



The working memory advantage for meaningful stimuli persists under high levels of proactive interference

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Abstract

Previous work has shown that visual working memory performance is higher for recognizable and meaningful stimuli relative to meaningless, but physically matched, stimuli (e.g., Asp et al., 2021). Here, we test whether the benefit for meaningful stimuli arises due to active storage in working memory or can, at least in part, be explained by reliance on more durable memories that persist across trials, such as episodic long-term memory that can substitute for active maintenance. We used ambiguous Mooney faces (Exp. 1, Exp. 3) and objects (Exp. 2) as well as scrambled versions of the same stimuli, resulting in some observers recognizing a given stimulus as meaningful and others not. To manipulate proactive interference, some items were repeated throughout the experiments and others were not. We found equivalent objective and subjective effects of meaningfulness on memory performance regardless of item repetition and thus the amount of proactive interference, consistent with items being actively stored in working memory and providing direct evidence against the idea that durable, cross-trial long-term memories play a critical role in eliciting the meaningfulness advantage. The meaningfulness advantage was strong even with significant proactive interference present. Overall, we find that proactive interference in these tasks is graded, governed by whether items are individuated by spatial or temporal context, and recognition of a stimulus as a face or object provides a strong benefit to working memory performance regardless of the level of proactive interference.

Keywords Visual working memory · Meaningfulness · Proactive interference · Capacity limits

Introduction

Visual working memory is a limited capacity system that allows information to be held in an active state for ongoing tasks. When memorizing simple, artificial stimuli (e.g., colored squares), observers can maintain only a small amount of information over a short delay (Adam et al., 2017; Awh et al., 2007; Bays et al., 2009; Luck & Vogel, 1997). However, emerging research demonstrates that visual working memory capacity depends on the nature of the stimuli: stimuli that are meaningful are better remembered than other, meaningless stimuli (e.g., Alvarez & Cavanagh, 2004; Brady & Störmer, 2022, 2023; Brady et al., 2009, 2016; Chung et al., 2026; Curby et al., 2009; Jackson & Raymond,

2008; Ngiam et al., 2019; O'Donnell et al., 2018; Sahar et al., 2020). Many of these studies put significant effort into perceptually matching the stimuli across conditions or even using the exact same stimulus while varying how meaningful a given stimulus is to a particular participant. For example, a recent study showed that when observers were asked to memorize ambiguous Mooney faces (Mooney, 1957) or scrambled versions of these stimuli, performance was better when more faces were shown relative to non-faces; most critically, performance was also better when more ambiguous stimuli were recognized as a face, demonstrating that the subjective perception of the stimulus and not its physical attributes is critical in driving these memory benefits (Asp et al., 2021). Another study used images of flags and compared performance for “real” national flags and “fake” flags that were matched in perceptual complexity and found higher performance for remembering real compared to fake flags in a visual working memory task (Conci et al., 2021). Together, these results indicate that working memory benefits are not driven by physical properties of the stimuli but arise from how the visual system interprets the information:

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if the stimuli activate structured and well-known representations and connect to pre-existing knowledge, such as what a face looks like, or how a colored pattern relates to the national flag of a country, these meaningful stimuli can be stored more effectively than arbitrary, meaningless visual features.

Thus, one kind of long-term memory is clearly involved in these results: pre-existing knowledge, for example knowing what a face looks like, which is what allows an ambiguous arrangement of light and dark regions to be seen as a face at all. However, this knowledge, while “long-term,” is not tied to any particular trial or experience, but is a kind of semantic memory. The second kind of long-term memory that could be involved, by contrast, is an episodic trace of a specific experimental image, laid down when that image appeared on an earlier trial. Some have claimed (e.g., Park & Awh, 2026) that this second kind of episodic-long-term memory could account for the working memory advantage for meaningful stimuli. That is, for such stimuli, observers may rely on more durable representations, including substituting episodic long-term memory from a previous trial, rather than using working memory in a trial-by-trial form of active maintenance, as is typically assumed to drive performance in working memory studies; thus, how often items repeat across trials may explain some aspects of the meaningfulness benefit. Consistent with the general possibility of people augmenting working memory performance with episodic long-term memories, several studies have shown that if episodic long-term memories are available, these long-term memory representations can be used in place of working memory representations, effectively increasing memory performance (Bartsch & Shepherdson, 2022; Carlisle et al., 2011; Hollingworth, 2007; Schurgin et al., 2018). However, nearly all studies showing the role of meaningfulness in working memory use novel stimulus sets and do not repeat items across the experiment, thereby eliminating the possibility of substituting specific episodic long-term memories for working memory in making a decision about which item was present in a particular location on this particular trial (the key index of performance in such studies). In addition, these benefits have repeatedly been found to occur even when meaningful and non-meaningful stimuli repeat equally often across trials (e.g., Asp et al., 2021; Thibeault et al., 2024). Thus, while long-term memory in the sense of existing knowledge is clearly relevant to these meaningfulness effects, the use of episodic long-term memory is generally seen as not related to these advantages.

A related but distinct possibility is that the meaningfulness advantage arises from a within-trial activated state (Cowan, 1988; Ericsson & Kintsch, 1995; Oberauer, 2002) rather than from sustained maintenance in the focus of attention. Contemporary models of working

memory, especially those outside the traditional visual working memory literature, conceptualize working memory as a multi-component system in which information can exist across different states of activation (Brady et al., 2024; Cowan, 2019; Logie et al., 2021; Oberauer, 2019), and not merely as the handful of items held in the focus of attention. Within these frameworks, some representations are in the focus of attention, while others, activated by the current trial, remain accessible without continuous attention (Brady et al., 2024; Oberauer, 2009). Such activated representations are still considered part of working memory (LaRocque et al., 2014; Lewis-Peacock & Postle, 2008): they were encoded on the very trial on which they are tested and held in an activated state across the maintenance period. The empirically important distinction, then, is not only between the focus of attention and the rest of working memory (both are working memory), but between relying on the current trial’s working-memory representation, in whatever activation state, and drawing on a durable memory of the item formed on a previous encounter. It is this latter, cross-trial contribution that we set out to test.

In some cases, such states of activation could be relevant. For example, in the case of the “flag” study cited above (Conci et al., 2021), it could well be the case that recognizing a familiar flag that is already stored in long-term memory will lead to that representation being re-activated, and that because this activation of this unique memory is likely to last for the full duration of the trial without being actively placed within the focus of attention, it can free up resources for other items, resulting in better overall performance. While it is unclear how activated memories alone are sufficient for conditions where the item’s location also needs to be known, it is possible that such activation could reduce the load on memory while the focus of attention is still required for location binding.

