Action history influences eye movements

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ABSTRACT
Recent research has revealed that simple actions can have a profound effect on subsequent perception – people are faster to find a target that shares features with a previously acted on object even when those features are irrelevant to their task (the action effect). However, the majority of the evidence for this interaction between action and perception has come from manual response data. Therefore, it is unknown whether action affects early visual search processes, if it modulates post-attentional-selection processes, or both. To investigate this, we tracked participants’ spontaneous eye movements as they performed an action effect task. In two experiments we found that participants looked more quickly to the colour of an object they had previously acted on, compared to if they had viewed but not acted on the object, showing that action influenced early visual search processes. Additionally, there was evidence for post-selection effects as well. The results suggest that prior action affects both pre-selection and post-selection processes – spontaneously guiding attention to, and maintaining it on, objects that were previously important to the observer.

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Vision does not typically occur in a static environment – humans rely on their senses as they navigate the kitchen, a jungle, or a busy city street. Recently, research has begun to highlight numerous ways in which the actions that people perform can influence how they perceive the world. For example, changes in a person’s ability to interact with the environment affect perception: when people are able to interact with an object (by using a reach-extending tool) they perceive the object to be closer than when they cannot interact with it (i.e., when it is out of reach; e.g., Abrams & Weidler, 2015; Brockmole, Davoli, Abrams, & Witt, 2013; Witt, Proffitt, & Epstein, 2005). In addition, momentary fluctuations in one’s capabilities can affect perception: for example, after making a successful return in tennis, individuals perceive the ball as having moved more slowly than after unsuccessful returns (Witt & Sugovic, 2010; see also e.g., Bhalla & Proffitt, 1999; Schnall, Zadra, & Proffitt, 2010, for evidence that energetic capabilities can affect perception). Additionally, preparing specific actions can affect perception differentially: Fagioli, Hommel, and Schubotz (2007) found that participants were more sensitive to object size when they prepared a grasping action than when they prepared a pointing action (see also Bekkering & Neggers, 2002; Heuer & Schubö, 2016).

Not only is perception influenced by one’s action capabilities, but perception is also affected by the actions that one has recently performed. In particular, after making a simple action toward an object, features of that object (such as its colour) receive priority during visual search. In the typical paradigm that investigates the phenomenon, participants press the space bar (i.e., make an action) to an object (the prime) on some trials but not others, based on a pre-cue. Then, participants are asked to perform an unrelated visual search task. Researchers manipulate the visual similarity of the target in the search display to the earlier prime. On some trials, the colour of the target matches that of the prime; on other trials, a distractor is presented in the prime colour. On trials when participants had merely viewed the prime object (i.e., they had not made an action) there is typically no (or only a small) benefit when the search target matches the prime’s colour. However, on trials on which participants had acted toward the prime they are faster to respond in the search task when the target colour matches that of the prime (e.g., Buttaccio & Hahn, 2011; Weidler & Abrams, 2014). This finding reveals that action influences subsequent perception: attention is allocated more quickly to a feature of the acted-on object (i.e., the prime’s colour), despite it
being irrelevant to the visual search task. This action effect is thought to aid behaviour by prioritizing features of objects that have been acted upon, presumably because such objects are considered important (e.g., Abrams & Weidler, 2015).

Recent research has revealed the generalizability of the action effect. For example, the action effect is not limited to influencing subsequent perception of colour – the effect occurs when the stimuli used differ only in shape (Weidler & Abrams, 2017a). In addition, simple actions can compete with bottom-up salience to affect subsequent perception – action still influences visual search performance when the target is a singleton that permits parallel search (Weidler & Abrams, 2017b).

Nevertheless, much remains unknown about the effects of simple action on subsequent perception. Specifically, it is unclear the precise level at which actions affect subsequent perception. Two general possibilities exist. First, it is possible that actions affect relatively early visual aspects of the search process prior to attentional selection of a target. Second, it is possible that action affects post-selection decision processes. Or, there might be both types of influences. Because the experiments conducted to date have all involved only manual responses (with one exception discussed below), it is not clear which of these possibilities holds. That is because manual response latencies include the time needed to complete all processes from target selection through response production, and would thus reflect influences on any of those processes. In the present study our goal was to more precisely identify the locus of the action effect.

