https://doi.org/10.1037/xge0001420

Effects of salience are long-lived and stubborn

Martin Constant[1,2] and Heinrich R. Liesefeld[1]
[1]Department of Psychology, University of Bremen, 28359 Bremen, Germany
[2]Graduate School of Systemic Neurosciences, Ludwig-Maximilians-Universität, 82152 Planegg, Germany

Abstract

Salience is a core determinant of attentional processing. Although information on salience has been shown to dissipate within a few hundred milliseconds, we recently observed massive effects of salience on the delayed recall from visual working memory (VWM) more than 1300 ms after stimulus onset. Here, we manipulated presentation duration of the memory display and found that effects of salience, albeit decreasing over time, were still markedly present after 3000 ms (2000 ms presentation; Exp. 1). In an attempt to overrule this persistent influence of salience we made less salient stimuli more relevant (by rewarding their prioritized processing in Exp. 2 or by probing them more often in Exp. 3). Participants were unable to reliably prioritize low-salience stimuli. Thus, our results demonstrate that effects of salience or their repercussions have surprisingly long-lasting effects on cognitive performance that reach even relatively late processing stages and are difficult to overrule by volition.

Public Significance Statement

Objects that stand out from their surround often grasp attention. This effect of salience has been used to avoid harm. For instance, safety equipment is often made of reflective material with bright unnatural colors (e.g., a lifebuoy). However, previous reports of effects of salience lasting for only a few hundred milliseconds and being quickly overridden by goal-driven processes, render this effort questionable: why bother if salience plays a role only for a glimpse? The present study shows that effects of salience last for a long time; even after 3 seconds and more they are not completely overridden by experience or volition. Thus, salience plays a much larger role for human cognition than has been previously assumed.

Keywords: Saliency, Guidance, Attentional priority, Visual short-term memory, Visual attention

Research on visual attention and on visual search, in particular, has long demonstrated that the allocation of *attentional* resources is based both on top-down and bottom-up factors (Awh et al., 2012; Corbetta & Shulman, 2002; Liesefeld et al., 2020; Wolfe, 2021). The major bottom-up factor for attentional resource allocation is salience. Salience arises mainly from the local feature contrast of a given stimulus and its surroundings; stimuli with a high level of salience subjectively stand out from their environment (Liesefeld et al., 2016; Nothdurft, 1993). It is assumed that salience drives overt and covert allocations of attention in the absence or in the service of a specific task (Itti & Koch, 2001). When stimuli share the same task relevance, salience determines the order of attention allocation (Christie et al., 2018; Woodman & Luck, 1999) and, under certain conditions, salience can even overrule task relevance (Liesefeld, Liesefeld, & Müller, 2022; Liesefeld et al., 2017).

While salience is a major driving factor of attention, it has been claimed that its effects are short-lived (Donk & van Zoest, 2008; van Heusden et al., 2022). Specifically, these bottom-up effects would quickly be relegated by top-down control effects (de Vries et al., 2011; van Zoest & Donk, 2006; van Zoest et al., 2004) or, under the right conditions, even be mitigated before their expression (Einhäuser et al., 2008; Folk & Remington, 1998; Gaspelin & Luck, 2018).

Considering this tension between the high behavioral importance of salience and the apparent short-livedness of its effects, we would like to point out that research on salience focuses almost exclusively on covert or overt (eye movements) shifts of attention, which are short-lived phenomena themselves. Recently, we have shown that salience can influence visual working memory (VWM), a much longer lasting cognitive mechanism; in a paradigm newly developed to examine effects of salience on VWM performance, we presented memory arrays with colored bars for 350 ms and one out of 3 tilted bars was probed for recall after a 1000-ms retention interval (see Figure 1 and https://doi.org/jbgf). Targets differed in salience, but were equally likely to be probed at recall thus, top-down factors cannot be responsible for any observed effects. Still, VWM recall performance more than 1300 ms after the memory-display onset was heavily affected by salience (Constant and Liesefeld, 2021; see also Klink et al., 2017).

Therefore, even if effects of salience on attentional processes and eye movements are short-lived, their repercussions at later processing stages, such as VWM, might affect behavior much more deeply than would be expected based on the findings from the attention community alone. In fact, VWM is considered the major cognitive bottleneck of visual processing with effects on even later stages such as object recognition, long-term memory formation, and action control (Liesefeld & Müller, 2019; Liesefeld et al., 2020; Rösner et al., 2022; van Ede & Nobre, 2023), so that any effect on VWM processing has strong implications for many cognitive functions and applied settings.

On that background, we wanted to see how stable effects of salience are, that is, how long after display onset they would affect behavior (Exp. 1) and how resistant they are against opposing top-down influences (Exps. 2 and 3). Results indicate that effects of salience are long-lived and quite resistant to top-down manipulations.

This paper was accepted for publication in *Journal of Experimental Psychology: General*.

We have no known conflict of interest to disclose.

Martin Constant

Heinrich R. Liesefeld

All experiments reported here were preregistered on OSF. The preregistrations, experimental programs, analysis scripts, and data files can be found at: https://osf.io/xq2ng/

We are grateful to Anna M. Liesefeld for her critical input on the paper and to Dimana Balcheva for her assistance in data collection. This research was supported by the German Research Foundation (DFG) under Grant LI 2868/3-1 awarded to HRL.

