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Reward-related distracters and working memory filtering

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Abstract

Reward-related stimuli capture attention, even when they are task irrelevant. A consequence of attentional prioritization of reward-related stimuli is that they may also have preferential access to working memory like other forms of emotional information. However, whether reward-related distracters leak into working memory remains unknown. Here, using a well-validated change detection task of visual working memory capacity and filtering, we conducted two studies to directly assess the impact of reward-related distracters on working memory. In both studies, the distracters consisted of colored bars or circles that were previously associated with monetary reward. In Experiment 1, results indicated that previously rewarded distracters did not impact behavioral measures of working memory filtering efficiency compared to neutral distracters. In Experiment 2, using ERPs, we measured the contralateral delay activity (CDA), a psychophysiological index of the number of items retained in working memory, to further assess filtering efficiency. We observed that the CDA for high reward distracters was similar to low reward and neutral distracters. However, in early trials, behavioral measures revealed that previously rewarded stimuli negatively impacted working memory capacity, an effect not observed with neutral distracters. This effect, though, was not found for the CDA in early trials. In summary, our findings across two studies suggest that attentional capture by task-irrelevant reward may have minimal impact on visual working memory—findings that have important implications for delineating the boundaries of reward-cognition interactions.

KEYWORDS
emotion, ERPs, reward, working memory

1 | INTRODUCTION

We are bombarded with a tremendous amount of rich environmental stimuli at any given moment. To cope with this, selective attention facilitates optimal allocation of our limited processing resources (Corbetta & Shulman, 2002). Two mechanisms work together to facilitate goal-directed behavior, while keeping the organism attuned to salient information in the environment, such as threatening (Schmidt, Belopolsky, & Theeuwes, 2015; Theeuwes, Schmidt, & Belopolsky, 2014) or motivationally relevant information (Vuilleumier & Huang, 2009). Top-down processes help us focus attention on goal-related stimuli, while bottom-up processes help us assess salience of incoming stimuli and draw attention toward such stimuli if warranted (Theeuwes, 2010).

Richard Ward and Tara Miskovich contributed equally to this study.

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Recently, several studies have highlighted the impact that reward associations have on visual selective attention, even when the reward association is no longer relevant (Anderson, Laurent, & Yantis, 2011a, 2011b; Della Libera & Chelazzi, 2006, 2009; Hickey, Chelazzi, & Theeuwes, 2010; Munneke, Belopolsky, & Theeuwes, 2016). It appears that, much like threatening information (Schmidt et al., 2015; Theeuwes et al., 2014), reward stimuli compete for processing resources at the expense of resources necessary for the ongoing task (Anderson, Laurent, & Yantis, 2011a, 2011b). Task-irrelevant reward stimuli distracters can even capture attention when one's focus is targeted elsewhere based on attentional cues (Munneke et al., 2016). Consistent with this, eye tracking studies have linked task performance impairment to increased oculomotor capture to a previously rewarded stimulus (Anderson & Yantis, 2012; Theeuwes & Belopolsky, 2012). Attentional capture of reward stimuli has been further supported by ERP research demonstrating initial attentional capture to reward distracters (Qi, Zeng, Ding, & Li, 2013). Collectively, these results provide evidence of attentional capture by irrelevant reward.

Although the attentional bias toward reward-related information has been well established in the literature, little is known about the downstream consequences of this bias. Working memory allows us to hold and manipulate information to direct goal-related behavior (Baddeley, 2012; Cowan et al., 2005), and attentional control is thought to act as the "gatekeeper" of information that is subsequently maintained in working memory (Awh, Vogel, & Oh, 2006). Given our limited capacity to hold information in working memory (Luck & Vogel, 1997), we must rely on attention to select the most important information in the environment and filter irrelevant information from entering working memory stores (Fukuda & Vogel, 2009; Vogel, McCollough, & Machizawa, 2005).

Despite substantial evidence demonstrating that affective stimuli (both threat and reward) capture attention (Anderson, 2013; Koster, Crombez, Van Damme, Verschuere, & De Houwer, 2004), little is known about how emotionally salient yet distracting information may also impact filtering information into (or out of) working memory (Stout, Shackman, & Larson, 2013). Stimuli representing threat impact working memory filtering by impairing recruitment of circuitry necessary for task-relevant information, and irrelevant threat is misallocated in working memory (Dolcos & McCarthy, 2006; Stout et al., 2013). However, whether reward distracters are similarly inefficiently filtered is not yet well understood.

Two studies have examined the impact of reward distracters on working memory performance (Gong & Li, 2014; Infanti, Hickey, & Turatto, 2015). Gong and Li demonstrated that, although stimuli presented in a color representing reward improved working memory performance when presented as a target, they did not impair working memory performance when the stimulus was presented as a distracter. In contrast, Infanti and colleagues (2015) found that reward-related information may bias working memory storage. They found an interference effect on working memory encoding of neutral probes when reward stimuli were present. Gong and Li had matched all stimuli for salience; therefore, reward distracters may only modulate working memory performance when the distracters are already inherently salient. Importantly, in both Gong and Li (2014) and Infanti and colleagues (2015), items are only perceived as distracters when items are probed but are task-relevant items upon encoding. Therefore, it is currently unknown how reward-related distracters impact working memory when explicitly instructed to be ignored at encoding.

The current studies aimed to examine how efficiently reward-related distracters are filtered from working memory. We hypothesized that attentional priority to reward may lead to reduced filtering of reward distracters, resulting in these distracters being unnecessarily stored in working memory. We addressed this question through two studies. In Experiment 1, we conducted a behavioral study in which participants performed two change detection tasks, with the second task requiring participants to ignore previously rewarded distracters. We used behavioral measurements of filtering cost and working memory capacity to assess one's ability to filter irrelevant reward-related information from working memory. In Experiment 2, we performed a similar study with the addition of neural indices of working memory storage. We adapted a lateralized change detection task to isolate the contralateral delay activity (CDA; Luria, Balaban, Awh, & Vogel, 2016; Vogel & Machizawa, 2004), an ERP component that reflects the number of items being maintained in working memory during the retention period. By measuring the CDA, we could test whether reward distracters are misallocated into working memory stores, despite being task irrelevant (Vogel et al., 2005). Such unnecessary storage of reward distracters may have downstream consequences on cognition and behavior, such as interfering with the completion of ongoing tasks and biasing subsequent processing and further disruption of goal-related behavior. Thus, understanding the downstream consequences of attentional capture of irrelevant reward may inform neurocognitive models of the etiology of psychopathology characteristic of reward dysfunction (e.g., addiction, depression; Anderson, Faulkner, Rilee, Yantis, & Marvel, 2013; Anderson, Leal, Hall, Yassa, & Yantis, 2014).

2 | EXPERIMENT 1

2.1 | Method

2.1.1 | Power analysis

In order to ensure that the study was adequately sampled to detect differences between conditions, we conducted a power analysis based on a similar study with a sample size of 30 and an effect size of partial $\eta^2 = 0.10$ (Infanti et al., 2015). Assuming a similar effect size, the power analysis indicated a required sample size of 15 with power of 0.80 and alpha of 0.05.

2.1.2 | Participants

Sixty-nine undergraduates (39 female) were recruited from University of Wisconsin-Milwaukee psychology courses and received course extra credit for their participation. Participants were at least 18 years old, proficient in English, and had no visual impairments. Incomplete data were collected from three participants due to possible color blindness and withdrawal. Additionally, seven participants were excluded from further analyses due to poor performance (below 50% in any of the key conditions), and another participant was excluded due to having more than 25% of all trials dropped during data cleaning (see below). Analyses were conducted on the remaining 57 (30 female) participants. Prior to participation, subjects provided written informed consent. The study was approved by the University's Institutional Review Board.

2.1.3 | Materials and procedure

Training phase—Establishment of reward-stimulus association

Participants first completed a variation of the visual search task presented in Anderson and colleagues (2011b) in order to learn the association of a monetary reward with a particular colored stimulus. Participants were instructed that they had the opportunity to win money contingent on their performance on the task but were not told that only a certain color would be rewarded. Participants completed a total of 240 trials during the training phase, based on experiment 3 from Anderson and colleagues (2011b). Figure 1a depicts the trial sequence for the training phase. Each trial began with a 2-s "Get ready" slide. This was followed by a 300-ms search array consisting of six colored circles (2.3° × 2.3°) with bars of varying orientation, positioned in a circle around a center fixation cross. Participants were told to pay attention to the orientation of a bar inside the target colored circle (red or green counterbalanced across subjects, one of which was presented in each trial). Participants were informed of the target colors prior to the training but were not informed of the reward associated with each color. After viewing the array, participants were required to remember targets across a brief delay (900 ms). After the delay, the search array was presented again, and participants were instructed to respond if there was a change (of 45°) or no change in orientation of the bar inside the target circle. On 80% of the trials, correct responses to one of the target colors (red or green) were rewarded with 10 cents. Correct responses for the other target color were never rewarded. The purpose of this phase was to train the participants to associate one colored circle with reward and the other colored circle with neutral affective valence.