There are some reasons to predict that action could produce either a relatively early, pre-selection, effect as well as a later post-selection one. For example, Buttaccio and Hahn (2011) proposed that action biases early selective attention. Some support for that comes from research which shows that the effect occurs even when the target is always a salient singleton (Weidler & Abrams, 2017b). Given that searching for a singleton is usually thought to be a rapidly completed early process (e.g., Treisman, 1988; Treisman & Gelade, 1980), if action can modulate such a search that implies that action exerts an early effect. In addition, one recent investigation tracked participants’ eyes while they performed an action effect task. Wang, Sun, Sun, Weidler, and Abrams (2017) found that the direction of participants’ first saccade was biased towards features from the action task to a greater degree after acting than after viewing the prime object. The fact that early saccades are influenced by prior action could be taken as strong evidence for a relatively early effect of action. Importantly however, in the Wang et al. study the target was easy to identify while remaining fixated, and participants’ main task was to execute their first saccade to the target (i.e., that was the imperative response instead of a key press). Therefore, it is an open question if early eye movements will be affected by prior action when saccades to the target may be required to identify it, and are not participants’ top-down goal. The present research addresses this question (see General discussion for further consideration of this issue).

However, although no post-selection accounts have been offered to explain the action effect per se, there are post-selection explanations of a similar phenomenon. More specifically, in a priming of pop-out (PoP) task, participants typically search for a uniquely coloured target and (as in the action effect paradigm) report about a non-colour feature of that target (e.g., which corner is missing from a diamond; Maljkovic & Nakayama, 1994). PoP occurs when participants are faster to respond on the current trial if the target’s features match features of the target from the previous trial (see Kristjánsson & Campana, 2010, for a review). For example, participants are faster to indicate the missing corner of a red target amongst green distractors if the previous trials’ target was also red. Importantly, some researchers have argued that the locus of this effect occurs after the target has been attentionally selected, while the participant is determining if the selected item is indeed the target (e.g., Huang, Holcome, & Pashler, 2004). According to this account, relatively late response-related processes are facilitated when the target shares features with the previous trial’s target. Given the high degree of similarity between these two tasks, a similar process could underlie the action effect.

Given these two possibilities, the goal of the present study was to attempt to learn more about the locus of simple action’s effect on subsequent visual search. To do that we recorded participants’ spontaneous eye movements during the visual search task and, importantly, we presented the
search stimuli far enough from fixation so that a saccade was required in order to assess them. If action affects early perceptual or attentional processes prior to selection of a candidate target object, then the initial eye movement during search would be expected to reveal such effects (e.g., Becker, 2008). That is, if participants are faster or more likely to first look to the search element matching features of the acted-upon prime, that would suggest that the action influenced processes prior to (and including) attentional selection. This conclusion follows because overt eye movements, when they occur, are presumed to reflect covert attention shifts (e.g., Deubel & Schneider, 1996; Kan, Niel, & Dorris, 2012). However, if action affects only post-selection processes then the initial eye movement should not reveal any effects of prior action. Instead, eye movement behaviours after object selection, such as the duration of object fixation, may reflect effects of the prior action. To anticipate the results, in two experiments we replicated the action effect in key press behaviour and found strong evidence for pre-selection influences of action: participants’ initial eye movements were more likely to go directly to the object that matched the prime after a prior action. In addition, there was also evidence for post-selection influences of action: evaluation of fixation durations revealed that prior action tended to prolong fixation on the target when it matched the prime colour, suggesting that the action effect may also influence post-selection processes.

Experiment 1

Method

Participants
In order to obtain useable eye-tracking data from 24 participants, 25 undergraduates (20 female, 5 male, \(M_{\text{age}} = 19.4\) years, age range = 18–22 years) were tested in exchange for course credit (one participant was replaced due to eye-tracker failure). This sample size was chosen based on sample sizes of 24 in past research on the action effect (Wang et al., 2017; Weidler & Abrams, 2014).

Apparatus
Participants viewed a 19-inch CRT monitor (85 Hz refresh rate) from 52 cm (with the distance fixed by a chinrest). Participants’ eye movements were recorded using an OptiTrack Slim U3 (NaturalPoint, Inc.) camera. An infrared LED light illuminated participant’s eyes.

