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# This is a test: Oculomotor capture when the experiment keeps score

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## Abstract

Physically salient stimuli are difficult to ignore, frequently eliciting fixations even when they are known to be task-irrelevant. A recent study demonstrated that distractor fixation-contingent auditory feedback was highly effective in reducing the frequency of fixations on such stimuli. The present study explores more specifically what it is about feedback that makes it effective in curbing oculomotor behavior. In one experiment, we removed the immediacy of the feedback by informing participants after each trial via textual feedback if they had fixated the distractor. A comparable reduction in the frequency of oculomotor capture was observed. In a second experiment, we only provided summary feedback concerning the frequency of oculomotor capture after each block of trials. Not only were the benefits of feedback again robustly comparable, but a benefit was observed even in the first block before any feedback had actually been presented. Simply knowing that the frequency of distractor fixations was being monitored was sufficient to substantially reduce the frequency of oculomotor capture. Interestingly, trial-level feedback predominantly reduced the frequency of capture by slowing oculomotor responses, reflecting a speed-accuracy tradeoff, whereas block-wise feedback resulted in a reduction in the frequency of capture with saccadic reaction time equated, reflecting a bona fide improvement in task performance. Our findings have implications for our understanding of the role of motivation, strategy, and selection history in oculomotor control.

**Keywords** Attentional capture · Eye movements · Selective attention · Feedback

## Introduction

Attention selects stimuli for cognitive processing (Desimone & Duncan, 1995). Although we have some control over what we direct our attention to (Wolfe & Horowitz, 2017), certain kinds of stimuli can automatically capture our attention in spite of our best efforts to ignore them. Task-irrelevant stimuli that possess a goal-related feature (Folk et al., 1992), previously reward-associated (e.g., Anderson et al., 2011) and punishment-associated stimuli (e.g., Anderson & Britton, 2020; Schmidt et al., 2015), and physically salient stimuli (Theeuwes, 1992, 2010) can all capture our attention under certain task conditions. When attentional capture results in an eye movement toward the eliciting stimulus, this is referred to as *overt attentional capture* or *oculomotor capture* (e.g., Adams & Gaspelin, 2021; van Zoest et al., 2004). Just how much control individuals have in curbing oculomotor capture, and the contexts and situations in which capture can be mitigated or even suppressed, have been of longstanding interest in research on attentional control (see Luck et al., 2021, for a recent review).

**Significance Statement** Distraction is a leading cause of accident and injury. The present study explores the ability for performance-related feedback to mitigate distraction. The results show that providing feedback when a task-irrelevant stimulus is overtly attended is effective in reducing the frequency of such distraction, primarily via motivation that comes from performance monitoring.

People have been shown to possess limited awareness of when their attention is captured by physically salient stimuli (Adams & Gaspelin, 2020, 2021; Theeuwes et al., 1998) and more generally exhibit limited awareness of how they move their eyes while performing visual tasks (Horowitz & Wolfe, 1998; Vo et al., 2016). Reasoning that raising participants' awareness of when they erroneously fixate a physically salient distractor might be effective in curbing such fixations, Anderson and Mrkonja (2021) developed an oculomotor feedback manipulation incorporating "near-real-time" reinforcement techniques applied to eye movements (see Anderson, 2021). Specifically, participants heard a tone play over headphones immediately upon fixating a physically salient but task-irrelevant distractor. Such feedback resulted in a rapid

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and dramatic reduction in the frequency of oculomotor capture, primarily via a slowing of oculomotor responses (Anderson & Mrkonja, 2021), consistent with findings that the effects of physical salience on the guidance of eye movements are short-lived (Donk & van Zoest, 2008; Godijn & Theeuwes, 2002; van Zoest et al., 2004). That is, the feedback led participants to respond more conservatively, effectively reducing the frequency of distractor fixations and thereby the frequency of error feedback (Anderson & Mrkonja, 2021).

From the findings of Anderson and Mrkonja (2021), it is clear that the frequency of oculomotor capture is modifiable and sensitive to feedback. The present study explores more specifically what it is about capture-related feedback that makes it effective in curbing distractor fixations. Experiment 1 examined whether the "near-real-time" element of the feedback used in Anderson and Mrkonja (2021) plays an important role. On the one hand, receiving feedback immediately upon fixating a distractor may help participants learn what it feels like to make an erroneous saccade to the distractor and this learning can be leveraged to minimize the frequency with which such distractor-going saccades are made in the future. On the other hand, perhaps simply being informed of when they fixate the distractor motivates participants to reduce the frequency of this error-related feedback. Therefore, in Experiment 1, we replicated the basic design of Anderson and Mrkonja (2021), but replaced the auditory feedback that occurred immediately upon distractor fixation with textual feedback that told participants if they had fixated the distractor after the trial was complete.

## Experiment 1

### Methods

**Participants** Forty-eight participants (26 female, 21 male (one not reported)]; mean age = 18.6 years (SD = 1.03 years)) were recruited from the Texas A&M University community and were compensated with course credit. All reported normal or corrected-to-normal visual acuity and normal color vision. All procedures were approved by the Texas A&M University Institutional Review Board and conformed with the principles outlined in the Declaration of Helsinki. The recruited sample provided power (1-β) > 0.90 to replicate an effect of feedback of the same size as Anderson and Mrkonja (2021), which was $\eta^2_p = 0.316$, assuming a modest correlation among repeated measures of 0.5.

**Apparatus** A Dell OptiPlex equipped with Matlab software and Psychophysics Toolbox extensions (Brainard, 1997) was used to present the stimuli on a Dell P2717H monitor. The participants viewed the monitor from a distance of approximately 70 cm in a dimly lit room. Eye position was monitored using an EyeLink 1000-plus desktop mount eye tracker sampling at 1,000 Hz. Head position was maintained using an adjustable chin and forehead rest (SR Research).