Data from Experiment 1 and 3 were presented at the VSS 2020 and VSS 2022 meetings, and data from Experiment 2 were presented at the VSS 2022 meeting (Constant & Liesefeld, 2020; Liesefeld, Constant, & Oberauer, 2022).

Correspondence concerning this article should be addressed to Martin Constant, Department of Psychology, University of Bremen, Hochschulring 18, 28359 Bremen, Germany, Email: martin.constant@uni-bremen.de

General Materials and 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. The experiments' designs and analyses were preregistered. All cleaned data, analysis code, preregistrations and research materials are available at https://osf.io/xq2ng/. Data were analyzed using CPython 3.9.13 with the following packages: *pandas* 1.4.4 (Reback et al., 2022), *numpy* 1.23.2 (Harris et al., 2020), *scipy* 1.9.1 (Virtanen et al., 2020) and *seaborn* 0.12.0 (Waskom, 2021). JASP 0.16.4 was also used to conduct Bayes Factors (*BF*) analyses (JASP Team, 2022; Love et al., 2019). For Experiment 1 and 3, convenience sampling was used, that is, participants were recruited through a mailing list used mostly for experiment recruitment at the LMU München. For these experiments, we did not gather ethnicity or race information about the participants and we asked their "Geschlecht", which is the German word covering both sex and gender. For Experiment 2, our sample was obtained through Prolific where participants indicated their sex and ethnicity. In this experiment, three participants were not from Europe, the ethnicity of two participant was "Mixed" and one was "Black", the rest of the participants were "White".

Sample size

For each experiment, sample size was determined via sequential testing with *BF*s, following the recommendations by Schönbrodt and Wagenmakers (2018) with a minimum of 10 and a maximum of 60 participants for Experiment 1 and 3, and 100 for Experiment 2. We stopped testing when sufficient evidence for either the null or the alternative ($BF \geq 6$) was reached for each critical test.

Participants received either course credits or monetary remuneration (9€/h). All participants provided informed consent prior to the experiment, reported normal or corrected-to-normal visual acuity and normal color vision, and were naïve as to the purpose of the study. The experimental procedures were approved by the ethics committee of the Department Psychology and Pedagogics at LMU München.

Stimuli, procedure & design

For Experiment 1 and 3, stimuli were displayed on a color-calibrated (120 cd/m² D65 whitepoint) 24" TFT-LCD monitor (ASUS VG248QE, 1920×1080 pixels, 144 Hz) at a viewing distance of 70 cm. The testing room was pitch dark and there were between one and four participants in each testing session. OpenSesame 3.2.8 (Mathôt et al., 2012) with the PsychoPy (Peirce, 2008) backend was used for stimulus presentation. Experiment 2 was coded in HTML and JavaScript. For this experiment, screen size and distance from the screen were estimated using the virtual chinrest method (Li et al., 2020).

Each trial began with the presentation of a central fixation dot (white, 0.18° radius) against a gray background (L* = 25.3, 14 cd/m²). After 1000 ms, a memory display was presented, consisting of 33 vertical and 3 tilted (12°, 28° and 45°) colored bars each subtending a visual angle of 1.30 × 0.33° (see Figure 1). The bars were arranged in three concentric rings (2°, 4° and 6° radius) with respectively 6, 12 and 18 bars on each. The relevant (tilted) bars were always presented on the middle ring.

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 (Mean ΔE2000 between two adjacent colors: 0.43). These parameters were chosen to ensure that all colors could be mapped onto the 24-bits sRGB color space. 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 (for a more detailed overview, see Fairchild, 2013).

The memory display (duration depending on the experiment) was followed by a delay period of 1000 ms during which only the fixation dot was shown. A response display was then presented containing a randomly rotated (30° steps) color wheel (360 colors) and outlined placeholder bars at the location of each bar from the memory display. One of the placeholders was filled in black to indicate which bar to report (hereafter: *probe*), and participants were instructed to report the color they remembered for that bar by using the computer mouse to select a point on the color wheel. The color wheel had a width of 0.66° and a radius of 8°. While the mouse hovered on the color wheel, the probe dynamically changed color according to the mouse position.

After each response, a feedback line appeared at the correct location on the color wheel to show the correct response (and, by implication, how far off the actual response was) to the participant.

Analysis

Our analyses focus on the mean absolute angular distance between the correct and the selected color (henceforth: *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).

Statistical analyses were performed with custom Python scripts and validated with JASP 0.16.4 (JASP Team, 2022; Love et al., 2019) with default settings for the priors. We did not implement the Bayesian directed t tests nor Bayesian ANOVAs in Python, thus we used the results from JASP. Bayesian repeated-measures ANOVAs and planned directed Bayesian t tests (Rouder et al., 2009) were conducted to analyze the differences between the conditions.

BayesFactors (BF) quantify the support for a hypothesis (first subscript) over another (second subscript), regardless of whether these models are correct. The subscript "0" always refers to the null hypothesis (H_0). When conducting undirected (two-sided) tests, the subscript "1" refers to the alternative hypothesis (H_1). When conducting directed (one-sided) tests, instead of "1", the subscripts "+" or "–" were used depending on the direction of the hypothesis (H_+ or H_-, respectively). Throughout the results, we reported the BF for the most favored hypothesis from the test we ran (e.g., if we ran a non-directed test and the null was more probable, BF_{01} was reported instead of BF_{10}), as we find it most intuitive to interpret. We also reported the traditional (frequentist) significance tests for reference and the effect sizes (mainly Hedges' g_z [Hedges, 1981; Hedges and Olkin, 1985], the unbiased equivalent of Cohen's d_z [Cohen, 1988]) followed by their 95% *CI* in brackets (Fitts, 2020; Goulet-Pelletier & Cousineau, 2018, 2019).