Stimuli and procedure
The experiment was programmed in Psychopy (Peirce, 2007). The procedure is shown in Figure 1. All stimuli were presented against a black background. Each trial began with the presentation of a central fixation cross (1°, white) for 506 ms. This was followed by a colour word (“blue”, “gray”, “green”, “purple”, “red”, “yellow”; displayed in white, 2° in height) presented centrally for 506 ms. After another fixation cross (for 118 ms), the prime, a single blue, grey, green, purple, red, or yellow circle 6° in diameter, centrally presented, appeared for 753 ms or until the participant responded. For the action task, participants were instructed to press the space bar on a computer keyboard with their left hand if the physical colour of the prime matched the identity of the colour word presented earlier (action trials), or to simply view the circle if the word and colour of the prime did not match (viewing trials). After the offset of the prime and another 506 ms fixation cross (during which time auditory feedback was presented for an incorrect response in the action task), the search display appeared. The search display contained two differently coloured 6° circles: one 12° to the left and one 12° to the right of the fixation cross. Each contained a black line (.12 × 4°); the target line was tilted −4 or +4 degrees whereas the distractor line was vertical (tilted 0 degrees). In this search task, participants were instructed to indicate the orientation of the target line by pressing either the left or right arrow key on the keyboard with their right hand. The colour of the prime circle was always present in the search display. On valid trials, that colour contained the tilted target line whereas on invalid trials that colour contained the vertical distractor line. The search display remained present for 1506 ms or until a response, and was followed by a 1506 ms inter-trial-interval that contained 506 ms of visual and auditory feedback for incorrect or omitted responses.

Design
There were 24 unique trials in the experiment (2 action type × 2 validity × 6 prime circle colour) that were each repeated eight times to create a test block of 192 trials. Presentation order was determined randomly without replacement from that set. The colour word stimulus
on viewing trials and the second colour in the search display (i.e., other than the prime colour) was chosen randomly on each trial from the other five possible colours. In addition, the target line orientation and the location of the target and distractor were chosen randomly on each trial.

**Eye tracking**

Eye position was recorded at a sampling rate of 120 Hz during the search task. A nine-point calibration was performed at the beginning of each block. Saccades were defined as eye movements whose velocity exceeded 50°/s, with acceleration above 9500°/s for at least two samples. No specific instruction was given to participants regarding their eye movements.

**Results**

**Manual response data**

**Action task.** Participants performed .982 (SD = .016) of action task trials correctly, and were equivalently accurate on action (M = .979) and viewing trials (M = .986), t (23) = 1.18, p = .25, d = .24 (all reported t-tests are two-tailed). Average action task reaction time (RT) was 403 ms (SD = 29).

**Search task.** Participants performed both the action task and the search task correctly on .962 of trials (SD = .021). RTs for those trials in which both tasks were correct were analysed with a 2 (action: action or viewing) × 2 (validity: invalid or valid) repeated-measures ANOVA and are shown in Figure 2 (left panel). Participants were no faster on action than viewing trials, F < 1, but were faster on valid compared to invalid trials, F(1, 23) = 21.93, p < .001, η^2_p = .49 (M_valid = 618, M_invalid = 645). Importantly, revealing the action effect, action and validity interacted, F(1, 23) = 7.77, p = .010, η^2_p = .25. This interaction arose because the validity effect (invalid RT – valid RT) was larger following an action (39 ms) than following viewing of the prime (16 ms), although it was significantly different in both cases (after an action, t(23) = 4.67, p < .001, d = .95; after viewing, t(23) = 2.80, p = .010, d = .57).

The same 2 (action) × 2 (validity) repeated measures ANOVA was conducted on search task accuracy (including only trials in which the action task was correct). There was no main effect of action F < 1, but there was a marginal effect of validity, F(1, 23) = 3.12, p = .091, η^2_p = .12, with better performance on valid
(M = .982) than invalid (M = .975) trials. The two factors did not interact, F < 1.

Eye movement data
Trials in which (1) a saccade occurred within 100 ms of the search array’s appearance, (2) the first detected saccade began more than 5° from fixation, and (3) an error was made during the action task (i.e., there was no response on action trials or an erroneous response on viewing trials) were considered as errors and removed from eye movement analysis (26.14% of trials).

We present five measures of eye movement behaviour. The first four – direction of the initial saccade, latency of target acquisition, number of saccades needed to reach the target, and scanning distance prior to fixating the target – index potential pre-selection effects (i.e., they measure processes that occur before the target is selected). The final measure – target fixation/decision time – indexes potential post-selection processes (i.e., processes after the target has been selected).

Saccade direction. We examined the proportion of trials on which the first saccade was directed to the search target (one search element was on each side of fixation). Saccades landing within 5° of the search target were considered as correct responses. These data are plotted in Figure 2 (right panel). We analysed the proportions using the same 2 (action) × 2 (validity) repeated-measures ANOVA as we had used for the manual response data. There was no main effect of action F < 1, but there was an effect of validity, F(1, 23) = 24.05, p < .001, ηp² = .51, with the initial saccade more likely to be directed toward the target on valid (M = .591) than invalid (M = .426) trials. Recall that on valid trials the target matched the colour seen during the action task, so this result means that participants were more likely to look to the element with that colour first. Importantly, prior action modulated the validity effect, F(1, 23) = 23.76, p < .001, ηp² = .51. Following an action (i.e., on action trials), the initial saccade went to the target significantly more often (.278) on valid trials than invalid trials, t(23) = 5.52, p < .001, d = 1.3, but after only viewing the prime (i.e., on viewing trials) there was no difference, t(23) = 1.84, p = .079, d = .38 (the first eye movement went to the target only .052 more often on valid trials).