**Stimuli** The fixation display consisted of a white plus sign presented at the center of the screen (Fig. 1). The search array consisted of six filled shapes, either five circles and one diamond or five diamonds and one circle (each approximately 5.7° x 5.7° in visual angle, centered on an imaginary circle 8.2° from fixation). The shapes were rendered in either red or green; on distractor-absent trials, all of the shapes were rendered in the same color, whereas on distractor-present trials, one of the non-targets was rendered in a different color than the other five shapes (salient color singleton distractor). For participants in the feedback group, the words "Oops, you looked!" were centrally presented as feedback if the distractor was fixated, and for all participants the word "Miss" was presented as feedback if the trial timed out without a target fixation being registered.

**Design** Within each block of trials, a color singleton distractor was presented on 62.5% of trials. This distractor was equally often red and green. For each color distractor, target and distractor position were fully crossed and counterbalanced (i.e., every combination was used equally often). On distractor-absent trials, the target appeared in each position equally often. The target was equally often a diamond among circles and a circle among diamonds. Trials were presented in a random order. Feedback was manipulated between-subjects, with half of participants assigned to the feedback group.

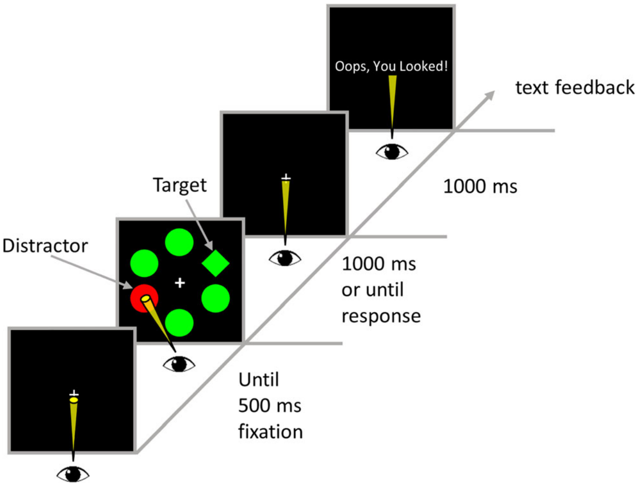

**Fig. 1** Example trial. For participants in the feedback group, text informed them if they had fixated the salient color distractor (text feedback); this was not true for participants in the no-feedback group (the text feedback was omitted), who were similarly instructed to do their best to orient to the target while trying not to look at color distractors

**Procedure** The experiment consisted of five blocks of 96 trials, which were preceded by practice trials with and without a time limit (during which no feedback was provided to either group). Participants were instructed to look for the unique shape, which served as the target of search. All participants were further instructed to look directly at the target as quickly as possible while trying to avoid looking at the distractor. Participants in the feedback group were informed that looking at the distractor would trigger feedback to let them know whenever this happened, but were given no further instructions concerning how they might utilize the feedback.

The fixation display remained on screen until eye position was registered within 1.2° of the center of the fixation cross for a continuous period of 500 ms. Drift correction was manually applied in the event that such a fixation could not be obtained on a given trial due to a shift in measured eye position (as in Anderson & Kim, 2019a, b). During the search array, fixation of a stimulus was registered if eye position remained within a region extending 0.7° beyond the borders of the stimulus for a continuous period of at least 50 ms. A fixation of at least 100 ms on the target was required to register a correct response (Anderson & Kim, 2019a, b). The search array remained on-screen for 1,000 ms or until a target fixation had been registered, and was then followed by a blank 1,000-ms screen. Participants in the feedback group were provided textual feedback indicating that they had looked at the distractor if a distractor fixation had occurred during the preceding search, followed by another 1,000-ms blank screen. If they failed to fixate the target before the timeout limit, the "Miss" feedback was presented, followed by a 1,000-ms blank. Feedback concerning oculomotor capture remained on-screen for 1,500 ms, and "Miss" feedback for 1,000 ms.

**Data analysis** Oculomotor capture was defined as the proportion of distractor-present trials on which the distractor was fixated. Oculomotor capture was computed for each block of the task and subject to an analysis of variance (ANOVA) with block (1–5) and group (feedback, no feedback) as factors. A follow-up analysis broke down oculomotor capture as a function of distractor-target distance (1, 2, and 3 stimuli from the target, with 1 reflecting trials in which the distractor was adjacent to the target), collapsed across block. We further compared overall rates of oculomotor capture in the present study with the feedback conditions of Anderson and Mrkonja (2021) using independent samples t-tests, taking only the first five blocks of Anderson and Mrkonja (2021) rather than all six to equate the number of trials going into each estimate (there was one fewer block in the present study because the text feedback takes additional time to present, slightly lengthening trials).

Subsequent analyses examined the distribution of saccadic reaction time (sRT) as well as the frequency of oculomotor capture as a function of sRT (see Donk & van Zoest, 2008; Paoletti et al., 2015; van Zoest et al., 2004). sRT was defined relative to the onset of the search array for the first saccade that landed outside of the fixation zone, with saccades defined as occurring when velocity exceeded 35°/s and acceleration exceeded 9,500°/s$^2$ (Anderson, 2021). sRTs < 70 ms were considered anticipatory saccades and eliminated from analyses. We combined all valid sRTs across both feedback conditions and computed five quintiles with which to bin sRT, and then computed the mean frequency of capture and the percentage of sRTs falling into each bin separately for each feedback condition. An ANOVA with bin and feedback condition as factors was performed on both the frequency of capture and proportion of sRTs falling into each bin: in the case of the latter, only the interaction term was of interest, as the proportions necessarily sum to 1 across bins for each participant. The interaction term for the analysis of the proportion of sRTs falling into each bin tests for a shift in the distribution of sRT between conditions (see Anderson & Mrkonja, 2021), and the analysis of the frequency of oculomotor capture across bins allows for assessment of whether the frequency of oculomotor capture was reduced with sRT more closely equated, reflecting a change in performance above and beyond a speed-accuracy tradeoff (see Paoletti et al., 2015).

Finally, we tested the immediate consequences of capture as a function of feedback. We identified distractor-present trials that were immediately preceded by another distractor-present trial and computed mean sRT and the frequency of oculomotor capture as a function of whether the distractor was fixated on the prior trial, separately for the two feedback conditions. Of interest was whether the feedback accentuated any immediate consequences of the distractor having captured overt attention.

