

Persistent effects of salience in visual working memory: Limits of cue-driven guidance

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Abstract

Visual working memory (VWM) is a core cognitive system enabling us to select and briefly store relevant visual information. We recently observed that more salient items were recalled more precisely from VWM and demonstrated that these effects of salience were quite resilient against manipulations of reward, probability, and selection history. Here, we investigated whether and how salience interacts with shifts of attention induced by pre- and retro-cueing. Across four experiments, we consistently found effects of salience on the precision of VWM. Spatial and feature cues presented before the memory display improved precision when they validly indicated the target but failed to modulate the salience effect. Feature retro-cues with moderate validity did not improve precision. However, effects on precision emerged when the validity of the retro-cue was increased and a spatial component was added. Overall, there was little interaction between cueing effects and target salience. This suggests that salience plays a critical role in how items are initially encoded into VWM and that once representations are formed, their relative priority based on salience appears difficult to fully override via top-down mechanisms. These findings highlight bottom-up and top-down processes in the interplay of visual attention and working memory.

Public Significance Statement

Our eyes are bombarded with far more information than we can thoroughly process. Therefore, objects that stand out from their surroundings are preferentially attended. It has been shown that these objects are also better remembered. However, even when we try to focus on less salient objects, this initial attentional capture has a lasting impact. The present study shows that even when we have information about the relevant objects, more salient objects are still remembered better.

Keywords: Salience, Attentional priority, Visual working memory, Cues

Visual working memory (VWM) holds visual information available for short periods of time and is a key component of human cognition. However, it is also severely limited in capacity. The reason for the limitation differs between models of VWM (Oberauer & Lin, 2017; Schurgin et al., 2020; Zhang & Luck, 2008). The slot model assumes that items are encoded in an all-or-nothing fashion. That is, each item in VWM occupies one or several slots and is represented with high precision, while the representation of items without a slot is random (Zhang & Luck, 2008). In contrast, the continuous-resource model posits that individuals have a limited but continuous resource that can be flexibly allocated between items in VWM (Bays et al., 2009; van den Berg et al., 2014). The allocation of this resource depends on attentional selection processes.

The selection process that allows the human visual system to efficiently sort through vast amounts of information to identify and process relevant stimuli is often called visual attention. This selection process is guided by an internal priority map, that is, a dynamic representation that highlights

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All experiments reported here were preregistered on OSF. The preregistrations, experimental programs, analysis scripts, and data files can be found at: https://osf.io/9gc3x/

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locations or features of higher behavioral relevance within the visual field (Awh et al., 2012; Corbetta & Shulman, 2002; Liesefeld et al., 2020, 2024; Wolfe, 2021; see also Anderson, 2024). Prioritization is created from a mixture of top-down and bottom-up factors, as well as selection history. In light of recent research, it seems that the precision of information in VWM is proportional to the level of attentional prioritization (Constant & Liesefeld, 2021, 2023; Dube et al., 2017; Emrich et al., 2017; Huynh Cong & Kerzel, 2022; Klyszejko et al., 2014; Lockhart et al., 2024; Ravizza & Conn, 2022). Therefore, the continuous-resources model seems like a more adequate framework than the slot model to explain effects of prioritization in VWM.

The main bottom-up (i.e., stimulus-driven) factor driving the allocation of these resources is salience, also defined as the local feature contrast (Liesefeld et al., 2016; Nothdurft, 1993). That is, the more an item's features differ from the surrounding items, the more salient it is. Highly salient stimuli "pop out" subjectively and can attract attention reflexively. For instance, a colored street sign may stand out in its grayish environment because its color differs from the surrounding objects. Consistent with bottom-up effects on the distribution of resources in VWM, salience was found to be a major determinant of VWM precision (Constant & Liesefeld, 2021).

Top-down processes, on the other hand, involve the goal-driven modulation of the priority map. Observers can willfully prioritize certain objects, features, or locations according to their current objectives while ignoring salience. For instance, the less salient stimuli in Constant and Liesefeld (2023) were probed more often and therefore had a higher top-down priority. However, the bottom-up effects of salience were hard to overrule, even at long encoding times. Possibly, attention was still attracted first to the most salient stimulus and redirected only later to the less salient but more relevant stimuli. This could have provided the most salient stimulus with a head start in the race for the allocation of VWM resources (Ravizza et al., 2021).

Based on these findings, we investigated whether shifts of attention occurring before or after the onset of the memory display can erase the effects of salience in a VWM task. We hoped to further disentangle the relative contributions of top-down and salience-driven shifts of attention on memory performance. To that effect, we designed four experiments using pre- or retro-cues. Pre-cues cues provide advance information about target features or locations and have been used in VWM and visual search tasks to enhance the priority of upcoming stimuli (Bays et al., 2011; Boettcher et al., 2021; Dodwell et al., 2024; Gazzaley & Nobre, 2012; Gresch et al., 2024b; Grubert & Eimer, 2018; Schmidt et al., 2002; Vogel & Machizawa, 2004). Retro-cues have also been extensively used to study VWM, and are generally assumed to work through internal attentional reprioritization (Gazzaley & Nobre, 2012; Gresch et al., 2024a, 2024b; Griffin & Nobre, 2003; Huynh Cong & Kerzel, 2020; Souza & Oberauer, 2016; Souza et al., 2014, 2016; van Ede & Nobre, 2023; van Ede et al., 2020). To preview the results, we find that effects of salience co-exist with the performance boost provided by the cues. Experiments 1 and 2 investigated effects of pre-cues, whereas Experiments 3 and 4 investigated effects of retro-cues.

