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# Reward associations impact both iconic and visual working memory

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## ABSTRACT

Reward plays a fundamental role in human behavior. A growing number of studies have shown that stimuli associated with reward become salient and attract attention. The aim of the present study was to extend these results into the investigation of iconic memory and visual working memory. In two experiments we asked participants to perform a visual-search task where different colors of the target stimuli were paired with high or low reward. We then tested whether the pre-established feature-reward association affected performance on a subsequent visual memory task, in which no reward was provided. In this test phase participants viewed arrays of 8 objects, one of which had unique color that could match the color associated with reward during the previous visual-search task. A probe appeared at varying intervals after stimulus offset to identify the to-be-reported item. Our results suggest that reward biases the encoding of visual information such that items characterized by a reward-associated feature interfere with mnemonic representations of other items in the test display. These results extend current knowledge regarding the influence of reward on early cognitive processes, suggesting that feature-reward associations automatically interact with the encoding and storage of visual information, both in iconic memory and visual working memory.

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## 1. Introduction

Rewards play a fundamental role in human cognition. The ability to learn reward contingencies in the environment is crucial to anticipate positive or negative outcomes and optimize value-oriented behavior. Rewards can accordingly act as motivational incentives, guiding the deployment of cognitive resources in order to effectively orient attention and prioritize processing of task relevant information (Engelmann et al., 2009; Pessoa, 2009; Pessoa & Engelmann, 2010; Watanabe, 2007).

A growing number of studies have shown that learned stimuli-reward associations can modulate the allocation of attention when rewards are no longer provided (for a review see Chelazzi et al., 2013). Reward associations appear to automatically bias selective attention in favor of the associated object or feature even when individuals are not aware of the established feature-reward associations. Importantly, the processing of reward associated stimuli is prioritized when this confers no strategic advantage, and perhaps even when it creates a performance cost (Anderson, Laurent, & Yantis, 2011a, 2011b; Della Libera & Chelazzi, 2006, 2009; Krebs, Boehler, & Woldorff, 2010). Initially neutral visual features that

have been linked to reward through experience seem to subsequently become salient, acquiring the ability to draw attention in space (Anderson, Laurent, & Yantis, 2011a, 2011b; Della Libera & Chelazzi, 2006, 2009; Hickey, Chelazzi, & Theeuwes, 2010a, 2010b, 2011) and time (Hickey, Los, & Los, submitted for publication; Raymond & O'Brien, 2009), and to drive oculomotor capture (Anderson, Laurent, & Yantis, 2012; Hickey & van Zoest, 2012, 2013; Theeuwes & Belopolsky, 2012). These results have led to the proposal that reward may act on attention through a mechanism that is independent of the traditional dichotomy of bottom-up and top-down processes (Awh, Belopolsky, & Theeuwes, 2012).

While increasing effort has been made in the last years to study the influence of learned value associations on attentional and visual search tasks, fewer studies have been dedicated to the relation between reward and other cognitive processes. With the present study, we aim to expand the existing literature addressing the non-strategic influence of reward-value associations on the encoding and storage of information in visual memory.

Memory is the “neurocognitive capacity to encode, store, and retrieve information” (Tulving, 2000). In the visual domain, the early stages of visual memory have been classically distinguished in iconic memory (IM) and visual working memory (VWM). IM is a high capacity, fast decaying storage system where visual representations are encoded and stored only for a few hundreds of milliseconds after

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the offset of briefly presented stimuli (Coltheart, 1980; Neisser, 1967). Only a limited subset of the information retained in IM is then selected and transferred into the limited-capacity system of VMW, where it can be actively maintained for several seconds (Cowan, 2001). VWM is a system with limited resources where capacity is limited in terms of number of items that can be remembered and accuracy of the encoded representations (Alvarez & Cavanagh, 2004; Bays, Catalao, & Husain, 2009; Bays & Husain, 2008; Zhang & Luck, 2008). Whether information is selected and transferred from IM to VWM depends on its relevance for subject's goals as well as perceptual properties of the visual input (Belopolsky, Kramer, & Godijn, 2008; Schmidt et al., 2002).

Recent studies have demonstrated that incentives can improve performance in a visual memory task, increasing VWM capacity (Kawasaki & Yamaguchi, 2013) and speeding response times for the most valuable stimuli (Krawczyk, Gazzaley, & D'Esposito, 2007). Interestingly, learned feature-reward associations have been shown to influence VWM also in the absence of direct incentive motivation, when rewards are no longer provided. Learned item-reward associations lead to enhanced VWM capacity for stimuli associate to high compared to low reward (Gong & Li, 2014).

The current study was designed to further characterize the influence of reward on the early stages of visual memory. On the one hand, we aimed to describe the influence of learned feature-reward associations on visual memory over time, from the earliest sensory storage of IM gradually moving to VWM. On the other, we wanted to investigate how the presence of a previously reward-associated item in the memory array influences the capacity to encode and store the identity of other neutral items in the display.

To address these issues, we combined a value-learning procedure with a visual memory task. During value-learning participants performed a visual search task loosely based on that employed by Anderson, Laurent, and Yantis (2011a, 2011b). Two magnitudes of reward outcome were associated to two colors that characterized the target object. Participants conducted a visual memory task immediately after this training. In this test phase they were presented with a number of items arranged in a circle, where a probe identified a single item in the array and participants reported the orientation of a line element within this item. Importantly, one of these items could have the color associated with reward during training, rendering it a *color singleton*. This item was no more likely to act as memory target than any of the other elements in the array.