Experiment 1

In the first experiment, we evaluated how different presentation times (14 ms – 2000 ms) would impact the effect of salience on VWM performance. Potentially, the 350-ms presentation time plus 1000-ms retention interval in our previous study (Constant & Liesefeld, 2021) might not have been enough time to see the dissipation of salience effects observed in attentional tasks (Donk & van Zoest, 2008; van Heusden et al., 2022). Presentation time rather than the retention interval was manipulated, because we wanted to maximize the opportunity to overcome effects of salience, for instance by spending more time encoding less salient targets (e.g., via re-sampling them) if these originally received less attention or by allowing more information on less salient targets to accumulate if the rate of accumulation depends on salience. We expected (preregistration: https://osf.io/byr2v) the effects of salience to decrease with increasing presentation time (i.e., the longer an array is presented the less salience should affect VWM performance).

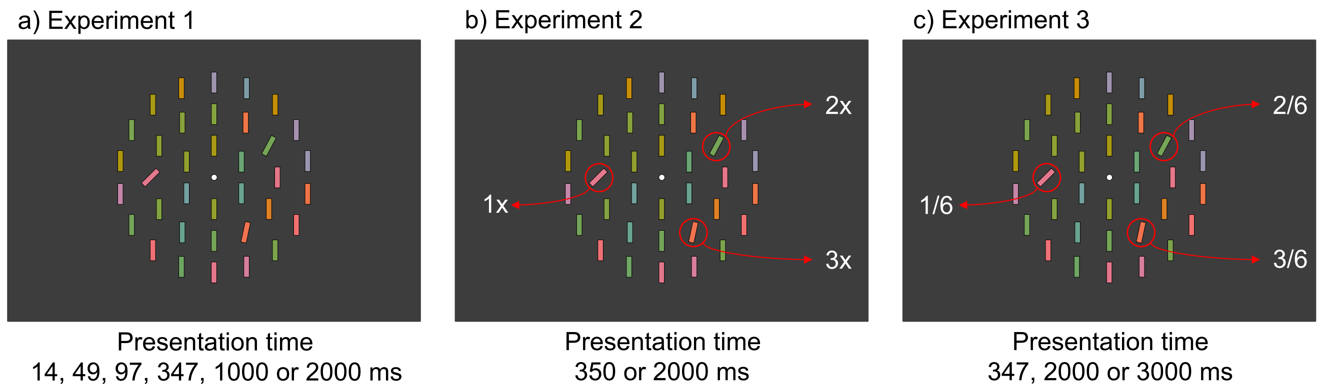
Methods

The critical tests determining the stopping rule for Experiment 1 examined whether VWM performance (*recall error*) would decrease with object salience (tilt). This resulted in a sample of 16 healthy human adults (Mean age: 26.88 ± 1.34 [*s.e.m.*], 9 female/7 male, 1 left-handed) collected in 2019. No participant was excluded.

In Experiment 1, the memory display was presented for either 14, 49, 97, 347, 500, 1000 or 2000 ms and all targets were equally relevant.

Figure 1

Memory displays used in the present study.



Note. Participants had to remember the color of only the tilted target bars. They were informed that vertical bars were completely irrelevant and these bars were never probed. In the present study the presentation time of the memory array was varied, followed by a fixed 1000-ms retention interval and a recall probe (see https://doi.org/jbgf). Participants' task was to indicate on a color wheel the color the probed (filled) bar had in the memory array. (a) In Experiment 1, each target (tilted bar) was equally relevant. (b) In Experiment 2, a performance-based bonus was awarded on each trial and multiplied by a factor dependent on target tilt (3x for 12°, 2x for 28°, 1x for 45°). (c) In Experiment 3, the probability that a target was probed depended on its tilt (3/6 of the trials for 12°, 2/6 for 28°, 1/6 for 45°).

Each participant completed a total of 1050 trials divided into blocks of 42 trials. Each condition (i.e., Tilt of the probe × Presentation time) was randomly presented 50 times (twice per block).

Results

The Bayesian Repeated-Measures ANOVA favored the most complete model (Presentation Time + Tilt + Presentation Time × Tilt) over all others, BF_{M} = 1.28e+10 (For the frequentist RM ANOVA, all $p_{\mathrm{s}} < .001$ (two main effects and the interaction); see OSF repository for full ANOVA reports).

For each presentation time, the recall error for 12° probes was significantly higher than for 45°, even when the array was presented for 2000 ms (Figure 2 and Table 1; see OSF repository for descriptive statistics).

Discussion

Experiment 1 shows that the effect of salience on VWM performance is extremely long-lasting: even after 2000 ms presentation and 1000 ms retention, it was not completely relegated by top-down control. While the tilted bars all share the same relevance, performance remains biased in favor of the most salient bar.