Target acquisition latency. We also examined the time at which the eye first landed at the target location, shown in Figure 3 (left panel). A 2 (action) × 2 (validity) repeated-measures ANOVA revealed that there was no effect of action F < 1, but there was an effect of validity, F(1, 23) = 22.08, p < .001, ηp² = .49,
with a saccade reaching the target sooner on valid \((M = 420)\) compared to invalid \((M = 463)\) trials. Importantly, the validity effect was modulated by type of action, \(F(1, 23) = 9.50, p = .005, \eta_p^2 = .29\), with the validity effect in target landing time greater following an action \((M = 64\) ms\), than following viewing \((M = 23\) ms\). The validity effect was significant in both cases (after an action, \(t(23) = 5.25, p < .001, d = 1.1\); after viewing, \(t(23) = 2.19, p = .039, d = .5\)).

**Saccade numerosity.** Next, the average number of saccades made before landing on the search target was examined with a 2 (action) \(\times 2\) (validity) repeated-measures ANOVA (Figure 3, middle panel). Again, the main effect of action was not significant \(F < 1\), but there was an effect of validity, \(F(1, 23) = 24.29, p < .001, \eta_p^2 = .51\), showing participants needed fewer saccades to reach the target on valid \((M = 1.38)\) compared to invalid \((M = 1.56)\) trials. There was a significant interaction between action and validity, \(F(1, 23) = 29.28, p < .001, \eta_p^2 = .56\). Following an action, participants made 0.3 more saccades on invalid compared to valid trials, \(t(23) = 5.69, p < .001, d = 1.2\). However, participants only made .05 more saccades for invalid than valid trials following viewing, \(t(23) = 1.83, p = .08, d = .37\).

**Scanning distance.** We also analysed the total distance traversed by the gaze movements prior to fixating the target. These are shown in Figure 3 (right panel). A 2 (action) \(\times 2\) (validity) ANOVA revealed no main effect of action, \(F < 1\), but a main effect of validity, \(F(1, 23) = 25.17, p < .001, \eta_p^2 = .52\), with shorter scanning distances on valid trials. Importantly, action and validity interacted, \(F(1, 23) = 19.5, p < .001, \eta_p^2 = .46\), showing that the reduction in scanning distance on the valid trials was much greater after an action, \(t(23) = 5.34, p < .001, d = 1.10\), than after viewing, \(t(23) = 2.61, p = .016, d = .53\).

**Target fixation/decision time.** Last, we analysed the duration of the first fixation on the target. Trials were included in this analysis regardless of where the preceding saccade originated. In 87% of the trials, the response key was pressed during that initial fixation — ending the eye movement recording — and we have included only those trials in the analysis. Because eye recording ended at the time of keypress, this measure indexes that amount of time spent fixating on the target prior to response. The data are shown in Figure 4. There was no main effect of action, \(F(1, 23) = 1.42, p = .25\), but participants fixated the target longer on valid trials compared to invalid trials, \(F(1, 23) = 9.10, p = .006, \eta_p^2 = .28\). Importantly, the effect of action interacted with validity, \(F(1, 23) = 8.16, p = .009, \eta_p^2 = .26\), with the difference between valid and invalid trials greater following an action, \(t(23) = 3.61, p = .001, d = .74\) \((t(23) = 1.08, p = .291, d = .22\) following viewing).
Discussion

The results of this experiment help to pinpoint the locus of action’s effects on perception. First, we found that simple actions affect relatively early search processes by showing that features associated with a prior action capture spontaneous eye movements during search even when they are task-irrelevant. More specifically, after an action, participants looked directly to the object that matched the prime’s colour more often than after merely having viewed the prime. Action also reduced the number of eye movements and the time participants needed to first reach the target, as well as the distance traversed before target acquisition. Taken together, the results clearly indicate that action has an effect on early visual search processes prior to attentional selection.

Second, we found that participants gazed at the target longer before responding after valid trials and that this effect was enhanced by action. This result suggests that at least some of the effect of a prior action is on processes occurring after attentional selection. However, the trials with the longer fixation/decision times are also ones on which participants arrived at the target sooner. As a result, the effect may be a consequence of the early arrival times and should be interpreted with caution. We return to this issue in General discussion.

