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REGISTERED REPORTS AND REPLICATIONS

Assessing the role of accuracy-based feedback in value-driven attentional capture

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Abstract

Despite being physically nonsalient and task-irrelevant, objects rendered in a color that once signaled monetary reward reflexively capture attention during visual search, a phenomenon known as *value-driven attentional capture* (VDAC). However, it remains a subject of empirical controversy whether learned reward associations are necessary to driving subsequent attentional capture: VDAC-like effects have been observed when accuracy-based feedback alone was used during the VDAC training phase, resulting in attentional capture by objects that were never associated with monetary reward; perplexingly, the presence of these VDAC-like effects in the literature conflicts with those of a number of control studies in which no such capture has been observed, leaving the issue currently unresolved. In this Registered Report, we present new empirical evidence of attentional capture by unrewarded former targets following limited accuracy-based training. We proposed to replicate these results in an independent sample and to test an empirically derived hypothesis concerning a methodological difference between the studies that have shown VDAC-like effects with accuracy-based feedback and those that have not. In short, we found no evidence that this methodological difference accounts for the inconsistencies in the literature, but our replication efforts were overwhelmingly successful, thus reinvigorating debate about the role that selection history may play in value-driven attentional capture.

Keywords Attention · Attentional capture

Voluntary attention facilitates selective processing of the sensory input most relevant for goal-directed action. However, intentionally disregarding irrelevant stimuli is not without limit. For example, voluntarily allocating covert attention to task-relevant locations can reduce, but not eliminate, the impact of abrupt-onset stimuli that trigger involuntary attentional allocation to task-irrelevant locations (Grubb, White, Heeger, & Carrasco, 2015). Physically nonsalient stimuli can also interrupt goal-directed behavior after associative learning: For example, irrelevant distractors rendered in a color that once signaled monetary reward slow responses and capture eye movements when they are presented in subsequent, unrewarded tasks, a phenomenon dubbed *value-driven attentional capture* (VDAC; Anderson, 2013; Anderson, Laurent, & Yantis, 2011; Anderson & Yantis, 2012).

In the seminal publication (Anderson et al., 2011), Anderson and colleagues presented a method for characterizing the effect of VDAC during visual search. Garnering an average of more than 40 citations per year since its initial publication (Web of Science citation report, 9/1/2017), Anderson's article has been extremely influential and has arguably spawned a new subfield of attention-related research. In this experimental paradigm, observers complete two phases: a training phase and a test phase. During the VDAC training phase, observers search for a color-defined target (e.g., a red or green circle), receive high or low monetary reward for correctly discriminating the orientation of a line contained inside, and thus learn to associate high or low reward with the target-defining colors. In the VDAC test phase, observers search for a shape-defined target (e.g., a circle among diamonds) and again discriminate the orientation of a line contained inside; the colors of the individual elements are task-irrelevant, but on half of the trials, one of the distractor elements is rendered in a color that previously signaled high or

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low monetary reward. The presence of VDAC is typically quantified by a change in response time (RT): Orientation judgments in the test phase are slowed when a high-value distractor is present, both relative to when a low-value distractor is present and relative to when no value distractor is present.

Because the VDAC training phase requires observers to repeatedly select target-defining colors for attentional prioritization, an alternative interpretation of these data is that selection history (Awh, Belopolsky, & Theeuwes, 2012) drives subsequent attentional capture, rather than reward per se (Kadel, Feldmann-Wüstefeld, & Schubö, 2017; Kyllingbaek, Schneider, & Bundesen, 2001; Shiffrin & Schneider, 1977). To rule out such an interpretation, Anderson and colleagues have repeatedly shown that replacing monetary reward with accuracy-based feedback during training eliminates the VDAC effect altogether (Anderson & Halpern, 2017; Anderson, Laurent, & Yantis, 2011, 2012, 2014).