Test phase—Filtering of reward-related distracters in working memory task

Following the training phase, participants completed the test phase, which allowed us to assess the impact of previously rewarded stimuli on working memory filtering. The test phase

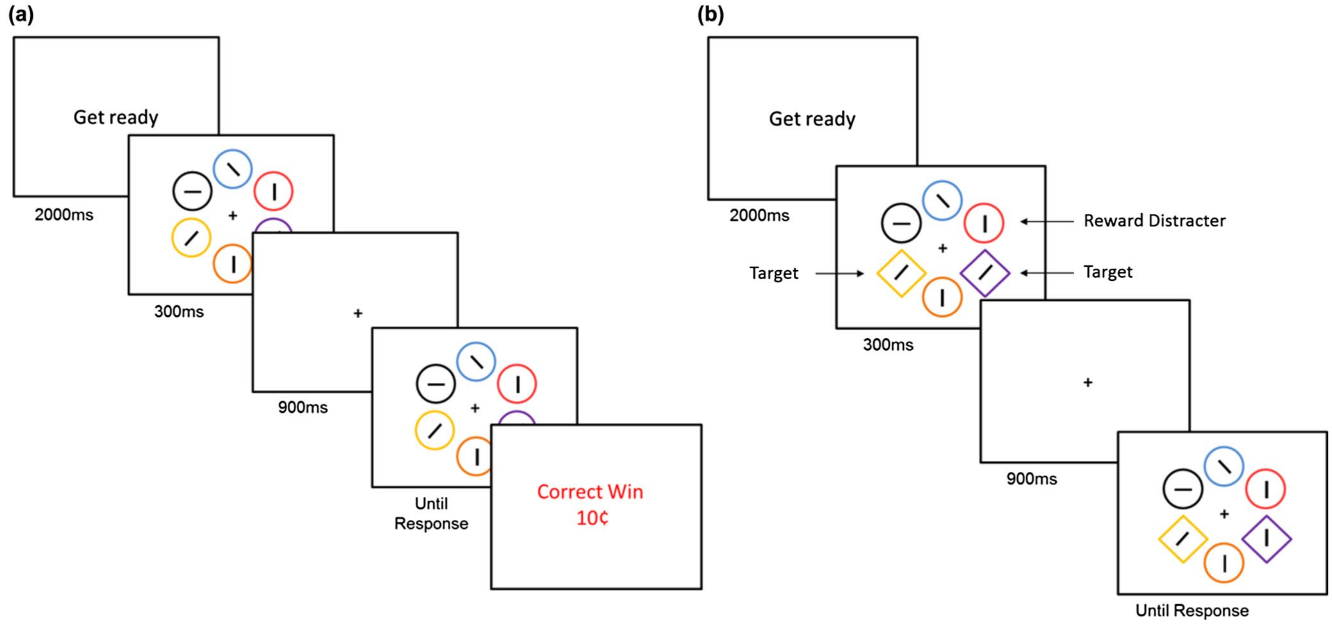

FIGURE 1 (a) Example of Experiment 1 training phase, in which reward was paired with a particular color with correct identification (+10 cents). (b) Example of the test phase, in which participants were instructed to detect a change over a short delay in the orientation of the bar within the target colored diamonds. Either target from the training phase could serve as a distracter (RD, ND), there could be all new distracters (NDnew), or there could be no distracters present (NT2)

consisted of a similar change detection task in which they were instructed to pay attention and remember the orientation of the bars within colored diamonds while ignoring all circles (Figure 1b). After a brief delay (900 ms), the array of shapes was presented again, and participants were instructed to respond if the orientation of the bars within the targets (diamonds) had changed or not changed. Participants were instructed that they would not receive any monetary rewards, and, therefore, the colored targets from the training phase now served as distracters in the array that the participants had to ignore. This allowed for examining whether reward distracters are difficult to filter from working memory. The sequence and timing of each trial was identical to the training phase, except without feedback about performance and reward at the end of each trial. There were four key conditions in the test phase (randomized order), each containing 34 trials: (a) two affectively neutral targets alone (NT2); (b) two neutral targets with four neutral distracters, including the non-rewarded target from the training phase (ND); (c) two neutral targets with three neutral distracters and the rewarded target from the training phase (RD); and (d) two neutral targets with four neutrals distracters, not including any target colors from the training phase (NDnew). Additionally, we included the same conditions with three targets and a condition with six targets, but due to poor performance in these conditions (three-target condition average accuracy = 75%; six-target condition average accuracy = 60%), they are not presented here (accuracy and reaction time data are presented in online supporting information, Table S1). This poor performance on trials with a load of three targets suggests that this set size was too taxing and that our selection of two target conditions would sufficiently tax working memory without yielding a significant decrease in performance. This set size, two targets with two distracting stimuli, is common in studies using the change detection task, particularly when assessing the influence of distracters in visual working memory (see Li, He, Wang, Hu, & Guo, 2017; Qi, Ding, & Li, 2014; Vogel et al., 2005).

Assessment of individual working memory capacity using non-emotional change detection task

Vulnerability to attentional capture to reward (Anderson et al., 2011b) and salience in general (Fukuda & Vogel, 2009) has been linked to working memory capacity, with high capacity being associated with better attentional control in the face of salient distraction. Thus, prior to the main task, participants completed a basic change detection task modeled after Luck and Vogel (1997) to determine visual working memory capacity. Participants were instructed to remember a brief (100 ms) array of colored squares across a short delay (900 ms). After the delay, one of the previous colored squares was presented again, at which time participants were instructed to respond if the probe square had changed in color (Luck & Vogel, 1997). The task consisted of 120 trials divided among three different conditions: two targets, four targets, or six targets, similar to the number of trials used by others (Shipstead, Harrison, & Engle, 2015). Working memory capacity was estimated using Cowan's K (Cowan, 2001), $K = S \times (H - FA)$, where K is capacity, S is set size, H is hits, and FA is false alarms (Pashler, 1988; Rouder, Morey, Morey, & Cowan, 2011).

Data cleaning

Subject data were removed from further analyses if accuracy was 50% or lower in any of the key conditions ($n = 7$). All trials in which the response to the probe was less than 150 ms or exceeded 5,000 ms were dropped. Within the training phase, the average amount of trials dropped was 0.7 (<0.01%). There was no difference in the number of trials dropped in the previously rewarded distracter condition (RD) versus the non-rewarded target from the training phases condition (ND), $p = 0.41$. The average number of trials dropped per subject in the test phase was 1.25 (0.01%) and did not differ among the different conditions, ($p = 0.15$) (NT2 ($M = 0.23$), RD ($M = 0.21$), ND ($M = 0.39$), NDnew ($M = 0.41$)). Reaction time (RT) analyses were conducted on trials with correct responses.

Behavioral estimates of working memory capacity and filtering during test phase: Pashler's K

Pashler's K, one of the primary dependent measures, is a behavioral measure of working memory capacity appropriate for conditions in which the probe includes all elements of the initial array (Pashler, 1988; Rouder et al., 2011). This formula $K = S \times (H - FA)/(1 - FA)$ uses target accuracy, hits, and false alarms to calculate an estimate of the average number of target items in a visual array held in working memory. Pashler's K scores were calculated for each of the four conditions in the test phase to estimate the effect of previously rewarded distracters on working memory capacity. K scores were analyzed using a repeated measures analysis of variance (ANOVA) with Greenhouse-Geisser adjustments for violations of sphericity. Pairwise comparisons following up on significant interactions and main effects were Bonferroni corrected based on the total number of comparisons to decompose that effect.

Filtering cost scores

Filtering cost, the second primary dependent measure, is a calculation of how efficiently the subject can prevent goal-irrelevant distracters from accessing working memory. The score was calculated as the difference of the average target accuracy for NT2 trials and trials with additional distracters (Fukuda & Vogel, 2009). As filtering cost scores decrease, filtering efficiency increases (a score of 0 would indicate perfect filtering). Filtering cost scores were calculated for the three distracter conditions, RD, ND, and NDnew, and were analyzed using a repeated measures ANOVA with Greenhouse-Geisser adjustments for violations of sphericity. All follow-up pairwise comparisons were Bonferroni corrected.

Bayesian tests of probability of null result

For all null results, Bayes factor 10 (BF_{10}) was calculated to determine the probability of obtaining a null result, with values greater than 1 indicating more evidence for the alternative hypothesis and values less than 1 indicating evidence for the null hypothesis.

Internal reliability of measures

In order to ensure that our variables of interest were reliable, we calculated Cronbach's alpha for the behavioral variables of interest used to calculate the filtering scores, accuracy, and reaction time. Our results indicated an acceptable range of reliability for accuracy (NT2, $\alpha = 0.71$; RD, $\alpha = 0.73$; ND, $\alpha = 0.76$; NDnew, $\alpha = 0.72$) and reaction time measures (NT2, $\alpha = 0.97$; RD, $\alpha = 0.71$, ND, $\alpha = 0.87$; NDnew, $\alpha = 0.80$) across all conditions. We also found adequate range of scores for the variables of interest (see Appendix, Table A1).

2.2 | Results

2.2.1 | Training phase—Establishment of reward-stimulus association

During the training phase in which reward was explicitly paired with a particular target, participants were quicker to correctly respond to the rewarded target ($M = 963.8$ ms, $SD = 290.23$) compared to the non-rewarded target ($M = 1{,}007.6$ ms, $SD = 290.23$), $t(56) = 3.75$, $p < 0.001$. We also found that accuracy for the rewarded target ($M = 0.91$, $SD = 0.07$) trended toward being significantly higher than the non-rewarded target ($M = 0.89$, $SD = 0.09$), $t(56) = -1.75$, $p = 0.09$. This indicates that participants responded more quickly and with greater accuracy when the target was a rewarded, indicating that participants learned the association between the reward and target color.

2.2.2 | Test phase—Filtering of reward-related distracters in working memory task RT

RT was significantly different across the four conditions, $F(2.83, 158.52) = 21.57$, $p < 0.001$ (Figure 2a). Follow-up pairwise comparisons showed that participants were quicker to respond in the NT2 condition compared to the distracter conditions (ND, $t(56) = -6.219$, $p < 0.001$; RD, $t(56) = -6.336$, $p < 0.001$; RDnew, $t(56) = -6.003$, $p < 0.001$). Additional analyses showed that RTs did not differ between any of the distracter conditions (ND − RD, $t(56) = -0.737$, $p > 0.99$, $BF_{10} = 0.187$; ND − RDnew, $t(56) = -0.465$, $p > 0.99$, $BF_{10} = 0.160$; RD − RDnew, $t(56) = 0.242$, $p > 0.99$, $BF_{10} = 0.149$).

Accuracy

The ANOVA for accuracy also revealed a main effect for condition, $F(2.7, 151.29) = 55.18$, $p < 0.001$ (Figure 2b). Follow-up pairwise comparisons showed that this main effect was driven by the difference between the NT2 condition and the distracter conditions (ND, $t(56) = 11.802$, $p < 0.001$; RD, $t(56) = 11.379$, $p < 0.001$; RDnew, $t(56) = 10.501$, $p < 0.001$). Additional analyses showed that accuracy did not differ between the distracter conditions (ND − RD, $t(56) = -0.197$, $p > 0.99$, $BF_{10} = 0.147$; ND − RDnew, $t(56) = 0.077$, $p > 0.99$, $BF_{10} = 0.145$; RD − RDnew, $t(56) = -0.154$, $p > 0.99$, $BF_{10} = 0.146$).

