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## Action selection as a guide for visual attention

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### ABSTRACT

We plan our actions in order to fulfil certain sensory goals. It is generally believed, therefore, that anticipation of sensory action-outcomes plays an essential role in action selection. In this study, we examined the role of action selection, prior to action execution, in the guidance of visual attention. The experiments began with an initial acquisition phase, in which participants learned to associate two actions (left/right keypress) with two visual outcomes (red/green colour). Next, participants performed in a test phase, in which they continued to select and perform the same actions while their attentional bias was measured for items that resembled the anticipated action-outcome. The findings indicate that learned action-outcome association contributes to the guidance of attention. This guidance, furthermore, was short-lived and disappeared with larger delays between action selection and execution. The findings help situate processes of visual attention in a context that includes action selection and action-outcome associative learning.

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### KEYWORDS

Visual attention; associative learning; ideomotor theory

Visual attention is guided by multiple factors, including display structure (e.g., Kimchi, Yeshurun, & Cohen-Savranski, 2007; Pomerantz & Portillo, 2011; Theeuwes, 1991, 1992), abrupt changes in the display (e.g., von Mühlhausen, Rempel, & Enns, 2005; Yantis & Johnson, 1990), observer's goals (e.g., Folk, Remington, & Johnston, 1992; Wykowska, Schubö, & Hommel, 2009), observer's prior experience (e.g., Awh, Belopolsky, & Theeuwes, 2012), and other concurrent tasks (e.g., Buttaccio & Hahn, 2011; Olivers, 2009). A common feature of studies of visual attention is that they often disregard the role of participants' own actions and, consequently, the action's sensory consequences, although these have been shown to be important determinants of behavioural efficiency (e.g., Herwig & Waszak, 2009; Hommel, 1996; Huestegge & Kreutzfeldt, 2012; Kunde, 2001). In most real-life situations, humans encounter visual stimuli as agents when actively controlling their own movements (e.g., Noë, 2004; O'Regan & Noë, 2001). Indeed, a substantial portion of our sensory input is caused by our own movements and, therefore, it is important for the visual system to discriminate self-caused and externally-caused events (e.g., Gibson, 1966). To examine the active role of observers, recent studies have begun to examine whether and how visual attention treats a stimulus differently

when it is caused by the observer's own movement, compared to when it is passively viewed (e.g., Gozli, Aslam, & Pratt, 2016; Kumar, Manjaly, & Sunny, 2015). In the present study, we examine the potential role of action selection in guiding visual attention. Particularly, we are interested in the time window after selection of an action and before executing the action.

Performing an action changes our sensory state and, therefore, preparing for an action involves anticipating such a change (e.g., Hommel, 2013). Pressing a key on the keyboard, for instance, can result in tactile and auditory outcomes, as well as the visual appearance of an alphanumeric character on the screen. After learning that a sensory outcome consistently follows an action, the outcome is thought to become an integral part of the action. Research on action control has supported this idea, by demonstrating that perceiving a stimulus that resembles an action-outcome facilitates selection of the corresponding action (e.g., Elsner & Hommel, 2001; Gozli, Goodhew, Moskowitz, & Pratt, 2013; Hommel, 1996; Huestegge & Kreutzfeldt, 2012; Ziessler & Nattkemper, 2002, 2011; Ziessler, Nattkemper, & Frensch, 2004). For instance, if participants learn that a keypress is consistently followed by the appearance of a red item (visual response-outcome), a new association can form between the keypress and the outcome. This

association is thought to be bidirectional, in the sense that encountering a red item can now bias participants toward pressing the associated key. This has been found both when participants freely choose their responses (e.g., after seeing a stimulus that resembles the learned outcome; Elsner & Hommel, 2001), and when they select responses based on a different stimulus (e.g., when the outcome-similar item appears as an irrelevant distractor; Gozli, Huffman, & Pratt, in press). Thus, selecting an action is thought to involve anticipating the action's known sensory outcomes (e.g., Hommel, 2013; Shin, Proctor, & Capaldi, 2010).

