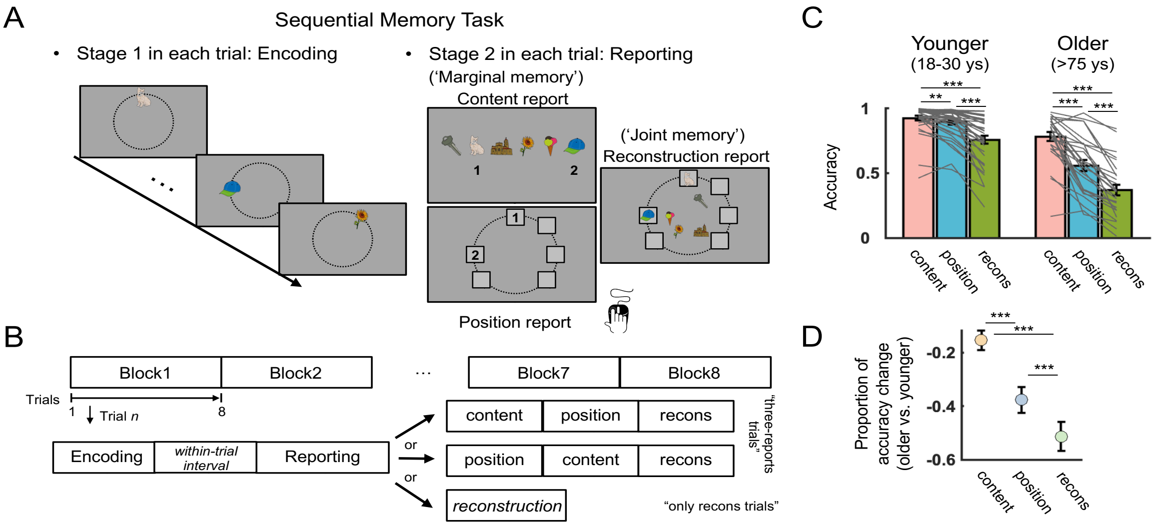

Figure 1. General experimental design and behavioral results of Experiment 1. (A) Sequential Memory Task (SMT). Each trial of the SMT involves two stages: encoding and reporting. During the encoding stage, participants need to encode an ordered sequence containing a content and a position dimension. After the encoding stage, participants completed a report about either the content, position, or joint content+position order. Here, they either click on the images/positions in their encoded order (content/position report) or they drag-and-drop the images to their corresponding positions in their encoded order (reconstruction report of joint content+position order). (B) Task structure. In Experiment 1-2, participants need to perform 8 blocks of the SMT, each consisting of 8 trials of encoding followed by a report. The *italicized* part is only introduced in Experiment 2. (C) Accuracy comparison in marginal and joint reports. Both, younger and older adults, showed better memory for content than position, and worst performance in the joint content/position reconstruction report. (D) Compared to the younger adults, older participants' memory decline in the content report was lowest, while their performance in the position and reconstruction reports reveals moderate and heavy decline. **: $p<0.01$, ***: $p<0.001$.

## Methods

### Participants

All participants were recruited via the Prolific platform (https://www.prolific.com/). In Experiment 1, 39 younger (aged 18 to 30) and 27 older (aged 75 to 85) adults participated. For Experiment 2, 3 subgroups of younger (aged 18 to 35, $N_s$=24, 24, 21) and older (aged 65 to 75, $N_s$=23, 25, 25) adults were recruited separately. All participants were fluent in English, had no history of head injury or mild cognitive impairment/dementia, and had a Prolific approval rate above 95. The study was approved by the Ethics Committee of the Max Planck Institute for Human Development. All participants provided informed consent prior to the experiment. The average duration of the formal study was 90 min. In addition to a base payment of £10/h, we awarded bonus of max. £3.6 depending on performance.

### Stimuli and Design

The experimental program was coded using PsychoPy/JS and run through Pavlovia (https://pavlovia.org/). Participants were informed that the study was only compatible with a desktop or laptop equipped with a mouse or a trackpad.