## Results

**Effect of feedback on oculomotor capture** An ANOVA computed over oculomotor capture with block (1–5) and feedback group (feedback, no feedback) as factors revealed a critical main effect of group in which oculomotor capture was markedly reduced as a result of the feedback, $F(1,46) = 8.75$, $p = 0.005$, $\eta^2_p = 0.160$ (Fig. 2). There was also a main effect of block, $F(4,184) = 2.61$, $p = 0.037$, $\eta^2_p = 0.054$, and an interaction between block and group, $F(4,184) = 3.18$, $p = 0.015$, $\eta^2_p = 0.065$. Further probing of the initially fixated stimulus confirmed that the feedback-related reduction in distractor fixations corresponded to an increase in the frequency with which the target was initially fixated, reflecting more accurate oculomotor performance in the feedback group. The frequency of trials on which the target was initially fixated on distractor-present trials was greater for participants in the

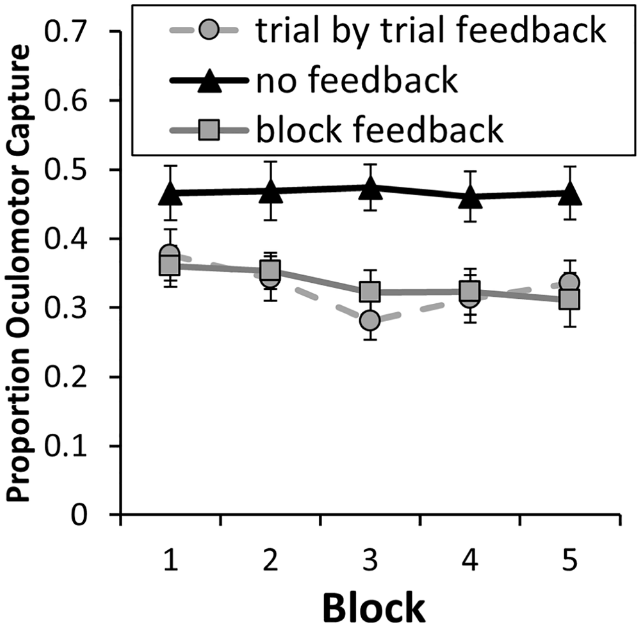

**Fig. 2** The proportion of oculomotor capture over the course of the experiment (trial block) separately for the three participant groups

feedback group ($M$ = 0.603, $SD$ = 0.182) relative to the no-feedback group ($M$ = 0.483, $SD$ = 0.184), $t(46) = 2.28$, $p = 0.027$, $d = 0.66$. Initial fixations on non-targets other than the salient distractor were generally infrequent and did not differ significantly between the feedback ($M$ = 0.062, $SD$ = 0.05) and no-feedback groups ($M$ = 0.053, $SD$ = 0.044), $t(46) = 0.64$, $p = 0.524$.

**Oculomotor capture as a function of distractor-target distance** An ANOVA computed over oculomotor capture with distractor-target distance (1, 2, and 3 stimuli apart) and feedback group as factors revealed a main effect of distractor-target distance, $F(2,92) = 89.37$, $p < 0.001$, $\eta^2_p = 0.660$, that was qualified by a distance-by-group interaction, $F(2,92) = 5.77$, $p = 0.004$, $\eta^2_p = 0.112$ (Table 1). When the distractor-target distance was smaller, oculomotor capture occurred more frequently and the consequence of feedback was correspondingly more substantial. There was also a significant main effect of group that reiterates the results of the prior analyses, $F(1,46) = 7.90$, $p = 0.007$, $\eta^2_p = 0.147$.

**Immediate consequences of capture as a function of feedback** An ANOVA computed over oculomotor capture with whether the distractor captured overt attention on the prior trial (capture, no capture) and feedback group as factors revealed a main effect of prior capture in which oculomotor capture was more frequent following a trial on which the distractor was fixated, $F(1,46) = 9.42$, $p = 0.004$, $\eta^2_p = 0.170$, potentially reflecting a bias to repeat recent stimulus selection. However, the interaction between prior capture and feedback group was not significant, $F(1,46) = 1.46$, $p = 0.233$ (see Table 2). There was also a main effect of group that reiterates the general effect of feedback noted in prior analyses, $F(1,46) = 13.00$, $p = 0.001$, $\eta^2_p = 0.220$. The same analysis computed over mean sRT yielded a main effect of group only, $F(1,46) = 9.65$, $p = 0.003$, $\eta^2_p = 0.173$; the main effect of prior capture, $F(1,46) = 3.60$, $p = 0.064$, and the interaction, $F(1,46) < 0.01$, $p = 0.955$, were not significant, with the trend in the main effect of prior capture being in the direction of a speed-accuracy tradeoff in which sRT is slower when capture is less frequent.

**Oculomotor capture as a function of sRT** Trials were binned by sRT as described in the *Methods*. There was a robust interaction between group and bin with respect to the proportion of sRTs falling into each bin, $F(4,184) = 6.23$, $p < 0.001$, $\eta^2_p = 0.119$, reflecting a pronounced shift in the distribution of sRTs toward slower responses in the feedback group (Fig. 3A). Multiple participants in the feedback group did not have any trials for which sRT fell within the fastest bin, so only the four other bins were included in the analysis of oculomotor capture as a function of bin. Furthermore, one participant in the no-feedback group had no sRTs that fell within the slowest two bins, so this participant was not included in this analysis (note that all other permutations for excluding participants vs. bins yield comparable results). There was a pronounced main effect of bin with respect to oculomotor capture, $F(3,184) = 156.30$, $p < 0.001$, $\eta^2_p = 0.776$, reflecting the well-established finding that oculomotor capture is more pronounced for faster sRTs (Donk & van Zoest, 2008; van Zoest et al., 2004). However, the main effect of group, $F(1,45) = 0.04$, $p = 0.837$, as well as

**Table 1** Proportion of oculomotor capture (SEM) as a function of distractor-target distance separately for the three participant groups

| | Distractor-target distance (number of stimuli apart) | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Trial-by-trial feedback | 0.389 (0.033) | 0.295 (0.03) | 0.28 (0.032) |
| No feedback | 0.566 (0.032) | 0.412 (0.038) | 0.38 (0.039) |
| Block-wise feedback | 0.403 (0.03) | 0.296 (0.03) | 0.272 (0.029) |