Interestingly, even at the lowest presentation time (14 ms), the most salient target was recalled quite precisely. In fact, the recall error for 45° probes at 14 ms was lower than 12° probes' recall error at all presentation times but 2000 ms. Certainly, some of the information on 45° targets was collected from iconic memory after display offset (note that we did not employ masking), but it is still impressive that the difference in salience between 12° and 45° is worth more than 1000 ms of presentation time in terms of VWM performance ($M_{45°/14\ \mathrm{ms}} = 46.67° \pm 2.64$ lies in between $M_{12°/1000\ \mathrm{ms}} = 53.24° \pm 4.92$ and $M_{12°/2000\ \mathrm{ms}} = 38.76° \pm 5.14$).

Experiment 2

Experiment 1 indicates that top-down control cannot overcome the effect of salience within any reasonable time frame, so that an ideal distribution of VWM resources across target objects with different degrees of salience in a display can never be achieved. An alternative explanation would be that overcoming the effect of salience requires effort and participants were not sufficiently motivated to invest that effort. To increase their motivation, we added a monetary reward to the experiment and lower-salience targets were rewarded more than higher-salience targets.

With this manipulation, participants should be highly incentivized to focus their available resources on less salient targets to maximize their gains. Recently, it has been called into question, whether reward can increase overall VWM performance (van den Berg et al., 2023), but that reward can affect the distribution of limited cognitive resources among concurrently presented stimuli is well established (reviewed in, e.g., Anderson, 2019) and, in fact, such an effect has been demonstrated also in VWM tasks (Allen and Ueno, 2018; Klink et al., 2017; for a VWM-focused review, Ravizza and Conn, 2022). As we believe that implementing top-down control takes more than a few hundred milliseconds, we expected (preregistration: https://osf.io/fxwyp) an effect of salience for displays presented for 350 ms. If top-down

Table 1

Paired Samples t *Tests for Experiment 1.*

Presentation Time	Comparison	$t(15)$	p	Hedges' g_z	BF_{+0}
14 ms	12° > 28°	4.89	< .001	1.16 [0.63, 2.05]	316.33
	28° > 45°	11.37	< .001	2.70 [1.88, 4.30]	2.59e+6
	12° > 45°	11.56	< .001	2.74 [1.92, 4.37]	3.22e+6
49 ms	12° > 28°	5.54	< .001	1.31 [0.76, 2.26]	935.97
	28° > 45°	7.66	< .001	1.81 [1.18, 2.99]	2.49e+4
	12° > 45°	11.10	< .001	2.63 [1.83, 4.21]	1.94e+6
97 ms	12° > 28°	7.57	< .001	1.80 [1.17, 2.96]	2.20e+4
	28° > 45°	5.95	< .001	1.41 [0.85, 2.41]	1851.30
	12° > 45°	11.54	< .001	2.74 [1.91, 4.37]	3.14e+6
347 ms	12° > 28°	7.21	< .001	1.71 [1.10, 2.84]	1.30e+4
	28° > 45°	3.02	.004	0.72 [0.22, 1.44]	12.36
	12° > 45°	7.38	< .001	1.75 [1.13, 2.90]	1.66e+4
500 ms	12° > 28°	5.93	< .001	1.41 [0.84, 2.40]	1774.43
	28° > 45°	2.45	.013	0.58 [0.09, 1.26]	4.82
	12° > 45°	6.26	< .001	1.48 [0.91, 2.51]	3009.04
1000 ms	12° > 28°	4.68	< .001	1.11 [0.59, 1.97]	218.08
	28° > 45°	3.29	.003	0.78 [0.28, 1.52]	19.39
	12° > 45°	5.47	< .001	1.30 [0.75, 2.24]	839.64
2000 ms	12° > 28°	3.50	.002	0.83 [0.33, 1.59]	28.09
	28° > 45°	1.69	.056	0.40 [−0.09, 1.02]	1.53
	12° > 45°	3.52	.002	0.83 [0.34, 1.59]	29.01

control can fully overrule the effect of salience, we expect a reversal of the pattern (according to the behavioral relevance) at 2000 ms. No performance difference for the three targets at 2000 ms would indicate an attenuation, but not a full elimination of the effect of salience.

Methods

In Experiment 2 the critical tests determining the stopping rule for the sequential testing procedure examined: (1) whether the directional effect of salience was present at 350-ms presentation time and (2) whether it disappeared at 2000-ms presentation time. This resulted in a sample of 20 healthy human adults (Mean age: 27.40 ± 1.31 [*s.e.m.*], 8 female/12 male, 2 left-handed) collected in 2022. Experiment 2 was run online (participant recruitment via Prolific) and was modeled after Experiment 1 with two key differences:

1. There were only two presentation times: 350 ms and 2000 ms.

2. Participants received points (which were converted to a monetary reward) based on their recall error and the tilt of the probe.