To distinguish accounts where meaningfulness helps working memory by providing an easier time creating activated states that persist for the entire trial (without continuous attention) from accounts where meaningfulness increases the resources available even within the focus of attention, neural markers of active working memory maintenance, in particular persistent neural delay activity observed during the retention interval of working memory tasks (Fuster & Alexander, 1971; Todd & Marois, 2004; Vogel & Machizawa, 2004), have been useful. The contralateral delay activity, an electrophysiological marker of sustained neural activation during the maintenance period (McCollough et al., 2007; Vogel & Machizawa, 2004; Vogel et al., 2005), is generally assumed to reflect the “focus of attention” in working memory, specifically. Thus, contralateral delay activity data have been useful in asking about the source within working memory of the meaningfulness advantage. For example, in the Mooney face

study, Asp et al. (2021) used EEG to record the contralateral delay activity, and found increased neural delay activity during working memory maintenance when more faces were shown and also when more faces were subjectively recognized as a face, paralleling the behavioral benefits. This suggests that the focus of attention within visual working memory was engaged more with meaningful stimuli (see also Brady et al., 2016; Chung et al., 2026; Thibeault et al., 2024), providing evidence in favor of the idea that the meaningfulness advantage reflects increased, not decreased, use of the focus of attention within working memory; that is, people do not seem to be relying on their ability to use activated long-term memories rather than the focus of attention to perform such tasks.

Neural measures of active storage can show that at least some of the benefit reflects active maintenance, but they cannot reveal whether the benefit also depends on more durable memories carried over from previous encounters with an item. To address this with converging behavioral evidence, we here capitalize on the phenomenon of proactive interference: the intrusion of memories from previous trials into performance on the current trial (Keppel & Underwood, 1962; Peterson & Peterson, 1959; Shoval & Makovski, 2022). Proactive interference provides a diagnostic measure because it grows with reliance on representations that persist across trials: if the benefit for meaningful items depends on durable, cross-trial memories of those specific items, those memories should intrude when the same items recur in new roles and locations. Importantly, proactive interference can itself be a property of working memory rather than a signature of a separate long-term store: interference-based models hold that items are retrieved through bindings to spatial and temporal context, and that intrusions scale with how similar the current context is to that of previous trials (Brown et al., 2007; Howard & Kahana, 2002; Oberauer & Kliegl, 2006; Oberauer & Lin, 2017, 2024). This is why proactive interference is typically minimal in standard visual working memory tasks that present several items simultaneously at distinct locations (Hartshorne, 2008; Lin & Luck, 2012; Makovski & Jiang, 2008; Oberauer et al., 2017): the trial-specific spatial location of each item provides a strong retrieval cue that separates it from prior trials (Makovski, 2016; Pertzov & Husain, 2014). This also implies that cross-trial memory contributions are unlikely to explain meaningfulness benefits observed in prior simultaneous tasks (Brady & Störmer, 2023; Brady et al., 2016; Chung et al., 2026), though this has not been directly tested. When that spatial cue is removed, for example, and items are presented one at a time at the same central location, items must be individuated by temporal context alone, and proactive interference is expected to be substantially larger. Proactive interference thus offers a window onto whether, and under what conditions, the meaningfulness benefit depends on memories that carry across trials.

If the meaningfulness advantage depends on such cross-trial memories, it should be disproportionately reduced by proactive interference. Meaningful, recognizable stimuli might be especially prone to forming durable memories that are reactivated on later trials; if so, repeating the same meaningful items in different locations and roles would create confusion between trials and erode their advantage. Meaningless stimuli, lacking pre-existing structure to latch onto, would have little to carry across trials and so should be little affected by repetition, as prior work suggests (Lin & Luck, 2012). Any such differential susceptibility would manifest as a smaller meaningfulness advantage under high proactive interference. Comparing the advantage across conditions in which items either repeat in different locations and roles or are always new therefore provides a direct test of whether durable cross-trial memories underlie the benefit. This question also bears on a recent proposal that real-world objects are better remembered than simple features such as colors partly because objects are repeated far less often within an experiment, and so accrue less proactive interference (Park & Awh, 2026). While this account is inconsistent with the broader meaningful benefit literature, with many existing findings where stimuli differ in meaningfulness but are matched on repetition (e.g., Asp et al., 2021; Thibeault et al., 2024), it provides further motivation for testing the precise role of proactive interference in meaningfulness effects in visual working memory.

To test this, we systematically varied how often participants saw a given stimulus, either repeating a small set frequently across the experiment or never repeating any item, inducing high versus minimal proactive interference, respectively (the latter matching most prior work; e.g., Asp et al., 2021; Brady & Störmer, 2022). If the meaningfulness advantage depends on durable cross-trial memories, it should shrink when items repeat in different locations and roles; if instead it reflects the current trial's working-memory representation, it should persist under high proactive interference. Following our previous work (Asp et al., 2021), we used ambiguous stimuli that may or may not be recognized as meaningful, matching visual complexity across conditions while varying participants' subjective impressions. Experiment 1 used ambiguous Mooney faces (Asp et al., 2021); Experiment 2 used a novel set of ambiguous Mooney objects to test generalization. In Experiment 3, we presented the same faces as in Experiment 1 sequentially rather than simultaneously, removing the distinct spatial cues that protect simultaneous displays from interference and thereby providing a stronger test of whether proactive interference, when it does occur, modulates the meaningfulness benefit.

Experiments 1 and 2: Proactive interference for Mooney faces and objects

Method

The inclusion criteria, hypothesis, and analysis plan for both experiments were preregistered (Exp. 1: <https://aspredicted.org/blind.php?x=5ag6g9>; Exp. 2: <https://aspredicted.org/blind.php?x=cw384j>).

Participants

Thirty-two participants met our inclusion criteria and were included in the final dataset for each of Experiments 1 and 2. Following our preregistration, participants were excluded (five participants in Exp. 1 and one participant in Exp. 2) if their memory performance averaged across conditions was 2.5 standard deviations below the mean, if their memory performance averaged across conditions was below 50% (chance), or if more than 10% of the trials were excluded as response-time outliers. Individual trials were excluded if the response time was less than 150 ms or greater than 5,000 ms. All participants were run through the UCSD SONA system and received course credit for participating. They gave informed consent prior to starting the experiment as approved by the Institutional Review Board at University of California San Diego. Sample sizes were set to match or exceed those of the studies this paradigm is based on (Asp et al., 2021; Brady & Störmer, 2022). Because our main hypotheses were tested with trial-level mixed-effects models, sensitivity depends significantly on the number of trials per participant, which was roughly 475. Via simulation, we find that our analysis at the current sample size and trial count could detect an interference by meaningfulness interaction of $|b| \geq 0.13$, 0.15, and 0.12 in log-odds (Experiments 1–3, respectively) with 80% power at $\alpha = .05$. The value b is the change in the log-odds of a correct response per additional meaningful item, so this reflects an ability to detect any change in the meaningfulness benefit as small as 3 percentage points. This is significantly smaller than previous meaningfulness benefits, suggesting the studies are well powered for detecting the benefit and any changes in it across conditions.