**Table 2** Proportion of oculomotor capture and mean saccadic reaction time (SEM) on trial *n* as a function of whether the distractor captured overt attention on trial *n*-1 (capture, no capture) separately for the three participant groups

| | | Whether the distractor was fixated on the prior trial | |
|---|---|---|---|
| | | Capture | No capture |
| Proportion oculomotor capture | Trial-by-trial Feedback | 0.305 (0.032) | 0.257 (0.028) |
| | No Feedback | 0.452 (0.034) | 0.431 (0.035) |
| | Block-wise Feedback | 0.340 (0.031) | 0.29 (0.029) |
| Mean saccadic reaction time (ms) | Trial-by-trial Feedback | 326 (18.8) | 334 (18.6) |
| | No Feedback | 256 (11) | 266 (13.2) |
| | Block-wise Feedback | 285 (15.4) | 300 (16.8) |

the group-by-bin interaction, $F(3,184) = 0.85$, $p = 0.468$, were not significant (Fig. 3B); with sRT equated by bin, capture was comparable across groups.

**Comparison of post-trial textual feedback to "near-real-time" auditory feedback (Anderson & Mrkonja, 2021)** In comparison with Anderson and Mrkonja (2021), rates of oculomotor capture with "near-real-time" auditory feedback did not differ from rates of oculomotor capture with textual feedback as observed in the present study, $t(40) = 0.64$, $p = 0.527$ (Fig. 4). Unsurprisingly, rates of oculomotor capture in the no-feedback condition did not differ across studies, $t(40) = 0.47$, $p = 0.641$. Comparing feedback to no feedback, all comparisons both across and within studies were significant, *p*s < 0.009. We do not see evidence that the consequence of feedback on oculomotor capture differed as a function of the nearness of temporal relationship between the feedback and the eliciting eye movement, with the present study producing effects of feedback that were comparable in magnitude to Anderson and Mrkonja (2021).

## Discussion

The results of Experiment 1 are wholly consistent with the findings of Anderson and Mrkonja (2021) even though the "near-real-time" aspect of the feedback had been removed. There was a substantial reduction in the frequency of oculomotor capture tied to the textual feedback, which coincided with a shift in the time to initiate a saccade as reflected in sRT. With sRT equated by bin, a difference in oculomotor capture was no longer evident, such that the feedback-related benefit we observed could be explained as the consequence of a speed-accuracy tradeoff. That is, in an effort to minimize the frequency of feedback telling participants their overt attention had been captured, participants defaulted to responding more conservatively, which was highly effective in achieving that end, producing generally slower responses that were less prone to capture. Apparently, the immediacy of the auditory feedback in Anderson and Mrkonja (2021) added little if anything to the utility of the feedback in mitigating oculomotor capture and is generally not helpful above-and-beyond the mere informativeness of the feedback with respect to whether capture occurred. The effect of feedback on the control of

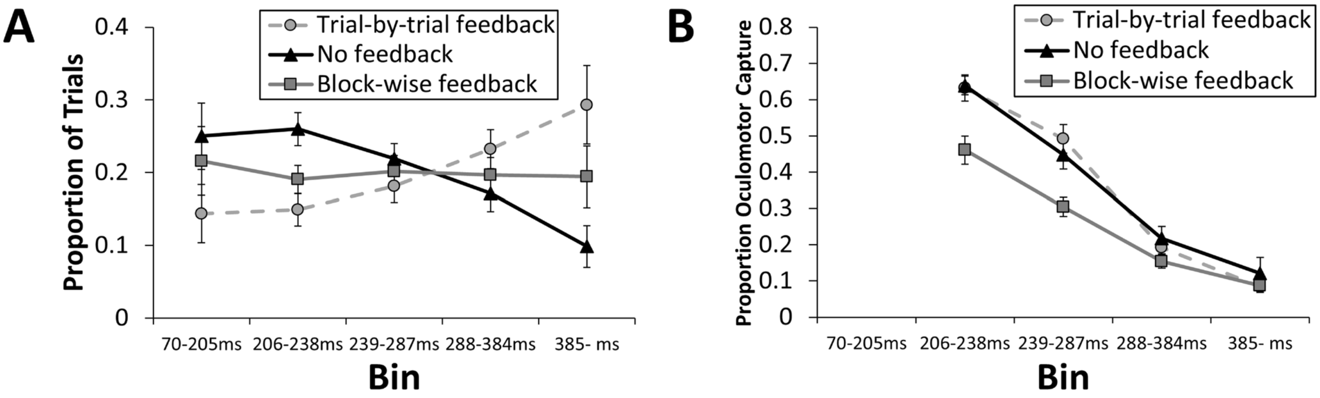

**Fig. 3** (**A**) The proportion of trials falling into each of five bins of saccadic reaction time (quintiles based on the combined data from the trial-by-trial feedback and no-feedback groups) and (**B**) proportion of oculomotor capture computed on the trials within each bin, separately for the three participant groups. Error bars reflect the SEM. The first bin was not included in the analysis of oculomotor capture as several participants in the trial-by-trial feedback group had no trials that fell within this bin