**Task structure.** Participants performed a Sequential Memory Task (SMT), in which they had to encode a sequence of events and then make a series of reports on each trial (see Fig. 1A, details below). Participants were first required to read the task instructions and complete a practice session that involved different stimuli. Then, they proceeded to the main task, which consisted of 8 blocks with each 8 trials (see below, Fig. 1B) in both Experiments. After completion of the main task, participants went through a 5-minute resting period, during which they had to perform a mildly engaging number judgment task (odd vs. even). Finally, participants were asked to complete a post-test where they were required to reconstruct previously seen event sequences. In the following data analysis, we focused only on the data from the 8 blocks of the main SMT task.

**Sequential Memory Task (SMT).** On each trial participants were first asked to encode an ordered sequence of five different objects (content) occupying five positions on a circle, with each transition being deterministic (Fig. 1A). Each joint sequence can be decomposed into two independent (or marginal) sequences: content (or object) and position. We employed non-abstract images (https://www.bcbl.eu/databases/multipic/) to make the task more feasible and clearly target the hippocampus for the future fMRI study. After the encoding stage, a within-trial interval (WTI) required participants to wait either between 15 and 20 s (6 out of 8 trials per block, uniform distribution) or between 500 and 5000 ms (truncated exponential distribution with a mean of 750 ms, see (Wittkuhn & Schuck, 2021), 2/8 trials per block). The WTI manipulation was irrelevant to the

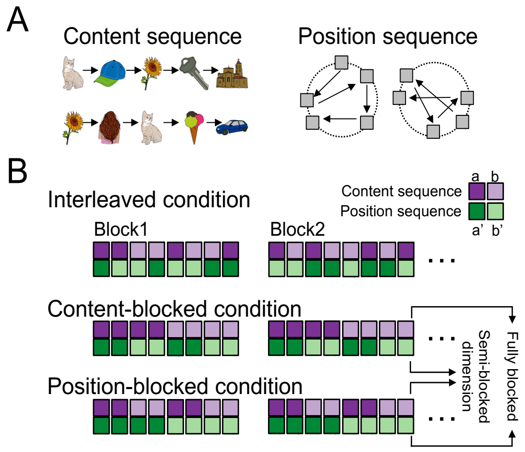

Figure 2. Transition sequences and learning curriculum. (A) Example marginal content and position sequences. (B) Interleaved and both blocked conditions.

current analysis. Following the WTI, participants were asked to report the experienced sequences as fast and accurate as possible. The reporting stage consisted of 3 types of reports (Fig. 1A): In the "content report", all 5 objects of the current sequence as well as a distractor object from another sequence were displayed in a row. The image array during the reporting stage was shuffled and differed from the original order. Participants then needed to click on the objects in succession to indicate in which order they saw them before. In the "position report", all 5 spatial positions of the current sequence as well as a distractor from another sequence were presented on the circle. Similarly, participants needed to make five selections to report the originally displayed order of positions. In the "reconstruction report", all 5 objects and 5 positions of the current sequence as well as one distractor object and one distractor position were displayed. Participants needed to drag an object to its corresponding position according to the original order. In Experiment 1, participants had to complete all 3 reports on each trial. The two independent memory ('content' and 'position') reports had to be completed before the reconstruction report in counterbalanced order ("three-reports trials"; Fig. 1B). In Experiment 2, participants had to complete only the reconstruction report on 2/8 trials ("recons only trials"; Fig. 1B), while the remaining 6 trials were 'three-reports trials' as in Experiment 1. For each report, the maximal decision time was 30 s, after which the next report began automatically. The encoding stage in the next trial began directly after an exponentially distributed inter trial interval. At the end of each block, a feedback screen indicated how many bonuses participants had been earned in this block and their accumulated score across blocks.