Experiment 1

In the first experiment, we evaluated whether a spatial pre-cue would erase the effects of salience. Spatial cues have been demonstrated to enhance memory performance in other VWM tasks (Bays et al., 2011; Emrich et al., 2017; Li & Saiki, 2015; Schmidt et al., 2002; Vogel & Machizawa, 2004). Participants were instructed to remember the color of three tilted bars shown among vertical filler bars. The bars in this memory set had a slight, medium, or strong tilt, which resulted in weak, medium, and strong salience. The pre-cue was a dot presented at the (future) location of a stimulus from the memory set. A trial was valid when the pre-cue appeared at the location of the tilted bar that was probed at the end of the trial and invalid when it appeared at the location of a tilted bar that was not probed. It is possible that in our earlier experiments, the bars with slight or medium tilt were not found in time because they were less salient, resulting in weaker encoding. It is also likely that they were not attended first and might therefore not benefit from the same boosted VWM resources as the strongly tilted bar, which was likely to be found first because it was the most salient stimulus in the display. When pre-cueing a stimulus from the memory set, the cued bar is likely to be attended first because the cue had a validity of 67%. We thus expected effects of salience to be absent with valid pre-cues.

Methods

Transparency and openness

We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study. All experiments were pre-registered. All cleaned data, analysis code, preregistrations and research materials are available on OSF (https://osf.io/9gc3x/). Data were analyzed using CPython 3.12.3 with the following packages: *pandas* 2.2.2 (The pandas development team, 2024), *numpy* 1.26.4 (Harris et al., 2020), *scipy* 1.13.0 (Virtanen et al., 2020) and *seaborn* 0.13.2 (Waskom, 2021). False discovery rate (FDR) corrections were computed with *pingouin* 0.5.4 (Vallat, 2018). JASP 0.18.3 was also used to conduct Bayes Factors analyses (JASP Team, 2024; Love et al., 2019).

For all experiments, convenience sampling was used, that is, first year psychology bachelor students were recruited and compensated with course credits. We did not gather ethnicity nor race information about the participants, and we asked them to report their gender. All participants provided informed consent prior to the experiment, reported normal or corrected-to-normal visual acuity, normal color vision and were naive as to the purpose of the study. The experimental procedures were approved by the ethics committee of the Faculty of Psychology and Educational Sciences of the University of Geneva. The experiments are reported in the chronologic order in which they were performed. All data were collected in 2023.

Sample size

For each experiment, sample size was determined via sequential testing with Bayes factors (*BF*), following the recommendations by Schönbrodt and Wagenmakers (2018) with a minimum of 10 and a maximum of 30 participants. We stopped testing when sufficient evidence for either the null or the alternative ($BF_{10} \geq 6$ or $BF_{01} \leq 3$) was reached for each pre-registered critical test. The critical tests determining the stopping rule for Experiment 1 examined whether recall error would decrease with object salience. We expect a decrease with salience when pre-cues were invalid, but no effect of salience with valid pre-cues because the target was attended first. As a manipulation check, we also examined whether performance was improved for valid compared to invalid pre-cues for each of the three tilts (12°, 28°, 45°). The stopping rule resulted in a sample of 25 adults (Mean age: 21.08 ± 2.22 [*SD*], 19 women/6 men, all right-handed). No participant was excluded.

Stimuli, procedure & design

Stimuli were displayed on a color-calibrated (80 cd/m² D65 whitepoint) 22.5" IPS-LCD monitor (VIEWPixx Lite, 1920 × 1200 pixels, 100 Hz, scanning backlight) at a viewing distance of 67 cm. All lights were turned off in the experimental room. OpenSesame 4.0 (Mathôt et al., 2012) with the PsychoPy backend (Peirce et al., 2019) was used for stimulus presentation.

The core task design was similar to our previous experiments (Constant & Liesefeld, 2021, 2023). Each trial began with the presentation of a central white fixation dot (radius: 0.18 degrees of visual angle [*dva*]) against a dark gray background (RGB: [60, 60, 60], 3.1 cd/m²). After 300 ms, a spatial pre-cue was presented for 50 ms and the memory display appeared 650 ms after the cue disappeared. The delay between cue disappearance and memory display appearance is comparable to the one used in Yoo et al. (2018). The spatial pre-cue was a small black circle (radius: 0.37 dva, thus subtending the same area as the bars) with a white outline presented at the (future) location of a stimulus from the memory set. The pre-cue indicated the stimulus from the memory set that was tested at the end of the trial in 2 out of 3 trials (66.7%; valid cue condition). Each of the remaining two stimuli from the memory set were cued on 16.7% of trials for a total of 33.3% invalid trials.

The memory display consisted of 33 vertical and 3 right-tilted (12°, 28° and 45°) bars each subtending 1.30 × 0.33 dva (see Figure 1). The bars were colored and arranged on three (invisible) concentric rings (radius of 2, 4 and 6 dva) with respectively 6, 12 and 18 bars on each. The tilted bars were presented on the middle ring (eccentricity of 4 dva). Colors were randomly drawn from a circle in a luminance plane of the CIE 1976 L*a*b* color space (L* = 63, center: a* = 9, b* = 27, illuminant: D65, 2° standard observer) with a radius of 40. This ensured that all colors could be mapped onto the 24-bits sRGB color space while being theoretically equally salient. Indeed, CIE L*a*b* is a device-independent color space based on the opponent color theory (Hering 1920/1964) that aspires to be perceptually uniform, taking into account the specificities of the human color vision system (see, Fairchild, 2013). The xyY coordinates of all colors were measured with an X-Rite i1Display Pro VPixx edition and are available on OSF.