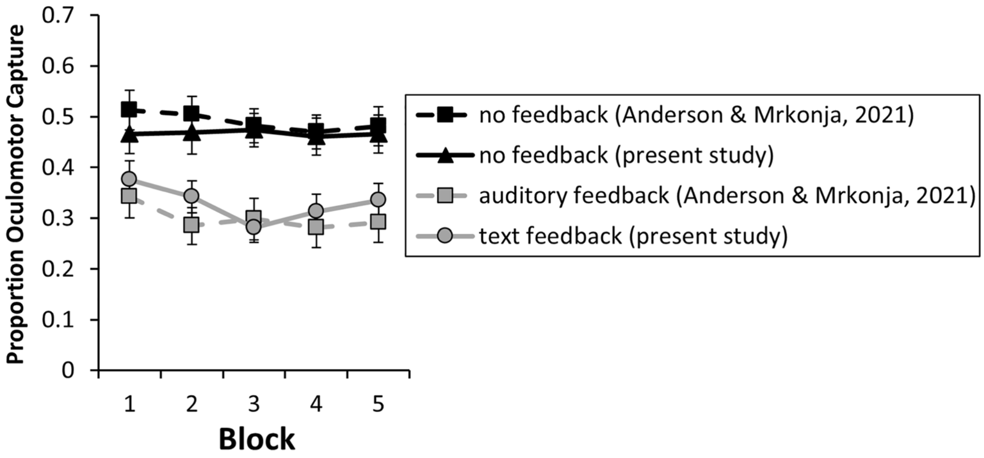

**Fig. 4** Comparison of oculomotor capture between Experiment 1 of the present study and Anderson and Mrkonja (2021)

attention in Experiment 1 appeared to be largely proactive and sustained over trials, with no evidence that receiving feedback modulated the consequence of having attention captured by the distractor on the subsequent trial. Oculomotor capture was in general most pronounced when the salient distractor was adjacent to the target, and the effect of feedback on reducing oculomotor capture was correspondingly larger on such trials, likely reflecting greater room for improvement, which is an issue we return to in the *General discussion*.

## Experiment 2

Experiment 1 demonstrates that the immediacy of feedback concerning the occurrence of oculomotor capture does not play a meaningful role in the effect that feedback has in curbing oculomotor capture. This raises the question of whether the timing of the feedback really matters at all, and more specifically whether the trial-by-trial information about the occurrence of oculomotor capture that is maintained with the textual feedback is consequential. It may be the case that simply knowing how frequently oculomotor capture occurs in general is sufficient to raise awareness of capture in such a manner as to provide participants with the information and motivation necessary to reduce its frequency. Therefore, in Experiment 2, we simply provided summary feedback at the end of each block of trials concerning the number of instances in which the participant fixated a salient distractor.

### Methods

**Participants** Twenty-seven new participants (eight female, 19 male; mean age = 18.7 years (SD = 0.82 years)) were recruited from the Texas A&M University community using the same protocol, compensation, and recruitment procedures. The sample size was slightly higher than each group in Experiment 1 due to a posting of more experiment slots than were needed to help ensure that the target *N* of 24 was reached in a timely fashion.

**Apparatus** Identical to Experiment 1.

**Stimuli** Otherwise identical to the feedback group of Experiment 1 with the exception that there was no trial-by-trial feedback in the event of oculomotor capture and participants were instead informed of the frequency with which they looked at a distractor at the end of each block. Specifically, at the end of each block, participants in the feedback group saw the text "'You looked at the different color on X/60 times it appeared"' where "X" was the number of trials on which the distractor was fixated.

**Design** Identical to Experiment 1.

**Procedure** Otherwise identical to the feedback group of Experiment 1 with the exception that participants were instructed that they would be informed of the number of times they fixated the distractor at the end of each block of trials.

**Data analysis** Conditional means were computed in the same manner as Experiment 1, using the same bins for sRT. Using the same analytic approach, the results of Experiment 2 were contrasted with each of the two feedback groups from Experiment 1 (as in Anderson & Mrkonja, 2021).

### Results

**Effect of feedback on oculomotor capture** Compared to the no-feedback condition of Experiment 1, an ANOVA computed over oculomotor capture again revealed a critical main effect of group, $F(1,49) = 8.60$, $p = 0.005$, $\eta^2_p = 0.149$ (Fig. 2); the main effect of block, $F(4,196) = 1.02$, $p = 0.397$, and the interaction, $F(4,196) = 1.00$, $p = 0.408$, were not significant. Even in the first block of trials, before any feedback had been presented, oculomotor capture was reduced in the feedback group compared to the no-feedback group, $t(49) = 2.18$, $p = 0.034$, $d = 0.61$. Compared to the trial-by-trial textual feedback of Experiment 1, in contrast, the main effect of group was not significant, $F(1,49) = 0.01$, $p = 0.915$; the interaction was also non-significant, $F(1,46) = 0.04$, $p = 0.835$, although in this case there was a significant main effect of block, $F(1,49) = 9.22$, $p = 0.004$, $\eta^2_p = 0.158$. The frequency of the target being initially fixated in Experiment 2 ($M = 0.611$, $SD = 0.166$) was greater than it was for the no-feedback group, $t(49) = 2.61$, $p = 0.012$, $d = 0.73$, and comparable to the trial-by-trial feedback group of Experiment 1, $t(49) = 0.15$, $p = 0.880$; the frequency of a non-salient non-target being initially fixated in Experiment 2 ($M = 0.052$, $SD = 0.045$) did not differ from either feedback group of Experiment 1, *t*s < 0.77, *p*s > 0.44. That is, block-wise feedback concerning the occurrence of oculomotor capture was effective in reducing the frequency of oculomotor capture compared to participants who received no feedback, and the magnitude of this reduction was comparable to that observed for trial-by-trial textual feedback.

**Oculomotor capture as a function of distractor-target distance** Compared to the no-feedback group of Experiment 1, there were significant main effects of group, $F(1,49) = 8.05$, $p = 0.007$, $\eta^2_p = 0.141$, and distractor-target distance, $F(2,98) = 131.33$, $p < 0.001$, $\eta^2_p = 0.728$, as well as a significant distance-by-group interaction, $F(2,98) = 3.95$, $p = 0.022$, $\eta^2_p = 0.075$ (Table 1). Compared to the trial-by-trial feedback group of Experiment 1, only the main effect of distractor-target distance was significant, $F(2,98) = 76.75$, $p < 0.001$, $\eta^2_p = 0.610$, other *F*s < 0.59, *p*s > 0.55. The results are again consistent with a comparable effect of block-wise and trial-by-trial feedback on capture.