There is, however, one interpretation of the present results that does not attribute the effects to the production of an action. In particular, it is possible that colour-word priming is responsible for the observed changes in eye movement behaviour. This is because participants made an action when the physical colour of the prime matched a colour word name presented earlier (as in previous research, e.g., Buttaccio & Hahn, 2011). Thus, on action trials, but not viewing trials, participants were exposed twice to the colour that was used to manipulate validity in the search display: through both a colour name and the physical colour of the prime (on viewing trials a different colour name would have been presented). Although previous research has shown that this priming cannot account for the action effect in key press RTs (Weidler & Abrams, 2014), it remains unknown whether such priming could influence eye movements during the search. No research to date has examined how prior action influences eye movements when action is not confounded with colour-word priming. Exploring this question was the goal of Experiment 2.

Experiment 2

Experiment 2 replicated Experiment 1 with the exception of one small but important change. Instead of seeing a colour word at the beginning of each trial, participants either saw the word “GO” or “NO”; they were instructed to act (by pressing the spacebar) to whatever object appeared next after the word GO, but to simply view the next object (and not act) after the word NO. Thus, in this experiment, participants were not required to process any of the prime’s features when making an action (or when viewing the prime). As a result, any effect of the prime would be likely to stem from automatic processing of its features. Additionally, by eliminating the colour name, action trials and viewing trials contained equal exposure to the prime colour (i.e., both types of trials displayed a coloured circle, but no trials displayed a colour name as they had in Experiment 1).
these conditions as it had in Experiment 1, then that would provide additional converging evidence regarding the locus of the action effect.

**Method**

**Participants**

Twenty-four new undergraduates (20 female, 4 male, $M_{age} = 20.7$ years, age range = 18–24 years) participated for course credit or payment. Three participants were removed from the analysis, one due to high errors in the search task (>2SD from the mean error rate) and the other two due to excessive eye movement errors (either no eye movement was detected or the initial eye movement did not start from the centre of the screen on more than 50% of the trials).

**Stimuli, apparatus, procedure and design**

The method was exactly as in Experiment 1 except that after the first fixation cross the word “GO” or “NO” appeared instead of a colour word. Participants were instructed after seeing the word GO to press the space bar whenever the next object appeared and after the word NO to just view the object. As in Experiment 1, 50% of trials were action trials.

**Eye tracking**

The procedure and apparatus were identical to those used in Experiment 1.

**Results**

**Manual response data**

**Action task.** Accuracy on the action task was .989, ($SD = .010$) and participants were more accurate in the viewing ($M = .994$) than action trials ($M = .984$), $t(20) = 3.13$, $p = .005$, $d = .68$. Average response time was 242 ms ($SD = 44$).

**Search task.** Participants’ conjoined accuracy was .958 ($SD = .026$). A (2 (action) × 2 (validity) repeated measures ANOVA on reaction times for trials in which both the action and search task was correct revealed a main effect of action, $F(1, 20) = 12.65$, $p = .002$, $\eta^2_p = .39$, with faster responses after acting ($M = 602$) than viewing ($M = 619$) the prime. The reaction times are shown in Figure 5 (left panel). In addition, there was a main effect of validity, $F(1, 20) = 11.02$, $p = .003$, $\eta^2_p = .36$; participants found the target more quickly on valid ($M = 602$) than invalid ($M = 619$) trials. Importantly, the interaction between action and validity approached significance, $F(1, 20) = 3.97$, $p = .060$, $\eta^2_p = .17$, and mirrored the typical action effect pattern found in Experiment 1: following an action, participants were reliably 27 ms faster on valid than invalid trials, $t(20) = 3.52$, $p = .002$, $d = .77$. However, following the viewing trials, RTs did not differ based on validity, $t(20) = 1.04$, $p = .309$, $d = .23$ (6 ms validity effect). The same 2 × 2 analysis on search task accuracy for trials in which the action task was correct revealed neither a main effect of action or validity, nor did the factors interact, all $Fs < 1$.

**Eye movement data**

Trials in which (1) a saccade occurred within 100 ms of the search array’s appearance, (2) the first detected saccade began more than 5° from fixation, and (3) no error was made during the action task were considered as errors and removed from eye movement analysis (26.91% of trials).

**Saccade direction.** The (2 (action) × 2 (validity) ANOVA on the direction of the initial saccade revealed no main effect of action, $F < 1$, but a main effect of validity, $F(1, 20) = 4.63$, $p = .044$, $\eta^2_p = .19$, with a greater proportion of saccades directed to the target on valid than invalid trials ($M_{valid} = .552$, $M_{invalid} = .490$). Critically, as in Experiment 1, action and validity interacted to affect the direction of the first saccade, $F(1, 20) = 9.27$, $p = .006$, $\eta^2_p = .32$ (see Figure 5, right panel). As in Experiment 1, following an action participants were .140 more likely to look towards the target on valid than invalid trials, $t(20) = 4.24$, $p < .001$, $d = .93$. However, after only viewing the prime, the relation of the prime’s colour to the target did not affect first saccades (i.e., there was no validity effect), $t(20) = .38$, $p = .707$, $d = .08$.

