Short Communication

Oculomotor feedback rapidly reduces overt attentional capture

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A R T I C L E   I N F O

A B S T R A C T

People often have limited awareness of the extent to which their attention is captured by salient-but-irrelevant stimuli. In the present study, we examined how providing feedback concerning the frequency of oculomotor capture by such stimuli modulates the control of attention. Our results show that the provision of oculomotor feedback produces a rapid and dramatic decrease in the frequency of distractor fixations. Further probing of this reduction in oculomotor capture by time to fixate the first stimulus revealed further insights into the nature of this experience-dependent effect. A higher frequency of relatively slow fixation latencies was observed in the feedback group, with such responses being generally less prone to capture, reflecting a speed-accuracy tradeoff. Fixations with slower latencies were also associated with a reduced frequency of oculomotor capture in the feedback group, whereas the fastest responses were almost exclusively stimulus-driven across participants and unaffected by feedback. These effects of feedback persisted when feedback was removed and they generalized to novel stimuli. Our findings suggest that, without any instruction concerning how to use the feedback, the oculomotor system defaults to delaying saccadic responses to allow more time for goal-directed influences on selection to come online, reflecting a history-dependent shift in oculomotor processing.

1. Introduction

How we direct our attention is not always under our control. Certain kinds of stimuli can automatically capture our attention in spite of our best efforts to ignore them. Stimuli that share a defining feature with a task-relevant stimulus (Folk, Remington, & Johnston, 1992), stimuli associated with valent outcomes including reward (e.g., Anderson, Laurent, & Yantis, 2011) and punishment (e.g., Schmidt, Belopolsky, & Theeuwes, 2015), and physically salient stimuli (Theeuwes, 1992, 2010) can all capture our attention under certain task conditions. Attentional capture by physically salient stimuli provides a particularly stark example of a failure of attentional control, as such capture can occur even when the eliciting stimulus was only ever task-irrelevant and attending to it has never carried a benefit. 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, Donk, & Theeuwes, 2004). Approaches to mitigating such distraction by salient-but-irrelevant stimuli have the potential for broad impact, as distraction is a leading cause of workplace accidents and injury (Namian, Albert, & Feng, 2018).

Overt attentional capture may be related to poor awareness of how an individual directs their attention and the true extent to which their eyes are actually directed to salient-but-irrelevant stimuli. Individuals generally have limited awareness of where they move their eyes while viewing a scene (Vo, Aizenman, & Wolfe, 2016) or performing visual search (Horowitz & Wolfe, 1998). In a foundational study on oculomotor capture, Theeuwes, Kramer, Hahn, and Irwin (1998) reported that participants generally believed that their visual search performance was unaffected by physically salient but task-irrelevant distractors, which contrasted with their actual performance which revealed frequent distractor fixations. Recent evidence further suggests that people have non-zero but limited awareness of when their attention is captured by physically salient distractors when awareness is probed trial-by-trial (Adams & Gaspelin, 2020, 2021). Perhaps raising people's awareness of the extent to which their attention is actually captured by a physically salient stimulus would allow them to calibrate attention in such a way as to mitigate the frequency with which capture occurs.

The extent to which oculomotor capture can be modulated as a result of feedback concerning the frequency with which it occurs is not known. In the present study, we adapted newly-developed methods for providing near-real-time oculomotor feedback (Anderson, 2021) to an oculomotor attentional capture task. One group of participants heard an auditory tone play immediately upon fixating a salient-but-irrelevant distractor, while another group was similarly instructed to ignore the

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distractor but was given no such auditory feedback. Of interest was whether the feedback manipulation would result in a reduction in the frequency of the oculomotor capture, which could be realized by more efficiently ignoring the distractor, more efficiently prioritizing the target for selection, or both. A follow-up experiment probed the persistence and generalizability of feedback-related influences on oculomotor capture.