Complementary to research on action control, the question for visual attention researchers is whether action-driven anticipation impacts selection among available visual items. A reasonable prediction would be that selecting an action should activate the sensory action-outcome, and thus bias visual attention toward stimuli that resemble the anticipated outcome. In the present study, we test this prediction in a setting where participants prepare a response and then encounter two stimuli, one of which is compatible with the anticipated outcome and the other is incompatible. Presenting both stimuli enables us to examine selective advantages for stimuli as a function of their compatibility with the known outcome of the selected action.

Several previous studies are directly relevant for our purpose. In the study by Ziessler and Nattkemper (2011), participants learned to associate a set of keypress responses with a set of visual outcomes. After learning the response-outcome associations, participants performed a modified flanker task, in which a visual target was presented with two irrelevant flankers. On some trials, the flankers matched the learned outcome of the correct response (compatible flankers). On other trials, the flankers matched the outcome of an incorrect response (incompatible flankers). Responses were faster with compatible flankers compared to incompatible flankers, particularly when the flankers were presented after or simultaneously with the target (Experiments 1 and 2). When flanker exposure was limited with visual masks, the effect was further confined to flankers that appeared after the target (Experiment 3). The findings suggest that participants' sensitivity to

action outcomes is increased once response selection processes are set in motion. In a very similar design, Nikolaev, Ziessler, Dimova, and van Leeuwen (2008) measured event-related potentials (ERP) to the outcome-compatible and outcome-incompatible flankers, and found larger visual P1 responses for compatible flankers, compared to incompatible flankers. Consistent with Ziessler and Nattkemper (2011), the P1 modulation was observed only when flankers appeared after the targets, suggesting that sensitivity to visual outcome increases after participants initiate response selection.<sup>1</sup> Thus, selecting an action makes the visual system sensitive to stimuli that resemble the action's known outcome.

Another study of visual sensitivity as a function of action selection was recently reported by Desantis, Roussel, and Waszak (2014). In this study, participants first learned that pressing one of two keys (voluntarily chosen) would transform a random dot kinematogram (RDK) into a coherent upward or downward motion. Participants then performed in a test phase, in which they were asked to carefully time their responses, such that each keypress occurred roughly 1100 ms after the go-signal (correct responses were counted as those within the 900–1300 ms window. Motion stimuli were presented at various times before or after each keypress, and participants were asked to report the direction of motion direction. Results showed that, within a span that began 280 ms before and ended 220 ms after response execution, participants were more sensitive to the motion direction that was compatible with their keypress. If we assume that participants began selection of their response after the go-signal—that is, ~1100 ms before execution—then the findings of Desantis et al. suggest that action execution, more than action selection, causes a visual bias in favour of the action's known outcome, although the authors did not aim to disentangle execution and selection of actions.

In the present study, we ask whether action selection, prior to execution, can influence visual attention. This question can be addressed by experimentally separating action selection and action execution. For instance, Ziessler, Nattkemper, and Vogt (2012) used two different stimuli to initiate selection and execution. The first, imperative, stimulus indicated

<sup>1</sup>Increased visual P1 has also been reported for a stimulus that is self-caused, compared to an identical stimulus that is passively viewed (Hughes & Waszak, 2011).

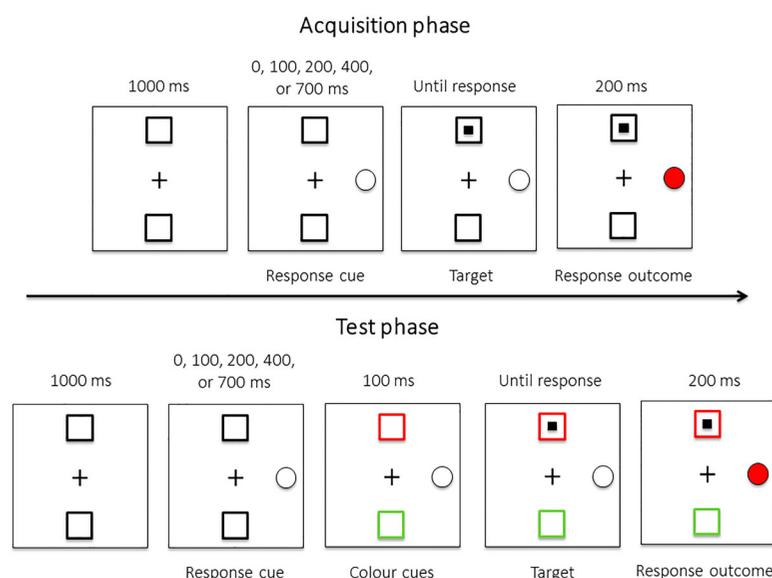
the correct response (which key to select) and the other serving as a “go signal” (when to press the selected key). By introducing a temporal gap between the two stimuli, the authors found faster performance when the go-signal was compatible with the selected action, and that this compatibility effect did not interact with the delay between the two stimuli. The compatibility effect reported by Ziessler et al. (2012) could be described either as faster visual processing of the action-compatible visual stimuli or as faster execution of the compatible action. In the present study, we aimed to separate selection and execution of actions, in a manner similar to Ziessler et al., while also isolating the contribution of visual attention.