**Target acquisition latency.** We again analysed the target landing latency with a (2 (action) × 2 (validity) ANOVA (Figure 6, left panel). The main effect of action was significant, $F(1, 20) = 4.20$, $p = .054$, $\eta^2_p = .17$, showing that the target landing latency was briefer following an action ($M = 346$) than viewing ($M = 359$). Also, a significant main effect of validity, $F(1, 20) = 8.55$, $p = .008$, $\eta^2_p = .30$, indicates that the first eye movement landed on the target sooner for valid ($M = 342$) than invalid ($M = 362$) trials. Again,
the interaction between action and validity was significant, $F(1, 20) = 10.91, p = .004, \eta^2_p = .35$. The validity effect was greater following an action (43 ms), $t(20) = 4.12, p < .001, d = .90$, than following viewing (−3 ms), $t(20) = .31, p = .759, d = .07$.

**Saccade numerosity.** Next, the average number of saccades made before landing on the search target was examined with a 2 (action) × 2 (validity) repeated-measures ANOVA (Figure 6, middle panel). There was no main effect of action, $F < 1$, but validity affected the number of saccades, $F(1,20) = 4.88, p = .039, \eta^2_p = .20$. Overall, participants made fewer saccades on valid (1.41) than invalid (1.47) trials. More importantly, a significant interaction was observed between action and validity, $F(1, 20) = 9.39, p = .006, \eta^2_p = .32$. Again, following an action, participants made 0.2 fewer saccades for valid than invalid trials, $t(20) = 3.83, p = .001, d = .84$. However, there was no difference in the number of saccades between

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**Figure 5.** Results from the search task in Experiment 2. The left panel shows key press RT to identify the target, revealing a typical action effect. The right panel shows the proportion of trials in which participants’ first saccade went to the target during the search. Replicating the results from Experiment 1, after an action the first saccade was much more likely to be directed to the target when it shared a colour with the acted on object (valid) than when that colour contained a distractor (invalid); after viewing the prime there was no effect of validity on eye movements. Error bars show 95% confidence intervals.

**Figure 6.** Results from the search task in Experiment 2. Left: the first time at which a saccade landed on the target. Middle: average number of saccadic eye movements made until the eye landed on the target. Right: average distance traversed by the eye prior to reaching the target. For each measure, the validity effect was greater following action than following viewing. Error bars show 95% confidence intervals.
valid and invalid trials after viewing, $t(20) = .84, p = .412, d = .18$.

**Scanning distance.** We also analysed the total distance traversed by the gaze movements prior to fixating the target, shown in Figure 6 (right panel). The analysis revealed no main effect of action, $F < 1$, but a main effect of validity, $F(1, 20) = 4.98, p = .004, \eta_p^2 = .34$, with shorter scanning distances on valid trials overall. Importantly, action and validity interacted, $F(1, 20) = 10.40, p = .004, \eta_p^2 = .34$, showing a reduction in scanning distance on the valid trials after an action ($t(20) = 4.65, p < .001, d = 1.01$), but no difference after viewing ($t(20) = .69, p = .499, d = .15$).

**Target fixation/decision time**
Lastly, we analysed the duration of the first fixation on the target for those trials on which the first fixation ended with the keypress response (86% of the total), shown in Figure 7. There were no main effects of action or validity, $F$s(1, 20) < 1. But action and validity interacted, $F(1, 20) = 6.5, p = .019, \eta_p^2 = .25$. While the overall trend was the same as in Experiment 1 – with relatively prolonged decision time on valid trials after an action, that comparison was marginal $t(20) = 1.98, p = .062, d = .43$. Decision time was significantly shorter for valid compared to invalid trials after viewing, $t(20) = 2.26, p = .035, d = .49$.

**Discussion**
During the action trials in the present experiment, participants made a completely arbitrary action in the presence of the prime without being required to evaluate any of its features. Nevertheless, the location of the prime’s colour in the visual search task affected key press reaction times (e.g., Weidler & Abrams, 2014) and eye movements. Even in the absence of colour word priming, prior action affected the direction of the first eye movement, the time and number of eye movements needed to reach the target, and the distance scanned prior to reaching the target: subjects were faster and more likely to look to the prime-coloured object first, but only after an action. Additionally, action had the marginal effect of increasing the duration of the decision time on the target if it matched the acted-on object, but when viewing, the decision time was briefer for valid targets. This suggests that some effects of action may be on processes occurring after attentional selection (see General discussion for more on this issue). Together with Experiment 1, this experiment provides strong evidence that a simple arbitrary action affects relatively early visual search processes, and possibly also later post-selection processes.