Our test task was modeled on the partial report technique introduced by Sperling (1960). By presenting the probe at short or long delays after stimulus offset, Sperling used this task to investigate the content of IM independent of the limitations of working memory. As compared to full report paradigms, where observers are able to report around 3–5 items from the memory array, partial report studies suggest the presence and availability of much more information at short probe delays (i.e. partial report superiority).

We approached our results with interest not only in raw accuracy, but also in the interference created when a singleton stimulus was present in the display and participants were probed to report a non-singleton item. We quantified this interference effect as the accuracy difference between conditions where the response associated with the line inside the singleton was congruent to that of the line inside the probed target (same response, *congruent trials*) vs. when it was incongruent (different response, *incongruent trials*; see Theeuwes & Burger, 1998). This measure was examined for modulation as a function of the color-reward association established during the training phase.

Our hypothesis was that learned reward associations could act on visual memory at different levels, influencing IM, VWM, or both. To foreshadow, we did not find direct evidence of enhancement of

visual memory performance for a reward associated item, but we did observe a stronger interference effect on performance when an irrelevant singleton had its color associated to high-magnitude reward. This interference effect was insensitive to the timing of the probe, suggesting that the entrained reward association impacted both IM and VWM.

## 2. Experiment 1

### 2.1. Methods

#### 2.1.1. Participants

Thirty students of the University of Trento (26 female) participated in the experiment. Mean age was 22 (ranging from 19 to 37). All had normal or corrected-to-normal vision, normal color vision, and were naïve to the purpose of the experiment. Participants were reimbursed for their participation, with compensation varying between 7.50€ and 9€ based on performance. Written informed consent was obtained from all participants and the experiment was carried out in accordance with the Declaration of Helsinki and was approved by the local Ethics Committee.

#### 2.1.2. Apparatus

Stimuli were presented on a gamma-calibrated ViewSonic Graphic Series G90fB 19" CRT monitor (1024 × 768) at a refresh rate of 100 Hz. Participants were seated in a dimly illuminated room approximately 60 cm from the display with their head supported by a chinrest. Stimuli were created using a custom Matlab script (Mathworks Inc., Massachusetts, USA) and the Psychophysics Toolbox 3.8 (Brainard, 1997; Pelli, 1997).