Aside from the aforementioned studies, a related area of research—which does not directly fall within the scope of the present study—is centred around the question of how perceptual processes differ for a self-caused event, compared to a passively received event (e.g., Cardoso-Leite, Mamassian, Schütz-Bosbach, & Waszak, 2010; Gozli et al., 2016; Roussel, Hughes, & Waszak, 2013, 2014; for reviews, see Hughes, Desantis, & Waszak, 2013; Waszak, Cardoso-Leite, & Hughes, 2012). These studies examine perceptual processes immediately *after* action execution, and the common finding is described as *sensory attenuation* (i.e., weaker physiological and behavioural responsiveness to a self-caused sensory event, compared to a passively received event). The present

study is designed to examine visual attention *before* the execution of a planned action and, as such, we are concerned with a time-window that precedes what is commonly regarded as sensory attenuation.

The present experiment began with an acquisition phase, in which participants learned to associate two keypress actions, respectively, with red and green action-outcomes. To test the influence of response selection on visual attention, we implemented a two-choice task in which a response is selected based on a response cue, and is then executed based on a detection target (i.e., go signal). The go signal could appear inside one of two placeholders. This design was based on previous studies on the role of visuospatial attention in detection performance (e.g., Posner, 1980). After the presentation of the response cue and prior to the presentation of the go-signal, the colour of both placeholders changed (Figure 1). One of the placeholders changed to the colour that is compatible with the outcome of the selected action, while the other placeholder changed to the incompatible colour. If selection of an action results in a bias in favour of the visual action-outcome, then the action-compatible colour should be selected faster than the action-incompatible location.

An important factor in this design is the delay between response selection and response execution. While Ziessler et al. (2012) found no interaction between this delay and their



**Figure 1.** Sequence of events on a sample trial of the acquisition phase (top row) and a sample trial of the test phase (bottom row).

compatibility effect, they employed a small range of delays (0–200 ms for their two-choice task; 0–450 ms for their four-choice task). Presumably, at large delays the task should turn into a one-choice (i.e., go/no-go) task, but the large response times at the longest delays in Ziessler et al.'s (2012) study (~ 470 and 650 ms, respectively, for the two- and four-choice tasks) suggest that response selection might have still been on-going when the go-signal was presented. In the present study, we employed a wider range of delays. We predicted that if activation of the visual action-outcome is integral to action selection, then visual bias for the action-compatible colour should be larger soon after the presentation of the response cue (while action-selection is still ongoing), and it should be smaller or absent with longer delays after the presentation of the response cue.

To ensure replicability of our results, we conducted two experiments that were identical, with one exception. In the acquisition phase of Experiment 1, each response cue was associated with the keypress action at the corresponding location (left cue → left key; direct stimulus-response [S-R] mapping), whereas in the acquisition phase of Experiment 2, each response cue was associated with the keypress at the opposite location (left cue → right key; inverse S-R mapping). Direct S-R mapping was used in the test phase of both experiments. The purpose of including an inverse S-R mapping in one of the acquisitions was to control for associative learning between response cues and the visual outcomes. That is to say, keeping constant the mapping between response cues, responding keys, and the response outcomes would not allow us to disentangle what exactly, if anything, causes the activation of the visual outcome. Thus, by varying the mapping between the response cues and responding keys, while maintaining the mapping between responding keys and outcomes, across the acquisition phase and test phase, we can more confidently assert that preparing the keypress response (and not observing the response cue) is the cause of activating the internal representation of visual outcomes. Indeed, the pattern of findings did not differ across the two experiments, suggesting that response-outcome associative learning was the primary source of the compatibility effect.