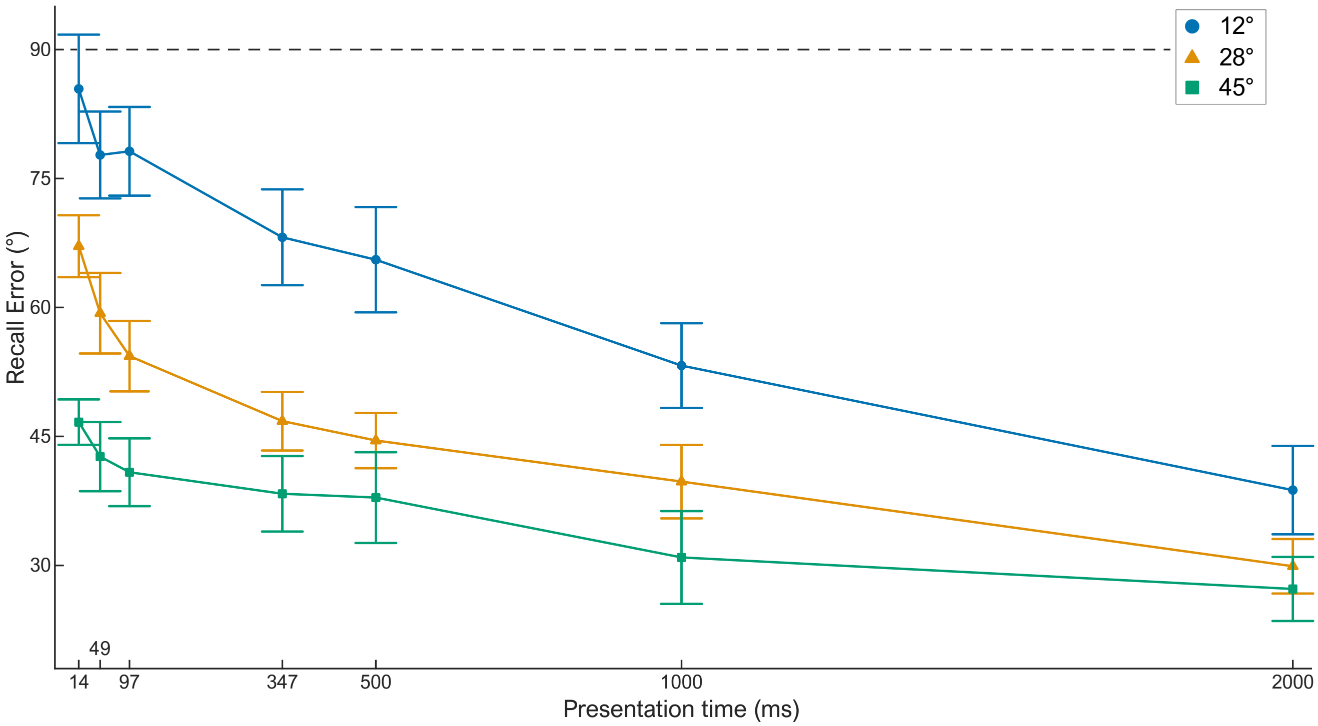
For the 45° probes (base formula), the number of points awarded decreased linearly from 8 (for a 0° recall error) to 0 (for 89° recall error) in 90 steps. All responses with a recall error equal to or above 90° were penalized with −1 point. Crucially, in order to incentivize prioritized processing of less salient targets, the reward and penalty were multiplied by 2 for 28° probes (from 16 to 0, penalty = −2), and for 12° probes they were multiplied by 3 (from 24 to 0, penalty = −3). Participants were made aware of these multipliers at the start of the experiment and the points earned on a given trial (rounded to 1 decimal) were shown simultaneously with the correct response after each trial (see https://doi.org/jbgg for an example of the task).

Participants' base compensation was estimated for 45 minutes of task duration and amounted to 4.5£. The monetary reward was awarded after all participants completed the experiment and was computed to average at 2£ (i.e., 45% of the base compensation). Given that participants on Prolific take part in experiments mainly for the money, this should be a very strong incentive to bias performance in favor of the more strongly rewarded/penalized 12° objects.

Each participant completed a total of 300 trials divided into blocks of 50 trials. Each condition (presentation time × tilt of the probe) was randomly presented 50 times. One participant was excluded and replaced in accordance with the

Figure 2

Results from Experiment 1.



Note. The dotted line indicates chance level. Targets were equally task-relevant. Error bars reflect 95% within-participant confidence intervals (Cousineau, 2005; Morey, 2008).

exclusion criteria defined in our preregistration (mean recall error ≥ 80°), thus the final sample size was still 20 participants.

Results

As expected, recall error was significantly higher for 12°- (63.06° ± 5.07) than 28°- (41.96° ± 3.80) probes at 350 ms presentation time, $t(19) = 8.29$, $p < .001$, $g_z = 1.78$ [1.21, 2.76], $BF_{+0} = 3.02e+5$ (see Figure 3). Similarly, it was also higher for 28°- than 45°- (30.20° ± 3.81) probes at this presentation time, $t(19) = 4.52$, $p < .001$, $g_z = 0.97$ [0.51, 1.66], $BF_{+0} = 261.47$.

Contrary to our expectation that top-down control can overcome or at least balance an effect of salience given enough time, at 2000 ms presentation time, recall error was still significantly higher for 12°- (30.61° ± 2.82) compared to 28°- (25.86° ± 3.19) probes, $t(19) = 3.00$, $p = .004$, $g_z = 0.64$ [0.20, 1.24], $BF_{+0} = 13.08$ and also when compared to 45° probes (24.11° ± 2.73), $t(19) = 3.39$, $p = .002$, $g_z = 0.73$ [0.28, 1.35], $BF_{+0} = 27.77$. There was however no longer a significant difference between 28°- and 45°- probes, $t(19) = 1.22$, $p = .119$, $g_z = 0.26$ [−0.18, 0.77], $BF_{0+} = 1.30$.