Stimuli

In Experiment 1, we used ambiguous Mooney faces (Mooney, 1957). The stimuli were a subset of the stimuli used in our previous work (Asp et al., 2021; Brady et al., 2019). Ambiguous face images were chosen based on rankings collected on 20 independent individuals

indicating whether they saw each stimulus as a face or not (for details, see Schwiedrzik et al., 2018). In Experiment 2, we created a novel set of ambiguous Mooney real-world objects to investigate whether the results generalize. In both experiments, the non-recognizable images were created by segmenting continuous regions of black and white from the face and object images and scrambling these parts by placing them at random locations and random angles within a new image, thus preserving the overall luminance and shape of each region while removing the holistic connection between regions that allow the images to be recognized (cf., Brady et al., 2019). Thus, the scrambled stimuli were on average much less likely to be recognized as something meaningful relative to the intact Mooney images, although it could still be the case that a participant would perceive a meaningful face or object in them.

Procedure

The procedure was identical across Experiments 1 and 2 (Fig. 1). Proactive interference level was a within-participants manipulation between blocks. In the high-interference block, the same 24 images (12 ambiguous/12 scrambled) were repeated such that participants saw each image 10× as a target, 10× as a foil, and 20× as non-targets; the particular images making up this set were selected at random for each participant. In the low-interference block, a distinct set of 240 images (120 ambiguous/120 scrambled) was used and repeated far less often, such that participants saw each image 1× as a target, 2× as a foil, and 2× as non-targets. Thus, each image was viewed 10× more often in the high-interference block than in the low-interference block.

On each trial, the memory display consisted of none, one, two, or three ambiguous Mooney images while the remaining stimuli were scrambled versions of the same images. Thus, there were always three images presented, but how many of these were ambiguous versus scrambled was varied across trials. The stimuli were displayed for 1 s, followed by an 800-ms delay and a spatial retrieval cue (500 ms). Subsequently, the target image and a foil image of the same stimulus type (intact or scrambled) were presented on either side of the fixation cross, and participants indicated which of the two images were in the initial memory display in a two-alternative forced-choice (2-AFC) task. Finally, at the end of each trial, participants reported how many images they perceived as meaningful objects during encoding.

Statistical analysis

Consistent with our preregistration, for our main analysis, we examined the effects of the objective number of meaningful stimuli shown, interference level, and their

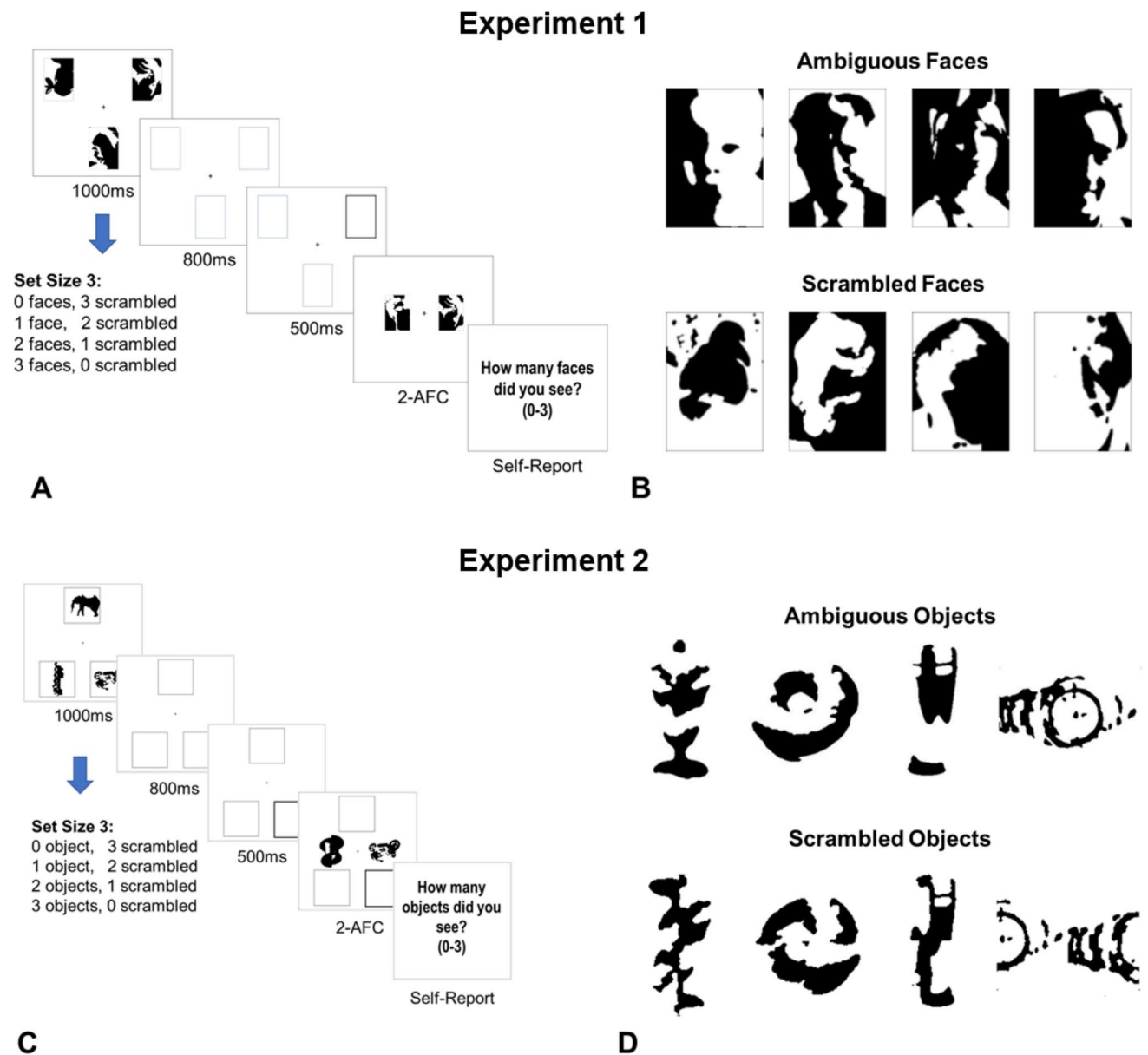


Fig. 1 Trial structure and example stimuli. **(A)** Experiment 1: Participants viewed three stimuli for 1 s at encoding; after a short delay, a location probe was presented and participants were asked to indicate which of two stimuli they saw at that location. After the two-alternative forced-choice (2-AFC) response, participants were asked how many faces they perceived in the initial display. Each trial contained

three stimuli but it was systematically varied how many of these stimuli were intact Mooney stimuli or scrambled versions of them. **(B)** Example stimuli for Experiment 1: ambiguous faces (top) and scrambled versions of these faces (bottom). **(C)** Trial structure for Experiment 2. **(D)** Example stimuli for Experiment 2: ambiguous objects (top) and scrambled versions of these objects (bottom)

interaction, after taking into account the random effects of participants and items using a generalized linear mixed effect model:

$$\text{WasCorrect} \sim 1 + \text{InterferenceLevel} * \text{ObjectiveFaceNum} + (1|\text{Item}) + (1|\text{Subject}).$$