Registered Report—Background study and proposed project

In the service of another research goal—assessing whether performance-contingent reward impacts the strategic balancing of speed and accuracy (Grubb & Li, 2017)—we employed the short-training VDAC paradigm (Anderson et al., 2011, Exp. 3) and added a control group that only received correct/incorrect feedback during training (i.e., no trial-by-trial reward). As a preliminary sanity check, we had expected to find evidence of VDAC in the trial-by-trial reward feedback group, but not in the correct/incorrect feedback group (Anderson et al., 2011). Surprisingly, this is not what we observed: The test-phase RTs slowed when the training phase target was present as a distractor relative to when it was absent, irrespective of the training-phase feedback, and we found no evidence of a between-group difference in the magnitude of the observed RT modulation. An assessment of error rates confirmed that these changes in RT were not driven by speed–accuracy trade-offs, and eyetracking data revealed that the presence of the training-phase target in the test phase biased the overt allocation of spatial attention to the same extent in both groups (see the supplemental material for the detailed results). Critically, because our control group only received correct/incorrect feedback during training, the attentional capture in this group could not be due to distraction by features that had once signaled monetary reward.

We are not the first to have observed significant capture by former targets that were never associated with monetary reward (Miranda & Palmer, 2014; Sha & Jiang, 2016; Wang, Yu, & Zhou, 2013). But the reason why nonmonetary feedback would yield capture in these cases but not others (Anderson et al., 2011, 2012, 2014; Qi, Zeng, Ding, & Li, 2013; Roper & Vecera, 2016) is currently an open empirical question. It has been proposed that a small sample (ten observers in Anderson et al., 2011, Exp. 2) precluded the detection of capture effects when accuracy-based feedback was substituted for reward-based feedback (Sha & Jiang, 2016; and see the supplemental material for empirically derived evidence that the null result reported in Anderson et al., 2011, Exp. 2, may have been due to a lack of statistical power). To address this possibility, Anderson and Halpern (2017, Exp. 2A) recently published a new, accuracy-based control experiment using the short-training procedure (240 training trials, followed by 240 test trials) and a sample size of 40 observers. Given the similarity between our background study design and that used by Anderson and Halpern (i.e., the same stimuli, same task, same number of training trials, and same number of test trials), it is perplexing that we observed significant capture effects in our study, whereas Anderson and Halpern failed to find any effect of previously unrewarded distractors in theirs. Furthermore, Anderson and Halpern recommended limiting training to 240 trials "[t]o maximize the robustness of value-dependent effects across rewarded and unrewarded training" (p. 1007), but the results from our background study suggest that this may not be sufficient.

Upon closer inspection of the methodological minutia, we noticed one small, but potentially critical, difference between our background study and that reported by Anderson and Halpern (2017). During training, we informed participants when they were correct by displaying the word "correct" on the screen during the feedback period; in Anderson and Halpern (2017, Exp. 2A, p. 1005), "participants were only informed whether their prior response was incorrect or too slow." Intriguingly, Anderson et al. (2012) also informed participants only when their responses were incorrect, and Anderson et al. (2014) withheld feedback during training altogether. Thus, when accurate responses were signaled by the withholding of negative feedback in the training phase, accuracy-based feedback consistently failed to produce attentional capture by previously unrewarded targets in the VDAC test phase. When accurate responses during training were instead signaled by the delivery of explicit positive feedback (e.g., the word "correct," in our study and Wang et al., 2013; points and elaborate sound effects, in Miranda & Palmer, 2014; or a rising succession of pure tones, in Sha & Jiang, 2016), accuracy-based feedback reliably engendered attentional capture during test by targets never associated with monetary reward.

In the study behind this Registered Report (*Attention, Perception, & Psychophysics*, 2013), we proposed to (1) replicate our accuracy-based VDAC results in an independent sample and (2) explicitly test the hypothesis that has emerged from our background study and the literature cited above—namely, that explicit positive feedback, delivered on a trial-by-trial basis during the training phase, is sufficient to drive attentional capture by unrewarded training-phase targets when they appear as distractors in the test phase. Accuracy-based feedback has been a popular control condition for many VDAC studies, and systematically characterizing the conditions under which a VDAC-like effect emerges with unrewarded feedback is a critical next step in advancing our theoretical understanding of this empirical phenomenon. When the experimental conditions during training are such that accuracy-based feedback does lead to significant attentional capture during test, another critically important question is whether such accuracy-based feedback leads to less powerful capture than does reward-based feedback, and the research proposed and presented here is a first step toward what will undoubtedly be a series of empirical studies on this issue.