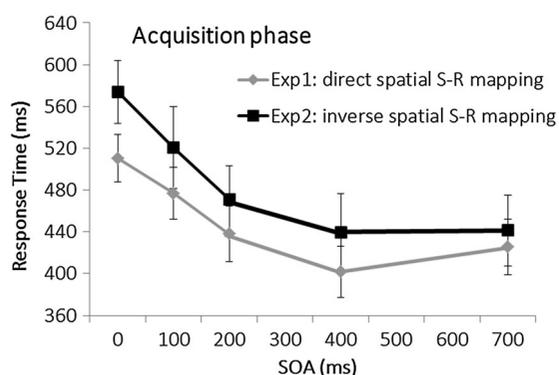
## Method

### Participants

Fifty-two students at University of Vienna participated in this study (26 in each experiment) in exchange for course credit or monetary compensation (5 Euros / 30 minutes). They all reported normal or corrected-to-normal vision, and were unaware of the purpose of the study. Prior to the experiments, informed consent was obtained from all participants.

### Procedure: acquisition phase

Each trial of the acquisition phase began with the presentation of the fixation cross and the two target placeholders (Figure 1). After 1 s, a response cue appeared at the left or right side of fixation, indicating the correct response on that trial. Experiments 1 and 2 differed only with respect to their acquisition phase. In Experiment 1, we used direct spatial S-R mapping. That is, participants in Experiment 1 were instructed to prepare the left and right keys, respectively, upon seeing the left and right response cues. By contrast, an inverse spatial mapping was used in Experiment 2, and participants were instructed to prepare the spatially non-corresponding key, namely the left key for the right response cue, and the right key for the left response cue. Following the response cue, after a stimulus-onset asynchrony (SOA) of 0, 100, 200, 400, or 700 ms, a target appeared inside one of two target placeholders above or below fixation. We instructed participants to press the prepared key as soon as they detected the target, regardless of the target location. Furthermore, on 20% of trials no target was presented after a response cue (catch trials), and participants were instructed to withhold responses on these trials. As soon as a keypress was recorded, the colour outcome corresponding to the performed keypress appeared inside the response cue and remained for 200 ms. The colour of the outcome was determined by the actual response regardless of its correctness. In both experiments, green and red were outcomes of left and right keypress responses, respectively. Just like the response cue, the response-outcomes in Experiment 2 also appeared at the opposite location to the response. An error feedback appeared at the end of the trial if participants made an anticipatory response, defined



**Figure 2.** Response time (RT) data from the acquisition phase of Experiments 1 and 2, graphed as the function of the spatial mapping between the response cue (which is also the response-outcome location) and the response key and the SOA between the onset of the response cue and that of the target. Error bars represent 95% between-subjects confidence intervals.

as response times shorter than 100 ms (“TOO QUICK”), or if they responded with an incorrect key (“MISTAKE!”). The error feedback would remain on display for 2 s.

### Procedure: test phase

Similar to the acquisition phase, every test trial began with the presentation of the fixation cross and the two placeholders (Figure 1). After 1 s, a response cue appeared at the left or right side of fixation, indicating the correct response on that trial. For the test phase, we used direct spatial S-R mappings in both experiments. That is, participants were instructed to prepare the left and right keys, respectively, when they saw the left and right response cues. Following the response cue with an SOA of 0, 100, 200, 400, or 700 ms, the two target placeholders changed colour, one of them turning red and the other turning green. The assignment of colour to placeholders was randomized (e.g., the upper placeholder turned red and green with equal frequency), and both colours and locations were equally likely to contain the target. The target appeared 100 ms after placeholders changed colours, except for catch trials in which no target was presented. When a keypress was recorded, the colour outcome corresponding to the performed keypress appeared inside the response cue and remained for 200 ms. Although the locations associated with each colour outcome were reversed across the two phases of Experiment 2, response-colour mapping did not change across the two phases of

the experiment (e.g., the left key continued to produce green). Similar to the acquisition phase, participants received error feedback after anticipatory or incorrect responses.