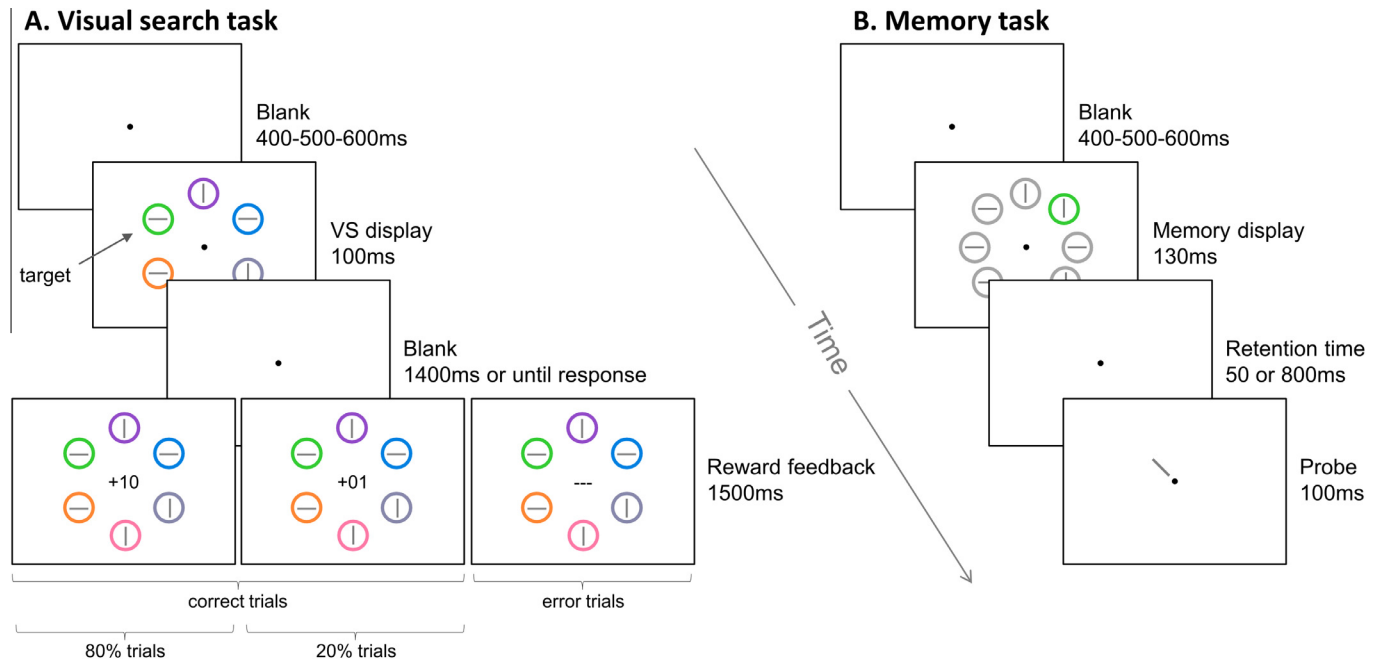
#### 2.1.3. Stimuli

All stimuli appeared on a uniform gray background (2.58 cd/m<sup>2</sup>) and were regularly displaced along an imaginary circle at a radius of 5° of visual angle from the fixation point (0.12° in diameter). Stimuli were light gray lines (36.1 cd/m<sup>2</sup>; 1.5° × 0.12°) oriented vertically or horizontally, presented inside a circle of 2° diameter (width 0.12°). We selected 7 colors to assign to the circles and these colors were adjusted to be physically equiluminant (~24 cd/m<sup>2</sup>).

#### 2.1.4. Procedure

The experiment lasted for about an hour and was structured in two parts.

**2.1.4.1. Visual search training.** In the training phase participants completed a visual search task where the target was defined by one of two colors, one associated to high reward and one associated to low reward (Fig. 1A). The training began with 40 practice trials which were followed by 480 experimental trials divided in 8 blocks. Each trial began with a fixation display; after a variable delay of 400, 500, or 600 ms a visual search display was presented for 100 ms. The search display consisted of 6 gray lines each surrounded by a uniquely colored circle. Targets were defined as circles of one of two possible colors and only one of them could be presented in each trial. Participants were instructed to report as fast and as accurately as possible the orientation of the line inside the target circle, pressing "m" for vertical or "z" for horizontal on a standard computer keyboard. Feedback was provided for 1500 ms beginning immediately after response. The feedback display was identical to the memory display except that light gray text indicating the number of earned points was overlaid at the center of the screen subtending about 1° of visual angle. Participants received either "+01" points or "+10" points for correct responses (10 points corresponded to €0.032). No points, indicated with three dashes



**Fig. 1.** Experimental design. (A) Visual search task. A visual search display of 6 elements was presented for 100 ms after a variable fixation delay. Either a green or a red target was presented in each trial and participants reported the orientation of the line inside it. Participants' response was followed by a feedback display that indicated the number of points that were earned on each trial. The feedback did not depend on participants speed, but was determined by means of the probabilistic schedule: for each participant either red or green target were associated to high reward in 80% of the trials and to low reward in the remaining 20% of the trials (green in the illustrated example); the opposite association was made for the other color. (B) Memory task. A memory array of 8 elements was presented for a 130 ms. All but one item were gray. The uniquely colored circle could be defined by a color previously associated to a high or low reward target or a distractor. After a variable delay (50 or 800 ms) a line appeared and indicated one of the 8 locations. Participants' task was to report the orientation of the line presented at the probed location. All locations were selected with the same probability. Neither reward nor feedback was provided during this task. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

“—”, were assigned for incorrect responses or trials where participants failed to respond within 1400 ms. At the end of each block participants received feedback about the overall number of points accumulated.

Participants were informed prior to beginning the training procedure that one of the two target colors was associated to high and the other to low reward. The reward schedule was probabilistic such that correct responses with high reward targets were followed by high reward on 80% of trials and by low reward in 20% of the trials (and vice versa for low reward targets). The two target colors were selected among three alternatives (red, green or blue). The non-target color was assigned to one of the distractors presented in the search array. Target color and value were counterbalanced across participants. Target identity and location were fully balanced for each participant and presented in random order.

**2.1.4.2. Iconic and visual working memory test.** In the test phase participants completed a visual memory task where the to-be-remembered target was identified by a probe (Fig. 1B). Importantly, at this stage of the experiment participants were not rewarded for performance. After 20 practice trials, the experimental session began with 480 experimental trials divided in 6 blocks. Memory trials started with a fixation cross that sustained for a random interval of 400, 500, or 600 ms before being replaced by the memory array for 130 ms. The memory array consisted of 8 circles evenly spaced around fixation, all of but one with gray color. The uniquely colored circle could be defined by a color that had characterized high-reward targets, low-reward targets, or distractors during training. After a 50 or 800 ms delay a line cue ( $3^\circ \times 0.05^\circ$ ) indicated the memory target for 100 ms.

Each item in the memory array was probed with equal probability. Participants were required to report the orientation of the line

seen at the probed location using the keyboard (“m” for vertical; “z” for horizontal). Responses were unspeeded and accuracy was emphasized, but no feedback was provided. Target identity and position was fully counterbalanced and trials were randomly presented during the experiment.