Discussion

It turns out that even when heavily incentivized to preferentially process less salient targets, participants cannot overcome the effect of salience, even at 2000-ms presentation time. Compared to Experiment 1, the effect seems somewhat attenuated at 2000 ms, but it's far from the reversal (better performance for the much more valuable 12°) that should have occurred if top-down control was able to dominate salience.

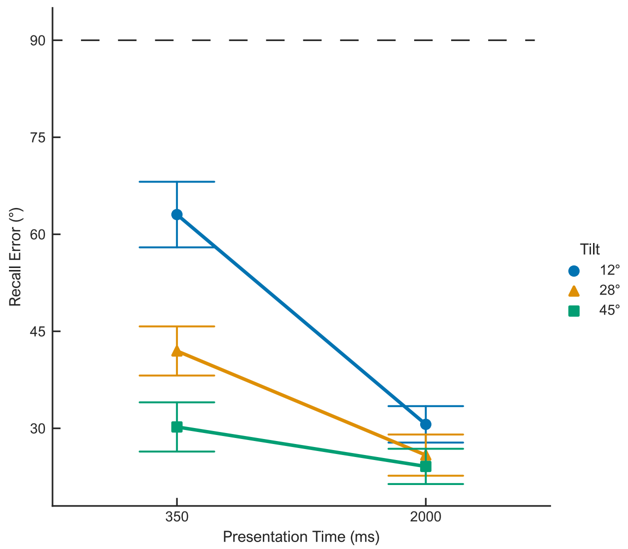
Experiment 3

It has been argued that prior experience constitutes an even stronger influence on attention allocation than observers' goals (Theeuwes, 2018). Specifically, if a certain feature or location has recently been behaviorally relevant (*intertrial priming*) or is, on average, more behaviorally relevant across a longer time period (*statistical learning*), objects with that feature or at that location increase in priority and therefore compete more vigorously for attention allocations. The same might be true for competition for VWM resources.

In Experiment 3, we boosted the less salient targets' priority by increasing the probability that they would be probed at the recall stage. As participants were told to prioritize less

Figure 3

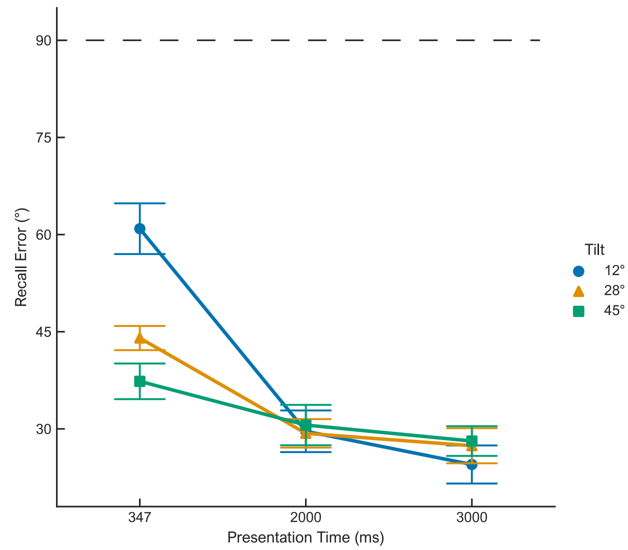
Results from Experiment 2.



Note. Participants were monetarily incentivized to prioritize processing of the least salient (12°) target. The dotted line indicates chance level. Error bars reflect 95% within-participant confidence intervals (Cousineau, 2005; Morey, 2008).

Figure 4

Results from Experiment 3.



Note. The least salient target (12°) was probed three times more often than the most salient target (45°). The dotted line indicates chance level. Error bars reflect 95% within-participant confidence intervals (Cousineau, 2005; Morey, 2008).

salient targets and that these were probed more often, influences from goals and experiences were aligned and should therefore constitute a maximally strong counterforce against salience. Furthermore, we added a third, even longer, presentation duration of 3000 ms to give top-down processes even more time to develop their full potential. We predicted (preregistration: https://osf.io/d7ku2) that participants would not be able to override the salience effect for memory displays presented for 347 ms but might be able to negate or even reverse it with longer presentation times (2000 & 3000 ms).

Methods

In Experiment 3, the critical tests determining the stopping rule for the sequential testing procedure examined whether the differences in recall error between the different tilts became smaller, or even reverted, as presentation time increased. However, due to the COVID-19 pandemic, testing had to be stopped earlier than originally planned in the pre-registration and, because of a change in affiliation, we could not resume testing in the laboratory. We can nonetheless draw conclusions from the present results (Schönbrodt & Wagenmakers, 2018). This resulted in a sample of 37 healthy human adults. One participant was excluded from the analyses, in accordance with the exclusion criteria defined in our pre-registration (mean recall error ≥ 80°), thus the final sample was composed of 36 participants (Mean age: 25.70 ± 1.31 [*s.e.m.*], 24 female/12 male, 6 left-handed) collected in 2019.