2. Methods

2.1. Experiment 1A

2.1.1. Participants

Thirty-six participants (20 female, mean age = 18.5 y) were recruited from the Texas A&M University community. Participants 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. Given the novelty of the experiment concept, there was no clear basis for estimating the anticipated effect size for the feedback manipulation; the closest analogue would seem to be the influence of near-real-time aversive oculomotor feedback on eye movements (d = 1.23; Anderson, 2021), which indicated power (1-β) > 0.90 with the collected sample size.

2.1.2. 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 1000 Hz. Head position was maintained using an adjustable chin and forehead rest (SR Research). Tones were played over Beyerdynamic DT 770 Pro 250 Ω studio headphones.

2.1.3. Stimuli

The fixation display consisted of a white plus sign presented at the center of the screen (Fig. 1). The stimulus 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, a 66 dB 500 Hz tone was played over the headphones upon fixating the distractor (see Section 2.1.5).

2.1.4. 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. Under such conditions, participants can either search for the target on the basis of its physical salience or its unique shape (Bacon & Egeth, 1994), with the former search strategy being more prone to distraction. Trials were presented in a random order. Feedback was manipulated between-subjects, with half of participants assigned to the feedback group.

2.1.5. Procedure

The experiment consisted of six blocks of 96 trials, which were preceded by practice trials with and without a time limit (during which no auditory 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 auditory feedback 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. During the stimulus 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. We have used the same fixation thresholds in a variety of studies of oculomotor capture (e.g., Anderson & Britton, 2020; Anderson & Kim, 2019a, 2019b, 2020; Grégoire, Britton, & Anderson, in press; Kim & Anderson, 2020). For the feedback group, when a fixation on the salient distractor was registered, the tone was played over the headphones for 50 ms and was immediately repeated as long as eye position remained within the 0.7° window surrounding the distractor. The stimulus array remained on screen for 1000 ms or until a target fixation had been registered.

2.1.6. Data analysis

Oculomotor capture was defined as the proportion of distractor-present trials on which the distractor was fixated. Fixation latency, or time to first fixate any stimulus in the array, was computed from the onset of the stimulus array until eye position first entered the window surrounding a stimulus on which a fixation was subsequently registered. On distractor-present trials, we generated ten equally-sized bins of RT
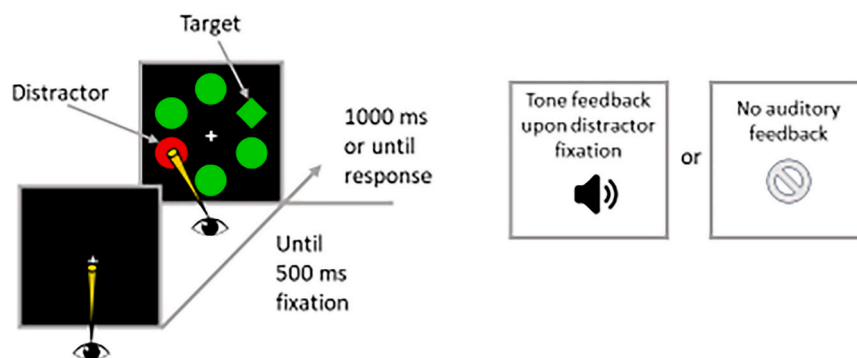

Fig. 1. Example trial. For participants in the feedback group, a tone was played upon fixating the salient color distractor, while this was not true for participants in the no feedback group, who were similarly instructed to do their best to orient to the target while ignoring color distractors.

(Vincintized) across all participants (blind to feedback group) and then computed the probability of oculomotor capture for trials falling into each bin for each participant along with the proportion of trials falling into each bin. This allowed us to determine (a) whether fixation latency was associated with the probability of capture, consistent with previous findings examining capture as a function of saccadic reaction time (Donk & van Zoest, 2008; Godijn & Theeuwes, 2002; van Zoest et al., 2004), (b) whether a shift in the distribution of fixation latency was associated with the feedback manipulation, and (c) whether, with fixation latency equated in each bin, a benefit of feedback on the frequency of oculomotor capture would be evident. Raw data for all experiments are available via the Open Science Framework at https://osf.io/2pvyj/.