**Interleaved and blocked condition.** Each participant was asked to memorize two object (content) sequences (coded as a and b) and two position sequences (a' and b'). Combining these independent (or marginal) sequences led to 4 unique joint sequences (Fig. 2A): aa', ab', ba' and bb'. In Experiment 1, the four combinations were shuffled and repeated twice in each block (i.e., 8 trials per block). In Experiment 2, to test whether learning curriculum within a block would influence participants' memory, three types of curriculum conditions were designed (between-subject). In the ***interleaved condition*** the **four** sequences **were shuffled** randomly while ensuring that each sequence occurred once in the first and second half of the block (Fig. 2B top; same design as in Experiment 1**).** In the ***content-blocked condition*** the 8 trials were arranged such that participants first experienced four repetition of the same object/content sequence, followed by four repetitions of the other object sequence, while the position sequences alternated every two trials **(**e.g. the trial organization was aa', aa', ab', ab', ba', ba', bb', bb', middle panel in Fig.2B). Finally, the ***position-blocked condition*** implemented the same principle, only now with four repeats of the same position sequence followed by four repeats of the other position sequence (bottom panel in Fig. 2B). For each condition, one group of younger and one group of older adults were recruited.

## Behavioral analysis

Independent (or marginal) memory report accuracy was defined as the proportion of correct responses among the 5 reported objects/positions, ranging from 0 to 1. Reconstruction report accuracy was scored as either jointly correct (a correct object placed at the correct position in the correct order), or marginally correct (either the correct image in the correct order and ignoring the position, or vice versa). When evaluating the effect of the blocked design on the corresponding fully blocked (i.e. less frequently changing) and semi-blocked (i.e. more frequently changing) dimension, we pooled participants from the two blocked conditions and then evaluated the benefit. The benefit was defined as the change in accuracy on the less frequently changing dimension (e.g., the content dimension in the content blocked condition) or the more frequently changing dimension (e.g., the position dimension in the content blocked condition) relative to the mean accuracy on the corresponding dimension in the interleaved condition. In order to understand (temporal) order memory, we calculated correctness separately for each ordinal rank across trials, ignoring sequence identities.

## Statistical analysis

Both, Generalized Linear and linear mixed effect models (LMM) were used to model participants' accuracy (or change). Fixed effects include an intercept, the main effects of the three learning curriculum conditions (between-group), the three memory types (content, position, and