### Stimuli

The display structure and the sequence of events are shown in Figure 1. Except for the colour cues and response-outcomes, all stimuli were presented in white against a black background. Target placeholders were two squares ( $1.4^\circ \times 1.4^\circ$ ; frame width =  $0.1^\circ$ ) positioned along the vertical midline. The centre of these placeholders deviated by  $3.4^\circ$  of visual angle from the display centre. A response cue was a circle (radius =  $0.7^\circ$ ; frame width =  $0.05^\circ$ ; centre of circle deviating by  $3.4^\circ$  from display centre) that could appear at the left or right side of fixation. Each response-outcome was a colour patch (red or green) that filled the response cue. The target was a white square ( $0.3 \times 0.3$ ) that appeared at the centre of a target placeholder. Responses were performed using the index fingers of each hand by pressing the “C” and “M” buttons on the keyboard which, respectively, corresponded to left and right keypress actions.

### Design

Each participant performed 200 trials in the acquisition phase and 400 trials in the test phase. In both phases, 20% of trials are catch trials. In the test phase, the target was equally likely to appear inside the placeholder with the action-compatible colour or the action-incompatible colour. All experimental variables, including target location (above vs. below), response cue (left vs. right), and SOA were randomized within each experiment and had equiprobable values. Experiment 2 was conducted after Experiment 1, to eliminate the consistency between response cue and colours as a potential confound, and in an attempt to replicate the pattern found in Experiment 1.

## Results

### Acquisition

Before calculating mean response times (RT), we excluded errors (3.2% of trials) and RTs that fell 2.5 SD beyond the mean (2.8% of trials). Mean RT data

from the acquisition phase were submitted to a  $5 \times 2$  mixed analysis of variance (ANOVA), with the SOA between response cue and target (0, 100, 200, 400, or 700 ms) as the within-subject factor and spatial cue-key mapping (Experiment 1: direct vs. Experiment 2: inverse) as the between-subjects factor (Figure 2). This analysis revealed a main effect of SOA,  $F(4, 192) = 181.97, p < .001, \eta_p^2 = .79$ , a main effect of cue-key spatial mapping,  $F(1, 48) = 4.05, p < .05, \eta_p^2 = .08$ , and a two-way interaction,  $F(4, 192) = 5.12, p < .01, \eta_p^2 = .10$ . The main effect of SOA reflects faster responses when participants had more time to prepare execution of the correct response. The main effect of spatial mapping reflects faster responses with direct mapping ( $M \pm SE = 450 \pm 12$  ms) compared to inverse mapping ( $489 \pm 17$  ms). Separate paired-samples *t*-tests found the advantage of direct spatial mapping to be reliable at SOA = 0 ms,  $t(50) = 3.31, p < .01$ , but not statistically reliable at larger SOAs, all non-significant,  $t_s < 1.85, p_s > .07$ .

Percentages of errors (PEs) were submitted to the same ANOVA, which revealed no main effect of SOA, a main effect of spatial S-R mapping,  $F(1, 50) = 4.52, p < .001, \eta_p^2 = .23$ , and a two-way interaction,  $F(4, 192) = 3.42, p < .05, \eta_p^2 = .06$ . Consistent with the RT results, errors were lower with direct spatial mapping ( $2.1\% \pm .2\%$ ) compared to inverse mapping ( $4.4\% \pm .6\%$ ). This advantage was statistically reliable with SOAs = 0 and 100 ms, respectively,  $t(50) = 2.96$  and  $5.10, p_s < .01$ , but not with larger SOAs, all non-significant  $t_s < 1.52$ , all  $p_s > .13$ . Finally, PE on catch trials were low ( $3.4\% \pm .6\%$ ), and did not differ across the two experiments,  $t(50) = 0.46, p = .65$ .