Working memory storage

To test the impact of a rewarding distracter on working memory capacity for target items, a repeated measures ANOVA was conducted to compare working memory for targets (Pashler's K) in each of the four conditions (NT2, RD, ND, NDnew). Results revealed a significant main effect of condition, $F(2.81, 157.12) = 47.85$, $p < 0.001$ (Figure 2c). Follow-up pairwise comparisons demonstrated that the NT2 condition was significantly higher than the distracter conditions (ND, $t(56) = 10.377$, $p < 0.001$; RD, $t(56) = 11.417$, $p < 0.001$; RDnew, $t(56) = 9.424$, $p < 0.001$). Additional analyses revealed that K scores did not differ between the distracter conditions (ND − RD, $t(56) = 0.258$, $p > 0.99$, $BF_{10} = 0.149$; ND − RDnew, $t(56) = 0.236$, $p > 0.99$, $BF_{10} = 0.149$; RD − RDnew, $t(56) = -0.029$, $p > 0.99$, $BF_{10} = 0.145$). This indicates that distracters did impair working memory capacity as NT2 was higher than the distracter conditions, but this effect was not greater for reward-related distracters compared to neutral distracters.

Filtering cost

To test the impact of a reward distracter on filtering efficiency, we calculated a repeated measures ANOVA comparing filtering cost scores for the three distracter conditions (RD, ND, NDnew). There was no significant effect of condition, $F(1.89, 105.91) = 0.02$, $p = 0.98$, $BF_{10} = 0.060$ (Figure 2d). Thus, filtering efficiency was similar across all distracter conditions, and there was no effect of distracter valence.

2.2.3 | Working memory capacity and distracter filtering in presence of reward

To examine whether greater working memory capacity was associated with better filtering of reward distracters, we calculated a difference score between neutral and reward distracters (ND − RD and NDnew − RD) for each of our

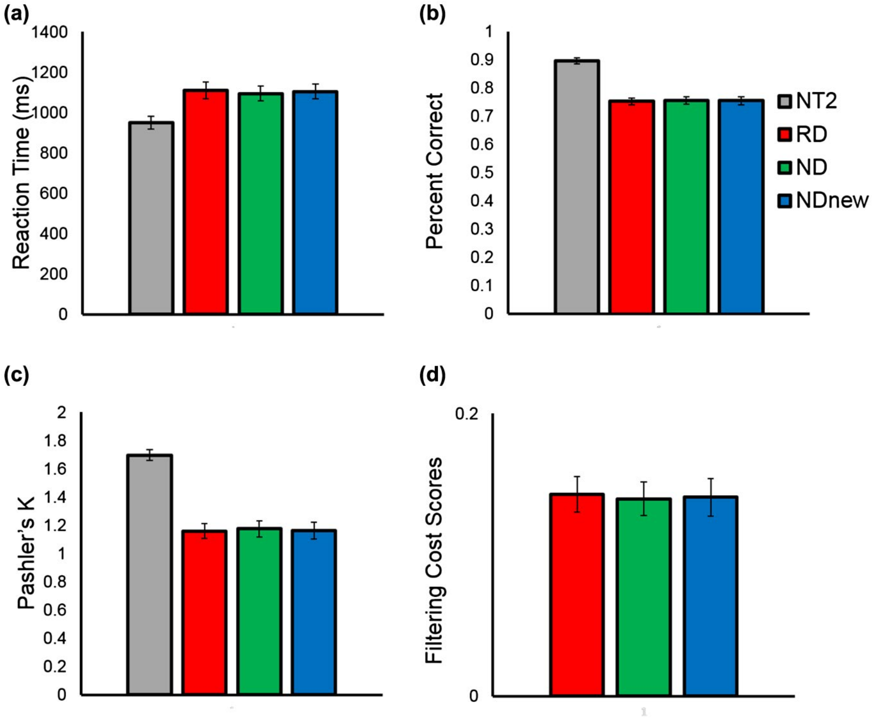

FIGURE 2 (a) Average reaction time (RT) was quicker for the two targets alone condition (NT2) than conditions where distracters were present, but there were no differences between any of the three distracter conditions. (b) Accuracy was also higher in two targets alone, but again there were no differences between distracter conditions. (c) Average working memory capacity for targets (K) was significantly higher in the condition with two neutral targets alone compared to conditions with distracters present. Again, the three distracter conditions did not differ. (d) There were no significant differences across condition in inefficiency or cost of filtering into working memory. Error bars represent standard error

dependent variables and correlated that value with individual working memory capacity as measured by Cowan's K on the basic change detection task. One subject did not complete the working memory capacity assessment task and was excluded from this analysis. Working memory capacity did not predict K difference scores between RD and ND ($r = 0.05$, $p = 0.70$, $BF_{10} = 0.180$) or RD and NDnew ($r = 0.1$, $p = 0.48$, $BF_{10} = 0.213$). Additionally, working memory capacity did not predict differences in filtering cost between RD and ND ($r = -0.02$, $p = 0.9$, $BF_{10} = 0.168$) or RD and NDnew ($r = -0.05$, $p = 0.72$, $BF_{10} = 0.178$). Finally, individual working memory capacity did not predict differences in RT between RD and ND ($r = -0.17$, $p = 0.20$, $BF_{10} = 0.368$), or RD and NDnew ($r = -0.06$, $p = 0.66$, $BF_{10} = 0.183$). This indicates that working memory capacity did not predict individual performance differences when a reward distracter was present.

In summary, results from Experiment 1 did not support the hypothesis that reward-related distracters would impair performance on a subsequent working memory task above and beyond non-emotional distracters. It is possible that participants simply searched for a global change rather than selectively committing each line stimulus to memory. While this is possible, it should be noted that behavioral performance was impacted by the addition of distracters, such that distracter conditions led to slower RTs, reduced accuracy, and lower K scores. Therefore, even if participants used a strategy of searching for global change, the introduction of distracters did impact performance.

Our next step was to assess whether or not reward-related distracters are unsuccessfully filtered out of working memory as indexed by a neural measure of working memory storage, the CDA (Vogel & Machizawa, 2004). This may be a more sensitive measure of working memory filtering than performance.

3 | EXPERIMENT 2

3.1 | Method

3.1.1 | Power analysis

To ensure that the sample size for the study was adequately powered to detect differences between conditions, we conducted a power analysis. Since this is the first study to our knowledge to test filtering efficiency of reward distracters using ERPs, we conducted a conservative estimate assuming a small effect size (partial $\eta^2 = 0.02$). The power analysis yielded a required sample size of 38 with power of 0.8 and alpha of 0.05.

3.1.2 | Participants

Fifty-nine undergraduates (39 female; no overlap with sample from Experiment 1) were recruited from the University of Wisconsin-Milwaukee. Compensation was provided in the form of course extra credit as well as the monetary amount earned during the task. Participants were at least 18 years old, proficient in English, and had no visual impairments. Data were incomplete for six participants due to technical difficulties (three) or withdrawal (three). Additionally, four participants were dropped from further analysis due to chance performance, and another eight participants were dropped due to artifact rejection exceeding 30% of ERP epochs. Finally, data from two participants were dropped because residual horizontal electro-oculogram (EOG) exceeded 4 μV. Final analyses were conducted on a sample of 39 individuals (24 female, $M_{\text{age}} = 21.69$, $SD = 4.95$). Participants provided written informed consent prior to the start of the experiment, and the University's Institutional Review Board approved the study.

3.1.3 | Materials and procedure

Training phase—Establishment of reward-stimulus association

As in Experiment 1, participants first completed a variation of a previously published reward attention training task (Anderson et al., 2011b) to train subjects to associate a particular monetary reward with a specific colored bar. Unlike in Experiment 1, this task did not have a working memory component and therefore just required visual search. This task began with fixation for 200–400 ms, followed by a search array that remained on screen for a maximum of 900 ms or until response. The search array consisted of six colored bars (0.41° × 1.42°) positioned in a circular pattern around a fixation (5° radius). Participants were told to attend to only green and red items in the array and to identify if the orientation of those bars was horizontal or vertical. In each trial, participants were presented with either a red or a green target in an array of color bars with equal probability. Non-target bars were only in tilted positions (left 45° or right 45°) and were one of the following colors: white, pink, purple, blue, yellow, orange, brown. All colors in the visual attention task were matched for luminance (120 cd/m^2). Feedback was presented after correct responses for 1,500 ms, with a screen indicating the earned amount for that trial as well as a running total (Figure 3a). For each participant, one of the target colors (red or green) was associated with a higher reward (10 cents) 80% of the time and a low reward (2 cents) 20% of the time. These contingencies were reversed for the other target color, and the color contingency association was counterbalanced. Thus, throughout the course of the training task, participants