Method

Overview

We replicated the data collection and analysis procedures used in our background study (see the supplemental material) with two exceptions:

1. Two separate groups received accuracy-based feedback during the training phase: The accuracy-based feedback for one group matched exactly what was used in our background study (i.e., "correct," "incorrect," and "too slow" were presented as visual feedback for accurate, inaccurate, and missed responses, respectively); for the other group of observers, only "incorrect" and "too slow" followed inaccurate and missed responses, respectively (i.e., correct responses for this group were signaled by the withholding of negative feedback).
2. Participants sat closer to the monitor (60 cm) and kept their chins in a chin rest. The stimulus units were degrees of visual angle (DVA), and thus the perceived stimulus size was unchanged.

Statistical power and sample size

A total of 80 observers (18–27 years of age; 58 female, 22 male) participated in the study. Among these observers, 40 were randomly assigned to each feedback group, and this sample size was justified by two sources: (1) Anderson and Halpern (2017) reported that 40 participants is sufficient to detect group differences in capture following rewarded and unrewarded training with $\beta = 0.85$; (2) a nonparametric power analysis from the control group in our background study (see the supplemental material) revealed that the probability of correctly rejecting the null hypothesis with 40 participants was .9081.

Variables

The two independent variables for this Registered Report were training-phase feedback type ("correct" delivered vs. "correct" withheld; between subjects) and training-phase target status (present vs. absent, within subjects). The primary dependent variable was the mean RT in the test phase (correct trials only, trimmed to remove responses occurring three standard deviations above or below the condition mean). Error rate served as a secondary dependent variable in order to verify that any observed changes in RT were due to changes in attention, rather than the results of simple trade-offs between speed and accuracy.

Planned analyses—Task performance

Mixed-design analyses of variance (ANOVAs), with training-phase target status as a within-subjects factor and training-phase feedback type as a between-subjects factor, were conducted for both dependent variables; nonparametric randomization tests (see the supplemental material) were also used to assess the interaction term and both main effects.

Data availability Upon publication, the data will be available for download from the author's website: www.AttentionPerceptionDecision.com.

Results

Preregistered analyses

Despite never having been associated with monetary reward, the training-phase targets slowed response times in the test phase (Fig. 1, Table 1), irrespective of training-phase feedback type. A mixed-design ANOVA, with training-phase target status as a within-subjects factor (present vs. absent) and training-phase feedback type as a between-subjects factor ("correct" delivered vs. "correct" withheld), revealed a significant main effect of training-phase target status {$F(1, 78) = 23.46$, $p < .001$; mean within-subjects difference = 12.8 ms, bootstrapped 95% CI = [7.81–18.06 ms]; randomization test on condition labels, $p < .001$}: RTs were slower when the training-phase target was present as a distractor ($M = 701.1$ ms) than when it was absent ($M = 688.3$ ms). We observed no evidence for a main effect of training-phase feedback type {$F(1, 78) = 0.38$, $p = .5382$; between-group difference = 9.7 ms, bootstrapped 95% CI = [– 20.37 to 40.06 ms]; randomization test on group labels, $p = .5294$} or a Training-Phase Target Status × Training-Phase Feedback Type interaction