## 2.2. Analysis and results

### 2.2.1. Visual search training performance

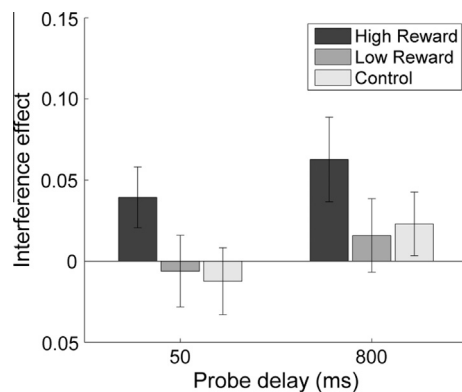
Statistical analysis of response times (RTs) over the course of training in the visual search task took the form of a repeated measures analysis of variance (ANOVA) with time (trials were divided in 4 bins of 120 trials each) and target-color-association (high-reward color vs. low-reward color) as factors. RT was significantly faster for high reward targets (main effect of reward  $F(1,29) = 4.80$ ;  $p = .037$ ;  $\eta_p^2 = .14$ ) and became faster over the course of the training (main effect of time  $F(1.8,51.9) = 19.03$ ;  $p < .001$ ;  $\eta_p^2 = .40$ ) but these factors did not interact ( $F(3,87) = .67$ ;  $p = .571$ ;  $\eta_p^2 = .02$ ). A similar ANOVA based on arc-sine transformed accuracy revealed an improvement over the course of training ( $F(2.3,65.3) = 28.1$ ;  $p < .001$ ;  $\eta_p^2 = .49$ ) but no effect involving target-color-association ( $F(1,29) = 3.08$ ;  $p = .090$ ;  $\eta_p^2 = .10$ ; interaction:  $F < 1$ ). Note that statistical results here and below reflect Greenhouse–Geisser corrected degrees of freedom where appropriate.

These results suggest that participants successfully learned the reward contingencies and became faster in recognizing the targets when they were associated to high reward value.

### 2.2.2. Iconic and visual working memory task performance

Statistical analysis of the visual memory task began with a repeated-measures ANOVA of arc-sign transformed accuracy values with factors for target color (unique color vs. gray), singleton





**Fig. 2.** Experiment 1: interference effect in memory task. The interference effect is an index of interference in memory performance for the target as a function of the congruency of the response to the singleton (it was computed as the difference in accuracy between congruent and incongruent trials). The interference effect was dependent on reward history and was strongest for high reward associated colors compared to low reward associated color or control. Errorbars here and below represent SEM.

color-reward association (high-reward vs. low-reward vs. distractor color) and probe-delay (50 ms vs. 800 ms). Accuracy was significantly higher for singletons than non-singleton items ( $F(1,29) = 58.33$ ;  $p < .001$ ;  $\eta_p^2 = .67$ ) and for short compared to long delay ( $F(1,29) = 6.26$ ;  $p = .018$ ;  $\eta_p^2 = .18$ ). We accordingly examined performance for singleton and non-singleton targets separately. Accuracy for singletons was significantly higher at the short delay ( $F(1,29) = 4.26$ ;  $p = .048$ ;  $\eta_p^2 = .13$ ), but no effect of reward-color association was observed ( $F(2,58) = .11$ ;  $p = .898$ ;  $\eta_p^2 = .00$ ) and these factors did not interact ( $F(2,58) = 1.16$ ;  $p = .321$ ;  $\eta_p^2 = .04$ ). Analysis of accuracy for gray items also revealed a main effect of delay (Fig. 2;  $F(1,29) = 4.59$ ;  $p = .041$ ;  $\eta_p^2 = .14$ ), but no effects of singleton-reward-association (reward:  $F(2,58) = 1.15$ ;  $p = .325$ ;  $\eta_p^2 = .04$ ; reward  $\times$  delay:  $F(2,58) = .16$ ;  $p = .850$ ;  $\eta_p^2 = .01$ ). Additional analyses of RTs for correct responses, in the form of a repeated-measures ANOVA with target color (unique vs. gray), probe-delay (50 ms vs. 800 ms) and reward (high-reward vs. low-reward vs. distractor color) as factors, revealed a trend for shorter RTs for singletons than gray items (color:  $F(1,29) = 4.16$ ;  $p = .051$ ;  $\eta_p^2 = .13$ ), but no other significant results (delay:  $F(1,29) = 3.34$ ;  $p = .078$ ;  $\eta_p^2 = .10$ ; color  $\times$  delay:  $F(1,29) = 3.45$ ;  $p = .073$ ;  $\eta_p^2 = .11$ ; all other  $F$ s  $< 1$ ).

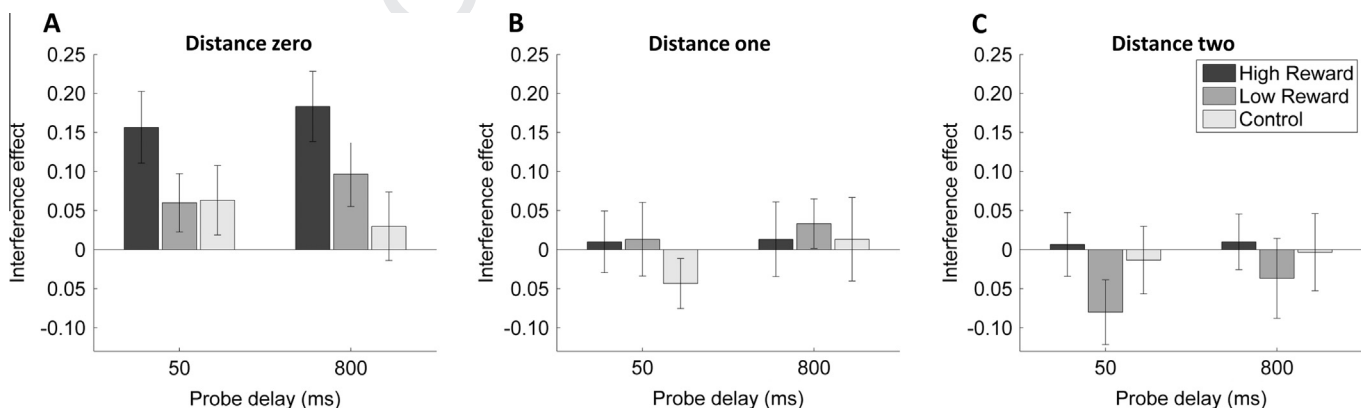
Analysis of interference took the form of a  $3 \times 2$  repeated measures ANOVA with factors for singleton-color-association (high-reward color vs. low-reward color vs. distractor color) and