2.2. Experiment 1B

An additional 18 participants (11 female, mean age = 21 y) were recruited. The experiment was identical to that for the feedback group in Experiment 1A with the following exceptions. First, auditory feedback was provided in the first three blocks of the task only, and not in the final three. Second, the colors used for the stimuli changed in the fourth block when feedback was removed. For half of participants, the stimuli were initially red and green and then changed to blue and yellow. For the other half of participants, the order of colors used was reversed.

3. Results

3.1. Experiment 1A

The frequency of oculomotor capture was submitted to a 6×2 analysis of variance (ANOVA) with block (1–6) and group (feedback, no feedback) as factors. The main effect of feedback was substantial, $F(1,34) = 15.69$, $p < 0.001$, $\eta^2_p = 0.316$ (Fig. 2A). There was a marginally significant effect of block, $F(5,170) = 2.15$, $p = 0.062$, and no interaction, $F(5,170) = 0.46$, $p = 0.806$.
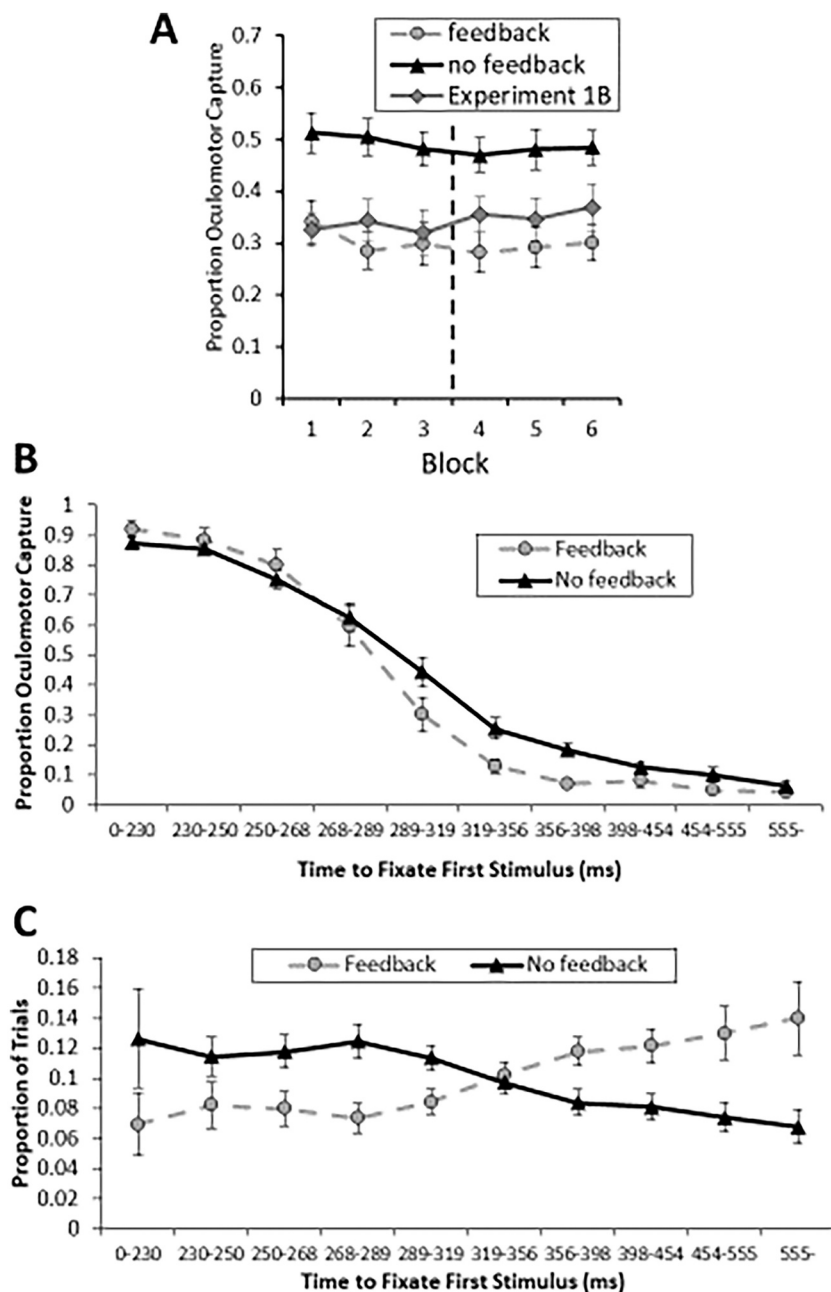