**General discussion**
The present study is the first to reveal that a simple arbitrary action can affect spontaneous eye movements in a visual search task. On every trial, participants saw an uninformative coloured object and then searched a display for a tilted line. On some trials, the target was embedded in the previously seen colour; on some trials, participants had made an earlier (and arbitrary) action towards the coloured object. The pattern of eye movements and manual responses in both experiments revealed that the action biased the subsequent search. In particular, after making an action, participants’ first eye movements were more likely to go to the previously seen colour, and they acquired a colour-matched target
sooner, and with fewer eye movements and less distance traversed by the eye, even though colour was irrelevant to the search. These findings show that the earlier action affected relatively early, pre-selection processes during the search. Additionally, when the target matched the acted upon colour, action tended to prolong the decision time spent fixating on the target, and it speeded manual response latencies.

Importantly, the present results are informative regarding the locus of action’s effect on perception. The first saccade was more likely to be directed to the prime colour following an action. Because the targets in the search task were far enough in the periphery to require an eye movement, these results suggest that action affected relatively early processes prior to attentional selection. This fits with recent findings that the action effect is eliminated in cases when attentional selection is not necessary – for example when a single target object is presented (Huffman & Pratt, 2017) or a pre-cue indicates the target’s location (Abrams & Weidler, 2017). The results are consistent with the suggestion that action biases the competition for selection amongst the elements in the search array (Huffman & Pratt, 2017). Given that the majority of existing data supporting the action effect has come from manual response time data (e.g., Buttaccio & Hahn, 2011; Huffman & Pratt, 2017; Weidler & Abrams, 2014, 2017a, 2017b), it was previously not possible to determine whether action’s effects occur before or after attentional selection.

Furthermore, having made an earlier action tended to prolong the duration of fixation on the target prior to response when the target matched the prime colour. That result seems more consistent with an effect of action after attentional selection has already taken place. Thus, if that conclusion is correct, action has effects both before and after selection: it biases the competition for attention amongst the elements in the display in favour of the acted upon colour and, once selection occurs, detailed evaluation of the item may be enhanced by prolonging the time spent evaluating the item when it matches the prime colour. (A similar prolonged inspection has also been observed for objects that are in close proximity to the hands and thus candidates for action; e.g., Abrams, Davoli, Du, Knapp, & Paull, 2008.) But this latter conclusion must be made cautiously because the conditions under which decision time was prolonged were precisely those in which the target was acquired most quickly. In particular, after an action, participants’ gaze arrived at the target sooner when it matched the prime colour than when it didn’t. Decision times were prolonged under those same conditions. Thus, it is possible that the lengthened decision time was merely a by-product of the early target acquisition time, and does not reflect an alteration of search processes per se. This seems possible because the action effect paradigm shares some features in common with dual task paradigms in which participants are also required to perform two tasks in close temporal proximity. A typical finding in such situations is that there is a cost associated with performing the second task, and the closer in time the two tasks must be performed, the greater the cost (e.g., Welford, 1952). Thus, responses in the visual search task that are closer in time to the action response may be delayed somewhat, and that may be what is causing the lengthened decision times that we observed.

It is worth pointing out that despite the elongation of decision times when the target colour matched the prime after an action, that elongation was less than the reduction of target acquisition latencies – thus, manual response latencies were faster after an action when the target matched the prime – the typical action effect result.

Additionally, it is worth noting that our search task was a relatively easy one – requiring on average less than two eye movements in order to acquire the target. It might be fruitful in the future to examine more difficult searches that require greater numbers of eye movements. Such searches might provide an even greater opportunity to observe the effects of action. Nevertheless, it is noteworthy that even in a relatively easy and fast search, the eye movement patterns clearly revealed an effect of the earlier action.