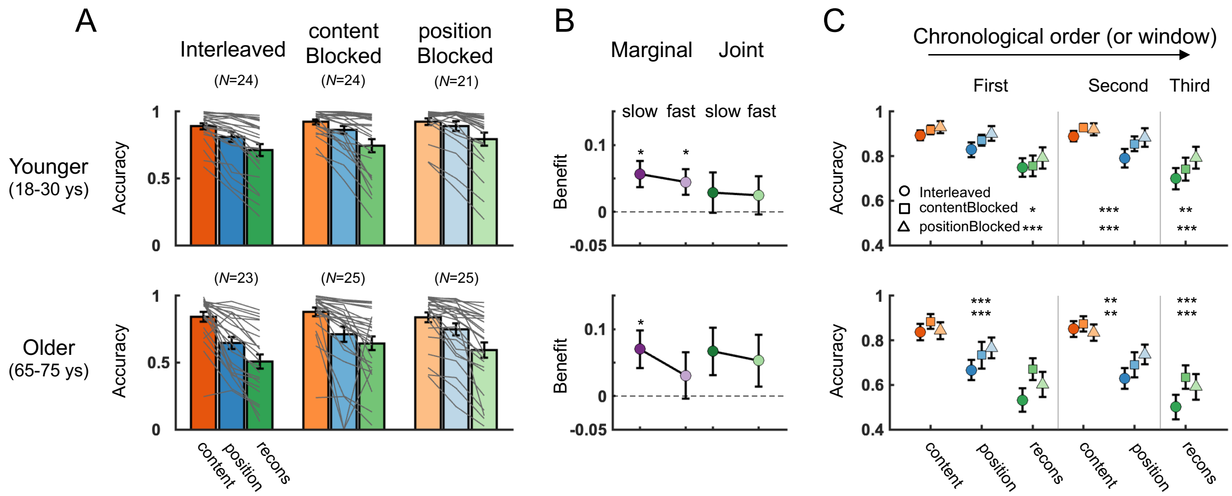

Figure 3. Influence of the interleaved and blocked designs on memory performance. (A) The blocked design facilitates both younger and older adults' memory but in different aspects. (B) The benefit of the blocked design on the slower and faster changing dimensions in a sequence. *: $0.01 \le p < 0.05$. (C) The long-standing influence of the blocked design. The first and second row of significance labels in each panel correspond to the comparison of interleaved versus content blocked and interleaved versus position blocked separately. *: $0.01 \le p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$. Error bars denote S.E.M. Dark color + dots/ moderate color + squares/ light color + triangles: interleaved/content/position blocked conditions.

reconstruction; within-group), and the interaction between curriculums and memory types; random effects include correlated random slopes of memory types, and random intercept for participants. For the estimation of marginal effects and the post hoc analysis, the "*emmeans*" package was used. In addition, standard statistical tests, such as one- or independent-sample *t*-tests, were used with multiple comparison correction by *FDR*.

## Results

Experiment 1 examined how age affects order memory for object, position, and joint object+position sequences. Experiment 2 tested how the learning curriculum can counteract age-related deficits in order memory observed in Experiment 1.

### Experiment 1: older adults show memory deterioration compared to younger adults.

As shown in Figure 1C, participants' accuracy was high for the content report, significantly lower for the position report and significantly worst for the reconstruction report (LMM on accuracy with multiple comparison; *younger*, content (con) minus position (pos): mean=0.031, $t(38)=3.182$, $p=0.008$; con minus reconstruction (recons): mean=0.167, $t(38)=7.780$, $p<0.001$; pos minus recons: mean=0.136, $t(38)=7.015$, $p<0.001$; *older*, con – pos: mean=0.225, $t(26)=6.061$, $p<0.001$; con – recons: mean=0.414, $t(26)=12.965$, $p<0.001$; pos – recons: mean=0.189, $t(26)=7.973$, $p<0.001$). While these results are in line with previous studies on the item-context binding, our findings generalize this pattern to memory of order sequences. The consistent pattern across age groups suggests that inferior memory for spatial location may be an intrinsic feature of humans across the lifespan. We further investigated the relative difference between older and younger participants separately for each report. We observed that content memory was not only highest, but also least impaired in older compared to younger adults, while position memory was impaired more heavily, followed by joint memory (Fig.1D) (LMM on accuracy change with post-hoc; con – pos: mean=0.222, $t(26)=5.392$, $p<0.001$; con – recons: mean=0.359, $t(26)=8.800$, $p<0.001$; pos – recons: mean=0.137, $t(26)=4.715$, $p<0.001$). The graded patterns of change in accuracy across the three report types indicate that memory decline in the different aspects does not change uniformly.

Briefly, the results of Experiment 1 revealed that both age groups displayed the same gradient of memory performance in a sequential memory task, while the aging intensified the gradient in the aspects requiring more cognitive load.

### Experiment 2: blocked designs facilitate human memory performance and optimize the mnemonic strategy.

In Experiment 2, we investigated whether organizing the trials such that either the object (content) or position sequences repeated more often across consecutive trials would improve performance. In the content blocked condition, the object (or content) sequences switched less frequently than the position sequences, whereas the reverse was true in the position blocked condition (Fig.2B, middle and bottom panels). Accordingly, we distinguish between the less frequently changing, fully blocked dimension, and the more frequently changing, semi-blocked dimension. Three subgroups of younger and older adults were recruited separately for the interleaved, content blocked and position blocked conditions (*Ns*=21~25, see Fig. 3).