Fig. 2. Behavioral results. (A) The proportion of oculomotor capture over the course of the experiment (trial block) separately for the three participant groups. The dotted line indicates the point at which feedback was removed from Experiment 1B. (B) Proportion of oculomotor capture as a function of fixation latency for the feedback and no-feedback groups in Experiment 1A. Each bin on the x-axis encompasses 10% of all responses on distractor-present trials without regard to participant group (Vincintized). (C) Proportion of distractor-present trials falling into each of the bins from panel C by participant group. Error bars reflect the SEM.

Binning of trials by fixation latency revealed two distinct effects of feedback. First, concerning the frequency of oculomotor capture, the data were subjected to a 10 × 2 ANOVA with bin (1–10) and group (feedback, no feedback) as factors. One participant from the feedback group was removed from the analysis due to having no fixation latencies represented in two of the bins—all other participants contributed some trials across the entire spectrum of fixation latencies. There was a substantial effect of bin in which initial fixations were nearly always on the distractor for shorter fixation latencies but very seldom on the distractor for longer fixation latencies, $F(9,297) = 281.17$, $p < 0.001$, $\eta^2_p = 0.895$ (Fig. 2B). Importantly, there was also a significant interaction between bin and group, $F(9,297) = 2.77$, $p = 0.004$, $\eta^2_p = 0.077$. As is evident from the figure, post-hoc pairwise comparisons revealed that the frequency of capture did not differ between groups in bins 1–4, 8, and 10, $ts < 1.31$, $ps > 0.199$, likely reflecting floor and ceiling effects; a significant difference was evident in bins 6, $t(33) = 2.84$, $p = 0.008$, $d = 0.97$, and 7, $t(33) = 4.37$, $p < 0.001$, $d = 1.49$, with marginally significant differences in bins 5 and 9, $ts > 1.86$, $ps < 0.072$.

The same ANOVA was conducted on the proportion of trials falling into each bin. An overall shift in the distribution of fixation latencies was linked to the feedback manipulation as reflected in an interaction between bin and group, $F(9,306) = 4.89$, $p < 0.001$, $\eta^2_p = 0.126$ (Fig. 2C), reflecting a prominent cross-over pattern in which fixation latencies are shifted toward the slower end of the distribution in the feedback group. Further consistent with this general slowing, time to fixate the target was overall significantly slower in the feedback group on distractor-absent trials ($M = 399$ vs. 355 ms), $t(34) = 2.34$, $p = 0.026$, $d = 0.78$. The time to fixate the target did not significantly differ on distractor-present trials although was numerically slower in the feedback group ($M = 474$ vs. 457 ms), $t(34) = 1.04$, $p = 0.306$, potentially reflecting offsetting influences of slower responses and less frequent errant fixations on the distractor.

3.2. Experiment 1B

The same ANOVA was conducted over oculomotor capture, comparing participants in Experiment 1B to each of the groups in Experiment 1A (two separate AONVAs). Oculomotor capture was reduced in Experiment 1B compared to participants in the no-feedback group, reflected in a main effect of feedback, $F(1,34) = 9.10$, $p = 0.005$, $\eta^2_p = 0.211$, with no significant main effect of block or interaction, $Fs < 1.26$, $ps > 0.287$ (Fig. 2A). This main effect of feedback remained significant when restricting analyses to the last three blocks of trials in which no feedback was provided to either group, $F(1,34) = 5.62$, $p = 0.024$, $\eta^2_p = 0.142$, indicating a persistence of the effect of feedback. Conversely, comparing to participants in the feedback group, there were no main effects or interaction, $Fs < 1.75$, $ps > 0.125$.