In a separate model, we examined the effect of both the objective and the subjective number of faces and their

interaction separately for the high-interference condition, again treating both subjects and items as random effects:

$$\text{WasCorrect} \sim 1 + \text{ObjectiveFaceNum} * \text{SubjectiveFaceNum} + (1|\text{Item}) + (1|\text{Subject}).$$

This analysis allowed us to determine whether the previous findings (Asp et al., 2021) replicated under high levels of proactive interference.

We fit these models using the `fitglme` function in MATLAB with a binomial distribution. These models allowed us to examine how accuracy is impacted by both the objective and the subjective number of faces present under different levels of proactive interference, while taking into account item effects.

Results

Based on our previous work (Asp et al., 2021), we expected increased memory performance when more meaningful stimuli were shown. In addition, we predicted that the number of subjectively perceived faces/objects, even with the same number of stimuli objectively present, would also modulate memory performance. Our key question was whether these benefits would be modulated by the amount of proactive interference (i.e., stimulus repetitions). Specifically, if the meaningfulness benefit depends on durable, cross-trial memories of specific items, there should be greater proactive interference and hence lower performance for meaningful stimuli when these stimuli repeat across the experiment. Alternatively, if the meaningfulness benefit reflects the current trial's working-memory representation, we would expect no specific effect of proactive interference on the meaningfulness benefit, and thus similar memory performance across both conditions.

Experiment 1

In Experiment 1, memory performance was greater when more ambiguous faces, rather than scrambled faces,

were shown, $p < .001$. In strong contrast to the proactive interference possibility, we found, unexpectedly, that memory performance was greater under the high proactive interference condition than under the low proactive interference condition, $p < .001$. This most likely reflects greater stimulus familiarity or priming for repeated items (Blalock, 2015). Participants did also report slightly more items as meaningful in the high-interference block (1.08 vs. 0.97 of three on all-scrambled trials, $p < .001$), but, as we discuss later, this increase is partly a shift in response criterion that cannot by itself improve memory. The interaction between interference and the objective number of faces was not statistically significant, $p = .98$.

In a separate model, we examined the effect of both objective and subjective number of meaningful objects and their interaction separately for the high-interference condition, again treating both participants and items as random effects. In Experiment 1, recognition memory was greater when more meaningful faces were shown, $p < .001$, and when more faces were subjectively reported, $p < .001$. The interaction between these two factors was significant, $p < .001$, suggesting the relationship between the number of faces reported and recognition memory was strongest when more faces were objectively shown. This is largely what would be expected if each individual (objectively presented) face had an individual chance of being recognized, as can be seen in Fig. 2.

Experiment 2

Replicating results from Experiment 1, in Experiment 2, recognition memory was greater when more real objects,

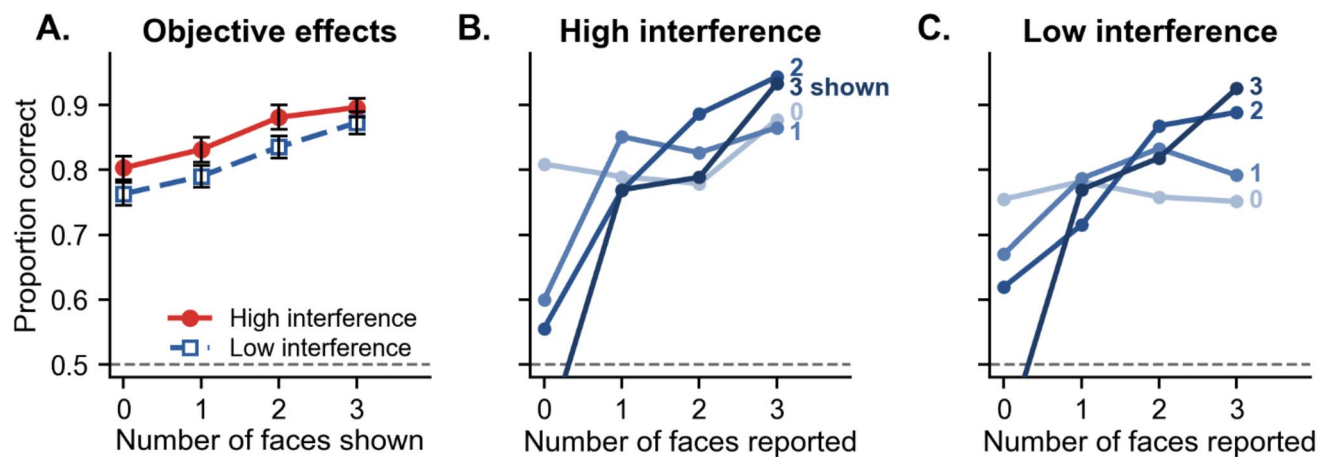


Fig. 2 Results from Experiment 1. (A) Visual working memory performance increases continuously when more faces are shown at encoding. Critically, there was no interaction between low- and high-interference conditions and the number of faces shown. However, there was a main effect of interference such that performance was overall higher for repeated (and thus more familiar) stimuli. (B)

For both the high-interference and (C) low-interference conditions, memory performance was higher when more faces were objectively shown (different-colored lines) and the more faces participants recognized (x-axis), with most of the effect of the number of faces shown captured by how many participants actually saw as faces

rather than scrambled objects, were shown, $p=.01$, and also greater under high interference than low interference, $p<.001$. The interaction between these conditions was also significant, $p=.02$, driven by higher performance in the high-interference block on trials where only scrambled objects were shown. This boost is once again most parsimoniously explained by stimulus familiarity: the repeated scrambled objects became more familiar with exposure and were therefore better remembered, independent of whether they were perceived as meaningful. Overall, these data indicate that meaningfulness improves memory during both high and low levels of proactive interference.