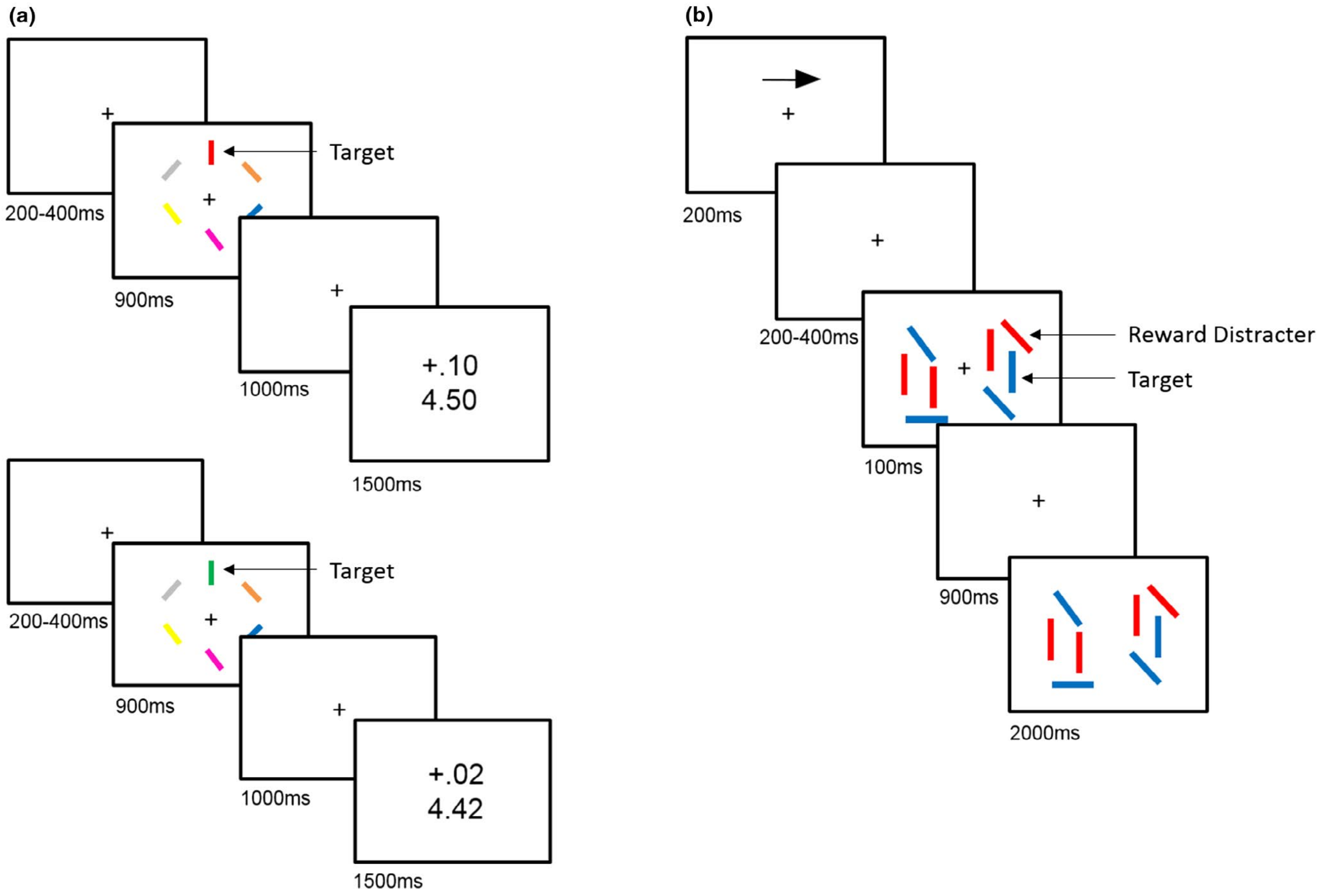

FIGURE 3 (a) Example of the training phase for Experiment 2, in which participants learned that one of the two colored targets (red or green) was associated with a high reward with correct identification (+10 cents), whereas the other target was associated with a low reward with correct identification (+2 cents). (b) Example of the Experiment 2 test phase, in which participants were instructed to pay attention to the orientation of the target bars (blue) in the directed side of the array while ignoring the other colored distracter bars (red). The two targets from the training phase, both high-rewarded and low-rewarded, now served as distracters to be ignored

would associate one color with a high probability of receiving high reward and one color with high probability of receiving low reward. In the case of incorrect responses, participants received a blank screen for the 1,500 ms. The training phase consisted of 240 trials.

Test phase—Assessment of reward associations in working memory task

Following the training phase, participants completed the test phase, a working memory change detection task in which some trials included distracter items that had been associated with reward in the training phase. We used this lateralized change detection task to assess the impact of goal-irrelevant reward distraction on the storage of goal-relevant neutral targets in working memory, as measured by CDA. Participants were told that they would not be rewarded for performance during this portion of the study. The change detection task was analogous to other working memory and filtering tasks (Vogel et al., 2005). The task used a bilateral display in order to isolate the CDA by taking the difference between brain activity ipsilateral and contralateral to the attended side of the screen.

The bilateral display consisted of two stimulus arrays within 4.1° × 7.72° rectangular regions each 3° away from fixation. Participants were instructed to attend to one side of a brief array of colored bars (each 0.41° × 1.42°) in any of four orientations (vertical, horizontal, left 45°, right 45°) and to remember the orientation of the blue (or yellow counterbalanced) bars present, while ignoring any other colored bars (Figure 3b). The rectangular bars' location and orientation were randomized but were at least 2° from each other center to center. Following the initial array and a retention period, participants were presented with a probe array and had to indicate with a button press whether there was a 45° change in orientation within one of the target bars. Each trial (total trial length = 5 s) consisted of (a) a 200-ms start fixation cross with an arrow above indicating direction of attention allocation, (b) a 200–400 ms jitter, (c) a 100-ms array display with equal number of colored bars left and right of the fixation cross, (d) a 900-ms retention period, and (e) a 2,000-ms (or until response) probe display (Figure 3b). The target color was either blue or yellow, both colors that were affectively neutral during the training phase. Additionally, two colored bars were presented as distracters during distracter conditions. The two distracter bars were the same color and were either red, green, or the non-target affectively neutral color (i.e., blue or yellow). As in the training phase, all colors were matched for luminance.

There were five conditions: (a) two affectively neutral targets (blue or yellow bars) with two distracters that were previously high-rewarded targets in the training phase (HD), (b) two neutral targets with two distracters that were previously low-rewarded targets in the training phase (LD), (c) two neutral targets with two neutral distracters (ND), (d) two neutral targets with no distracters (NT2), and (e) four neutral targets with no distracters (NT4). There were 160 trials of each condition, which were presented in a random order.

Assessment of individual working memory capacity using non-emotional change detection task

Before the main task, we assessed participants' visual working memory capacity using a basic change detection task modeled after Luck and Vogel (1997), as described in Experiment 1.

Behavioral data cleaning

Trials with RTs < 150 ms were removed from further analyses. No trials were dropped during the training phase. The average number of trials dropped per subject in the test phase was 5.54 (<0.01%). There was no difference in the number dropped across the five different conditions, $p = 0.44$. RT analyses were conducted on trials with correct responses.

Internal reliability of measures

We conducted internal consistency statistics for each variable of interest as in Experiment 1. Our results indicated acceptable reliability for accuracy measures across all conditions (HD, $\alpha = 0.82$; LD, $\alpha = 0.84$; ND, $\alpha = 0.87$; NT2 $\alpha = 0.79$; NT4, $\alpha = 0.88$) and reaction time measures across all conditions (HD, $\alpha = 0.98$; LD, $\alpha = 0.98$, ND, $\alpha = 0.98$; NT2, $\alpha = 0.99$; NT4, $\alpha = 0.98$). We found adequate range for the variables of interest (see Appendix, Table A2).

Psychophysiological data acquisition and reduction

EEG activity was recorded using an *asalab* EEG system and a 32 Ag-AgCl electrode fitted nylon cap (Advanced Neuro Technologies B.V., Netherlands) referenced to the left mastoid. Impedances did not exceed 10 kΩ, and data were low-pass filtered (138.24 Hz). All signals were digitized at 512 Hz. Horizontal and vertical EOG activity was recorded from electrodes placed on the left and right outer canthi and above and below the left eye, respectively. ERP analyses were conducted using EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014). Raw EEG data were rereferenced to the mean of the left and right mastoids and filtered with a Butterworth band-pass of 0.1–30 Hz (24 db/octave). Independent component analyses were run using EEGLAB's *runica* routine. Components representing blink artifacts were identified based on visual inspection and removed from the EEG data. ERP data were segmented at − 200 to 1,400 ms from the onset of the target array with a 200-ms baseline correction. Trials with residual eye blinks (VEOG exceeding 80 μV), saccades (HEOG exceeding 40 μV), or excessive movement (channels of interest exceeding 80 μV) were removed from further processing. Participants with residual HEOG exceeding 4 μV were excluded from further analyses as well. Overall, an average of 87.05 (11.88%; *SD* = 54.89) out of the total 800 trials (160 per condition) were rejected for the remaining subjects.

3.1.4 | CDA component

To calculate the CDA, contralateral and ipsilateral waveforms were first computed at the lateral posterior sites of O1/O2, P3/P4, and P7/P8 electrode sites (Figure 4). Contralateral waveforms represent activity from the right hemisphere when the stimulus appears in the left visual field and from activity from the left hemisphere when the stimulus appears in the right hemisphere. Ipsilateral waveforms represent activity from the left hemisphere when the stimulus appears in the left visual field and from activity from the right hemisphere when the stimulus appears in the right hemisphere. The CDA was then calculated as the averaged contralateral minus ipsilateral activity pooled across O1/2, P3/4, and P7/8 electrodes (Figure 5). The CDA for each condition (HD, LD, ND, NT2, NT4) was calculated as the mean amplitude using a time window of 400–900 ms postarray onset, which corresponds to the working memory delay period (Vogel & Machizawa, 2004). For the CDA, we calculated a repeated measures ANOVA (with Greenhouse-Geisser adjustment) comparing the five conditions. We also assessed a measure of filtering efficiency or how well individuals filter in only relevant information into working memory for each distracter condition, by taking the absolute difference in amplitude between the high load condition and each distracter condition. Therefore, higher scores indicate better filtering efficiency (Jost, Bryck, Vogel, & Mayr, 2011).

Bonferroni corrections were used for follow-up pairwise comparisons. BF_{10} was calculated the same as in Experiment 1.

3.2 | Results

3.2.1 | Training phase—Establishment of reward-stimulus association

During the training phase, there were no differences in accuracy between the high ($M = 0.88$, $SD = 0.07$) and low ($M = 0.88$, $SD = 0.07$) reward targets, $t(38) = 0.01$, $p > 0.99$, $BF_{10} = 0.173$. There were also no differences between high ($M = 575.71$, $SD = 44.82$) and low ($M = 580.47$, $SD = 49.68$) reward in RT, $t(38) = -1.34$, $p = 0.19$, $BF_{10} = 0.396$. This indicates that performance was similar for both high and low reward conditions during training, which is consistent with previous studies (Gong & Li, 2014).