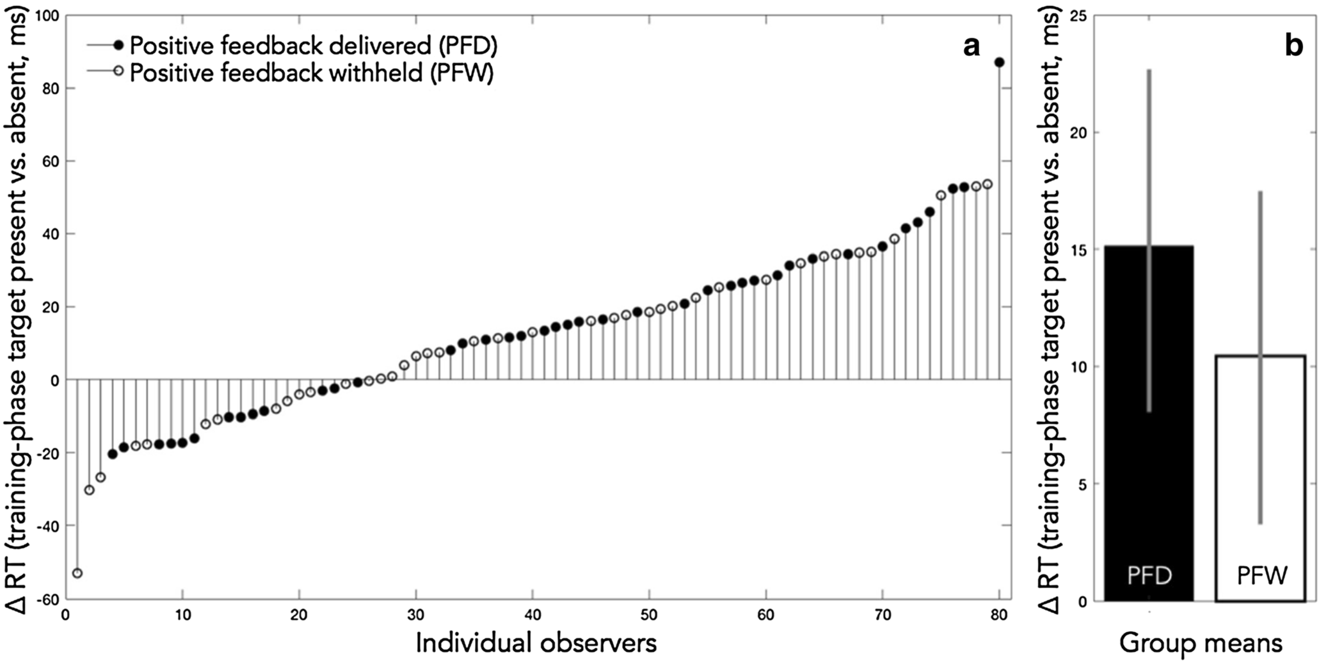

Fig. 1 Unrewarded former targets modulate response times in the test phase. (A) Individual observers. (B) Feedback-type group means; error bars indicate bootstrapped 95% confidence intervals.

{$F(1, 78) = 0.78$, $p = .3786$; between-group difference = 4.68 ms, bootstrapped 95% CI = [– 5.39 to 14.98 ms]; randomization test on group labels, $p = .3826$}, indicating that the groups did not differ in terms of their overall RTs or the degree to which the presence of former targets slowed those RTs.

An additional mixed-design ANOVA on the accuracy data revealed a significant main effect of training-phase target status {$F(1, 78) = 5.00$, $p = .0253$; mean within-subject difference = – 1.16, bootstrapped 95% CI = [– 2.16 to – 0.16]; randomization test on condition labels, $p = .0265$}: Accuracy was lower when the training-phase target was present as a distractor ($M = 82.26\%$) than when it was absent ($M = 83.42\%$), confirming that the RT modulation reported above cannot be accounted for by a speed–accuracy trade-off. There was no evidence for a main effect of training-phase feedback type {$F(1, 78) = 0.46$, $p = .4983$; between-group difference = 1.55, bootstrapped 95% CI = [– 2.78 to 6.08]; randomization test on group labels, $p = .5091$} or a Training-Phase Target Status × Training-Phase Feedback Type interaction {$F(1, 78) = 0.0004$, $p = .9840$; between-group difference = 0.02, bootstrapped 95% CI = [– 2.02 to 2.04]; randomization test on group labels, $p = .9993$}, indicating that the groups did not differ in terms of their overall accuracy or the degree to which the presence of former targets decreased that accuracy.

Unregistered analyses

Although we found ample evidence to support the conclusion that unrewarded training-phase targets modulated task performance in the test phase, failing to find evidence that the training-phase feedback type altered the magnitude of this modulation may still be of concern. Despite careful, a priori consideration of sample size, inadequate statistical power could have precluded the detection of a feedback-based effect. To address this possibility, we followed up our preregistered analyses with a Bayesian statistical procedure that allowed for the quantification of evidence in favor of the null hypothesis, given the observed data (Masson, 2011; Wagenmakers, 2007).