In the second model for Experiment 2, there was no main effect of the number of objects objectively shown, $p=.19$, but recognition memory was higher when more objects were subjectively reported, $p<.001$, and the two factors interacted, $p=.047$. Collapsing across the objective number shown, accuracy rose from 0.83 when no objects were reported as meaningful to 0.91 and 0.92 when one or two were reported, and then dipped slightly to 0.89 when three were reported. This non-monotonicity was concentrated on trials with few objectively present objects: when participants reported more meaningful objects than were actually shown (e.g., reporting three on all-scrambled trials: 0.86), accuracy was lower than when subjective reports matched a high objective number (e.g., three reported with three shown: 0.90; two reported with two shown: 0.92). Subjective recognition was thus associated with better memory when it was veridical (tracking objects that were in fact present), which is the source of the positive objective-by-subjective interaction, although there were a small number of trials where people reported more objects than were actually present,

which tracked with worse performance in these conditions. Performance was therefore driven by objects that were genuinely perceived as meaningful, not simply by the number of meaningful reports participants made (Fig. 3).

Was proactive interference induced?

These two experiments showed a general facilitation effect for repeated stimuli rather than a decrease in performance, which is the usual index for proactive interference. For the purposes of asking whether the meaningfulness effects arise from memory traces that last beyond a given trial, this provides strong evidence against this possibility: there was no interference for meaningful or non-meaningful stimuli reliably observed in this paradigm when items repeated across trials, suggesting none of the conditions here depended in any substantial way on memory traces beyond the particular trial. However, it is also informative to probe more directly for evidence of proactive interference within the high repetition block, to see if the manipulation of repeating items many more times had any effects on proactive interference.

On every high-interference trial, the two-alternative test pits the target against a foil that is also drawn from the small set of repeating images; proactive interference should therefore produce familiarity-driven false alarms when the foil was itself shown recently. For each high-interference trial we computed the lag since the foil was last presented and fit a generalized linear mixed-effects model predicting accuracy, with random intercepts for participant and item and covariates for within-block position, the foil's cumulative number of prior exposures, and target type. In Experiment 1 (faces,

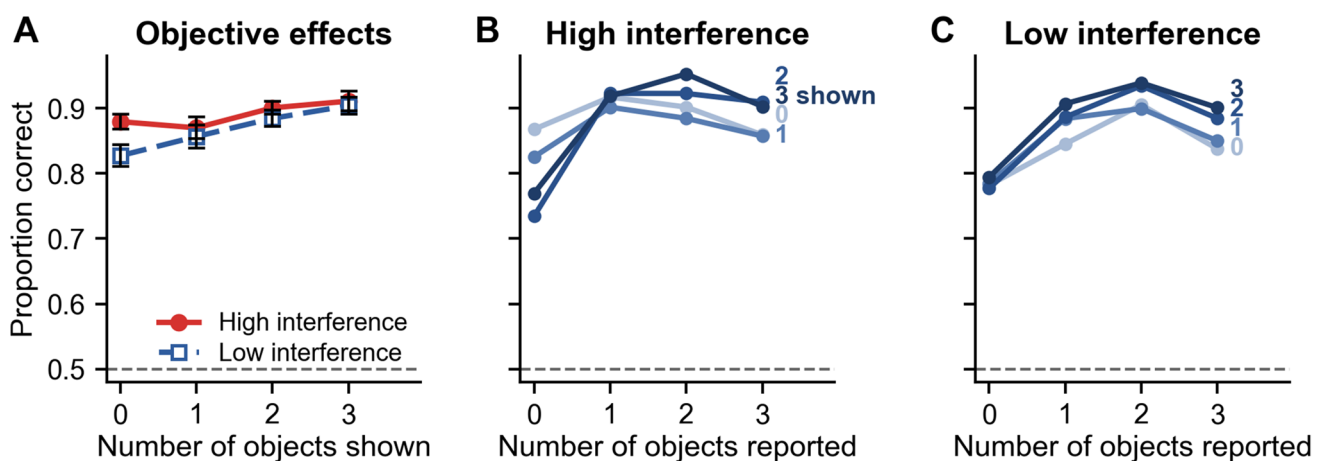


Fig. 3 Results from Experiment 2. (A) Visual working memory performance increased when more recognizable objects were shown at encoding. Interestingly, memory performance was higher for the high-interference condition when only scrambled objects were shown, possibly because the repeated scrambled objects became more

familiar with repetition (Blalock, 2015). (B) For the high-interference and (C) low-interference conditions, memory performance was again higher when more objects were subjectively recognized as meaningful

simultaneous), accuracy was unrelated to foil recency: a foil shown within the last five trials did not lower accuracy (odds ratio = 0.92, 95% CI [0.80, 1.05], $p = .21$). In Experiment 2 (objects, simultaneous), the same analysis revealed small but reliable interference (odds ratio = 0.80, 95% CI [0.69, 0.94], $p = .006$).

Thus, we find that in the experiment using faces, there is little proactive interference effect at all: people seem to largely benefit from increased exposure to the images, and there seems to be no evidence of reliance on an enduring memory trace that goes beyond a single trial. By contrast, a small effect of proactive interference was observed in the experiment using objects, suggesting that although there was little specificity in the proactive interference (with no effect on the meaningfulness effect), there was some proactive interference between trials observed.

Experiment 3: Sequential presentation

The first two experiments suggest that under standard, simultaneous visual working memory conditions, there is little effect of repetition on performance for either meaningful or non-meaningful stimuli. This argues against the use of enduring memory traces that go beyond a single trial in task performance overall and in the meaningfulness benefit in particular.

In Experiment 3, we sought to increase proactive interference substantially to see if there was any increase in, or elimination of, the meaningfulness benefit under conditions where across trial memories would be more likely to be relevant. To do so, we tested a sequential presentation with no spatial cue: all items shown at the center of the screen one after another.

This manipulation was chosen because presenting items at a single location forces them to be individuated by temporal rather than trial-specific spatial context; interference-based models of working memory predict that this should increase proactive interference (Makovski, 2016; Oberauer & Lin, 2024), providing a stronger test of whether interference modulates the meaningfulness benefit when items cannot be separated by distinct spatial cues (Brady & Störmer, 2022; Shoval & Makovski, 2022). Removing the spatial cues that allow items to be separated by location places the heaviest possible demand on temporal-context individuation and therefore provides the strongest available test for proactive interference, the regime in which interference-based models expect cross-trial intrusions to be largest (Makovski, 2016; Oberauer & Lin, 2024).

Methods

Participants

Experiment 3 used the same inclusion and exclusion criteria and the same recruitment procedure, and 30 participants met our inclusion criteria and were included in the final dataset (nine participants excluded).

Procedure

Experiment 3 used the same face stimuli as Experiment 1 (ambiguous Mooney faces and their scrambled counterparts), the same high- and low-interference block structure, and the same end-of-trial report of how many of the three images were perceived as faces. However, rather than appearing simultaneously for 1 s at three distinct spatial locations (as in Experiments 1 and 2), the three items were presented sequentially at the center of the screen: each item appeared for 500 ms, separated by 500-ms blank intervals, beginning after a 500-ms pre-trial fixation period.