The memory display appeared for 350 ms and was followed by a delay period of 1000 ms. Then, the color wheel appeared. Its rotation was randomly selected from 12 possible rotations and there were 360 different colors. The color wheel had a diameter of 8 dva and was 0.67 dva thick. Inside the color wheel, the bars from the memory display were shown in their original tilts, but as black outline placeholders. All placeholder bars were filled in the same dark gray as the background except for the target, which was initially filled in black. Participants were instructed to report the color they remembered for the target bar (Wilken & Ma, 2004). After being initially black, the color of the probed bar changed dynamically to match the color at the current mouse position. After selecting the remembered color by mouse click, the correct color was briefly indicated on the color wheel. Each participant completed a total of 504 trials divided into blocks of 36 trials. Thus, for each of the three tilts, there were 112 valid trials and 56 invalid trials.

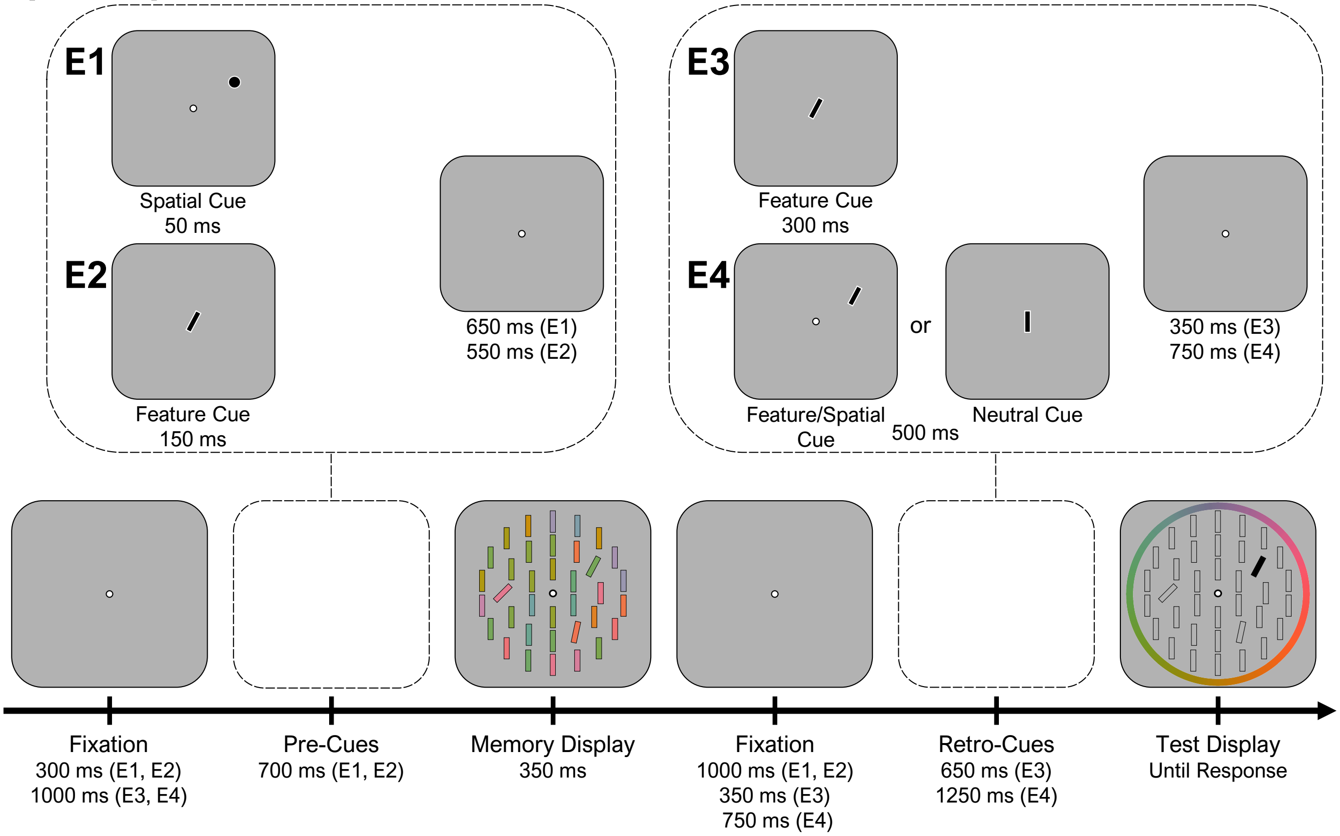
Analysis

Our analyses focused on the mean absolute angular distance between the correct and the selected color (*recall error*). As stated in our preregistrations, participants with an average recall error above 80° were excluded. Unless otherwise stated descriptive statistics are reported as mean ± 95% within-participant confidence interval (Cousineau, 2005; Cousineau & O'Brien, 2014; Morey, 2008). Although we did not preregister a correction for multiple comparisons, we checked that *p* values remained significant after FDR correction (Benjamini & Yekutieli, 2001).

Statistical analyses were performed with custom Python scripts and validated with JASP 0.18.3 with the default prior for the Bayesian analyses, that is, a Cauchy distribution with

Figure 1

Experimental procedures.



Note. A valid or neutral cue trial is shown. That is, the cue indicated the location or tilt of the target. In Experiments 1, 2 and 3, the cue was valid in 67% and invalid in 33% of the trials. In Experiment 4, the cue was either 100% valid or neutral (non-informative). The gray background in the figure is lighter than in the experiments.

a location of 0 and scale of $\frac{\sqrt{2}}{2}$). Planned directed Bayesian t tests (Rouder et al., 2009) were conducted to analyze the differences between the conditions. Since the Python implementation of the Bayesian directed t tests did not always converge, we used results from JASP for these.