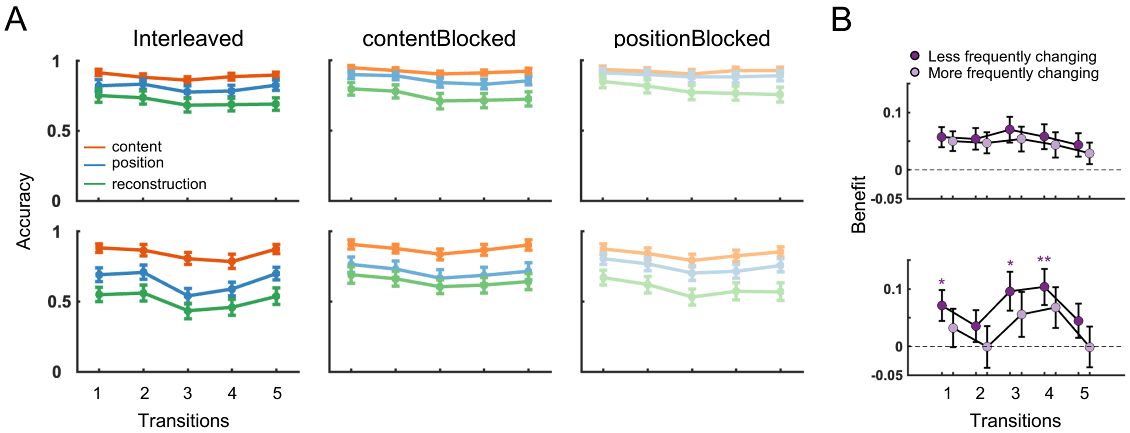

Figure 4. Blocked designs differently affect memory strategies in younger and older adults. (A) Ordinal position accuracy in the transition sequences. (B) Benefit across transitions in the less and more-frequently changing dimensions. *: $0.01 \leq p < 0.05$, **: $p < 0.01$.

**Blocked design improved younger and older participants' performance in different aspects.**

Consistent with Experiment 1, both younger and older adults showed a graded memory pattern in the interleaved condition, and age differences were strongest in the reconstruction report (Fig. 3A, left column; decline proportion: $\text{con} = -0.053 \pm 0.040$, $\text{pos} = -0.202 \pm 0.056$, $\text{reconstruction} = -0.285 \pm 0.075$). A similar performance pattern was observed in both blocked conditions. Notably, however, the blocked design exerted distinct influence on the performance of younger and older adults (Fig. 3A, middle and right columns). For the younger group, the overall performance was improved in both the content blocked and position blocked conditions compared to the interleaved condition (LMM on accuracy; content blocked condition: $t = 2.782$, $p = 0.005$; position blocked condition: $t = 2.793$, $p = 0.005$). In contrast, older adults' memory performance was improved significantly only in the content blocked condition ($t = 2.236$, $p = 0.025$). In addition, the overall decline proportion of older relative to younger adults was significantly reduced in the content blocked condition compared to the other two conditions (post-hoc test on accuracy differences between age groups: interleaved minus content blocked condition: $\text{mean} = -0.055$, $t = -5.961$, $p < 0.001$; interleaved – position blocked: mean < 0.001, $p = 0.99$; content – position, $\text{mean} = 0.055$, $t = 6.169$, $p < 0.001$).

To test the effect of fully and semi-blocked dimension on both age groups, we pooled participants in the two blocked conditions and focused on the relative advantage of the slower changing and faster changing dimension compared to the mean accuracy on the corresponding dimension in the interleaved condition. The output measure, called "benefit", was calculated separately for the fully (slower changing) and semi-blocked (faster changing) dimensions in the marginal and joint reports. The results are summarized in Figure 3B: for the younger group, their performance on both the slower and faster changing dimension was increased in the independent (or marginal) memory report of objects and positions (one-sample $t$ test right-sided, with *FDR* correction; slow: $t(44) = 2.884$, $p = 0.012$; fast: $t(44) = 2.364$, $p = 0.023$) but not in the joint report. For the older group, the blocked design specifically improved memory on the corresponding slower changing dimension in the marginal report ($t(49) = 2.505$, $p = 0.031$), but not in the faster changing dimension, with a weak effect on joint reports ($t(49) = 1.874$, $p = 0.067$). Hence, the blocked design may relieve the memory load for younger and older adults through different internal processes.