After the third item, a 500-ms blank followed by a 1,300-ms retention interval (an 800-ms delay plus a 500-ms period, matching the delay and location-cue period of Experiments 1 and 2) preceded the 2-AFC test. Because the items appeared one at a time at a single central location, there was no spatial retrieval cue at test: the target (one of the three studied items, chosen at random) and a new foil of the same stimulus type appeared to the left and right of fixation, and participants indicated in a 2-AFC which of the two had been studied.

Results

As in Experiments 1 and 2, memory performance was greater when more ambiguous faces were shown, $p < .001$, and was greater under high than under low proactive interference, $p < .001$. The objective meaningfulness benefit interacted with interference, $p < .001$: more faces shown improved memory in both blocks (high, $p < .001$; low, $p < .001$). The effect of subjective recognition was undiminished: memory increased with the number of faces participants reported perceiving in both the high- and the low-interference blocks (both $p < .001$), and this relationship was, if anything, numerically stronger under high interference.

Within the high-interference block, both the objective and subjective number of faces predicted memory (both $p < .001$) and interacted, $p < .001$, indicating that the effect of how many faces were shown was carried largely by how many were actually perceived as faces. Thus, even under the strongest proactive interference, the core signature of the

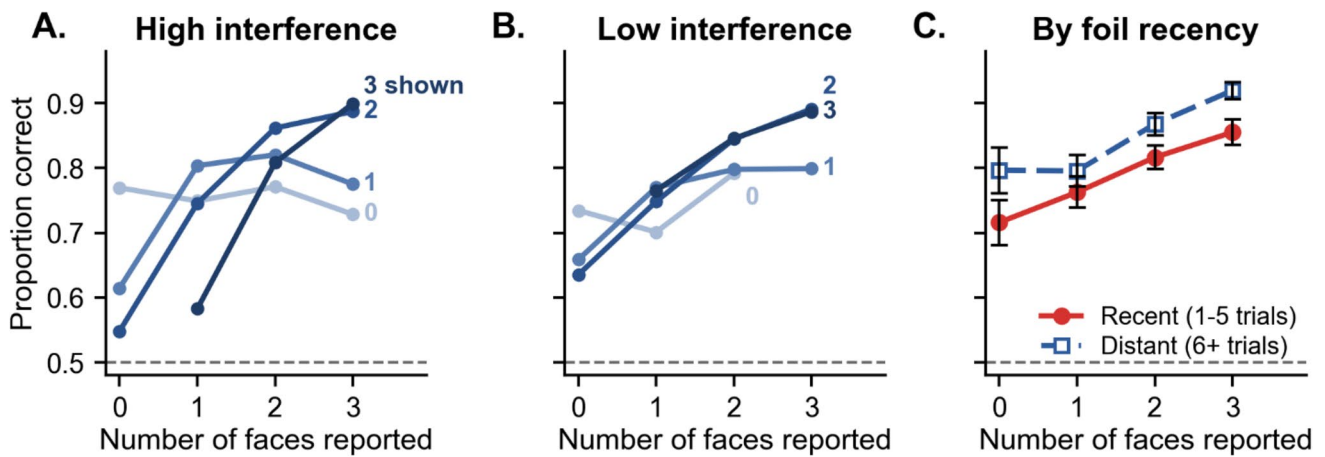


Fig. 4 Results from Experiment 3. Accuracy as a function of the number of faces participants reported perceiving, within the high-interference block (A) and the low-interference block (B), with separate lines for the number of faces objectively shown. In both cases, participants performed better the more faces they saw, and they saw more faces, and remembered items better, when more faces were shown. Cells with fewer than 15 participants are not plotted. (C)

The high-interference block split by how recently the test foil had last been seen. While performance is overall worse when foils have recently been seen, the meaningfulness advantage is identical in both cases, with more faces being seen resulting in better performance regardless of proactive interference. Error bars are ± 1 SEM; dashed gray lines mark chance

meaningfulness benefit, better memory for stimuli subjectively recognized as meaningful, was fully preserved. These results are shown in Fig. 4.

Was proactive interference induced?

In Experiment 3, unlike the other two experiments, proactive interference was substantial: a foil shown within the last five trials reduced the odds of a correct response by a third (odds ratio = 0.67, 95% CI [0.59, 0.76], $p < .001$), with accuracy falling from roughly 0.86 when the foil had last appeared many trials earlier to 0.73 when it had appeared on the immediately preceding trial.

Thus, while proactive interference was minimal in the canonical simultaneous task with faces, it was large under sequential presentation. This suggests that the lack of proactive interference in Experiment 1 is not a failure of the method or analysis: the identical analysis detects clear interference in Experiment 3, exactly where interference-based working-memory models predict more interference, namely when items must be individuated by temporal rather than trial-specific spatial context (Makovski, 2016; Oberauer & Lin, 2024). Instead, Experiments 1 and 2 suggest that the standard visual working memory paradigm with simultaneous presentation is largely unaffected by proactive interference (see Hartshorne, 2008; Lin & Luck, 2012), as is the meaningfulness benefit in that paradigm. Increasing proactive interference with sequential presentation in Experiment 3 also did not diminish the impact of meaning on memory.

General discussion

The present study was designed to test whether the meaningfulness benefit in visual working memory can, at least in part, be explained by reliance on more durable, cross-trial memory traces for meaningful stimuli, or whether it is driven by the current trial's working-memory representation. To examine this, we used proactive interference, a behavioral marker of reliance on memories that persist across trials (Engle, 2002; Lin & Luck, 2012). We either repeated stimuli frequently over the course of a block, in different locations and roles, or showed each stimulus only once, reasoning that this should introduce high versus low levels of proactive interference, respectively. We predicted that if the meaningfulness benefit depends on durable cross-trial memory, there should be greater proactive interference, and thus lower performance, for meaningful stimuli when they frequently repeat than when they do not. Across three experiments using different sets of ambiguous stimuli, we found that the meaningfulness advantage was consistent across levels of stimulus repetition, regardless of whether proactive interference was negligible (as in the canonical simultaneous presentation paradigm) or substantial (as in a sequential presentation with no spatial cues). Performance increased continuously with stimulus meaningfulness across all conditions, indicating that durable cross-trial memories play little role in driving this advantage.

These data are consistent with electrophysiological data demonstrating stronger active maintenance in working

memory for more meaningful stimuli relative to non-meaningful shapes (Asp et al., 2021; Brady et al., 2016; Chung et al., 2026; Park & Awh, 2026; Thibeault et al., 2024). In these studies, the contralateral delay activity, an event-related potential that is sensitive to how much information is actively maintained in visual working memory (Vogel & Machizawa, 2004; Vogel et al., 2005), was measured and it was found that neural delay activity contralateral to the to-be-remembered side increased with more meaningful stimuli, mirroring the behavioral improvements. The current data provide converging evidence that participants are using an active maintenance system within a single trial to perform this task and thus the meaningfulness benefit in typical, simultaneous presentation-style visual working memory situations is due to active storage of the individual items on each trial and does not depend primarily on less active and potentially more durable memory representations that persist across trials. If the latter were the case, we should have seen a smaller meaningfulness benefit in conditions of proactive interference (i.e., repeated stimuli). The meaningfulness benefit was present and equally strong for both repeated and non-repeated items. Thus, we conclude that durable, cross-trial memories do not play a critical role in the meaningfulness benefit.