BayesFactors (BF) quantify the support for a hypothesis over another (first vs. second subscript), regardless of whether these models are correct. The subscript "0" always refers to the null hypothesis (H_0). For two-sided tests, the subscript "1" refers to the alternative hypothesis (H_1). When conducting one-sided (directed) tests, the subscripts "+" or "–" were used depending on the direction of the hypothesis (H_+ or H_-, respectively) in place of the subscript "1". Throughout the results, we report the BF for the most favored hypothesis from the test we ran (e.g., if the null is more probable in a two-sided test, BF_{01} is reported instead of BF_{10}), as we find it most intuitive to interpret. We also report the traditional (frequentist) significance tests for reference as well as the effect sizes (mainly Hedges' g_p [Hedges, 1981; Hedges and Olkin, 1985], the unbiased equivalent of Cohen's d_p [Cohen, 1988]) followed by their 95% CI in brackets (Fitts, 2020, 2022; Goulet-Pelletier & Cousineau, 2018, 2019). The subscript "p" in g_p and d_p reflects the fact that the pooled standard deviation was used to compute the effect size (instead of e.g., the standard deviation of the differences for Cohen's d_z). This allows for a direct comparison with effect sizes obtained in between-participants designs.

Results

The results of the pre-registered statistical tests (https://osf.io/6y9k5/) are shown in Table 1. As expected, performance improved for all tilts with valid compared to invalid pre-cues. In the invalid pre-cue conditions, performance was also significantly better for more salient targets. However, contrary to our expectation that performance would be equal between all tilts in the valid pre-cue condition, there was an effect of tilt. Thus, salience facilitated memory performance even though attention was shifted to the target position before onset of the memory display.

An exploratory ANOVA showed a significant interaction between Pre-cue validity and Target tilt, $F(2, 48) = 5.28$, $p = .008$, $\omega^2 = .027$. Based on visual inspection of Figure 2 (left panel) and effect sizes of the post hoc *t* tests, it appears that the effect of tilt was stronger for the invalid than for the valid pre-cue condition (see OSF repository for the full ANOVA table and descriptive statistics).

Discussion

These results indicate that valid spatial pre-cues could not erase the effects of salience despite significantly boosting VWM performance. Even when participants attended the position of the target before it appeared, performance remained superior for more salient targets. Possibly, VWM information accumulates at a faster rate for more salient targets. Alternatively, salient targets may have captured attention on most trials, even when the less salient targets were cued. Finally, more salient targets may have been harder to attentionally disengage from, leading to a longer encoding time.

The exploratory ANOVA showed a slightly weaker effect of salience for validly cued stimuli, which might be explained by a ceiling effect. Indeed, the recall error for the 45° valid pre-cue condition was 22.44° ± 3.67, which is comparable to the best performance observed in Experiment 1 of Constant and Liesefeld (2023) at 2000 ms of encoding time (24.11° ± 2.73). Thus, there was less room for improvement between 28° and 45° in the valid cue condition.

Experiment 2

Experiment 1 demonstrates that effects of spatial cueing and effects of salience co-exist and do not appear to be in competition. If there had been competition, we would have expected no effects of salience with valid pre-cues, notably because the higher relevance of the cued stimulus would have caused little to no inspection of the non-cued stimuli from the memory set. In Experiment 2, instead of using spatial pre-cues to guide spatial attention, we presented feature pre-cues. By priming the tilt of the bar from the memory set that would be probed, we aim to boost its priority within the search process. We will first determine whether feature pre-cues improve color memory for bars with the cued tilt. Attention can be guided in a spatially global manner to stimuli sharing the attended feature (e.g., Sàenz et al., 2003; Treue & Trujillo, 1999). As a result, stimuli matching the pre-cues may be found earlier and additionally, processing of the color pertaining to the attended tilt may be enhanced. Both the earlier localization and the enhancement are expected to improve recall.

Methods

In Experiment 2 the pre-registered hypotheses (https://osf.io/apuy6/) were similar to Experiment 1 with one notable exception. Because of the unexpected effect of salience in the valid pre-cue condition of Experiment 1, we now expect to replicate this effect in Experiment 2.

We collected data from 31 participants, and one was excluded because they did not finish the experiment, thus the final sample size was composed of 30 participants (Mean age: 21.16 ± 4.22 [*SD*], 27 women/3 men, 2 left-handed).

Experiment 2 was modeled after Experiment 1 with one key difference. We used a feature instead of spatial pre-cue. That is, at the start of a trial, we presented a black right-tilted bar (12°, 28° or 45°) with a white outline in the center of the display. The tilt of the bar validly indicated the orientation of the target in 67% of the trials. The presentation time was increased to 150 ms (from 50 ms in Experiment 1), while the delay between the cue disappearance and onset of the memory display was reduced to 550 ms (from 650 ms), resulting in the same SOA of 700 ms. As in Experiment 1, each participant completed a total of 504 trials divided into blocks of 36 trials. Thus, for each tilt, there were 112 valid trials and 56 invalid trials.

Results

The outcome of the pre-registered statistical tests is shown in Table 2 (descriptive statistics available on OSF). As expected, in the invalid pre-cue condition, the precision of color judgments improved with the salience of the probed stimulus. Similar to Experiment 1, however, this effect was also observed with valid pre-cues. Further, the precision was better with valid than invalid pre-cues for 12° and 45° targets, but surprisingly, there was no difference between invalid and valid pre-cues for the 28° target.

After visual inspection of Figure 2, it looked like the effect of cues was weaker in this experiment than in Experiment 1. To investigate this, we performed an exploratory mixed ANOVA with the difference between valid and invalid cues (for each target tilt) as the dependent variable, Target Tilt as the repeated-measure factor and Experiment (spatial pre-cue vs. feature pre-cue) as the between-participant factor. The main effect of Experiment was significant, $F(1, 53) = 50.51$, $p < .001$, $\omega^2 = .314$, showing that the valid spatial pre-cues enhanced performance more than the valid feature pre-cues (recall error decrease of 31.69° ± 5.06 vs. 6.06° ± 1.60). The interaction Experiment × Target Tilt was also significant, $F(2, 106) = 12.68$, $p < .001$, $\omega^2 = .046$, but the pattern of results is clear enough that we can still interpret the main effect of Experiment.