Given that only three blocks of the task were performed without feedback in Experiment 1B, the data did not lend itself to an ANOVA concerning oculomotor capture as a function of trials binned by fixation latency as in Experiment 1A (several participants did not contribute a data point to a particular bin and thus contributed an empty cell to the analysis). However, in the last three blocks, the difference in oculomotor capture in bin 7 (356–398 ms, to which each participant contributed at least 7.2% of trials) was replicated when comparing participants in Experiment 1B to participants in the no-feedback group of Experiment 1A, $t(34) = 2.15$, $p = 0.039$, $d = 0.71$ (see Table 1 and Supplemental

Fig. 1). Time to fixate the target was slower in the last three blocks in Experiment 1B compared to the no-feedback group of Experiment 1A, a difference that was significant on distractor-absent trials ($M = 370$ vs. 341 ms), $t(34) = 2.25$, $p = 0.031$, $d = 0.75$, but not on distractor-present trials ($M = 457$ vs. 438 ms), $t(34) = 1.34$, $p = 0.191$.

4. Discussion

Prior research has established that individuals possess limited awareness of when their attention is captured (Adams & Gaspelin, 2020, 2021; Theeuwes et al., 1998), and here we tested whether feedback concerning the occurrence of overt attentional capture could have a beneficial effect in mitigating capture. Using a near-real-time feedback manipulation tied to eye movements (see Anderson, 2021), the present study establishes a causal link between the provision of immediate feedback concerning oculomotor capture and the frequency with which such capture occurs. When individuals are made aware of the extent to which their eyes are captured by a salient distractor via feedback, they are able to leverage this feedback to adjust their visual search in a manner that reduces the frequency of errant eye movements to the distractor.

Probing of oculomotor capture as a function of fixation latency revealed further insights into the underlying mechanisms involved. Participants in the feedback group were generally slower to fixate a stimulus, with slower fixation latencies associated with a reduced frequency of capture. Fixations with slower latencies were also less likely to reflect distractor fixations in the feedback group. These findings are broadly consistent with a competitive integration model in which the attentional priority of a physically salient stimulus is initially elevated at the outset of the trial and dissipates as the priority of the target gradually builds due to goal-directed selection processes, with competition between the distractor and target unfolding dynamically over time (Godijn & Theeuwes, 2002; see also Donk & van Zoest, 2008; van Zoest et al., 2004). As a result of feedback, participants engaged in compensatory processes in which oculomotor selection was overall slowed, allowing more time for competition between the target and distractor to unfold. Faster fixation latencies reflected almost exclusively stimulus-driven influences on selection regardless of condition, being themselves unaffected by feedback. Such fast fixations were less frequent for participants who had experienced the feedback, while fixations with slower latencies were more frequent and also more strongly biased toward the target following feedback.

Experiment 1B revealed that the effects of feedback on oculomotor capture can persist once feedback is removed and can generalize to physically salient stimuli that differ in color from the stimuli to which the feedback has been applied. Not only does this serve to replicate the main result and provide a window into the scope of the effect of feedback, but it also serves to rule out more acute effects of the feedback on performance. This includes online motivation to avoid the feedback per se and immediate effects of post-error slowing (Laming, 1968) that could be amplified by feedback, as well as arousal-related effects tied to hearing or anticipating the sound. When fixating a salient distractor produces an aversive sound, attentional capture by this aversively-conditioned stimulus is magnified (Mikhael, Watson, Anderson, & Le Pelley, in press), and negative arousal by aversive sounds is associated with an amplified influence of salience on information processing (Mather & Sutherland, 2011), making it unlikely that the tone used in

Table 1
Proportion of oculomotor capture as a function of fixation latency for the last three blocks of Experiment 1B and the no-feedback group in Experiment 1A. Cells with a dashed line indicate cells for which at least one participant in Experiment 1B did not contribute a datapoint.