probe-delay (50 ms vs. 800 ms). This revealed a main effect of reward (Fig. 2;  $F(2,58) = 3.17$ ;  $p = .049$ ;  $\eta_p^2 = .10$ ), but no effect of probe-delay ( $F(1,29) = 2.33$ ;  $p = .138$ ;  $\eta_p^2 = .07$ ) and no interaction ( $F(2,58) = 0.69$ ,  $p = .933$ ,  $\eta_p^2 = .00$ ). Given that delay had no reliable impact on the memory performance we collapsed the data across this factor in subsequent analyses. Pairwise comparisons ( $t$  test) revealed significant differences in the interference effect when the singleton was characterized by the high-reward vs. neutral color ( $t(29) = 2.26$ ;  $p = .030$ ; Cohen's  $d = .50$ ) and a trend toward a difference when the singleton was characterized by high-reward vs. low-reward color ( $t(29) = 1.99$ ;  $p = .056$ ; Cohen's  $d = .52$ ). There was no difference when the singleton was characterized by the low-reward vs. neutral color ( $t(29) = -.02$ ;  $p = .981$ ; Cohen's  $d = -.01$ ).

We conducted an additional analysis to examine the impact of target-singleton distance on the interference effect (Fig. 3). To this end we conducted an ANOVA similar to that described above but with an added factor for the distance of the probed item from the singleton (distance zero: no items between target and singleton, distance one: one item between; distance two: two items between). This revealed (a) that the interference effect was strongest for items closer to the singleton (main effect of distance  $F(2,58) = 9.08$ ;  $p < .001$ ;  $\eta_p^2 = .24$ ), and (b) that the interference effect was dependent on reward ( $F(2,58) = 3.31$ ;  $p = .044$ ;  $\eta_p^2 = .24$ ). No significant interaction between reward and distance was observed ( $F(4,116) = 1.74$ ;  $p = .145$ ;  $\eta_p^2 = .06$ ) and no other main effects or interactions were detected (all  $F$ s  $< 1$ ). An analogous measure of interference was computed for RTs (difference in RTs for congruent and incongruent trials), but analysis revealed no significant effects (delay:  $F(1,29) = 1.54$ ;  $p = .224$ ;  $\eta_p^2 = .05$ ; reward:  $F(2,58) = 1.59$ ;  $p = .213$ ;  $\eta_p^2 = .05$ ; delay  $\times$  reward:  $F(2,58) = .16$ ;  $p = .849$ ;  $\eta_p^2 < .01$ ).

Follow-up analyses revealed that when the probed item was adjacent to the singleton a strong main effect of reward could be detected (10% difference in accuracy;  $F(2,58) = 5.29$ ;  $p = .008$ ;  $\eta_p^2 = .15$ ). Planned contrasts confirmed that the interference effect was larger when the singleton had high-reward vs. low reward color ( $t(29) = 2.28$ ;  $p = .030$ ; Cohen's  $d = .51$ ) and when the singleton had high-reward vs. neutral color ( $t(29) = 3.2$ ;  $p < .001$ ; Cohen's  $d = .72$ ), but that there was no difference when the singleton had low-reward vs. neutral color ( $t(29) = .8$ ;  $p = .429$ ; Cohen's  $d = .18$ ). The interference effect was negligible and was not significantly modulated by reward at other target-singleton distances (1-away: mean =  $-2\%$ , se =  $2\%$ , 2-away: mean =  $0\%$ , se =  $2\%$ ).

A core goal of Experiment 1 was to test the idea that an object characterized by a reward-associated color would be better represented in visual memory. Results in fact show that such an object will interfere with the mnemonic representation of other items in



**Fig. 3.** Experiment 1: interference effect as a function of target-singleton distance. The strength of the interference effect is modulated as a function of distance of target and color singleton. (A) Interference effect at distance zero (no items between target and singleton). (B) Interference effect at distance one (one item between target and singleton). (C) Interference effect at distance two (two items between target and singletons).

the array, supporting this notion. Experiment 1 had an additional purpose, namely to test whether the reward effect might be specific for a particular type of memory, and thus differentially impact IM or VWM representations. To test this we included two probe-delays in Experiment 1, 50 ms and 800 ms, under the assumption that the short probe would index representation in IM and the long probe VWM. However, results showed no difference as a function of this manipulation. This null result may simply reflect insufficient power to detect a difference, and with this in mind we ran a second experiment. This importantly included a larger number of probe-delays with the intent of identifying a systematic variation in the reward effect over levels of this manipulation.