Discussion

The results of Experiment 2 largely replicate the key findings of Experiment 1. Feature pre-cues, like spatial pre-cues, significantly improved VWM performance overall. It therefore seems that feature pre-cues accelerated access or enhanced processing of the target, which improved VWM per-

Table 1

Paired Samples t *Tests for Experiment 1.*

Comparison	$t(24)$	p	Hedges' g_p	*BF*	Favors
12° Valid ≠ 28° Valid[Ø]	6.08	$< .001$	0.73 [0.46, 1.12]	6901	H_1
28° Valid ≠ 45° Valid[Ø]	4.57	$< .001$	0.46 [0.25, 0.75]	223.65	H_1
12° Valid ≠ 45° Valid[Ø]	6.94	$< .001$	1.14 [0.76, 1.68]	4.70e+4	H_1
12° Invalid > 28° Invalid	5.79	$< .001$	0.89 [0.55, 1.34]	7219	H_+
28° Invalid > 45° Invalid	4.04	$< .001$	0.48 [0.24, 0.80]	134.78	H_+
12° Invalid > 45° Invalid	8.45	$< .001$	1.35 [0.96, 1.92]	2.22e+6	H_+
12° Invalid > 12° Valid	7.97	$< .001$	2.44 [1.74, 3.37]	8.24e+5	H_+
12° Invalid > 28° Valid	11.99	$< .001$	3.59 [2.78, 4.72]	1.37e+9	H_+
12° Invalid > 45° Valid	14.35	$< .001$	4.19 [3.32, 5.44]	5.05e+10	H_+
28° Invalid > 12° Valid	4.91	$< .001$	1.35 [0.78, 2.04]	962.98	H_+
28° Invalid > 28° Valid	8.40	$< .001$	2.19 [1.59, 3.00]	1.98e+6	H_+
28° Invalid > 45° Valid	10.25	$< .001$	0.76 [0.18, 1.41]	6.89e+7	H_+
45° Invalid > 12° Valid	2.60	.008	0.76 [0.18, 1.41]	6.43	H_+
45° Invalid > 28° Valid	5.48	$< .001$	1.46 [0.91, 2.16]	3530	H_+
45° Invalid > 45° Valid	6.99	$< .001$	1.83 [1.25, 2.57]	1.04e+5	H_+

Note. The Ø symbol marks comparisons for which the outcome was opposite to our expectation. All p values remain significant after FDR correction (15 comparisons; Benjamini & Yekutieli, 2001).

Table 2

Paired Samples t *Tests for Experiment 2.*

Comparison	$t(29)$	p	Hedges' g_p	*BF*	Favors
12° Valid > 28° Valid	10.80	$< .001$	1.40 [1.05, 1.90]	1.60e+9	H_+
28° Valid > 45° Valid	10.40	$< .001$	1.68 [1.27, 2.27]	6.89e+8	H_+
12° Valid > 45° Valid	16.31	$< .001$	3.14 [2.51, 4.03]	2.98e+13	H_+
12° Invalid > 28° Invalid	13.44	$< .001$	1.75 [1.35, 2.35]	2.53e+11	H_+
28° Invalid > 45° Invalid	4.31	$< .001$	0.66 [0.35, 1.05]	317.32	H_+
12° Invalid > 45° Invalid	13.14	$< .001$	2.44 [1.91, 3.18]	1.48e+11	H_+
12° Invalid > 12° Valid	3.92	$< .001$	0.50 [0.24, 0.81]	124.09	H_+
28° Invalid > 28° Valid[Ø]	0.45	.327	0.05 [−0.17, 0.27]	3.51	H_0
45° Invalid > 45° Valid	6.58	$< .001$	1.05 [0.70, 1.51]	1.00e+5	H_+

Note. The Ø symbol marks comparisons for which the outcome was opposite to our expectation. All significant p values remain significant after FDR correction (9 comparisons; Benjamini & Yekutieli, 2001).

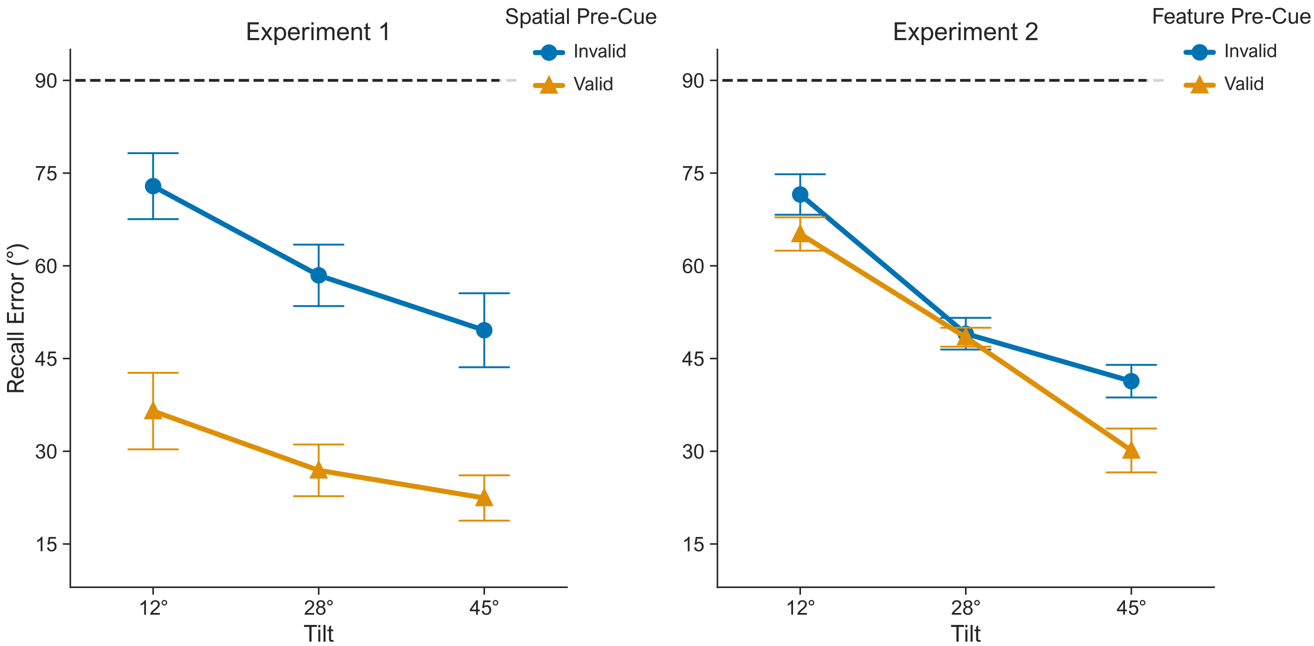
formance. However, as can be observed in Figure 2, the magnitude of that effect was smaller than with spatial pre-cues. This probably led to the lack of difference between valid and invalid conditions for targets with 28° tilt. It could be that the feature pre-cues worked not only for the cued feature, but also for similar features. Thus, 28° pre-cues would not only enhance the 28° tilt, but also the 12° and 45° tilts, which would attenuate the difference between valid and invalid 28° pre-cues. Overall, even with this top-down guidance, the impact of salience persisted. Targets with higher salience were consistently recalled with greater accuracy. This finding strengthens the conclusion that the influence of salience on VWM performance seems to interact minimally with top-down cueing strategies.