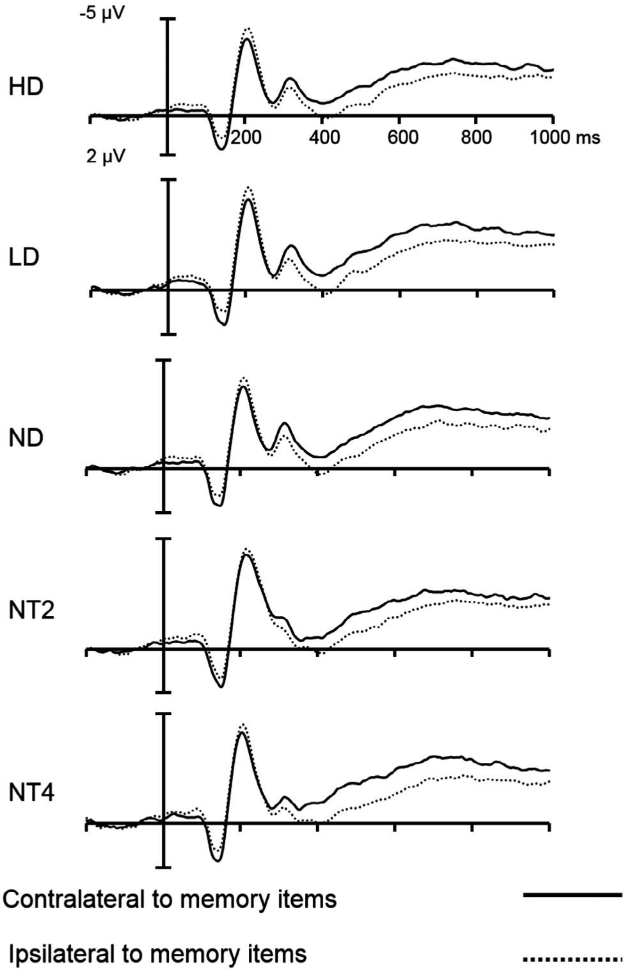

FIGURE 4 Contralateral and ipsilateral wave forms for each condition for the entire test phase

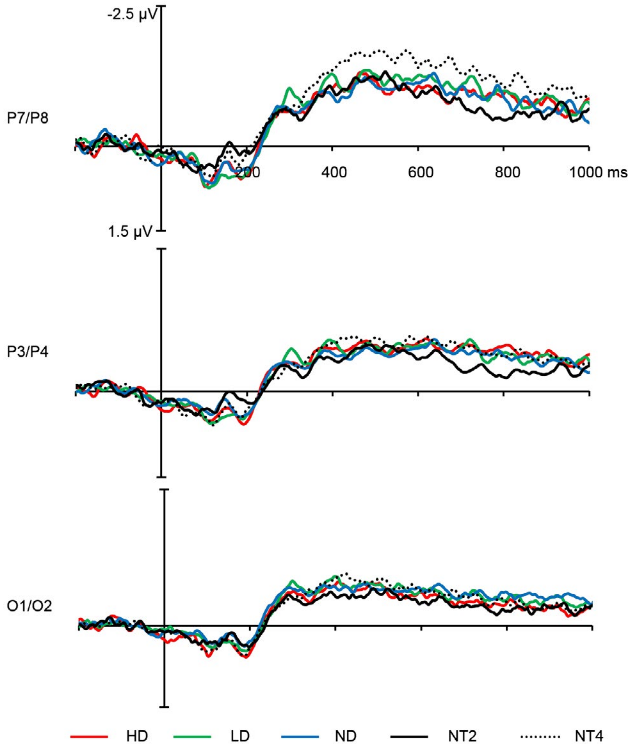

FIGURE 5 Contralateral minus ipsilateral wave forms for each channel cluster of interest for the entire test phase

3.2.2 | Test phase—Filtering of reward-related distracters in working memory task

A repeated measures ANOVA of RT indicated a significant main effect of condition, $F(2.53, 96.03) = 11.64$, $p < 0.001$ (Figure 6a). Follow-up pairwise comparisons demonstrated that RT for the NT4 condition was significantly longer than the NT2 condition, $t(38) = 5.219$, $p < 0.001$. However, there were no significant differences in RT between the high load (NT4) and distracter conditions (ND, $t(38) = 1.432$, $p => 0.99$, $BF_{10} = 0.442$; LD, $t(38) = 2.259$, $p = 0.30$, $BF_{10} = 1.651$; HD, $t(38) = 2.504$, $p = 0.17$, $BF_{10} = 2.664$). Participants were also slower when distracters were present compared to when there were two targets alone (NT2), ND, $t(38) = -5.605$, $p < 0.001$; LD, $t(38) = -3.838$, $p < 0.01$; HD, $t(38) = -4.327$, $p < 0.001$. Further analyses revealed that the distracter conditions did not differ in RT (ND – LD, $t(38) = 1.715$, $p = 0.95$, $BF_{10} = 0.665$; ND – HD, $t(38) = 1.964$, $p = 0.57$, $BF_{10} = 0.975$; HD – LD, $t(38) = 0.141$, $p > 0.99$, $BF_{10} = 0.174$).

The repeated measures ANOVA for accuracy revealed a significant main effect of condition, $F(2.96, 112.28) = 81.67$, $p < 0.001$ (Figure 6b). Follow-up pairwise comparisons demonstrated that accuracy was poorer in the NT4 condition compared to all other conditions (NT2, $t(38) = -15.734$, $p < 0.001$; ND, $t(38) = -10.838$, $p < 0.001$; HD, $t(38) = -11.062$, $p < 0.001$; LD, $t(38) = -12.129$, $p < 0.001$). Additional analyses revealed that performance on trials with two targets alone (NT2) was significantly better than trials with low reward distracters (LD, $t(38) = 3.182$, $p < 0.05$) and approached significant differences compared to neutral and high reward distracters (ND, $t(38) = 2.840$, $p = 0.07$, $BF_{10} = 5.446$; HD, $t(38) = 2.910$ $p = 0.06$, $BF_{10} = 6.369$) conditions. The distracter conditions did not differ in accuracy (ND – LD, $t(38) = 0.306$, $p > 0.99$, $BF_{10} = 0.180$; ND – HD, $t(38) = 0.114$, $p > 0.99$, $BF_{10} = 0.174$; HD – LD, $t(38) = 0.223$, $p > 0.99$, $BF_{10} = 0.177$).

To examine whether the presence of a previously rewarded stimulus distracter impaired working memory capacity for targets, we conducted a repeated measures ANOVA on

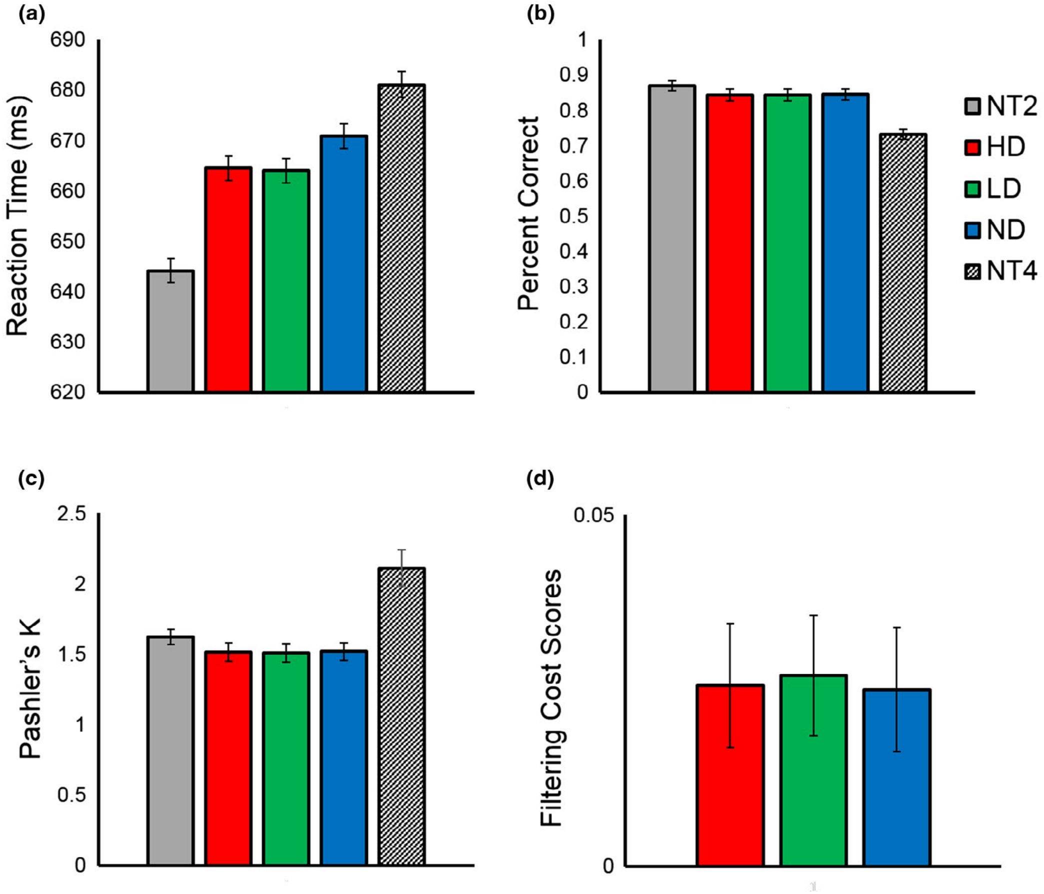

FIGURE 6 (a) Participants were quicker to respond to the two targets alone condition (NT2) compared to the distracter present conditions or the four targets alone condition (NT4). (b) Participants were less accurate when they had to remember four targets alone compared to two targets, regardless if there were distracters present. (c) Working memory capacity was impaired when distracters were present compared to when no distracters were present (NT2). (d) Filtering cost scores did not differ across the different distracter conditions, indicating that rewarding stimuli did not impair filtering more than neutral stimuli. Error bars represent standard error

K scores, which revealed a significant effect of condition, $F(1.39, 52.97) = 35.68$, $p < 0.001$ (Figure 6c). Follow-up pairwise comparisons demonstrated that K scores for the NT4 condition were significantly greater than all other conditions (NT2, $t(38) = 5.244$, $p < 0.001$; ND, $t(38) = 6.442$, $p < 0.001$; LD, $t(38) = 6.830$, $p < 0.001$; HD, $t(38) = 6.743$, $p < 0.001$). Additional analyses revealed K scores in the NT2 condition were greater than in the distracter conditions (HD, $t(38) = 3.305$, $p < 0.05$; LD, $t(38) = 3.263$, $p < 0.05$; ND, $t(38) = 3.051$, $p < 0.05$). The distracter conditions did not differ in K scores (ND − LD, $t(38) = 0.332$, $p > 0.99$, $BF_{10} = 0.182$; ND − HD, $t(38) = 0.220$, $p > 0.99$, $BF_{10} = 0.177$; HD − LD, $t(38) = 0.210$, $p > 0.99$, $BF_{10} = 0.176$). These results indicate that, no matter the reward salience of the distracter (including neutral), working memory capacity for targets was equally impaired when a distracter was present.