**Immediate consequences of capture as a function of feedback** Compared to the no-feedback group of Experiment 1, we again see a main effect of group with respect to oculomotor capture, $F(1,49) = 8.31$, $p = 0.006$, $\eta^2_p = 0.143$, in addition to a main effect of prior capture, $F(1,49) = 11.53$, $p = 0.001$, $\eta^2_p = 0.190$, and no significant interaction, $F(1,49) = 1.92$, $p = 0.172$ (Table 2). With respect to mean sRT, the main effect of prior capture was now significant, $F(1,49) = 9.75$, $p = 0.003$, $\eta^2_p = 0.166$, while the main effect of group, $F(1,49) = 2.31$, $p = 0.135$, and the interaction, $F(1,49) = 1.05$, $p = 0.310$, were not significant. That is, we again see evidence that capture occurred more frequently and sRT was faster following a trial on which the distractor was fixated, although in this case we do not see evidence that participants in the block-wise feedback group of Experiment 2 were overall slowed with respect to sRT compared to participants receiving no feedback. When comparing to the trial-by-trial feedback group of Experiment 1, with respect to both oculomotor capture and sRT, there was only a main effect of prior capture in each case, *F*s > 6.40, *p*s < 0.016, $\eta^2_p > 0.115$ (all other *F*s < 2.41, *p*s > 0.127).

**Oculomotor capture as a function of sRT** Comparing to the no-feedback group of Experiment 1, the interaction between group and bin with respect to the proportion of sRTs falling into each bin was not significant, $F(4,196) = 1.59$, $p = 0.178$. Nor was this interaction significant when comparing to the trial-by-trial feedback group of Experiment 1, $F(4,196) = 1.58$, $p = 0.182$ (Fig. 3A). It appears that the distribution of sRT for the block-wise feedback group of Experiment 2 fell somewhere in between that of the other two feedback groups. With respect to oculomotor capture as a function of bin, two participants from Experiment 2 were removed from analysis for not having any trials represented in at least one bin. Compared to the no-feedback group of Experiment 1, there was the expected main effect of bin, $F(3,138) = 112.48$, $p < 0.001$, $\eta^2_p = 0.710$, in addition to a main effect of group, $F(1,46) = 12.13$, $p = 0.001$, $\eta^2_p = 0.209$, and interaction between group and bin, $F(3,138) = 3.20$, $p = 0.025$, $\eta^2_p = 0.065$ (Fig. 3B). The same effects were evident when comparing to the trial-by-trial feedback group of Experiment 1, main effect of bin: $F(3,141) = 136.01$, $p < 0.001$, $\eta^2_p = 0.743$, main effect of group: $F(1,47) = 16.71$, $p < 0.001$, $\eta^2_p = 0.262$, interaction: $F(3,141) = 7.01$, $p < 0.001$, $\eta^2_p = 0.130$.

## Discussion

Although the trial-by-trial aspect of the feedback had been removed from Experiment 2, simply informing participants of how frequently they fixated the distractor at the end of each block of trials was sufficient to produce a pronounced reduction in the frequency of oculomotor capture. The overall pattern of results with respect to the frequency of oculomotor capture was markedly similar to that produced by the trial-by-trial manipulation of Experiment 1. Strikingly, the feedback manipulation reduced the frequency of oculomotor capture even in the first block of trials, before any feedback actually occurred that participants might use as a basis for adjusting their behavior. It seems that the mere expectation that distractor fixations would be recorded and shared with participants was sufficient to significantly reduce the frequency of oculomotor capture, motivating participants to achieve more desirable feedback.

In stark contrast with the trial-by-trial feedback manipulation of Experiment 1, however, the distribution of sRTs was not overall shifted compared to that of participants receiving no feedback, and capture remained markedly reduced with sRT more closely equated by bin. That is, there was a beneficial effect of feedback above and beyond any speed-accuracy tradeoff, with participants engaging in generally more efficient oculomotor behavior as a consequence of the feedback manipulation. It may be that trial-by-trial feedback promotes more conservative responding whereas block-wise feedback primarily influences motivation to restrict attention to the target. We further explore potential implications of this different pattern of results as a function of the nature of the feedback in the *General discussion*.

## General discussion

In two experiments, we replicate the finding that feedback concerning oculomotor capture is effective in reducing the frequency of capture (Anderson & Mrkonja, 2021), and further explore how the nature of the feedback influences the control of attention. Our findings have a variety of implications for our understanding of the role of motivation, strategy, and selection history in attentional control.

### The time course of feedback-related adjustment to oculomotor control

In Anderson and Mrkonja (2021), care was taken to provide oculomotor feedback almost immediately after the distractor was fixated, in "near-real-time." Experiment 1 of the present study suggests that participants do not leverage or otherwise benefit from such temporal precision. Simply providing text-based feedback at the end of each trial produced wholly comparable shifts in performance: there was a similar reduction in the frequency of oculomotor capture coinciding with an overall slowing of oculomotor responses. It might have been the case that receiving feedback the moment capture occurs would allow participants to learn what distraction "feels like" and adjust their oculomotor behavior accordingly, but we see no evidence of participants being better able to adjust their performance as a result of such temporally precise feedback.

Participants were in fact no better at resisting capture than when feedback concerning the frequency of oculomotor capture was provided at the end of each block. Feedback at the resolution of a single trial was no more helpful than even the mere prospect of summary-level feedback. In spite of the fact that awareness of eye movements (Horowitz & Wolfe, 1998; Vo et al., 2016) and oculomotor capture (Adams & Gaspelin, 2020, 2021; Theeuwes et al., 1998) is quite limited, it appears that providing performance-related feedback after each distractor fixation does not promote error-based learning (see Huang et al., 2011) in a manner that confers any unique performance benefits. Consistent with this conclusion, feedback in the present study was not found to modulate any post-error adjustments immediately following oculomotor capture.

Overall, our findings suggest that attentional control processes that might mitigate capture is not something that lends itself to fine-tune adjustments from trial-level feedback. We see no evidence that information about specifically when oculomotor capture occurs is something that the attention system takes into account in adjusting attentional strategy or otherwise engaging processes that could mitigate capture. As will be discussed more fully in the sections that follow, the mere prospect of performance-related feedback alone seems to promote the best attentional performance.