**Benefits of the blocked curriculum was interference and time resistant.**

In some trials of Experiment 2, participants completed all three reports following the encoding phase, while in other trials they completed only the reconstruction reports. This allowed us to investigate the influence of a blocked curriculum when reports were either given directly after encoding, or only after other forms of reports had to be provided beforehand, which added more time until first explicit retrieval of learned information and could possibly introduce interference. According to our design, the first report after the encoding stage could be any of the three report types, whereas the second and third reports corresponded only to independent (or marginal) and joint reports respectively (see Fig. 1B). By splitting the trials based on the specific chronological order (after encoding) and running the similar LMM as Figure 3A on accuracy in each reporting window, we found that the blocked design not only improved performance on the first report immediately after the encoding stage in both younger (LMM on accuracy with post-hoc; interleaved (int) minus content blocked condition (cb): $\text{mean} = -0.026$, $t = -2.715$, $p = 0.018$; int–position blocked condition (pb): $\text{mean} = -0.051$, $t = -4.993$, $p < 0.001$; cb–pb: $\text{mean} = -0.024$, $t = -2.408$, $p = 0.043$) and older groups (int–cb: $\text{mean} = -0.073$, $t = -6.687$, $p < 0.001$; int–pb: $\text{mean} = -0.047$, $t = -4.310$, $p < 0.001$; cb–pb: $\text{mean} = 0.026$, $t = 2.450$, $p = 0.038$), but also impacted the second report (*younger*, int–cb: $\text{mean} = -0.043$, $t = -3.100$, $p = 0.006$; int–pb: $\text{mean} = -0.095$, $t = -6.467$, $p < 0.001$; cb–pb: $\text{mean} = -0.052$, $t =$

$-3.518$, $p$=0.001; *older*, int–cb: mean= $-0.119$, $t$= $-8.125$, $p$<0.001; int–pb: mean= $-0.076$, $t$= $-5.167$, $p$<0.001; cb–pb: mean = 0.043, $t$ = 3.052, $p$=0.007) and even the reconstruction reports performed at the very end of each trial, sometimes more than 1 min after the encoding (Fig. 3C).

**Blocked design compensated for the age-related memory deficits by redeploying the cognitive resources.**

In serial recall tasks, such as the one we adopted, a more appropriate learning or memory strategy for any agent with limited cognitive resources is to allocate slightly more resources to the first item in a sequence (Logan, 2021), rather than the last element, as this will make the retrieval initialization (or forward retrieval) easier. To probe how age and blocking affect this resource allocation, we calculated the proportion of correct responses across trials for each ordinal rank.

Compared to the younger group, older adults showed both larger primacy and recency effects in the position and reconstruction reports (primacy = accuracy in the 1st slot minus that in the 3rd slot; recency = 5th slot minus 3rd slot) in the interleaved condition, indicating relatively greater difficulties in retrieving the intermediate elements in a sequence (Fig. 4A, left column). For the participants exposed to the stimuli in a blocked style, especially the older group, the overall increase in accuracy was accompanied with a reduction in curvature (Fig. 4A, middle and right columns). But how did the blocked design quantitatively change the accuracy pattern across ordinal ranks (proxy for resource allocation) for the younger and older adults? Here we focused on the accuracy change in the less and more frequently changing dimension of the marginal report by pooling the participants across two blocked conditions. Specifically, we calculated the benefit (accuracy change) in each ordinal rank (or transition) for each participant, given the corresponding average accuracy in the interleaved condition as a reference. As shown in Figure 4B, the benefits for the younger adults were stable for almost all ranks except the fifth on the fast-changing dimension, while for older participants, they attentively invested more resources to the initial and middle transitions for the slow-changing dimension (one-sample $t$-test, right-sided, with *FDR*; 1st rank: $t$(49)=2.633, $p$=0.019; 3rd: $t$(49)=2.832, $p$=0.017; 4th: $t$(49)=3.295, $p$=0.009).