A repeated measures ANOVA of filtering cost scores (distracter accuracy − NT2 accuracy; Fukuda & Vogel, 2009) indicated that there was no significant effect of condition for filtering cost scores, $F(1.90, 72.14) = 0.06$, $p = 0.94$, $BF_{10} = 0.094$ (Figure 6d). In other words, the reward association with certain distracters did not impact individual's behavioral filtering performance more or less than a neutral distracter.

3.2.3 | Test phase—CDA and unnecessary storage of distracters

A repeated measures ANOVA of CDA amplitude (400–900 ms) revealed a significant main effect of condition, $F(3.72, 141.23) = 4.32$, $p < 0.001$ (Figure 7a,b). Follow-up pairwise comparisons demonstrated that the amplitude of the NT2 condition was significantly greater than the NT4 condition, indicating that more items were being stored in the four targets alone condition compared to the two targets alone condition, $t(38) = -3.752$, $p < 0.01$. Further examination revealed that the NT4 condition did not differ in amplitude compared to any of the distracter conditions (ND, $t(38) = -2.094$, $p = 0.430$, $BF_{10} = 1.221$; LD, $t(38) = -1.650$, $p > 0.99$, $BF_{10} = 0.596$; HD, $t(38) = -2.145$, $p = 0.384$, $BF_{10} = 1.336$), nor were there any differences between the two targets alone condition compared to the distracter conditions (ND, $t(38) = 1.719$, $p = 0.937$, $BF_{10} = 0.660$; LD, $t(38) = 2.418$, $p = 0.205$, $BF_{10} = 2.224$; HD, $t(38) = 1.781$, $p = 0.830$, $BF_{10} = 0.725$). The distracter conditions did not differ in amplitude (ND − LD, $t(38) = 0.615$, $p > 0.99$, $BF_{10} = 0.206$; ND − HD, $t(38) = -0.025$, $p > 0.99$, $BF_{10} = 0.173$; HD − LD, $t(38) = 0.666$, $p > 0.99$, $BF_{10} = 0.212$).

3.2.4 | Test phase—Working memory capacity and filtering of reward distracters

To understand whether individual differences in working memory capacity were related to unnecessary storage of reward distracters, we first calculated HD − LD and HD − ND CDA amplitude difference scores. We then correlated these with Cowan's K estimates of working memory capacity. We found that Cowan's K did not predict CDA amplitude differences between the HD and LD ($r = -0.16$, $p = 0.33$, $BF_{10} = 0.318$) or ND ($r = -0.07$, $p = 0.69$, $BF_{10} = 0.215$). We also correlated working memory capacity with behavioral measurements and found that working memory capacity did not correlate with RT differences between HD and LD ($r = 0.18$, $p = 0.27$, $BF_{10} = 0.355$) or HD and ND ($r = 0.11$, $p = 0.51$, $BF_{10} = 0.245$). Working memory capacity also did not correlate with the difference in K scores between HD and LD ($r = 0.11$, $p = 0.52$, $BF_{10} = 0.244$) or HD and ND ($r = 0.13$, $p = 0.45$, $BF_{10} = 0.264$). Finally, working memory capacity did not correlate with differences between filtering cost scores between HD and LD ($r = 0.05$, $p = 0.75$, $BF_{10} = 0.210$) and HD and ND ($r = -0.001$, $p = 0.99$, $BF_{10} = 0.199$). These results suggest that the effect of a high reward distracter on working memory performance, compared to low reward and neutral distracters of the same perceptual salience, was not related to working memory capacity.

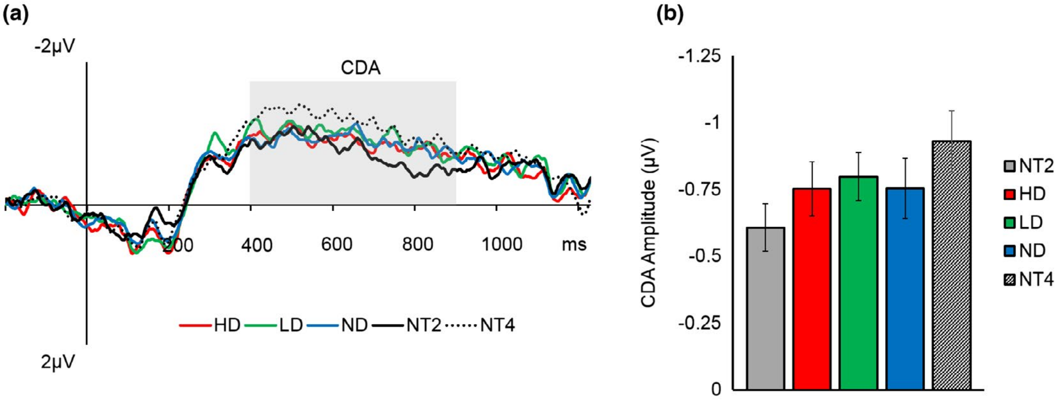

FIGURE 7 (a) Contralateral minus ipsilateral wave forms for each condition. (b) Storing four targets alone (NT4) versus two targets alone (NT2) resulted in larger contralateral delay activity (CDA), but CDA amplitude for distracter conditions did not differ from the high or low load target-only conditions. Error bars represent standard error

3.2.5 | Test phase—Change-detection performance during early test phase

Our training phase was based on the robust training phase presented in experiment 3 of Anderson et al. (2011b), in which participants completed a short version of both training and test phases (240 trials each). Since our test phase was substantially longer (800 trials), it is possible that our current results showing no differences between the three distracter conditions may be due to the length of the test phase and progressive extinction of the association between stimulus and reward. Therefore, we conducted another analysis of our behavioral measures on only the first 240 trials of the test phase. We found a significant main effect of condition for RT, $F(3.01, 114.46) = 6.25$, $p < 0.01$ (Figure 8a). Follow-up pairwise comparisons demonstrated that RTs for the NT4 condition were significantly longer than for the two targets alone condition, $t(38) = 4.464$, $p < 0.01$, but did not differ from the distracter conditions (ND, $t(38) = 1.263$, $p > 0.99$, $BF_{10} = 0.360$; LD, $t(38) = 1.683$, $p > 0.99$, $BF_{10} = 0.625$; HD, $t(38) = 1.686$, $p > 0.99$, $BF_{10} = 0.628$). In addition, RTs of the NT2 condition were significantly faster than in the distracter conditions (ND, $t(38) = -3.880$, $p < 0.01$; LD, $t(38) = -3.829$, $p < 0.01$; HD, $t(38) = -3.141$, $p < 0.05$). RTs in the distracter conditions did not differ (ND − LD, $t(38) = 0.442$, $p > 0.99$, $BF_{10} = 0.189$; ND − HD, $t(38) = 0.398$, $p > 0.99$, $BF_{10} = 0.186$; HD − LD, $t(38) = -0.018$, $p > 0.99$, $BF_{10} = 0.173$).

There was also a significant main effect of condition for accuracy, $F(3.58, 135.85 = 36.57$, $p < 0.001$ (Figure 8b). Follow-up pairwise comparisons demonstrated that accuracy for the four targets alone condition was worse than in all other conditions (NT2, $t(38) = -12.105$, $p < 0.001$; ND, $t(38) = -8.747$, $p < 0.001$; LD, $t(38) = -6.955$, $p < 0.001$; HD, $t(38) = -7.207$, $p < 0.001$). Additional analyses revealed that accuracy was greater for the two targets alone condition compared to the reward distracter conditions (LD, $t(38) = 4.067$, $p < 0.01$; HD, $t(38) = 3.155$, $p < 0.05$), but did not differ from the neutral distracter condition (ND, $t(38) = 1.805$, $p = 0.79$, $BF_{10} = 0.752$). The distracter conditions did not differ in accuracy (ND − LD, $t(38) = 2.905$, $p = 0.43$, $BF_{10} = 1.233$; ND − HD, $t(38) = 0.970$, $p > 0.99$, $BF_{10} = 0.267$; HD − LD, $t(38) = 1.104$, $p > 0.99$, $BF_{10} = 0.304$). These results indicate