Cross-trial memories

We emphasize that this conclusion concerns a specific kind of long-term memory contribution: the substitution of durable, cross-trial episodic memories for active maintenance (Bartsch & Shepherdson, 2022; Schurgin et al., 2018). It does not rest on the strong assumption that working memory consists only of the items in the focus of attention. According to contemporary multi-state accounts, working memory includes representations beyond a narrow focus of attention that are nonetheless maintained within working memory and remain subject to interference (Cowan, 2011, 2019; Oberauer, 2019). Proactive interference is therefore not, by itself, a signature of long-term memory as opposed to working memory; interference-based models treat it as an intrinsic property of working memory, with intrusions that scale with similarity in spatial and temporal context (Oberauer & Lin, 2024). What our manipulation isolates is whether the meaningfulness benefit depends on durable episodic traces that accumulate across trials, which would cause it to shrink as items repeat. Across both sequential and simultaneous displays, it does not.

Notably, despite their potentially high susceptibility to proactive interference, repeated stimuli produced higher overall working memory performance than non-repeated stimuli. Because we used ambiguous stimuli, one possibility is that repeated exposure made the faces and objects more recognizable, and indeed participants reported more items

as meaningful in the high-interference (repeated) blocks. However, decomposing these reports by the objective number of meaningful items present shows that the increase was, especially in Experiment 2, largely a shift in response criterion rather than improved recognition. In Experiment 2, participants reported roughly 0.35 more items as meaningful in the high-interference block irrespective of how many meaningful items were objectively present (a uniform effect of block, $b=0.36$, $p<.001$), with no change in how steeply subjective reports tracked the objective number (block by objective-number interaction, $b=-0.02$, $p=.14$). Experiment 1 showed a similar though smaller criterion shift ($b=0.09$, $p<.001$) together with a genuine gain in recognition (block by objective-number interaction, $b=0.04$, $p<.001$). A shift in the criterion for the end-of-trial report cannot improve accuracy on the two-alternative test, which is scored against the objective target independently of what participants reported, so it cannot be the source of the higher performance under repetition. That benefit is better explained by stimulus-specific familiarity and perceptual fluency accrued through repeated exposure (Blalock, 2015; Starr et al., 2020), which aid memory without a genuine change in perceived meaning.

Previous work on proactive interference in visual working memory

Our results also speak to why proactive interference has been observed in some prior visual working memory studies but not others. Most studies that, like our Experiments 1 and 2, use simultaneous, brief presentations of several spatially separated stimuli (the canonical visual working memory task) find little proactive interference (e.g., Hartshorne, 2008; Lin & Luck, 2012), whereas tasks that present objects sequentially at the center of the screen find much more (e.g., Endress & Potter, 2014; Shoval & Makovski, 2022). Our own Experiment 1 versus Experiment 3 reproduces this contrast: presenting the same faces sequentially at one location, rather than simultaneously at distinct locations, produced robust proactive interference whereas the simultaneous version produced essentially none. On an interference-based account this is expected, because sequential central presentation forces items to be individuated by temporal rather than spatial context, increasing cross-trial intrusions (Burgess & Hitch, 1999; Makovski, 2016; Oberauer & Lin, 2017, 2024).

Our results contrast in several ways with Shoval and Makovski (2022) and Park and Awh (2026). Shoval and Makovski (2022) varied stimulus repetition in a sequential task and, like us, found a robust meaningfulness benefit; however, unlike our simultaneous experiments, their benefit was strongest for non-repeated items. Whereas our Experiments 1 and 2 used a standard display of three images at distinct locations, they presented eight items sequentially at the same central location, which, given the dependence

of proactive interference on spatial separation (Makovski, 2016), would be expected to maximize interference. There are other significant differences between the Shoval and Makovski (2022) work and ours that could also play a role. For example, the no-repeat condition in their study used novel items on every trial for encoding as well as at test (foil); thus, each image only appeared once across the entire experiment; in contrast, for the repeat-condition, two different sets of images were used and the foils at test (requiring a “new” response) were drawn from this repeating item set as well. Thus, higher performance in the no-repeat condition could be explained by a novelty detection mechanism rather than an effect of proactive interference – and thus activated long-term memory involvement – in the repeat-condition (Nosofsky et al., 2021). Here, we dissociated these by probing memory performance with a 2-AFC test that included repeated images in both conditions (i.e., there were no unique novel foils in the no-repeat condition). Finally, the nature of the stimuli differed: while we used stimuli that were ambiguous but could potentially also be recognized after multiple repetitions, Shoval and Makovski (2022) used scrambled versions of real-world objects that were likely not recognizable even after multiple repetitions.

Another recent study examined working memory for simple icons versus colors, finding an advantage for icons only when they were unique, not when they were repeated (Park & Awh, 2026). The authors argued that the working memory advantage for meaningful objects reflects reduced proactive interference and thus long-term familiarity rather than expanded active storage. As noted above, this inference assumes that susceptibility to proactive interference marks a representation as belonging to long-term memory rather than working memory; yet on contemporary multi-state accounts of working memory (Cowan, 2019; Oberauer, 2019), and interference-based models in particular (Oberauer & Lin, 2024), proactive interference is an intrinsic property of working memory, so interference-sensitivity does not by itself denote a benefit as arising from long-term memory. We also note that the behavioral conclusions of Park and Awh (2026) are difficult to assess because their analyses focus on *K* values, despite ROC data that strongly violate the assumptions required for *K* to be a valid measure (see Brady et al., 2023; Robinson et al., 2025; Williams et al., 2022). This concern is not merely theoretical as criterion shifts are visible in their raw hits and false alarm scores. Their dual-process model analysis similarly assumes that high-confidence “old” responses reflect a qualitatively distinct, noiseless memory process, which is not well supported (see Wixted, 2007). Together, these measurement concerns make it difficult to draw firm conclusions from their data about the role of proactive interference for the meaningfulness benefit.