### The role of motivation in resisting distraction

Our findings provide important new context for how the frequency of oculomotor capture in attention tasks is interpreted with respect to motivation. The raw frequency of oculomotor capture was markedly reduced in the present study even when only the indication of future feedback was provided (block 1 of Experiment 2). Motivation to avoid oculomotor capture apparently had significant room for increase, which the promise of feedback engaged, even though in all conditions participants were explicitly instructed to try to avoid looking at the color singleton distractor. Typical experiments probing salience-based capture that do not monitor and inform participants about the frequency of capture (e.g., Theeuwes, 1992, 2010; Theeuwes et al., 1998) should therefore be interpreted as likely probing performance in a motivational state that is far from ceiling, with the ability to avoid capture being somewhat greater than what the frequency of distractor fixations in such experiments might be taken to suggest.

Strikingly, performance in Experiment 2 was generally improved as a result of block-wise feedback, in a manner that cannot be wholly accounted for by a speed-accuracy tradeoff. Even with sRT equated by bin, oculomotor capture was significantly less frequent in this condition relative to both no feedback and trial-by-trial feedback. Particularly for faster oculomotor responses, participants receiving block-wise feedback were simply less prone to oculomotor capture. When sufficiently motivated, it appears that individuals are capable of generally superior attentional performance, some of the implications of which are further explored later in this discussion, along with outstanding questions raised by this finding.

### Feedback, selection history, and the strategic control of attention

Our findings are consistent with the idea that the ability to ignore a salient distractor can be heavily dependent on the strategies that participants bring to bear when they perform a task. For example, forcing participants to search for a specific shape rather than a unique shape significantly reduces the performance impairment linked to a physically salient color singleton (Bacon & Egeth, 1994), an effect that can be observed using identical stimulus displays when prior experience predisposes a participant towards either a feature-based or a singleton-based search strategy (Leber & Egeth, 2006a, b). It is also the case that attentional strategies can be influenced by what participants have been rewarded for finding in the past (Lee et al., 2022). The findings of the present study can be similarly interpreted within the lens of a strategic shift in performance. Knowing that the frequency of distractor fixations was being monitored changed how participants approached the task, and this shift in approach produced a pronounced decrement in the frequency of distractor fixations.

Although the task and stimuli to which participants were exposed were equated across feedback conditions in the present study, how participants processed and interacted with the stimuli differed as a function of the feedback condition to which they were assigned. At a minimum, this was reflected in how frequently they overtly attended to the distractor in previous encounters with the stimulus, but as described above, feedback may have also influenced the attentional strategies participants employed, and thus the manner in which they processed visual information. In this respect, our feedback manipulation likely modulated *selection history* (Anderson et al., 2021; Awh et al., 2012). Given the bias to repeat attentional selection processes over trials (Anderson et al., 2021; Awh et al., 2012), any effect the feedback manipulation had in facilitating ignoring on one trial might have snowballed via selection history, with the act of successfully ignoring the distractor itself facilitating ignoring of the distractor on subsequent trials. That is, through selection history, the manner in which the feedback manipulation influenced information processing likely served to perpetuate and potentially accentuate this feedback-dependent shift in information processing.

Participants can learn to more effectively ignore a physically salient color singleton when it appears in a high-probability distractor location via statistical learning (Britton & Anderson, 2020; Wang & Theewues, 2018, 2019). Recent evidence demonstrates that the reduction in oculomotor capture associated with such statistical learning is evident even for the fastest-to-initiate saccades and can be explained by a slowing of priority accumulation for the distractor rather than a general slowing in the time to initiate a saccade or a speed-accuracy tradeoff (Kim & Anderson, 2022). In this way, the idea that selection history can modulate the priority accumulation of a physically salient distractor has precedent. Simply instructing participants to ignore a particular stimulus is often ineffective (Moher & Egeth, 2012), in contrast, and signal suppression is more generally hypothesized to be at least to some degree experience-dependent (Gaspelin & Luck, 2018; Luck et al., 2021; Stilwell et al. 2019; see also Grégoire et al., 2022). Findings such as these further suggest that the results of the present study might be at least partially driven by selection history-dependent processes, with feedback motivating participants to process visual information differently in a manner that facilitates reduced distractor processing in the future.

## Implications for theories of stimulus-driven attentional control

Consistent with Anderson and Mrkonja (2021), the benefits of trial-by-trial feedback in the frequency of oculomotor capture coincided with a slowing of oculomotor responses, reflecting a speed-accuracy tradeoff. This suggests that the "pull" from physically salient distractors on attention was fairly impervious to such feedback, with the feedback instead encouraging participants to allow more time for the attentional priority of the target to compete with that of the distractor via processes of goal-directed attentional control. Such a finding supports competitive integration models of oculomotor control (Godijn & Theeuwes, 2002; see also Donk & van Zoest, 2008; van Zoest et al., 2004) and theories that attention is predominantly stimulus-driven at the earliest stages of information processing independently of task goals, with goal-directed processes being slower to exert an influence on attentional priority (e.g., Theeuwes, 2010, 2018).

The findings from Experiment 2, however, suggest that with sufficient motivation it is possible to alter the time course of competition such that the target can become more likely to win the competition for oculomotor selection earlier in time. Experiment 2 provides strong evidence that the time course of competition between stimulus-driven versus goal-directed attentional control is not an inflexible property of the human attention system. As described in the prior section of the *General discussion*, selection history as modulated by the feedback manipulation may play a significant role in producing the observed feedback-related benefits to performance. In the present study, however, any influence of the feedback was at least initiated endogenously, since the displays to which participants were exposed did not differ as a function of the feedback they experienced. We can therefore conclude that, through endogenous processes, it is at least possible to learn how to more efficiently resolve the competition between a goal-consistent target and a more physically salient distractor.

## Limitations, outstanding questions, and future directions

Perhaps the most intriguing finding from the present study is the significant reduction in oculomotor capture with blockwise feedback that remained when trials were binned by sRT, indicating a benefit to oculomotor performance that was not reducible to a speed-accuracy tradeoff (see Paoletti et al., 2015). The feedback-related benefit was robustly significant across the first two bins tested ($ps < 0.005$) and numerically in the same direction across all bins, such that a peculiarity in exactly where trials fell within a bin without any actual improvement to performance is unlikely to provide an adequate account of the data. The pattern of results we observe here suggests that, using a feedback manipulation, it is possible to generally improve oculomotor control.