### Test phase

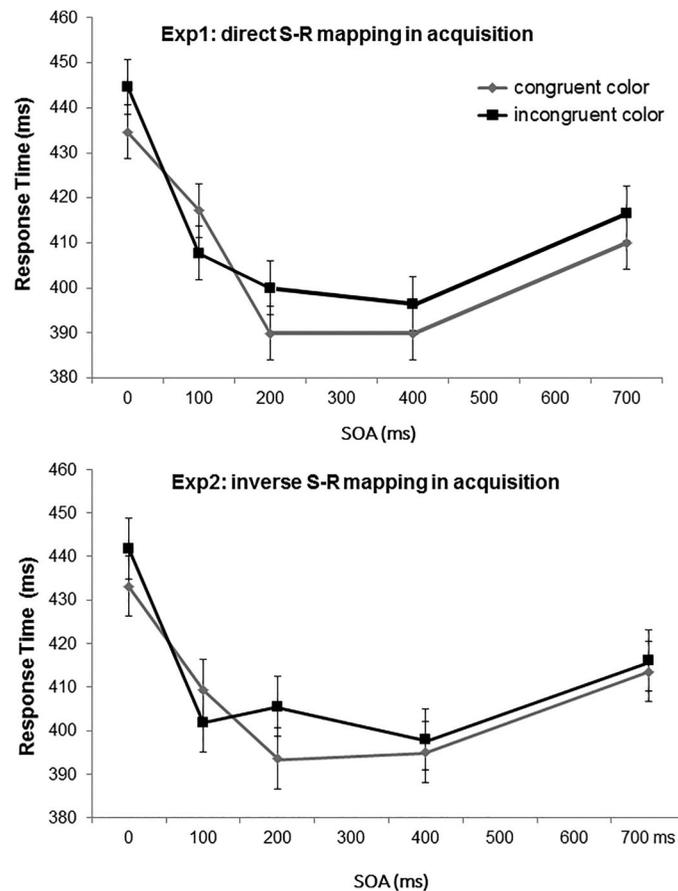
Before calculating mean response times (RT), we excluded errors (2.1% of trials) and RTs that fell 2.5 SD beyond the mean (3.0% of trials). Mean RT data were submitted to a  $5 \times 2 \times 2$  mixed ANOVA, with SOA (0, 100, 200, 400, or 700 ms) and target location Compatibility (compatible vs. incompatible colour) as the within-subject factors and Acquisition Type (Experiment 1: direct spatial S-R mapping vs. Experiment 2: inverse S-R mapping) as the between-subjects factor (Figure 3). This analysis revealed a main effect of SOA,  $F(4, 200) = 85.49, p < .001, \eta_p^2 = .63$ , a main effect of Compatibility,  $F(1, 50) = 9.12, p < .01, \eta_p^2 = .15$ , and a two-way interaction between SOA

and Compatibility,  $F(4, 200) = 5.50, p < .001, \eta_p^2 = .10$ . The main effect of Acquisition Type,  $F(4, 50) < .001, p > .90, \eta_p^2 < .001$ , the SOA  $\times$  Acquisition Type,  $F(4, 200) = 1.49, p = .21, \eta_p^2 = .03$ , Compatibility  $\times$  Acquisition Type,  $F(1, 50) = 0.10, p = .75, \eta_p^2 = .002$ , and three-way interaction,  $F(4, 200) = 0.21, p = .93, \eta_p^2 = .004$ , were not statistically significant. The main effect of Compatibility indicates overall faster responses on trials when the target appears inside the action-compatible colour ( $409 \pm 8$  ms), compared to the action-incompatible colour ( $413 \pm 8$  ms). The benefit of action-compatible colour, however, was reliable only at SOAs of 0 ms,  $t(51) = 2.52, p = .015$ , and 200 ms,  $t(51) = 3.01, p < .01$ , while it was not statistically significant at longer SOAs of 400 ms,  $t(51) = 1.37, p = .18$ , and 700 ms,  $t(51) = 1.70, p = .10$ . At SOA = 100 ms, there was a significant disadvantage for the action-compatible colour,  $t(51) = 3.01, p = .015$ . Finally, and less relevant for our purpose, is the main effect of SOA that indicates faster responses with more preparation time, except for the rise in RT at 700 ms, which could indicate a tendency to regard late target onset as a catch trial.