Beyond these measurement concerns, the comparison between icons and colors raises a more fundamental

design issue: It is inherently difficult to compare memory performance across different stimuli sets, because performance always strongly depends on foil and stimulus dissimilarity (see Brady & Störmer, 2023). Notably, according to CLIP embedding space – the simplest computer vision model of confusability that also captures semantics – real objects (even randomly paired ones) are approximately twice as dissimilar as the icons used by Park and Awh, raising concerns about the fairness of the comparison. Our design avoids this issue by comparing identical stimuli across the critical conditions. Performance was higher when an identical Mooney image was subjectively perceived as a face or object than when it was not, regardless of how often it was repeated. Our foil-recency analyses, as a more direct measure of the presence of interference, revealed that proactive interference was minimal in the simultaneous face task (Experiment 1), modest in the simultaneous object task (Experiment 2), and substantial in the sequential task (Experiment 3); critically, the meaningfulness benefit persisted across all three, directly demonstrating that it does not depend on the level of proactive interference.

Our conclusion that meaningful stimuli engage active storage more, not less, is consistent with the increased contralateral delay activity observed for meaningful stimuli (Asp et al., 2021; Brady et al., 2016; Park & Awh, 2026; Thibeault et al., 2024). For example, Asp et al. (2021) found that recognized Mooney faces resulted in larger CDA (contralateral delay activity) and higher behavioral performance, consistent with many previous claims that the CDA generally tracks how much information is held actively in mind and thus tends to correlate with better behavioral performance.

Even though Park and Awh (2026) replicate the now well-established finding of increased CDA with more meaningful objects (Asp et al., 2021; Brady et al., 2016; Chung et al., 2026; Thibeault et al., 2024), they interpret this differently, arguing that CDA amplitude cannot be compared across stimulus types, even when it tracks perfectly with behavior. We disagree: the simplest and most parsimonious interpretation is that participants remembered more information from each object than color, at all set sizes, consistent with both the behavioral pattern and standard practice in the literature, where CDA is routinely compared across conditions that differ in stimulus properties (e.g., across set sizes, Vogel & Machizawa, 2004; letters vs. colors: Rajsic et al., 2019; well-learned Pokemon vs. distinct ones, Xie & Zhang, 2018; perceptually different groups of faces, Ye et al., 2026). While CDA amplitude is not a process-pure index of how many items are stored, since attention and perceptual demands modulate it as well (Emrich et al., 2022), in all of these situations both memory performance and CDA move together in a way reflecting more information about the items being held in mind in the

meaningful object conditions. Previous work also suggests that experiments that match the stimuli and equate how often they are seen across the experiment still find the object benefit in both behavior and the CDA (e.g., Asp et al., 2021; Thibeault et al., 2024), even though in these experiments a difference in proactive interference between conditions is not a possible explanation. Thus, taken together, neither the behavioral nor the neural evidence from Park and Awh (2026) compels the conclusion that the meaningfulness benefit reflects reduced proactive interference rather than expanded working memory storage.

That the meaningfulness benefit survived the complete removal of spatial cues in Experiment 3 fits a broader pattern in which the advantage of meaningful stimuli does not depend on spatial scaffolding to the same extent as simpler stimuli. Meaningful, recognizable objects improve working memory even for low-level features that must be held without relying on the object's location (Chung et al., 2023, 2024), and the benefit for object identity is preserved under sequential, single-location encoding (Brady & Störmer, 2022; Chung et al., 2024). Our results extend this principle to ambiguous, subjectively recognized stimuli: perceiving an item as meaningful aids its maintenance whether items are individuated by their spatial location, as in the simultaneous displays of Experiments 1 and 2, or by temporal context alone, as in the sequential displays of Experiment 3. Meaning thus provides a basis for individuating and maintaining items in working memory that is complementary to, and independent of, spatial cues.

Several further points bear on interpretation. First, the meaningfulness benefit may operate in part through binding: recent work shows that meaning improves the binding of items to their locations rather than the number or precision of locations stored (Sahar et al., 2024). Relatedly, the benefit for meaningful object identity can exceed what binding alone would provide (Chung et al., 2024). Proactive interference is only one window onto the contribution of durable memory; other approaches, such as retro-cueing, can complement it, and future work combining these methods would be valuable. Finally, because participants reported the number of meaningful items at the end of each trial, meaningfulness was an explicit part of the task; although this report was identical across interference conditions and stimulus types, and so cannot explain the dissociations we observe, it may have encouraged attention to the meaningful items during encoding, and an implicit measure of perceived meaning would be a useful complement in future work.

In conclusion, across three experiments, we found clear evidence that meaningful stimuli were better remembered relative to non-meaningful abstract shapes; critically, this memory advantage was strongly driven by an individual's subjective experience with the stimulus rather than its physical properties: when participants recognized an ambiguous

stimulus as meaningful (as a face in Experiments 1 and 3, or as an object in Experiment 2), performance was increased compared to when these stimuli were not recognized as meaningful. Furthermore, the physical properties of these stimuli were matched on average across our participants, but when this same physical input was perceived as meaningful, memory performance for that stimulus was increased (Asp et al., 2021; Brady et al., 2019). This replicates previous findings that perceived meaningfulness rather than physical properties of a given stimulus are key in enhancing visual working memory capacity (Asp et al., 2021; Conci et al., 2021, 2023). The present experiments expand significantly on this previous work by showing that these effects generalize to ambiguous objects (Experiment 2), persist under proactive interference, and remain robust, at least for subjectively recognized stimuli, even under the strong interference produced by sequential presentation (Experiment 3). Overall, we found that participants were able to maintain more items in working memory when more of these items were perceived as meaningful, replicating previous work and extending it to a new set of ambiguous stimuli. These effects were strongest when participants reported subjectively perceiving more of the items as meaningful, indicating these effects were not driven by physical differences between the stimuli but by how meaningful they were to the individual observer. Most critically, we found that this advantage for meaningful stimuli persisted even at high levels of proactive interference, providing evidence that the meaningfulness benefit is not due to participants relying on more durable memory traces, such as cross-trial episodic memories, but instead, consistent with neural data of working memory engagement, is likely because such stimuli allow for more resources within the focus of attention in working memory. Moreover, repeating the same stimulus set did not impair overall performance, which would be unexpected if participants relied on durable memories that were persistent across trials to perform the task. Overall, these results add to growing evidence that pre-existing knowledge can be leveraged to increase active storage in working memory.

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Data availability Data and code are available at <https://osf.io/c9xhp/>

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Declarations

Ethics approval Approval was obtained from the ethics committee of the University of California San Diego. The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Consent to participate All participants gave informed consent in line with Institutional Review Board requirements.

Consent for publication Not applicable.

Conflicts of interest/Competing interests The authors have no relevant financial or non-financial interests to disclose.

Open practices statement The inclusion criteria, hypothesis, and analysis plan were preregistered (Exp. 1: <https://aspredicted.org/blind.php?x=5ag6g9>; Exp. 2: <https://aspredicted.org/blind.php?x=cw384j>). Data and code are available at <https://osf.io/c9xhp/>

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