	Time to Fixate the First Stimulus (ms)									
	0–230	230–250	250–268	268–289	289–319	319–356	356–398	398–454	454–555	555-
Experiment 1B	–	0.899	0.799	0.703	0.461	–	0.117	0.102	–	–
No feedback	0.874	0.853	0.751	0.625	0.443	0.253	0.184	0.125	0.099	0.063

the present study was processed as aversive and that attentional capture was reduced via aversive conditioning or negative arousal.

Recent research highlights an important role for selection history in mitigating attentional capture by physically salient stimuli (Anderson et al., 2021). Specifically, statistical learning concerning the frequency of distractors appearing in a particular spatial location (e.g., Wang, Samara, & Theeuwes, 2019; Wang & Theeuwes, 2018) or possessing a characteristic feature such as a particular color (e.g., Stilwell, Bahle, & Vecera, 2019) can result in less frequent attentional capture by high-probability distractors, and this learning-dependent reduction in salience-driven attentional capture can be persistent (Britton & Anderson, 2020). Our findings extend the role of selection history in mitigating salience-driven attentional capture to endogenous influences linked to learning from feedback. Experiment 1B demonstrates that such learning is not restricted to immediate effects of feedback on attention but instead reflects a persistent shift in how visual information is processed.

The present study provides evidence of a persistent, history-dependent influence of learning from feedback on oculomotor capture. A host of further questions can be raised concerning the scope of this influence. Although oculomotor capture occurred significantly less frequently for participants receiving feedback, this reduction came at the expense of overall response speed, particularly on distractor-absent trials. Future research could explore whether, when encouraged to respond more quickly, a reduction in the frequency of oculomotor capture can still be evident without a concomitant slowing of overall response speed (and perhaps with a benefit to speed on distractor-present trials due to a less frequent need to reorient). Future research might also further explore the generalizability of feedback-related benefits on oculomotor capture (e.g., to a completely different task or context), along with the persistence of these benefits (e.g., over weeks or months). It is unclear how critical the near-real-time element of the feedback was in the present study and to what degree more generic performance-related feedback could have similarly persistent effects.

The present study examined the influence of feedback on oculomotor capture when the target was defined as a shape singleton, which produces large baseline rates salience-driven capture and thus provides a sensitive test for feedback-dependent modulation. However, as stated in the Methods, participants might to some degree search intentionally for physically salient stimuli in general in this task (Bacon & Egeth, 1994; Leber & Egeth, 2006), which feedback might have discouraged. More specifically, participants who did not receive feedback might default to explicitly searching for a physically salient stimulus, which produces generally efficient task performance and presumably requires limited attentional effort, but is also prone to distraction (Bacon & Egeth, 1994; Leber & Egeth, 2006). Participants who received the feedback may have switched to a strategy of searching more specifically for a shape singleton, slowing performance on distractor-absent trials while more effectively restricting attention to the target. In this respect, our findings demonstrate that without any explicit feedback, participants search in a generally efficient manner, actually localizing the target faster on distractor-absent trials than participants who do receive feedback; it is not the case that feedback concerning the occurrence of oculomotor capture merely serves to increase global attentional effort. A similar pattern of decreased frequency of attentional capture with concomitant slowing of responses on distractor-absent trials was observed with increasing distractor frequency, which was interpreted as reflecting second-order singleton suppression (Won, Kosoyan, & Geng, 2019). It would be interesting to examine the extent to which the beneficial effect of feedback on capture is tied to a shift in search strategy versus a more general shift in how physically salient stimuli are processed.

4.1. Conclusions

The provision of oculomotor feedback results in a rapid and substantial decrease in the frequency of oculomotor capture by a salient-but-irrelevant stimulus. Apart from establishing a causal role for oculomotor feedback in the ability to resist distraction, the present study offers a straightforward methodological approach to rapidly reducing the frequency of attentional capture, which with further development may have translational implications. Our findings reveal a novel role for selection history in the mitigation of attentional capture by physically salient stimuli, in this case reflecting endogenous influences brought about as a result of performance-related feedback.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2021.104917.

Declaration of Competing Interest

The authors declare no conflict of interest.

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