Table 1 Response times and accuracy in the test phase

Positive Feedback	Training-Phase Target	RT (ms)		% Correct	
		Mean	*SD*	Mean	*SD*
Delivered	Present	707.2	70.1	83.0	9.2
	Absent	692.0	70.0	84.2	8.9
Withheld	Present	695.1	76.9	81.5	11.9
	Absent	684.6	67.7	82.6	11.5

SD, standard deviation

For each of the four null results reported above (between-group and interaction effects for the three mixed-design ANOVAs), we found "positive" evidence in favor of the null hypothesis, and for the two within-subjects effects, we found "very strong" and "weak" evidence in favor of the alternative hypothesis that the training-phase target slowed RTs and decreased accuracy when a former target was present as a distractor in the test phase (Table 2; descriptive labels following Raftery, 1995). It is important to note that the "weak" evidence found for a change in accuracy is not problematic for our interpretation, since the purpose of these accuracy-focused analyses was to rule out the possibility that the changes in RTs were due to a speed–accuracy trade-off. Thus, the results of the Bayesian statistical approach and those found with null-hypothesis significance testing support the same conclusions.

Discussion

Using a pre-peer-reviewed data collection and analysis plan, we evaluated the role of accuracy-based feedback in a modification of the "short-training" VDAC paradigm (Anderson & Halpern, 2017; Anderson et al., 2011, Exp. 3). The results from a preliminary study had indicated that observers who had been randomly assigned to receive accuracy-based feedback during training showed significant attentional capture effects during test (see the supplemental material), and that the magnitude of this capture was statistically indistinguishable from that observed in participants who had been randomly assigned to receive monetary-reward-based feedback (i.e., the conventional VDAC approach). Thus, our first aim in this Registered Report was to replicate the accuracy-based feedback approach and verify the reliability of this finding in an independent group of observers. Our second aim was to test the specific hypothesis, derived from the relevant literature, that explicit positive feedback delivered on a trial-by-trial basis during training (e.g., displaying the word "correct" on the screen) is necessary to produce the attentional capture observed in our background study. In short, our replication efforts were successful, but we found no evidence that explicit positive feedback during training is necessary to produce attentional capture during test: After only 240 training trials, the presence of the unrewarded training-phase target at test slowed RTs and decreased accuracy to the same extent whether the word "correct" had been delivered or withheld during training. Interestingly, the magnitude of the reward-based RT modulation observed with a comparable amount of training (10 ms: high-value target present vs. absent; Anderson & Halpern, 2017, Exp. 1) falls well within the 95% confidence intervals bootstrapped for each of our accuracy-based feedback groups (Fig. 1).

On the one hand, finding that attentional prioritization during training leads to biases in attention when a former target appears as a distractor during test may seem unsurprising, given that selection history effects have been well documented in the literature (Awh et al., 2012; Le Pelley, Mitchell, Beesley, George, & Willis, 2016). On the other hand, these results are perplexing given the multiple null findings reported when accuracy-based feedback has been used in VDAC control experiments (e.g., Anderson & Halpern, 2017; Anderson et al., 2011, 2012, 2014). In the most relevant previous study, 40 observers received accuracy-based feedback during training (in the same manner as our "correct-withheld" group), and no VDAC effect was observed during test (Anderson & Halpern, 2017, Exp. 2A). We, however, found very strong evidence of attentional capture by unrewarded former targets, despite the two studies featuring identical numbers of training and test trials. Our results also indicate that the type of accuracy-based feedback seems not to matter, because the magnitudes of the observed capture were statistically indistinguishable between our two feedback groups. Thus, why accuracy-based feedback yields capture in some studies that use the short-training VDAC paradigm and not in others, the question that motivated this Registered Report, remains an open empirical issue that any comprehensive theoretical account of VDAC will need to address.