Experiment 3 was again modeled after Experiment 1 with the following differences:

1. The presentation times of the memory display were 347, 2000 or 3000 ms.

2. Less salient targets were probed with a higher probability.

In particular, the 12° tilted bar was probed on 3/6 of the trials, the 28° bar was probed on 2/6 of the trials and the 45° bar was probed on the remaining 1/6 of the trials. Participants were made aware (and reminded each block) that the 12° bar was more likely to be probed than the 28° bar and that the 28° bar was also more likely to be probed than the 45° bar.

Each participant completed a total of 900 trials divided into blocks of 36 trials. Each presentation time was randomly presented 300 times (12 times per block). Within each presentation time, each tilt was probed 150, 100 or 50 times (18, 12 or 6 times per block) in accordance with the aforementioned probabilities.

Moreover, at the end of the experiment, an additional block of 36 trials was run, in which a single vertical bar was presented 2° above the fixation dot for 2 seconds and participants had to recall its color. The colors of the targets were the same for all participants (from 0° to 350° on the colorwheel, in steps of 10°) but the order of presentation was randomized. This additional block (which we call the baseline block) provides us with an estimate of the maximally achievable performance for each participant. As holding one color is not particularly taxing for VWM, this estimate should mainly reflect perceptual and motor error. The latter means that participants might not click on the exact part of the color wheel they want to select (but see Sutterer et al., 2022). Perceptual errors might occur at encoding or retrieval, that is, the color of the target at presentation or at the aimed-at position during response-selection might be slightly misperceived (i.e., mistaken for colors very close on the colorwheel, below participants' JND threshold). For these and other reasons, one would not expect to observe perfect performance (an average recall error of 0°), even if the color of a given target was perfectly encoded into and maintained in VWM (or even displayed on the screen, see Schurgin et al., 2020); our baseline block serves to quantify these non-memory related imprecisions, so that we can compare performance on the actual task against this maximally achievable performance.

Results

As expected, recall error was significantly higher for 12°- (60.91° ± 3.92) than 28°- (44.02° ± 1.87) probes at 347 ms presentation time (Figure 4 and Table 2). Similarly, it was also higher for 28°- than 45°- (37.34° ± 2.75) probes at this presentation time. At 2000-ms presentation time, recall error was not significantly higher in 12°- (29.63° ± 3.22) compared to 28°- (29.31° ± 2.20) probes, nor in 28°- compared to 45°- (30.59° ± 3.12) probes. Finally, at 3000 ms recall error was not significantly lower for 12°- (24.50° ± 2.94) compared to 28°- (27.40° ± 2.71) probes nor for 28°- compared to 45°- (28.12° ± 2.30) probes. When comparing 12° and 45° at 3000 ms, performance was a little better for 12° targets.

The 12° target was thus processed slightly better than the behaviorally much less relevant 45° target ($M_{\text{diff}} = -3.62° \pm 4.51$) but this reversal is far from convincing statistically: the *BF* is in the indecisive range (*BF* = 1.44) indicating almost no evidence for a difference; the *p* value also does not survive FDR correction ($p = .261$, corrected for 9 tests; Benjamini and Yekutieli, 2001).

To rule out that performance had reached ceiling, that is, to exclude that effects of salience/top-down control were merely disguised by ceiling effects, we ran an exploratory paired samples *t* test between the mean performance in the best condition (12°, 3000 ms) and the mean performance in the baseline block. The mean performance in the baseline block ($M = 11.44°$, 95% between-participant $CI = 1.05$) was significantly better than for the 12°, 3000-ms condition, $t(35) = 11.88$, $p < .001$, $g_z = 1.94$ [1.47, 2.64], $BF_{10} =$ 9.47e+10. This excludes the possibility that we failed to see a reversal of the effect of salience just because top-down influences had no room for improvement.

Discussion

In Experiment 3, we observed weak evidence for the reversal expected if top-down influences can override and dominate effects of salience. Yet, it took participants 3000 ms to "implement" top-down control, which provides much leeway for extraneous strategies to be employed (see General Discussion).

At 2000-ms presentation time, already much longer than in typical VWM experiments, effects of salience and the top-down effects induced in Experiment 3 seem to have hit an equilibrium, with evidence (in terms of *BF*s) for the absence of effects of these manipulations. It seems interesting to relate this situation to the recently proposed "attentional limbo" where (overt) attention allocations apparently were not affected by either salience nor task relevance and which occurred around 250 ms after display onset (van Heusden et al., 2022). By comparison, VWM performance at 350 ms presentation time (which actually manifested 1350 ms after display onset) was still heavily dominated by salience.

General Discussion

In three experiments, we have tried to overcome effects of salience on VWM performance. It has been proposed that the effects of salience are short-lived because top-down control replaces bottom-up orienting after a few hundred milliseconds (Donk & van Zoest, 2008; van Heusden et al., 2022). In contrast to this clear prediction, our Experiment 1 showed salience effects on VWM performance for several seconds, that is, an order of magnitude longer than expected based on previous work. Enhancing the relevance of less salient targets with monetary incentives (Exp. 2) or probing them more often (Exp. 3) did not erase effects of salience for up to 2 seconds of memory-array presentation. As task goals and prior experience (Awh et al., 2012) were aligned in these experiments, we conclude that neither of these top-down influences is able to overrule effects of salience (see also, Melcher & Piazza, 2011). Only with 3-s presentation duration in Experiment 3 were the effects of salience slightly reversed in favor of less salient targets. This *slight* reversal still indicates residual effects of salience, because full top-down control would have caused a *strong* reversal, that is, much better performance for less salient targets.