One prior study did examine eye movements in an action effect paradigm. Wang et al. (2017) found, as we did here, that participants looked more quickly to the target sharing previously seen features after an action than after viewing. However, a number of features of the Wang et al. study prevent extrapolation of their results to the issues being considered here. In particular, the Wang et al. study required eye movements as the imperative response because their goal was specifically to eliminate speeded manual responses from the search task. Thus, their
participants were instructed to produce an initial saccade directly to the target, whereas in the present study the eye movements observed were spontaneous movements that supported the search. Importantly, the targets in the Wang et al. study were closer to fixation (6.4° vs. 12°), thicker (.24° vs .12°), and more salient (tilted 20° vs. 4°) than those used here. Additionally, Wang et al. included three vertical-line distractors in their search displays, compared to one distractor used here, further enhancing the distinctiveness of their targets. As a result, participants were able to identify the target in the Wang et al. study prior to any eye movements on the majority of trials – and then they could simply execute an eye movement as a response, whereas in the present study, eye movements were more likely to be needed in order to find the target. As a result, the eye movements in the present study are well suited to making inferences about the underlying search processes while those in the Wang et al. study are less so (but the eye movements in the earlier study did succeed in removing speeded manual responses from the task, and thus they fulfilled their intended goal).

Additionally, Experiment 2 is the first to investigate if prior action can influence eye movements when action is not confounded with double priming of the colour. More specifically, Experiment 2 eliminated semantic priming of the prime colour as a possible explanation for the findings by using the words GO and NO to indicate whether participants should or should not make an action to the prime. Experiment 1, as well as the experiments of Wang et al. (2017) and others (Huffman & Pratt, 2017), asked participants to make an action when a colour word cue matched the physical colour of the prime. Hence, on action trials participants might have been influenced by the colour word cue in addition to the action produced in response to the cue. With the words GO and NO used in Experiment 2, no such priming was possible.

Our findings of relatively early effects of action on search processes fits with recent findings that action can also influence search performance in a pop-out search (i.e., when the target is a salient singleton; Weidler & Abrams, 2017b). The fact that we found both early and late effects of action also bears on the relation between the action effect and a similar phenomenon: PoP. As noted earlier, some researchers (e.g., Huang et al., 2004) have argued that the benefit of finding targets that share features with previous targets (i.e., the hallmark finding of PoP that mirrors the action effect) arises from processes occurring after the target is selected. Nevertheless, other researchers have argued that PoP stems from pre-selection processes (i.e., facilitated attentional shifts to the target; e.g., Maljkovic & Nakayama, 1994). Indeed, as reported here, action may affect both pre-selection and post-selection processes. Ultimately, understanding the relation between PoP and the action effect will require more research on both phenomena.

Our results are also broadly consistent with the influence of “selection history” in guiding attention, as described by Awh, Belopolsky, and Theeuwes (2012). According to that model, attentional selection is not merely the product of bottom-up influences such as stimulus salience and top-down influences such as one’s current goals. Instead, the recent history of previous attentional deployments, such as what visual attributes were selected or whether earlier selections did or did not lead to a reward, may have persisting effects on subsequent attentional selection. In the present situation, the action made toward the prime may constitute “selection” of the prime. Since the prime-coloured targets were no more salient than the distractors (because all possible colours served as both targets and distractors), and since colour was both irrelevant to and uninformative in the search task, the influence of the earlier action might reasonably be regarded as an influence of selection history. This characterization suggests that action exerts its influence by augmenting attentional processing of the prime – a suggestion that remains to be tested.

The present results fit well with previous findings that have revealed connections between manual action and eye movements. For example, it is known that people will spontaneously look to the target of an aimed movement around the time of movement onset, enhancing information about the location of the target and also improving possible visual feedback (Abrams, Meyer, & Kornblum, 1990). It has also been shown that people are more likely to look to distractors that share perceptual features with the desired target (e.g., Bekkering & Neggers, 2002). The present results extend these earlier findings by showing that people are also more likely to look to objects that share features of previously acted upon objects.
It is still an open question as to why a prior irrelevant action affects vision in an unrelated task. Some insight into the phenomenon may come from research on affective responses to action. A growing literature has revealed that actions that are made (e.g., Cacioppo, Priester, & Bernston, 1993), imagined (e.g., Beilock & Holt, 2007), or observed (e.g., Hayes, Paul, Beuger, & Tipper, 2008) can affect emotional responses to the acted-on object. In a similar way, the action effect shows that merely acting toward an object can also affect responses to the object later—by capturing eye movements and biasing visual search. Given the connection between emotional stimuli and low-level visual mechanisms (e.g., Bocanegra & Zeelenberg, 2009), it seems possible that the influence of action on vision revealed here may rely on some of the same mechanisms, although more work is certainly needed to confirm the possibility.

Finally, the present results fit broadly with the growing literature indicating the importance of action for perception. It has been shown that preparing to make an action (e.g., Fagioli et al., 2007), being in a position to make an action (e.g., Abrams et al., 2008), or changing the ability to interact with the environment (e.g., Witt et al., 2005) can all affect perception. As shown here, the objects of a previous action are also important—so important that they appear to bias early mechanisms of selective attention.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**References**