### 3. Experiment 2

#### 3.1. Methods

##### 3.1.1. Participants

A new group of 20 students of the University of Trento (13 females) took part in Experiment 2. The mean age of participants was 22 (ranging from 19 to 36). All had normal or corrected-to-normal visual acuity and color vision and were all naïve to the purpose of the experiments. Participants were reimbursed for their participation; the overall compensation could vary between 8€ and 10€ based on their performance. All participants gave their written consent to the participation to the experiment. The experiment was carried out in accordance with the Declaration of Helsinki and was approved by the local Ethics Committee.

##### 3.1.2. Stimuli and procedure

Display settings and stimuli were as in Experiment 1 and the training procedure was unchanged. The aim of Experiment 2 was to better characterize the temporal dynamics of the effect of reward on memory. To this end we had the memory probe appear at four temporal delays (10 ms, 50 ms, 100 ms and 500 ms).

While we maintained the structure of the memory display as in Experiment 1, only a subset of the 8 possible locations was probed. The rationale behind this change was to increase power to detect modulation of the interference effect, which was strongest at the location adjacent to the singleton in Experiment 1. Only 5 of the 8 locations of the memory display were probed: the position occupied by the color singleton (16% of trials), the two adjacent locations at distance zero (20% of the trials at each location) and the two locations at distance two (22% of the trials at each location). We adopted this distribution in order to avoid participant adoption of a strategic bias toward the items centered around the color singleton. Note that while probe location was not fully random in this design, the target location was not rendered predictable and the location of the singleton was fully counterbalanced and randomly presented during the experiment.

Experiment 2 was substantially longer than Experiment 1, with 320 additional working memory trials. With this in mind we divided the experiment into two identical sessions, each consisting of a training and test procedure. Each of the two training sessions comprised 240 trials of the visual search task, with each test session constituting 400 trials of the memory task. Participants took a short break between sessions. Our purpose here was to reduce the potential for extinction of the reward-color association over the course of the memory task (e.g. Anderson, Laurent, & Yantis, 2011b).

#### 3.2. Analysis and results

##### 3.2.1. Visual search training performance

Participants were faster ( $F(1, 19) = 15.81$ ;  $p = .001$ ;  $\eta_p^2 = .45$ ) and more accurate ( $F(1, 19) = 6.28$ ;  $p = .021$ ;  $\eta_p^2 = .25$ ) in responding to

high reward targets. Moreover, a significant improvement in performance over time was measured in accuracy ( $F(3, 57) = 32.84$ ;  $p < .001$ ;  $\eta_p^2 = .63$ ), but not response latency ( $F(3, 57) = 1.71$ ;  $p = .174$ ;  $\eta_p^2 = .08$ ). No significant interactions were observed (all  $F_s < 1$ ).

##### 3.2.2. Iconic and visual working memory task performance

As was the case in Experiment 1, we first analyzed the raw accuracy in the visual memory task by means of repeated measures ANOVA with factors for color (unique color vs. gray) and probe-delay (10 ms vs. 50 ms vs. 100 ms vs. 500 ms). Accuracy was significantly greater for singletons as compared to non-singleton items ( $F(1, 19) = 57.89$ ;  $p < .001$ ;  $\eta_p^2 = .75$ ). A main effect of delay was also observed ( $F(3, 57) = 3.64$ ;  $p = .018$ ;  $\eta_p^2 = .16$ ) as was a color  $\times$  probe-delay interaction ( $F(3, 57) = 2.95$ ;  $p = .040$ ;  $\eta_p^2 = .13$ ). This motivated follow-up analyses for singletons and non-singleton targets separately. Memory performance for non-singleton targets was better for short delays (main effect of probe delay:  $F(3, 57) = 10.03$ ;  $p < .001$ ;  $\eta_p^2 = .35$ ), and for targets adjacent to the color singleton (main effect of distance:  $F(1, 19) = 11.31$ ;  $p = .003$ ;  $\eta_p^2 = .37$ ), but reward had no effect on this measure ( $F(1, 19) = .42$ ;  $p = .523$ ;  $\eta_p^2 = .02$ ). No significant interactions were observed between reward and distance ( $F(1, 19) = 2.79$ ;  $p = .111$ ;  $\eta_p^2 = .13$ ) or reward, distance and delay ( $F(3, 57) = 1.12$ ;  $p = .350$ ;  $\eta_p^2 = .06$ ; all other  $F_s < 1$ ). The analysis of accuracy for singletons revealed no significant effects (delay:  $F(3, 57) = 1.31$ ;  $p = .279$ ;  $\eta_p^2 = .07$ ; reward  $\times$  delay:  $F(3, 57) = 2.03$ ;  $p = .120$ ;  $\eta_p^2 = .10$ ; all other  $F_s < 1$ ). Additional analyses of RTs, with color, probe-delay and reward as factors, revealed a main effect of color reflecting shorter RTs for singletons than gray targets ( $F(1, 19) = 20.5$ ;  $p < .001$ ;  $\eta_p^2 = .52$ ) and a trend for color–delay interaction ( $F(3, 57) = 2.77$ ;  $p = .05$ ;  $\eta_p^2 = .13$ ), no other effects were significant (reward  $\times$  delay:  $F(3, 57) = 2.25$ ;  $p = .09$ ;  $\eta_p^2 = .11$ ; all other  $F_s < 1$ ).