Indeed, previous studies have shown that top-down manipulations with presentation times shorter than 2000 ms can have strong effects on VWM performance for equally salient stimuli (Bays et al., 2011; Dube et al., 2017; Emrich et al., 2017; Klink et al., 2017; Ravizza & Conn, 2022; Ravizza et al., 2021). Some of these studies have also looked at the interplay of salience, presentation time and top-down influences, but none of them contained a non-confounded and direct manipulation of to-be-remembered stimuli's salience (for a discussion, see Constant and Liesefeld, 2021).

Table 2

Paired Samples t *Tests for Experiment 3.*

Presentation Time	Comparison	$t(35)$	p	Hedges' g_z	BF	Favors
347 ms	12° > 28°	10.32	< .001	1.68 [1.25, 2.32]	4.73e+9	H_+
	28° > 45°	4.23	< .001	0.69 [0.35, 1.11]	323.82	H_+
	12° > 45°	9.03	< .001	1.47 [1.07, 2.06]	1.77e+8	H_+
2000 ms	12° > 28°	0.15	.442	0.02 [−0.31, 0.36]	4.97	H_0
	28° > 45°	−0.96	.828	−0.16 [−0.51, 0.17]	10.14	H_0
	12° > 45°	−0.36	.640	−0.06 [−0.40, 0.28]	7.21	H_0
3000 ms	12° < 28°	−1.31	.100	−0.21 [−0.57, 0.12]	1.43	H_0
	28° < 45°	−0.49	.314	−0.08 [−0.42, 0.25]	3.67	H_0
	12° < 45°	−1.79	.041	−0.29 [−0.66, 0.04]	1.44	H_-

Although salience affected performance even at the longest presentation times, less salient targets benefitted most from increased presentation times. It is therefore possible that the effect of salience could disappear with even longer presentation time (see Klink et al., 2017, Exp. 3). However, with such long presentation times, we likely do not measure pure VWM anymore, as participants probably supplement their VWM performance with other strategies such as verbalization (Overkott & Souza, 2022) that would not be affected by salience. They might also actively suppress information on the most salient object and resample from the less salient object, a strategy unlike what is traditionally assumed (or possible) in research on VWM and which probably does not play much of a role for the rapidly changing visual stimulation in real life.

In Experiments 2 and 3, we manipulated the relative relevance of the to-be-encoded target stimuli and observed only limited effects; this indicates that weighting by relevance is much less powerful than weighting by physical salience. Future research might study how making a salient object completely irrelevant (i.e., introducing a salient distractor) affects its VWM representation. It appears possible that fully suppressing a salient distractor (e.g., Chelazzi et al., 2019; Gaspelin & Luck, 2018) is more powerful than simple weighting by relevance. A challenge for such research will be that the VWM representation of the irrelevant (i.e., never probed) distractor can only be assessed indirectly via its influence on the (biased or otherwise impaired) recall of relevant stimuli.

Going beyond the observation that salience has long-lasting effects on VWM performance, some speculation on *how* salience might affect VWM performance seems in order. Notably, our findings are not easily explained by the assumption that encoding progresses sequentially starting with the most salient object; rather, we believe that some parallel processing or re-sampling is involved. First, estimates of the speed of serial attention allocations for concurrently presented targets are well below 100 ms (Grubert & Eimer, 2016), so that 350 ms should already be more than sufficient to attentionally visit and process all three target objects in our displays. It therefore appears implausible that the less salient targets were not encoded at all on some trials. Second, if there was only one run of salience-dependent serial encoding, the most salient targets would be encoded first and the least salient targets last. This assumption would predict an effect of salience opposite to what we have observed, because when targets are presented sequentially (thus enforcing sequential encoding), VWM performance for early items is far worse than for later items (*recency effect*; Gorgoraptis et al., 2011).

The apparent discrepancy between our findings and Donk and van Zoest (2008; see also, van Heusden et al., 2022) can be resolved by differentiating between direct effects of salience on attention allocation and indirect effects on later cognitive processes. It is possible that focal attention quickly moves on after visiting the most salient stimulus. However, being attended first might endow stimuli with a head start in the (parallel) race for VWM resources (Bundesen, 1990; Ravizza et al., 2016) that is effective early on (Exp. 1, 14-ms condition) and takes several seconds to outrun for the less salient stimuli even when reinforced by top-down influences (Exps. 2 and 3).

Thus, while the effects of salience on attention allocations might be short-lived, they have long-lasting repercussions that are hard to overcome. As VWM is considered the bottleneck for further visual and conceptual processing, these repercussions might have even later repercussions that are yet to be discovered.

Constraints on generality

To the best of our knowledge, our samples were mostly composed of European young adults. Given that our task is not tied to any origin-specific behavior (such as reading direction), we do not think that the geographic origin of our participants would influence the present results. However, our results might not be generalizable to all people, especially not to those for whom the basic task is too challenging. Moreover, the observed effect of salience and its robustness to top-down influences likely requires a task where extensive processing of targets (such as encoding them into VWM) is needed and where it is a reasonable strategy to look for salience signals (see Liesefeld, Liesefeld, and Müller, 2022; Liesefeld et al., 2021).

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