In sum, the blocked design might improve memory performance through deploying cognitive resources in a more optimized way.

## Discussion

In the current study, we designed a new sequential memory task to investigate whether and how memory changes differently with age and whether their memory could be facilitated by a blocked learning curriculum. In Experiment 1, we found that the paradigm was sensitive to detect memory gradation across performance for object (or content), position and joint content + position in both younger and older adults, with aging exaggerating the memory gradient. In the Experiment 2, we demonstrated that reorganizing the joint sequences in such a way of switching the two independent (or marginal) dimensions with a different frequency would facilitate memory in both younger and older groups. Specifically, switching the object (or content) dimension less frequently (i.e., blocked) enhanced older participants' performance, whereas younger participants benefited more from the less frequently changing position condition. The results partly align with the previous finding that younger and older participants have different processing efficiency for the object identity and location (Dai et al., 2018). The effect cannot be explained by the attentional load of devoting more resources to the more salient dimension, the fast-changing dimension, as suggested by the pattern in Figure 3B.

However, it remains unclear which computational mechanisms might explain the disparity between content and position reports, and which cognitive processes are targeted by the blocked design to counteract the deficits for an agent with limited cognitive resources. One possibility is, for instance, that the content-position discrepancy is driven by a higher learning rate for the content sequence, or less decay. Previous models, such as the context maintenance and retrieval model (CMR; Kahana, 2020) or the context retrieval and updating theory (CRU; Logan, 2021), have already attempted to explain a series of benchmark phenomena in the free recall task and serial order task without learning. However, neither of them can be applied to our case without the inclusion of additional hypotheses. In ongoing work, we aim to disentangle the process contributing to aspect- (i.e., object/position/reconstruction) and age-related decline, and ask whether memory performance was driven by two independent processes related to the representation of the two marginal sequences, with different learning rates and/or decay parameters (e.g., which element is more likely to be the successor in the next state), and how abstracted ordinal representations have been learned (Schuck et al., 2012a; 2012b). Another line of inquiry concerns the formation of the feature-to-context association, which is essential to initiate the first element retrieval in a sequence (Kahana, 2020; Logan, 2021). We assume that the unique stimuli displayed on the screen in the beginning of reports act as a contextual cue to achieve the initial retrieval. It is also probable that the memory changes occur in a binding process in which humans learn the association strength between content and position during the encoding. Accordingly, the age-related memory decline would occur in these processes.

Previous studies have already provided robust evidence that neural replay, a phenomenon in which previously experienced activity is reactivated spontaneously during wakefulness (Liu et al., 2019; N. W. Schuck & Niv, 2019) or sleep (Ólafsdóttir et al., 2018), plays a critical role in memory consolidation (Schapiro et al., 2018; Wimmer et al., 2020). The current paradigm, which includes the within-trial-interval (WTI) before reporting and post-test sessions, allows for the investigation of replay priority and its influence on the subsequent learning/memorization. Furthermore, it would be intriguing to see the convergence of replay priority from the imaging data and the learning/memorization efficiency from the modeling part.

# Acknowledgements

NWS was funded by the Federal Government of Germany and the State of Hamburg as part of the Excellence Initiative, a Starting Grant from the European Union (ERC- StG-REPLAY-852669; https://erc.europa.eu/)

# References

Beukers, A. O., Collin, S. H. P., Kempner, R., Franklin, N. T., Gershman, S. J., & Norman, K. A. (2023). *Blocked training facilitates learning of multiple schemas* [Preprint]. PsyArXiv. https://doi.org/10.31234/osf.io/9bptj

Dai, R., Thomas, A. K., & Taylor, H. A. (2018). Age-related differences in the use of spatial and categorical relationships in a visuo-spatial working memory task. *Memory & Cognition*, *46*(5), 809–825. https://doi.org/10.3758/s13421-018-0794-8