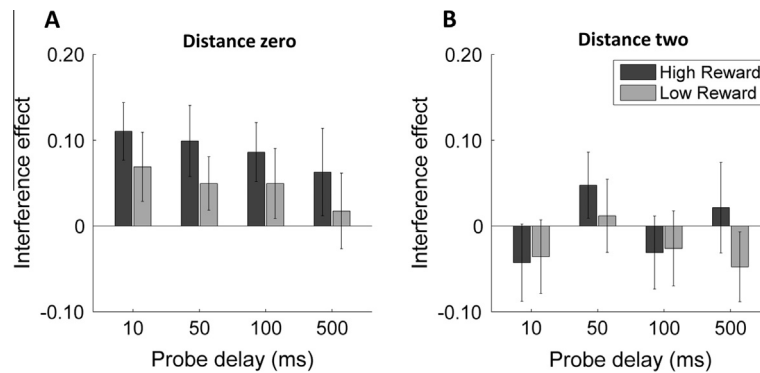
Statistical analysis of the interference effect took the form of a  $2 \times 4 \times 2$  repeated measures ANOVA with factors for singleton color-reward association (high-reward color vs. low-reward color), probe-delay (10 ms vs. 50 ms vs. 100 ms vs. 500 ms) and distance (adjacent-to-singleton vs. far-from-singleton).

This confirmed that the feature-reward association established in the training phase induced a stronger interference effect when singletons' color was associated to high than low reward ( $F(1, 19) = 5.90$ ;  $p = .025$ ;  $\eta_p^2 = .24$ ), and this effect was strongest for stimuli adjacent to the singleton ( $F(1, 19) = 12.34$ ;  $p = .002$ ;  $\eta_p^2 = .39$ ; Fig. 4). The interference effect did not vary reliably over probe delay conditions ( $F(3, 57) = 1.11$ ;  $p = .352$ ;  $\eta_p^2 = .06$ ) and no interaction was observed ( $F(3, 57) = 1.21$ ;  $p = .316$ ;  $\eta_p^2 = .03$ ; all other  $F_s < 1$ ). An analogous measure of interference for RT showed no significant effects of probe-delay or reward manipulations (delay:  $F(2.44, 46.46) = 2.03$ ;  $p = .133$ ;  $\eta_p^2 = .10$ ; reward:  $F(1, 19) = 1.77$ ;  $p = .200$ ;  $\eta_p^2 = .09$ ; delay  $\times$  reward:  $F(3, 57) = 1.92$ ;  $p = .136$ ;  $\eta_p^2 = .09$ ).

### 4. Discussion

Features and objects associated with delivery of reward become salient and draw attention in space and time, even when they are no longer rewarded (Anderson, Laurent, & Yantis, 2011a, 2011b, 2012; Della Libera & Chelazzi, 2006, 2009; Hickey, Chelazzi, & Theeuwes, 2010a, 2010b, 2011, 2014; Krebs, Boehler, & Woldorff, 2010; Raymond & O'Brien, 2009). Recent studies have also shown that reward-associated items are better maintained in visual working memory (Gong & Li, 2014).

The present study expands the existing knowledge about the influence of reward on visual memory, addressing content of visual memory at different delays from display offset and investigating



**Fig. 4.** Experiment 2: interference effect as a function of target-singleton distance. The interference effect decreased as a function of target-singleton distance for all delays. (A) Interference effect at distance zero (no items between target and singletons). (B) Interference effect at distance two (two items between target and singletons).

both IM and VWM. This manipulation opens the opportunity to speculate at which stage reward associations can influence the memory process. A further element of novelty in our design is that we investigated VWM and IM not only for items directly associated to reward, but also for simultaneously presented items presented alongside such a reward-associated non-target. To index changes in the mnemonic representation of such items we employed an index reflecting the difference in accuracy between congruent and incongruent trials, which we term the *interference effect*. Importantly, our results show that memory performance for neutral items was influenced by the information contained in the color singleton, in a way that was dependent on the learned color-reward association, but not on the probe-delay.

Our results suggest that the interference effect was dependent on the distance between target and singleton. Memory of the target was not affected by the orientation of the line inside the singleton when they were separated by one or more objects. This observation is in line with a recent study by Anderson, Laurent, and Yantis (2012) in which participants learned a feature-reward association by means of a visual search value learning procedure before performing a flanker task. The flanker target could be surrounded by two letters with the congruent or incongruent identity, and these letters could have high-reward or low-reward associated color. Results showed an increased cost in RTs when the flanking distractors had the high-reward color. Thus, as in our results, proximal stimuli characterized by the reward-associated color interfered more strongly with the target representation. This pattern is evocative of results in the visual search literature showing that salient stimuli such as color singletons will disrupt the representation of targets in close proximity (Caputo & Guerra, 1998; Hopf et al., 2006; Mounts, 2000). This is thought a product of the misdeployment of attention to the salient object, whose selection would cause the suppression of surrounding stimuli including the target. However, in the current results we do not see an impact of proximity as a raw decrease in accuracy, but rather an increase in interference. It is not immediately clear how this effect is related to the suppression described in prior works, and there is a clear opportunity here for further dedicated research.