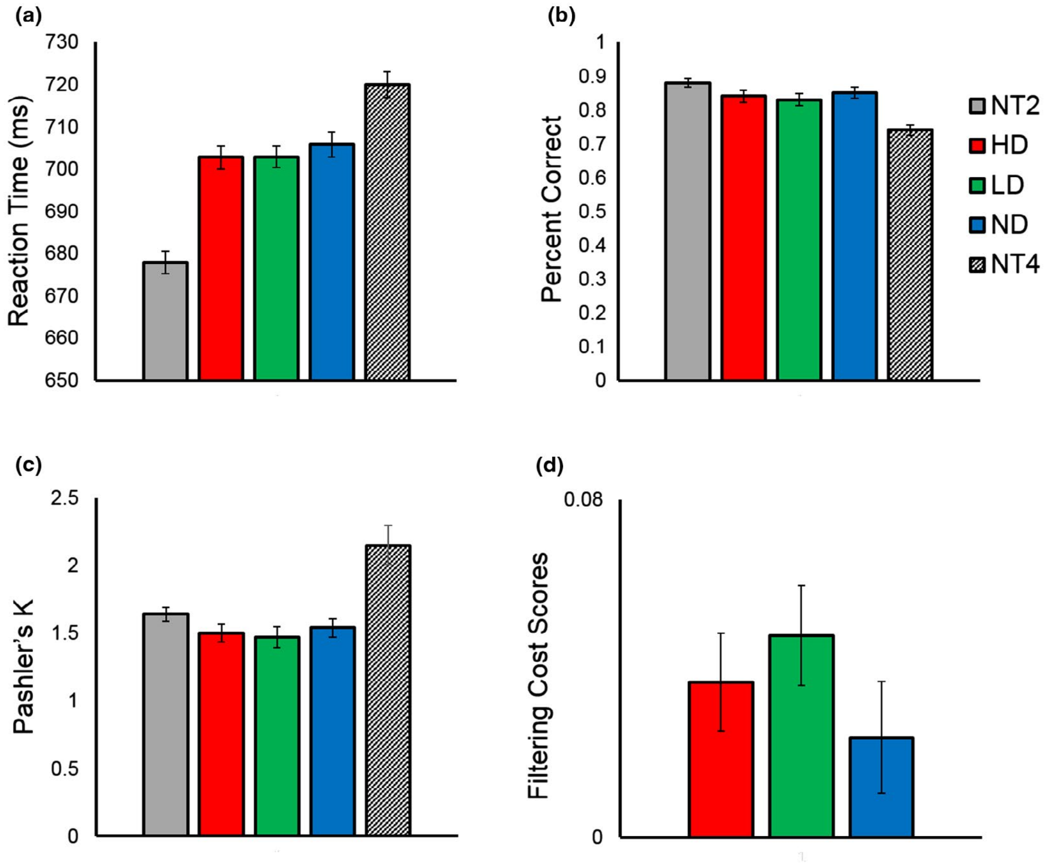

FIGURE 8 (a) Participants were quicker to respond when there were only two targets on the screen (NT2) compared to the distracter present conditions or the four targets alone condition (NT4). (b) Participants were less accurate when they had to remember four targets alone compared to two targets, regardless if there were distracters present. (c) Working memory capacity was impaired when low and high reward distracters were present compared to when no distracters were present (NT2). (d) Filtering cost scores did not differ across the different distracter conditions, indicating that rewarding stimuli did not impair filtering more than neutral stimuli. Error bars represent standard error

that, in the early training phase, accuracy for conditions with previously rewarded distracters was impaired compared to when there was no distraction, a result not found in the initial analyses with all trials.

There was also a significant main effect of condition for working memory capacity (K scores), $F(1.69, 64.03) = 25.24$, $p < 0.001$ (Figure 8c). Follow-up pairwise comparisons demonstrated that K scores for the NT4 condition were significantly greater than for all other conditions (NT2, $t(38) = 4.329$, $p < 0.01$; ND, $t(38) = 5.425$, $p < 0.001$; LD, $t(38) = 6.607$, $p < 0.001$; HD, $t(38) = 5.808$, $p < 0.001$). The NT2 condition also had greater average K scores compared to the reward distracter conditions (LD, $t(38) = 3.446$, $p < 0.05$; HD, $t(38) = 3.287$, $p < 0.05$) but not the neutral distracter condition (ND, $t(38) = 2.057$, $p = 0.47$, $BF_{10} = 1.143$). The distracter conditions did not differ in K scores (ND − LD, $t(38) = 1.340$, $p > 0.99$, $BF_{10} = 0.394$; ND − HD, $t(38) = 0.726$, $p > 0.99$, $BF_{10} = 0.221$; HD − LD, $t(38) = 0.820$, $p > 0.99$, $BF_{10} = 0.236$). This indicates that, early in the test phase, previously rewarded distracters of either high or low value did impair working memory capacity to a greater degree than neutral distracters.

When comparing filtering cost scores in the first 240 trials, we found no significant differences between any of the three distracter conditions, $F(1.8, 68.81) = 2.12$, $p = 0.13$, $BF_{10} = 0.445$ (Figure 8d). This suggests that reward-related distracters had no impact on filtering performance in the early test phase.

3.2.6 | Test phase—CDA and unnecessary storage of distracters during early test phase

A repeated measures ANOVA of the CDA for the first 240 trials revealed similar results as our results for the entire test phase. We found a significant main effect of condition, $F(3.74, 142.0) = 4.30$, $p < 0.01$ (Figure 9a,b). Follow-up pairwise comparisons demonstrated that the two targets alone condition amplitude was significantly lower than that of four targets alone condition, indicating that more items were being stored in the NT4 condition, $t(38) = 3.730$, $p < 0.01$. The NT4 condition did not differ in amplitude compared to any of the distracter conditions (ND, $t(38) = -2.235$, $p = 0.31$, $BF_{10} = 1.576$; LD, $t(38) = -0.674$, $p > 0.99$, $BF_{10} = 0.214$; HD, $t(38) = -2.686$, $p = 0.11$, $BF_{10} = 3.896$). In addition, the NT2 condition did not differ in amplitude compared to the neutral distracter condition (ND, $t(38) = 1.429$, $p > 0.99$, $BF_{10} = 0.441$) and high reward distracter condition (HD, $t(38) = 0.616$, $p > 0.99$, $BF_{10} = 0.206$) but did approach significant differences with the low reward distracter condition (LD, $t(38) = 2.754$, $p = 0.09$, $BF_{10} = 4.512$). Further examination found no differences in amplitude between distracter conditions (ND − LD, $t(38) = 1.714$, $p = 0.95$, $BF_{10} = 0.655$; ND − HD, $t(38) = -0.710$, $p > 0.99$, $BF_{10} = 0.218$; HD − LD, $t(38) = 2.093$, $p = 0.43$, $BF_{10} = 1.219$).

4 | DISCUSSION

Previous literature has demonstrated that reward-related information draws attention, even when irrelevant to current task goals (Anderson et al., 2011a, 2011b; Anderson & Yantis, 2012; Della Libera & Chelazzi, 2006, 2009; Hickey & van Zoest, 2012; Theeuwes & Belopolsky, 2012). Given the strong relationship between attention and working memory (Awh et al., 2006), we sought to investigate the downstream consequences of reward-related attentional capture and how it may impact behavior. Here, we presented two studies aimed to test whether the presence of a reward-related distracter would impair working memory performance and storage.

In Experiment 1, we assessed behavioral measurements of working memory capacity of target items and filtering cost scores for distracting items. In contrast to our hypotheses, we found working memory performance impairment was no different when distracters were reward-related compared to neutral. In Experiment 2, we extended these findings to

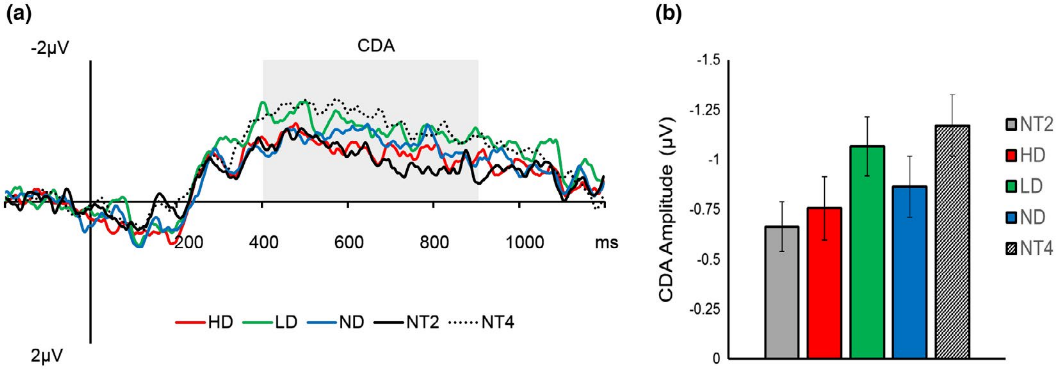

FIGURE 9 (a) Contralateral minus ipsilateral wave forms for each condition for the first 240 trials. (b) Storing four targets alone (NT4) versus two targets alone (NT2) resulted in larger CDA, but CDA amplitude for distracter conditions did not differ from the high or low load target-only conditions. Error bars represent standard error

demonstrate that neural indices of working memory storage did not reflect greater impaired filtering of reward-related distracters compared to neutral distracters. Within Experiment 2, we examined behavioral performance in early trials, and we did find that previously rewarded distracters impaired working memory performance compared to a novel neutral distracter, suggesting a potential early effect of reward distracters. However, the impact of performance was not dependent on the reward value of each distracter (low vs. high). In addition, analyses of the CDA during the early trials also demonstrated no difference between reward-related distracters compared to neutral distracters. An alternative interpretation, therefore, is that attention was captured due to the stimuli being targets in the previous task, which cannot be ruled out in the current study. Here, we discuss the conditions in which reward may (and may not) influence attention and working memory processes and how this impacts our understanding of emotion and cognition interactions.

There is extensive evidence that the presence of reward-related information impacts information processing in several cognitive domains, including modulating working memory (Jimura, Locke, & Braver, 2010; Kawasaki & Yamaguchi, 2013). Two previous studies examined the influence of reward-related stimuli on working memory performance when this reward information was presented as a distraction from task goals (Gong & Lie, 2014; Infanti et al., 2015). Gong and Li examined the influence of reward-feature associations on working memory performance using a similar approach to the current study. Using a change detection task, they found improved working memory performance when a probe item was presented in a color that was previously associated with reward. However, they found no impairment in working memory performance of a probed item when a reward-related distracter was presented in the array. Both Gong and Li's and our findings are inconsistent with the attentional capture hypothesis, suggesting that the influence of reward stimuli on visual attention may not be entirely due to attentional capture but may be modulatory through feature-based attention (Gong & Li, 2014). Alternatively, Infanti and colleagues (2015) examined the impact of task-irrelevant reward on iconic memory as well as visual working memory. They found that the presence of a reward-related stimulus interfered with the encoding of other non-reward-related stimuli in a visual array, a finding consistent with the attentional capture hypothesis, indicating attentional prioritization of reward-related stimuli even when that information is irrelevant. One important methodological difference between our findings and those reported by others (Gong & Li, 2014; Infanti et al., 2015) is that participants in the current study were explicitly instructed to ignore non-target stimuli, including those that represent reward. In Gong and Li's (2014) and Infanti and colleagues' (2015) studies, participants were instructed to treat all stimuli as important information to retain in working memory, even though the reward association was irrelevant. Therefore, our results would suggest that reward-related associations may have less of an impact on attentional priority into working memory storage when the explicit goal is to ignore them.