Flesch, T., Balaguer, J., Dekker, R., Nili, H., & Summerfield, C. (2018). Comparing continual task learning in minds and machines. *Proceedings of the National Academy of Sciences*, *115*(44). https://doi.org/10.1073/pnas.1800755115

Hayes, W. M., & Wedell, D. H. (2023). Effects of blocked versus interleaved training on relative value learning. *Psychonomic Bulletin & Review*. https://doi.org/10.3758/s13423-023-02290-6

Kahana, M. J. (2020). Computational Models of Memory Search. *Annual Review of Psychology*, *71*(1), 107–138. https://doi.org/10.1146/annurev-psych-010418-103358

Liu, Y., Dolan, R. J., Kurth-Nelson, Z., & Behrens, T. E. J. (2019). Human Replay Spontaneously Reorganizes Experience. *Cell*, *178*(3), 640-652.e14. https://doi.org/10.1016/j.cell.2019.06.012

Logan, G. D. (2021). Serial order in perception, memory, and action. *Psychological Review*, *128*(1), 1–44. https://doi.org/10.1037/rev0000253

Muffato, V., Hilton, C., Meneghetti, C., De Beni, R., & Wiener, J. M. (2019). Evidence for age-related deficits in object-location binding during place recognition. *Hippocampus*, *29*(10), 971–979. https://doi.org/10.1002/hipo.23099

Nyberg, L., Lövdén, M., Riklund, K., Lindenberger, U., & Bäckman, L. (2012). Memory aging and brain maintenance. *Trends in Cognitive Sciences*, *16*(5), 292–305. https://doi.org/10.1016/j.tics.2012.04.005

Ólafsdóttir, H. F., Bush, D., & Barry, C. (2018). The Role of Hippocampal Replay in Memory and Planning. *Current Biology*, *28*(1), R37–R50. https://doi.org/10.1016/j.cub.2017.10.073

Peterson, D. J., & Naveh-Benjamin, M. (2016). The role of aging in intra-item and item-context binding processes in visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *42*(11), 1713–1730. https://doi.org/10.1037/xlm0000275

Schapiro, A. C., McDevitt, E. A., Rogers, T. T., Mednick, S. C., & Norman, K. A. (2018). Human hippocampal replay during rest prioritizes weakly learned information and predicts memory performance. *Nature Communications*, *9*(1), 3920. https://doi.org/10.1038/s41467-018-06213-1

Schuck, N., Gaschler, R., & Frensch, P. (2012). Implicit learning of what comes when and where within a sequence: The time-course of acquiring serial position-item and item-item associations to represent serial order. *Advances in Cognitive Psychology*, *8*(2), 83–97. https://doi.org/10.5709/acp-0106-0

Schuck, N. W., Gaschler, R., Keisler, A., & Frensch, P. A. (2012). Position–item associations play a role in the acquisition of order knowledge in an implicit serial reaction time task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*(2), 440–456. https://doi.org/10.1037/a0025816

Schuck, N. W., & Niv, Y. (2019). Sequential replay of nonspatial task states in the human hippocampus. *Science*, *364*(6447), eaaw5181. https://doi.org/10.1126/science.aaw5181

Tran, T., Tobin, K. E., Block, S. H., Puliyadi, V., Gallagher, M., & Bakker, A. (2021). Effect of aging differs for memory of object identity and object position within a spatial context. *Learning & Memory*, *28*(7), 239–247. https://doi.org/10.1101/lm.053181.120

Wimmer, G. E., Liu, Y., Vehar, N., Behrens, T. E. J., & Dolan, R. J. (2020). Episodic memory retrieval success is associated with rapid replay of episode content. *Nature Neuroscience*, *23*(8), 1025–1033. https://doi.org/10.1038/s41593-020-0649-z

Wittkuhn, L., & Schuck, N. W. (2021). Dynamics of fMRI patterns reflect sub-second activation sequences and reveal replay in human visual cortex. *Nature Communications*, *12*(1), 1795. https://doi.org/10.1038/s41467-021-21970-2