Why this feedback-related improvement was observed for block-wise feedback, whereas trial-by-trial feedback merely resulted in a reduction in capture attributable to a speed-accuracy tradeoff, is unclear. Perhaps trial-by-trial feedback is more salient and aversive to participants and thereby quickly promotes more conservative responding in an immediate attempt to avoid such feedback, which with success becomes the default strategy that participants persist in using to perform the task (see Leber & Egeth, 2006a, b), whereas with block-wise feedback participants are simply motivated to avoid capture. Such an account might predict that trial-by-trial feedback would have resulted in more pronounced post-capture slowing, but this need not be the case if the effect of such feedback is rapid and systemic, which the robustness with which it manifests within the first block of trials is broadly consistent with. Another possibility is that trial-by-trial feedback might serve to over-emphasize the distractor, resulting in an "attentional white bear" effect by which concern for the distractor results in elevated attentional priority to the distractor (Cunningham & Egeth, 2016), at least with respect to covert attention, and generally conservative responding to compensate. Concerning future research aimed at curbing distraction and improving attentional performance, the present study suggests that trial-level feedback might not be optimal and that more summary-level feedback, when used as a motivator, may be a more fruitful avenue to explore.

One limitation of the present study is that it focuses on overt attentional capture, which reflects a more extreme case of distraction in which a task-irrelevant stimulus wins the competition for selection. Physically salient distractors can capture covert attention without necessarily drawing eye movements (e.g., Theeuwes, 2010; see also Talcott & Gaspelin, 2021), and it is unclear whether the effectiveness of the approach to feedback adopted in the present study could translate to the modulation of covert attention. Oculomotor capture is by definition a discrete event, which naturally lends itself to unambiguous feedback, whereas the degree to which a task-irrelevant stimulus is covertly attended varies along a continuum (Anderson, 2017; Anderson & Folk, 2010; see also Anderson, 2014). Attentional capture can be reflected in the speed of manual responses in target identification and shows some promise in the assessment of introspective awareness of attentional capture (Adams & Gaspelin, 2020), although feedback contingent on the speed of manual responses would run the risk of simply promoting compensatory adjustments in response selection and execution.

With that said, the results of Experiment 2 suggest that the mere anticipation of feedback and the belief that attentional performance will be monitored is alone sufficient to reduce the frequency of oculomotor capture. Although the believability of our feedback-related instruction was likely helped by the physical presence of an eye tracker that participants were calibrated on, our results suggest that as long as participants believe their attentional performance is being monitored, they are capable of improved ignoring. Cleverly worded instructions that achieve this end could potentially result in a reduction in markers of covert attentional capture, and more broadly, it may be possible to achieve similar levels of improved performance without the use of an eye tracker or feedback tied explicitly to oculomotor responses.

Another outstanding question concerns the generalizability of the observed reduction in oculomotor capture to other attention tasks, especially attention tasks in which stronger guidance from goal-directed processes is possible (e.g., Bacon & Egeth, 1994; Gaspelin et al., 2017). The present study employed an additional singleton paradigm in which the target shape and distractor color varied unpredictably across trials, which is known to limit the effectiveness of goal-directed processes and thereby promote the frequency of attentional capture by physically salient stimuli (Bacon & Egeth, 1994; Leber & Egeth, 2006a, b). This was done to increase sensitivity by maximizing the room participants had for improvement, and the findings concerning how the effect of feedback varied with distractor-target distance is broadly consistent with the idea that an effect of feedback is easier to detect when there is more room for improvement. At the same time, sensitivity issues aside, one might hypothesize that situations more conducive to goal-directed attentional control would provide a more substantial context for feedback- and/or motivationally dependent processes to be implemented. At a minimum, according to a competitive integration framework (Godijn & Theeuwes, 2002), a slowing of responses motivated by feedback should alone reduce the probably of oculomotor capture in almost any attentional task, and the more interesting question concerns the generalizability of the kind of benefit observed in Experiment 2.

The prospect of performance-contingent reward is known to enhance both cognitive control broadly (e.g., Etzel et al., 2016; Jimura et al., 2010; Locke & Braver, 2008) and the control of attention specifically (e.g., Esterman et al., 2014, 2016, 2017; Padmala & Pessoa, 2011; Pessoa & Engelmann, 2010). Another interesting question for future research concerns the potential similarities and differences between such mechanisms of motivated cognition tied to extrinsic rewards and the mechanisms at play in the present study. Would the prospect of financial rewards for avoiding distraction improve attentional performance above and beyond what was observed with feedback in the present study? Many studies using performance-contingent rewards involve the provision of finer-grained performance feedback (e.g., whether response time was at or below a particular threshold more stringent than that required to register a correct response; see, e.g., Etzel et al., 2016; Jimura et al., 2010; Locke & Braver, 2008; Padmala & Pessoa, 2011). The present study invites further investigation into the value of such performance-contingent feedback per se in improving task performance and to what degree the beneficial effects of extrinsic reward might be tied to the increased performance monitoring motivated by this kind of feedback.

Finally, future studies should explore the limits of feedback-related improvements in attentional control. To mitigate the potential of feedback promoting a speed-accuracy tradeoff, tasks could be used in which participants are required to make eye movements quickly upon trial onset. Under conditions that more strongly tax the limits of attentional performance, the beneficial effects of feedback may be more substantial, motivating participants to make adjustments to their behavior and strategy until more desirable performance is achieved. Broadly, the findings of the present study raise questions about the limits of human performance with respect to the control of attention, and these limits are worthy of dedicated scientific exploration.

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**Author contributions** BAA developed the experiment concept with input from ML. BAA and ML jointly coded the experiment and BAA supervised data collection. BAA performed the data analyses. BAA and LM interpreted the data. BAA drafted the manuscript with input from LM. All authors approved the final version of the manuscript for submission.

## Declarations

**Declaration of interest statement** The authors declare no conflict of interest.

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