Experiment 3

It has been demonstrated in other VWM tasks that it is possible to flexibly reallocate resources during the maintenance period, the underlying assumption being that internal selective attention is reallocated to the relevant stimulus as

Figure 2

Results from Experiments 1 and 2.



Note. The y-axis represents recall error for the target color (in degrees on the colorwheel) as a function of target tilt (degrees of rotation relative to vertical) and validity of the pre-cue. The spatial pre-cue appeared at the location of a stimulus from the memory set. The feature pre-cue shared its tilt with a stimulus from the memory set. Cues indicated the correct bar in 67% of the trials. The dotted lines represent chance level. Error bars reflect 95% within-participant confidence intervals (Cousineau, 2005; Morey, 2008).

opposed to external attention being guided to the relevant stimulus in pre-cue paradigms (Gresch et al., 2024b; Souza & Oberauer, 2016; van Ede & Nobre, 2023; van Ede et al., 2020). In Experiment 3, by presenting a retro-cue that indicated the tilt of a stimulus from the memory set after the memory display disappeared, we aimed to isolate potential timepoints where salience impacts VWM. There are two possibilities. If salience primarily affects the speed or quality of VWM encoding, retro-cues should have little impact. However, if salience influences the stability of VWM representations over time, retro-cues could potentially "rescue" less salient items by shifting the internal selective attention towards them during the maintenance period. We hypothesized that retro-cues would increase recall performance, but that they would not modulate the effect of salience.

Methods

In Experiment 3, the pre-registered hypotheses (https://osf.io/gscr4/) were identical to that of Experiment 2. This resulted in a sample of 21 participants (Mean age: 20.24 ± 1.83 [*SD*], 18 women/3 men, 2 left-handed).

Experiment 3 was modeled after Experiment 2. The key difference was that the central tilt cue was presented after the memory display instead of before. More specifically, the retro-cue appeared 350 ms after the memory display and stayed for 300 ms. After its disappearance, another 350 ms preceded the appearance of the response display. As in the previous experiments, each participant completed a total of 504 trials divided into blocks of 36 trials. Thus, for each probed tilt, there were 112 valid trials and 56 invalid trials.

Results

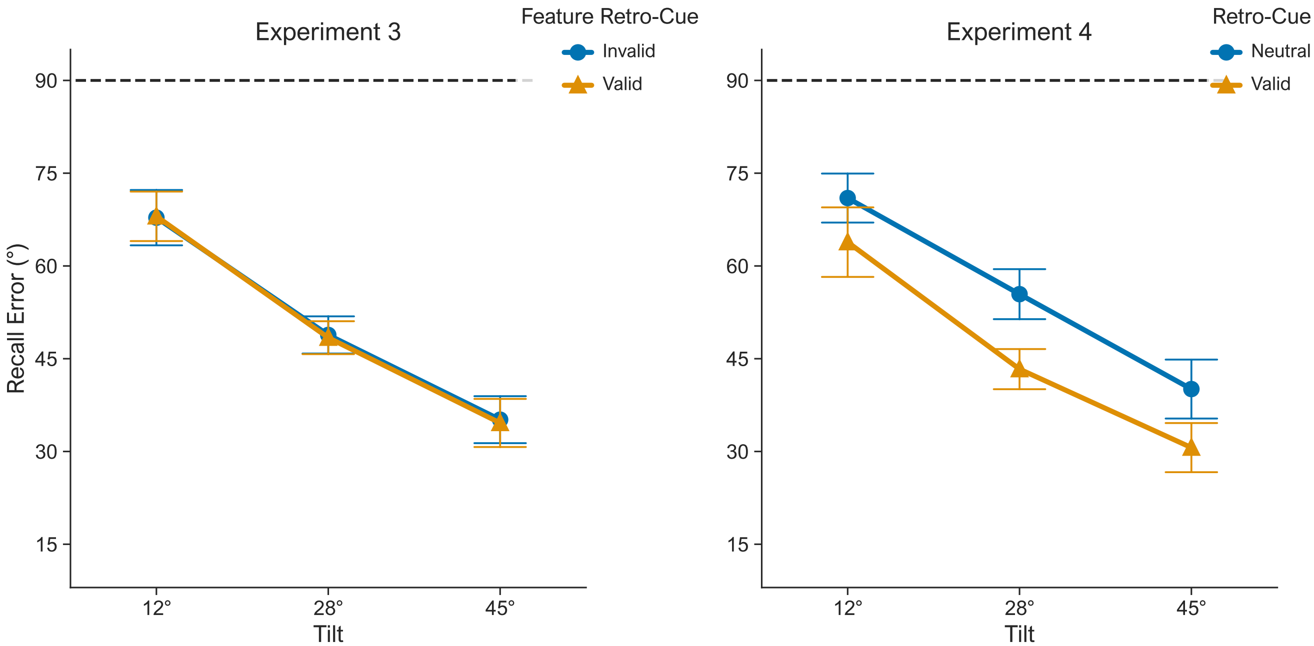
As shown in Table 3 and consistent with previous experiments, effects of salience were observed both for valid and invalid retro-cue conditions. However, in this experiment, there was virtually no effect of the retro-cue validity on performance (see Figure 3, left panel).