We tested visual memory at different time intervals from the display offset in order to address the content of both IM and VWM. Our goal was to investigate whether feature-reward associations could have a variable impact on performance at different stages of the memory process. Interestingly, our results show that reward-associated singleton influenced the representation of the target element at very short delays, starting already 10 ms after the offset of the memory array. Moreover, at least for the temporal intervals we have tested, the interference effect was not modulated by the temporal delay of the probe. There are a number of possible

accounts for this pattern of results. One is that such early observed interference may arise at the level of encoding of visual information. Several studies have suggested that the VWM capacity depends on an item/resolution trade-off, with mnemonic precision decreasing as the number of to-be-remembered items increases (Alvarez & Cavanagh, 2004; Bays, Catalao, & Husain, 2009; Bays & Husain, 2008; Zhang & Luck, 2008). In the relatively difficult memory task adopted here, the mnemonic representation of stimuli may be low in precision and thus particularly susceptible to interference from other sources of information. Alternatively, it could be the case that stimuli features were represented with adequate precision, but stored information about location was degraded (e.g. Bays, Catalao, & Husain, 2009). In a memory task like the one we adopted, the target was probed with a line that indicated one of the previous items locations. To accurately perform the task, participants needed to correctly remember both the orientation of the items in the array, and the exact location indicated by the probe. Misremembering the location indicated by the probe and responding with the remembered orientation of another item could contribute as a further source of errors. The presence of a reward-associated singleton could bias the remembered location toward that of the singleton itself, interfering with performance. In either case, it appears that the relatively low-precision of the visual memory representation created an opportunity for the reward-associated object to interfere with memory for other items.

Another possible explanation of the interference effect is that items associated to reward are more persistent over time and less prone to decay. The decay of information from iconic to visual working memory is not abrupt but it follows a smooth decaying function (Graziano & Sigman, 2008). If reward reinforces the persistence of the memory trace, one would expect a slower decay of information for reward-associated items. This suggests that a larger impact of reward associations should be observed at longer probe delays, when the memory trace for neutral items has already faded away while reward-associated items are still accurately represented in memory. However, we failed to detect such a pattern in our results, with no hint of a statistical trend. The apparent stability of the effect over time speaks for an early influence of reward on the encoding of information in visual memory, which remains constant within the first 800 ms. However, it should be noted that we tested only the early period of transfer of information from IM to VWM. Further work with longer probe delays is necessary to directly address the hypothesis of the influence of reward on the maintenance stage of information into working memory.

Finally, there is the possibility that the interference effect arises at the level of response selection, such that the response triggered by the singleton biased participants' performance. The orientation indicated by the singleton could have automatically triggered a



motor response that interfered with the selection of the appropriate motor act required for the target. One feature of our design argues against this interpretation: participants performed the memory task with no time pressure and were encouraged to be as accurate as possible, presumably minimizing response-selection errors. Moreover, the interference effect was strongest for items adjacent to the singleton, consistent with the idea that interference occurred during perceptual or selective processing. However, strong evidence for or against this interpretation would also require further dedicated work.

Our results importantly suggest that both IM and VWM for a visual object are significantly modulated by reward history. In particular, memory was affected by the value that each color assumed through a previous procedure of learning: features associated to high value led to a stronger interference effect than features associated to low value or features that were never presented as targets in the previous learning procedure.

Whereas Gong and Li (2014) observed a direct influence of feature reward associations on memory accuracy, we found an influence only on the interference effect, with raw accuracy unaffected. This may stem from our use of color singleton stimuli. Such stimuli automatically attract attention (e.g. Hickey, McDonald, & Theeuwes, 2006) and are better represented in memory (Schmidt et al., 2002). The possibly subtle impact of reward may have been overwhelmed by this raw visual salience. Moreover, our experiment was not designed to have the power to directly detect such change since we had only few trials in which we tested memory performance for singleton targets. On the other hand, in our experiments we tested relatively short delays, ranging from 10 to 800 ms, compared to 1000–2500 ms employed in Gong and Li. It is possible that reward directly affects maintenance of information in memory, but this is detectable only after longer intervals than were employed here.

While a clear interference effect emerged in our work, the paradigm we adopted was not specifically designed to disentangle whether reward associated items affect IM and VWM by means of an attentional capture phenomenon (Anderson, Laurent, & Yantis, 2011a, 2011b; Della Libera & Chelazzi, 2006, 2009; Hickey, Chelazzi, & Theeuwes, 2010a, 2010b, 2011), or if reward produces a proper reinforcement of the information that is encoded and stored in visual memory (Gong & Li, 2014). On the one hand, a shift of attention toward the location occupied by the high reward singleton should be accompanied by a modulation of accuracy at the neighboring locations. While in Experiment 2 we observe an improvement in performance in the locations near the singleton, suggesting that indeed it does attract attention, we fail to observe any modulation of this effect as a function of the reward value associated to the singleton. On the other hand, the stronger interference exerted by the information contained in the high-reward associated singletons seems to suggest facilitated representation of the visual information. However, further studies are necessary to directly investigate these two possibilities and understand the nature of the mechanisms involved in the influence of reward on the earliest stages of visual memory.

To conclude, we have shown that learned feature-reward associations can have an important impact on the encoding of information in memory. Previous experience and learned reward associations not only prioritize processing of associated visual stimuli, but also changes how these objects are stored in visual memory.

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