One avenue for future exploration concerns the interaction of selection history and nonspecific monetary reward. A direct comparison is difficult, because compensation details were

Table 2 Bayesian statistical results

	Response Time ANOVA		Evidence Strength	Accuracy ANOVA		Evidence Strength
Target present vs. absent (within subjects)	$p_{BIC}(H_0\|D)$ =	.0002		$p_{BIC}(H_0\|D)$ =	.4271	
	$p_{BIC}(H_A\|D)$ =	.9998	Very strong	$p_{BIC}(H_A\|D)$ =	.5729	Weak
Feedback type (between subjects)	$p_{BIC}(H_0\|D)$ =	.8803	Positive	$p_{BIC}(H_0\|D)$ =	.8759	Positive
	$p_{BIC}(H_A\|D)$ =	.1197		$p_{BIC}(H_A\|D)$ =	.1241	
Interaction	$p_{BIC}(H_0\|D)$ =	.8571	Positive	$p_{BIC}(H_0\|D)$ =	.8994	Positive
	$p_{BIC}(H_A\|D)$ =	.1430		$p_{BIC}(H_A\|D)$ =	.1006	

H_0, null hypothesis; H_A, alternative hypothesis not reported for Anderson and Halpern's control participants, but it may be important that each observer in our preregistered study received \$18.25 for a 1-h session; this was required in order to replicate the compensation structure used for our background study's accuracy-based feedback group, who were paid a flat rate calculated to match the average earnings for the background study's rewarded group. Because it was known in advance, the participation compensation (i.e., non-specific reward) could have influenced how our observers approached the task in general, which could have in turn strengthened selection history effects, potentially by increasing their motivation and/or a willingness to expend effort. Because this is an entirely speculative proposal, future research will be needed to systematically evaluate whether participation compensation (e.g., participating for "free," for course credit, or for increasingly large monetary amounts) modulates the magnitude of selection history effects when compensation is not contingent on task performance.

The role that selection history may or may not play in the VDAC phenomenon has been extensively discussed in the literature. In an extremely thorough review, Le Pelley et al. (2016) pointed to selection history as a potential alternative interpretation for data gathered with the VDAC paradigm, stating directly that "[t]he majority of studies that rely on a comparison between high-value distractor versus no-distractor trials to claim an effect of learned value on attention do not include an unrewarded control condition at all, so evidence from these studies should be regarded with caution" (p. 1126). In support of a *value-modulated attentional capture* interpretation, however, Le Pelley and colleagues then suggested that assessing differences in capture between high-value and low-value former targets provides an easy solution to this problem: Because both types of targets appear equally often in the training phase, they argued, selection history is equated, and thus, any differences between the two conditions must be due to the learned reward.

We argue against this proposal, however, and suggest that selection history may not in fact be equated, despite the two target types appearing equally often in the training phase. For one target color, high reward is delivered with 80% reliability, and once this color is learned, observers are free to voluntarily preallocate feature-based attention (FBA; see Carrasco, 2011) in a manner that biases selection for the high-value target. Should an observer's goal be to maximize take-home earnings, the temporal constraints of the training phase itself (i.e., 800 ms to localize the target and make an accurate response in the short-training paradigm) may actually incentivize such a strategy. It is important to note that a reward-maximization strategy would also need to take speed–accuracy trade-offs into account (Wickelgren, 1977), and thus, asymmetrical attentional allocation to the high-value target during training need not always manifest as faster RTs (i.e., FBA can be used to facilitate the localization of the colored target, but then it may be beneficial to delay the orientation judgment until sufficient visual information has accumulated and one is confident about the response). An observer cannot delay too long, however, because once the trial times out, her probability of reward drops to zero, which is far worse than the 50% chance of reward that could be obtained by guessing at the trial onset. That observers face this complicated reward-maximization problem during reward-based VDAC training is what motivated our background study, and we discuss it here simply to propose that after learning which is which, equivalent attentional allocation to the high- and low-value targets during training would be disadvantageous from a reward-maximization standpoint.

In conclusion, the data presented here provide strong evidence that accuracy-based feedback, for as few as 240 training trials, can lead to significant VDAC-like effects, confirming that such attentional capture need not always be value-dependent. Despite reinvigorating important questions of interpretation concerning the conventional, reward-based VDAC paradigm, our findings are nonetheless consistent with a growing body of empirical work that challenges traditional conceptualizations of attentional control as being either top-down or bottom-up (Awh et al., 2012; Le Pelley et al., 2016) and highlight the importance of past goals on future ones.

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