Discussion

In Experiment 3, the retro-cue had virtually no effect. Given that feature pre-cues had a smaller effect than spatial pre-cues (Experiment 2 vs. Experiment 1; see also Li & Saiki, 2015), and that probabilistic retro-cues were shown to have a smaller effect than deterministic retro-cues (Dube & Al-Aidroos, 2019; Gözenman et al., 2014; Günseli et al., 2015), it could be that the combination of these factors rendered the retro-cue ineffective. It could also be that partic-

Figure 3

Results from Experiments 3 and 4.



Note. The feature retro-cue in Experiment 3 shared its tilt with a stimulus from the memory set and indicated the correct tilt in 67% of the trials. The retro-cue in Experiment 4 either shared its tilt and location with the target (100 % valid cue) or was a centrally presented vertical bar. The dotted lines represents chance level. Error bars reflect 95% within-participant confidence intervals (Cousineau, 2005; Morey, 2008).

ipants disregarded the retro-cue if they perceived it as less informative than their initial internal memory representation, and thus felt it did not help them enough. Another reason that the retro-cue wasn't effective could be that there might not have been enough time between the memory and the response display, which could further reduce the usefulness of the retro-cue (Luo et al., 2023). Finally, the lack of retro-cue effect might suggest that once stable initial representations are formed, their relative priority may be difficult to alter within the maintenance period. The expected effect of retro-cues in VWM tasks might thus be only observed when attentional priority in the memory set is roughly equal during encoding, which was not the case in the current experiments because of the differences in salience.

Experiment 4

The findings of Experiment 3 suggest that the influence of salience on VWM may be primarily established during encoding and may be difficult to modify during the maintenance phase. However, the null effect of retro-cues could also stem from some methodological choices. We therefore made the following adjustments to make the retro-cue more effective. First, the retro-cue was both featural and spatial instead of only featural. Second, the maintenance interval was doubled from 1 to 2 seconds with the assumption that the longer cue-to-test interval might improve the retro-cue efficiency (Gözenman et al., 2014). Third, retro-cue validity was increased to 100%, which makes the retro-cue deterministic and more effective (Dube & Al-Aidroos, 2019; Günseli et al., 2015). Because there was no invalid condition, the efficiency of the retro cue was evaluated through comparisons with neutral retro-cues.

Overall, Experiment 4 provides a more robust test of whether salience-based biases in VWM can be modulated after encoding. If performance remains influenced by salience despite more effective retro-cues, it is likely that salience shapes the initial VWM encoding process in a way that is resistant to subsequent top-down intervention.

Methods

In Experiment 4, the pre-registered hypotheses (https://osf.io/7qtvn/) were identical to that of Experiment 3. This resulted in a sample of 15 participants (Mean age: 20.73 ± 1.83 [*SD*], 17 women/4 men, 2 left-handed).

Experiment 4 was modeled after Experiment 3 with the following differences. The retro-cue could either be neutral or 100% valid. Furthermore, it was a combined feature/spatial retro-cue. That is, when it was neutral, it was a

Table 3

Paired Samples t *Tests for Experiment 3.*

Comparison	$t(20)$	p	Hedges' g_p	BF	Favors
12° Valid > 28° Valid	9.25	< .001	1.56 [1.12, 2.26]	2.23e+6	H_+
28° Valid > 45° Valid	6.61	< .001	1.26 [0.83, 1.89]	1.95e+4	H_+
12° Valid > 45° Valid	10.72	< .001	3.00 [2.26, 4.07]	2.24e+7	H_+
12° Invalid > 28° Invalid	6.73	< .001	1.38 [0.92, 2.05]	2.44e+4	H_+
28° Invalid > 45° Invalid	6.81	< .001	1.15 [0.76, 1.73]	2.85e+4	H_+
12° Invalid > 45° Invalid	10.63	< .001	2.60 [1.94, 3.57]	1.94e+7	H_+
12° Invalid > 12° Valid^{Ø}	−0.12	.549	−0.02 [−0.29, 0.25]	4.81	H_+
28° Invalid > 28° Valid^{Ø}	0.29	.386	0.03 [−0.21, 0.29]	3.47	H_+
45° Invalid > 45° Valid^{Ø}	0.32	.375	0.05 [−0.29, 0.40]	3.39	H_+

Note. The Øsymbol marks comparisons for which the outcome was opposite to our preregistration. All significant p values remain significant after FDR correction (9 comparisons; Benjamini & Yekutieli, 2001).

vertical black bar presented centrally and otherwise, it was a tilted bar (sharing its tilt with the target) presented at the target's location. This also means that the analyses now compare neutral vs. valid retro-cue conditions, instead of invalid vs. valid previously. Half of the trials featured the neutral retro-cue and the other half the valid retro-cue.