The results presented here, together with work by others (Gong & Li, 2014; Sha & Jiang, 2016), suggest that the presence of task-irrelevant reward does not necessarily lead to a robust or persistent impairment in attention and working memory performance. However, more research is necessary to better understand the conditions in which reward influences attention and working memory processes. The amount of cognitive demand placed on participants may be one important factor to consider. Both the current study and Gong and Li (2014) had cognitive loads that were much higher than that of Anderson and colleagues (2011b), since participants had to encode and maintain multiple items in working memory rather than detect a singleton in an array. Prior research has demonstrated that increasing working memory load increases the impact of distracters (de Fockert, Rees, Frith, & Lavie, 2001; Lavie & de Fockert, 2005; Lavie, Hirst, de Fockert, & Viding, 2004). It is possible that increasing the load on working memory increases the impact of distracters to a point at which any differences in distracter valence are no longer evident. If cognitive load, in fact, decreases the impact of attentional bias toward affective distracters, this could explain why Gong and Li (2014) and the current study did not find evidence of attentional capture by reward distracters. Another recent study also found an effect of attentional capture from previously learned targets in the test phase but found no differences based on their associated values (Sha & Jiang, 2016).

Saccade latencies also contribute to the effects of reward-driven attentional capture (Failing, Nissens, Pearson, Le Pelly, & Theeuwes, 2015). High reward distracters have been shown to capture attention when task demands result in early saccade onsets; however, reward-facilitated capture is reduced when saccade latency increases. The current study used a change detection task, which is associated with longer saccade latencies. Therefore, it is possible that the effect of task-irrelevant distracters associated with reward is diminished due to the increased processing time in our change detection task.

Training duration is another factor that may impact the robustness of reward-driven attention during a later test phase. The length of the training phase in the current study was shorter than that used in previous studies (Anderson et al., 2011a, 2011b; Della Libera & Chelazzi, 2006, 2009). Despite the short training interval used in the current study (i.e., 240 trials), work by Anderson and colleagues (2011b) demonstrated that 240 trials should be adequate to facilitate the learning of reward contingencies (see their experiment 3). It is also important to note that our observed behavioral effects replicated across both Experiments 1 and 2, despite different training paradigms and training lengths. Moreover, others have also reported null effects of the presence of task-irrelevant reward stimuli and the persistent impairment in attention and working memory performance, despite incorporating a greater number of trials in their training phases (Gong & Li, 2014; Sha & Jiang, 2016). Thus, the current study is consistent with a growing body of work failing to find an effect of reward distracters on performance. Nonetheless, it is important to note that the current study's task procedures were somewhat different than those used by these aforementioned studies. For example, compared to Anderson and colleagues (2011b), our training trials consisted of a visual working memory task, whereas Anderson and colleagues used a visual search task. Other studies have used different trial durations (Gong & Li, 2014), provided feedback on performance (Sha & Jiang, 2016), or completed training and test on different days (Gong & Li, 2014). Despite these differences, our findings provide additional evidence consistent with a lack of impact of reward distracters on working memory filtering.

The length of the test phase in Experiment 2 was longer in order to capture the CDA component. However, since we found no effect across the whole test phase in Experiment 2, we assessed behavioral measures of working memory performance and capacity in only the first 240 trials of the test phase, to mimic the length of Anderson and colleagues' experiment 3 (2011b). While we did not find an effect of reward distracters in Experiment 1 (306 trials total), we did find association in early (first 240) trials of the test phase for accuracy in Experiment 2, demonstrating that the presence of both high and low reward distracters impaired working memory capacity compared to the no distracter condition, while the neutral distracters did not. However, our findings for RT, filtering cost, and the CDA for the early test phase were similar to our results obtained for the entire test phase, such that reward-related distracters did not differ from neutral distracters. These results for accuracy are potentially consistent with a value-driven account (Anderson, 2013). However, given that in this early phase of the experiment there was no difference in impairment between the high and low reward and that the reward distracters were used as targets in the visual search training task but the neutral distracters were not, it is also possible that participants' attention was biased toward previously presented targets, rather than valence. Indeed, previous literature demonstrates attentional biases to previously sought targets (Kyllingsbæk, Schneider, & Bundesen, 2001). Overall, the analysis of the first 240 test trials in Experiment 2 did not yield strong support for the detrimental impact of reward distracters on working memory performance.

The current study was in part based on work investigating the influence of threat distracters on access to working memory (Stout et al., 2013). However, as these and other recent findings show, reward and threat may have different attentional effects on access to working memory despite both demonstrating attentional capture. Gong and Li (2014) argued that reward may influence attention by enhancing the representation of task-relevant stimuli in working memory, but, in contrast to what has been found with task-irrelevant threat (Bishop, 2007; Stout et al., 2013), task-irrelevant reward does not necessarily impair task-relevant representations. The potential differential effects of reward and threat on selective attention may reflect the different neural circuitry instantiating detection of threat and reward (Choi, Padmala, & Pessoa, 2015; Choi, Padmala, Spechler, & Pessoa, 2014). Detection of threat is dependent on amygdala-prefrontal circuitry (Bishop, 2007; Shechner et al., 2012), while detection of reward typically involves fronto-striatal circuits (Frank & Fossella, 2010; Shechner et al., 2012). In addition, this reward detection system may interact with regions implicated in attentional control to boost these processes (Engelmann, Damaraju, Padmala, & Pessoa, 2009). Interestingly, activation of basal ganglia-prefrontal circuitry has also been associated with better filtering of distracters (McNab & Klingberg, 2007).

Consistent with these findings, Gong, Yang, and Li (2016) demonstrated enhanced visual search performance when individuals were cued to ignore stimuli associated with a high reward compared to low reward and non-reward stimuli features. Therefore, it is possible that reward may in fact enhance suppression when it is explicitly task irrelevant. However, our findings are not consistent with this interpretation, at least in the context of working memory, since reward associations did not seem to impact performance differently than non-reward distracters. Alternatively, it is possible that these differences between our findings and that of Gong and colleagues (2016) are due to the varied properties of the target stimuli. For example, Gong, Jia, and Li (2017) demonstrated that reward-related distracters were easier to suppress when target identification was more difficult and when the target was unknown before the onset of stimuli. In Gong and colleagues' (2016) work, the distracters (rewarded and neutral) were cued prior to the onset of the stimuli and the target was unknown, making it more difficult to identify the target stimuli. In contrast, in the current study the target stimuli were already known and the distracter stimuli were unknown until stimulus onset. The easier target detection in our study may have led to a reduced need for top-down control in order to suppress the reward-related distracters in the current study. Despite the present inconsistencies in the reward literature, differential recruitment of attention and attentional control circuits may be an important factor in understanding why irrelevant threat may have privileged access to working memory stores while reward does not.

Overall, there may be several important considerations in understanding under what conditions reward influences visual attention and working memory processes. At this point, it is clear that reward history impacts attention selection in a biased and persistent manner, even when it is contrary to task goals (Anderson, 2013; Anderson et al., 2011a, 2011b; Thomas, FitzGibbon, & Raymond, 2016).

However, the literature is mixed on how this attentional bias to task-irrelevant reward impacts subsequent attention and working memory processes, with evidence supporting a number of possibilities, including an attentional capture account (Anderson, 2013; Anderson et al., 2011b; Anderson & Yantis, 2012; Hickey & van Zoest, 2012), a feature-based account (Gong & Li, 2014), and contingent capture by previously learned targets stimuli independent of reward (Sha & Jiang, 2016).

In sum, the current study provided limited support for the impact of reward associations on ongoing working memory and behavioral processes when the reward association is no longer relevant. Across both experiments, we found that reward distracters did not impact working memory storage to a greater extent than neutral distracters. Furthermore, we did not find evidence that reward value modulated the impact of distracters (no difference between high and low reward distracters). Given the close link between attention and working memory, it is unclear at this point how attention processes recover from initial attentional capture of reward so that reward does not gain preferential access to working memory stores. However, in Experiment 2, we found some evidence that working memory performance was impacted by the presence of reward distracters in early trials. Together with recent work by others, these data indicate that the influence of task-irrelevant reward on working memory may be subtler than for threat and that more work is needed to clarify conditions under which reward does and does not impact performance.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1

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APPENDIX

TABLE A1 Experiment 1 range for variables of interest

Variable	Condition	Min	Max
Accuracy (%)	NT2	0.67	1.00
	RD	0.55	1.00
	ND	0.53	0.97
	NDnew	0.53	0.97
Reaction time (ms)	NT2	560.97	1775.14
	RD	538.90	1924.77
	ND	444.05	1671.93
	NDnew	608.50	1829.10
K scores	NT2	0.94	2.00
	RD	0.29	2.00
	ND	0.15	2.00
	NDnew	0.10	2.00
K score filtering	RD – ND	0.83	1.43
	RD – NDnew	−0.92	1.05
Accuracy filtering costs	RD – ND	−0.38	0.22
	RD – NDnew	−0.26	0.20
Reaction time filtering	RD – ND	−281.10	721.25
	RD – NDnew	−346.57	799.23

Note: Abbreviations: NT2, two neutral targets alone; RD, two neutral targets with three neutral distracters and a previously rewarded target from the training phase; ND, two neutral targets with four neutral distracters including the non-rewarded target from the training phase; ND_{new}, two neutral targets with four neutrals distracters, not including any target colors from the training phase.

TABLE A2 Experiment 2 range for variables of interest

Variable	Condition	Min	Max
Accuracy (%)	HD	0.58	0.98
	LD	0.58	0.98
	ND	0.58	0.98
	NT2	0.59	0.98
	NT4	0.52	0.87
Reaction time (ms)	HD	503.56	949.28
	LD	488.57	982.55
	ND	496.31	962.43
	NT2	479.49	946.29
	NT4	465.17	983.11
K scores	HD	0.32	1.95
	LD	0.37	1.97
	ND	0.40	1.90
	NT2	0.43	1.97
	NT4	0.17	3.29
CDA filtering	HD – LD	−0.78	0.95
	HD – ND	−0.99	0.91
K score filtering	HD – LD	−0.35	0.29
	HD – ND	−0.29	0.28
Accuracy filtering costs	HD – LD	−0.08	0.07
	HD – ND	−0.08	0.10
Reaction time filtering	HD – LD	−46.32	46.36
	HD – ND	−63.42	38.28

Note: Abbreviations: HD, two neutral targets and two high reward distracters. LD should be two neutral targets and two low reward distracters. ND should be two neutral targets and two neutral distracters; NT2, two neutral targets alone; NT4, four neutral targets alone.