Another difference is that the delay interval between memory display and response display was extended to 2000 ms and the retro-cue appeared 750 ms after memory display offset for 500 ms. Thus, another 750 ms separated retro-cue offset from response display onset.

Each participant completed a total of 504 trials divided into blocks of 36 trials. Thus, for each probed tilt, there were 84 valid trials and 84 neutral trials.

Results

All pre-registered hypotheses were confirmed in Experiment 4 (see Table 4 and Figure 3, right panel). There was an effect of salience both for neutral and for valid retro-cue conditions. The effect of retro-cue was also significant with performance in the valid retro-cue condition being better than in the neutral retro-cue condition.

Discussion

The results of Experiment 4 again demonstrate the remarkable resilience of salience effects on VWM. Despite stronger effects of combined feature and spatial retro-cues, the effect of salience remained virtually intact. This replicates the core findings of previous experiments, further solidifying the conclusion that salience shapes the initial VWM encoding process in a manner highly resistant to later top-down manipulation.

General Discussion

It has previously been demonstrated that effects of salience on VWM are robust to top-down and selection history effects (Constant & Liesefeld, 2023). However, this observed robustness could have been related to the fact that the manipulations in Constant and Liesefeld (2023) were performed across trials. In other words, it could be that these were not trial-specific enough to counteract the trial-specific salience effects. Here, across four experiments, we have tried to manipulate the effects of salience on VWM using trial-specific top-down manipulations. That is, using various cues, we tried to bias priority towards a given stimulus from the memory set in each trial.

In Experiment 1, spatial pre-cues were used to make sure that all targets were reliably found. Indeed, when the pre-cue was valid in this experiment, it is almost certain that the less salient targets were found, and likely that they were attended first. Nonetheless, and contrary to our expectations, there was still a strong effect of salience when the pre-cue was valid. This observation provides evidence against the explanation that the effects of salience might be due to a head start in the race for VWM resources (Bundesen, 1990; Ravizza & Conn, 2022; Ravizza et al., 2016, 2021).

The feature pre-cues of Experiment 2 allowed us to demonstrate that, as expected, boosting the goal-relevance of a target enhanced its recall precision (Bays et al., 2011; Constant & Liesefeld, 2023; Dube & Al-Aidroos, 2019; Dube et al., 2017; Emrich et al., 2017; Yoo et al., 2018; Zokaei et al., 2011). However, again, this didn't impact the effect of salience. Although irrelevant, salience seemed to still be the main driver of the performance differences. It could be that salience intrinsically influences the speed or quality of VWM encoding (Krüger et al., 2016, 2017; Tünnermann et al., 2015).

Table 4

Paired Samples t *Tests for Experiment 4.*

Comparison	$t(14)$	p	Hedges' g_p	BF	Favors
12° Valid > 28° Valid	7.25	< .001	1.14 [0.74, 1.85]	9585	H_+
28° Valid > 45° Valid	6.13	< .001	0.97 [0.59, 1.62]	1871	H_+
12° Valid > 45° Valid	9.81	< .001	2.11 [1.47, 3.30]	2.41e+5	H_+
12° Invalid > 28° Invalid	6.36	< .001	0.82 [0.51, 1.37]	2667	H_+
28° Invalid > 45° Invalid	5.93	< .001	0.86 [0.52, 1.45]	1390	H_+
12° Invalid > 45° Invalid	10.03	< .001	1.96 [1.38, 3.01]	3.12e+5	H_+
12° Invalid > 12° Valid	2.74	.008	0.38 [0.10, 0.78]	7.53	H_+
28° Invalid > 28° Valid	5.31	< .001	0.66 [0.38, 1.14]	527.20	H_+
45° Invalid > 45° Valid	5.14	< .001	0.76 [0.43, 1.31]	403.71	H_+

Note. All p values remain significant after FDR correction (9 comparisons; Benjamini & Yekutieli, 2001).

The fact that these experiments did not alter the effect of salience is also evidence that VWM encoding in our displays does not seem to be performed sequentially without resampling (i.e., encoding stimuli one by one, from the highest to the lowest priority). Indeed, should encoding be sequential, we would expect that the first item encoded is remembered worse than items encoded at later point (due to recency effects; Gorgoraptis et al., 2011). The expectation would also be that either the cued item or the most salient item is encoded first because it has the highest priority, and would therefore have the worst performance, which is completely opposite to the present data patterns. A more likely hypothesis is that the target with the highest priority is sampled more than targets with lower priority, thus building a more robust memory trace.

Experiments 3 and 4 used retro-cues to determine whether the memory representation of the targets could be enhanced after encoding. One possibility was that the performance for less salient targets could be enhanced while the performance of more salient targets would be relatively unaffected. However, the retro-cue had no effect in Experiment 3. In Experiment 4, the retro-cue was designed to be much stronger but still had little to no impact on the effect of salience. This further underscores the early and persistent influence of salience on VWM encoding, suggesting a limited capacity for subsequent top-down adjustments (Constant & Liesefeld, 2023).

We started out with the idea that goal-directed guidance provided by cues might be better suited to counteract the effects of salience than guidance provided by instructions alone. However, despite trying several types of cues, at different times in the VWM processing pipeline with different validity, effects of salience always persisted.

Due to its pivotal role on any further cognitive processes that rely on it, VWM is the major bottleneck of visual processing (Liesefeld & Müller, 2019; van Ede & Nobre, 2023). Any influence on VWM is likely to propagate to further processing stages. Therefore, since the effects of salience on VWM were shown to be immune to most top-down manipulations, any study on VWM or more advanced processing should be designed to carefully control for salience.

Constraints on generality

Our sample was composed of first-year psychology students at the University of Geneva, who were mostly young women. Therefore, our results might not generalize to the entire population.

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