Percentages of errors (PEs) on non-catch trials were submitted to the same ANOVA, which revealed only a main effect of SOA,  $F(4, 192) = 3.89, p < .01, \eta_p^2 = .072$ , and a main effect of Compatibility,  $F(1, 50) = 7.95, p < .01, \eta_p^2 = .14$ . The main effect of SOA was driven by the reliably higher PEs at SOA = 200 ms ( $2.2\% \pm .2\%$ ), compared to SOA = 100 ms ( $1.2\% \pm .2\%$ ,  $t[51] = 2.73, p < .01$ ), 400 ms ( $1.3\% \pm .2\%$ ,  $t[51] = 2.95, p < .01$ ), and 700 ms ( $1.3\% \pm .3\%$ ,  $t[51] = 2.86, p < .01$ ). Otherwise, PEs did not differ as a function of SOA. The main effect of Compatibility further supports the influence of the learned associations between responses and colours, with higher errors when the target appeared inside the incompatible colour ( $1.8\% \pm .2\%$ ) compared to the compatible colour ( $1.3\% \pm .2\%$ ). This finding could reflect the effect of visually selected colour on response activation, presumably selecting the incompatible colour would activate its associated, incorrect response (Elsner & Hommel, 2001; Gozli et al., *in press*). Finally, PEs on catch trials were low ( $2.1\% \pm .4\%$ ) and did not differ across the two experiments,  $t(50) = 0.86, p = .39$ .

### Discussion

In the present study we asked whether response selection, prior to execution, would induce a visual bias in



**Figure 3.** Response time (RT) data from the test phase of Experiments 1 and 2, graphed as a function of the compatibility (target location being at the compatible vs. incompatible colour in relation to the learned action-outcome colour) and the SOA between the onset of the response cue and that of the target. The top graph represents data from Experiment 1 (direct S-R spatial mapping in the acquisition phase), and the bottom graph represents data from Experiment 2 (indirect S-R spatial mapping in the acquisition phase). The test phases of the two experiments were identical. Error bars represent 95% within-subjects confidence intervals.

favour of the action's learned visual outcomes. In an initial acquisition phase, participants learned to associate left and right keypresses with green versus red colour outcomes. The test phase from two experiments revealed that response selection can modulate visual selection of these colours. Specifically, immediately after the onset of the response cue (SOA = 0 ms) and 200 ms after the onset of the response cue, participants showed a bias to select the colour that was associated with their correct response. That is, responses were faster when the go-signal appeared inside the placeholder of the compatible colour, compared to when the go-signal appeared inside the placeholder of the incompatible colour.<sup>2</sup> At SOA = 100 ms this pattern was

reversed and, moreover, no bias was observed at later SOAs of 400 and 700 ms. These findings suggest, first, that even prior to response execution, the process of response selection can induce a visual bias to attend to colours that is driven by the learned response-outcome associations. Second, the modulated visual bias appeared only at earlier phases of response selection, consistent with the idea that the internal response to the learned visual outcome is activated as a result of response selection. With enough time after response selection, response uncertainty is reduced to a point where observers are no longer susceptible to external, irrelevant sources of information that could help discriminate the required correct from the incorrect response.

<sup>2</sup>One might ask how the compatible and incompatible colours would be treated differently compared to a "neutral" colour. Unfortunately, a neutral condition is difficult to implement in such a design (see Gozli et al., 2014). If we define a neutral condition as no change in colour at all, then the alerting effect that comes with the colours is also removed. Note, in particular, the longer RTs in the acquisition phase (no change of placeholder colour) compared to the test phase that supports this possibility. If, on the other hand, we introduce a third colour, for the neutral trials, that colour might be more salient due to its rarity of occurrence. Given that our crucial comparison was between action-compatible and action-incompatible colours, presenting both colours at the same time seemed to be the best strategy

It should be noted that Experiment 2 served two important purposes. First, it replicated the findings of Experiment 1. Second, it helped rule out an explanation in terms of perceptual associative learning between response cues (location of circular) and outcomes (colours), because the mapping between cues and outcomes switched across the two phases of Experiment 2. Despite the inconsistency between cue-outcome mappings in Experiment 2, we found the same pattern of findings as Experiment 1. The similarity supports the role of consistent mapping between keypress responses and colour outcomes in observing the visual bias for colours. Further evidence for the unique role of response-outcome associative learning comes from another recent study, in which inconsistent response-outcome mapping, despite consistent stimulus-outcome mapping, eliminated the traces of associative learning (Gozli et al., *in press*, Experiment 3).

The general notion that action selection involves anticipation of sensory outcomes has received strong empirical support, primarily from studies on action selection and execution (for reviews, see Hommel & Elsner, 2009; Shin et al., 2010). For instance, Kunde (2001) reported that selecting one of four keys was faster when each key generated a visual stimulus at a spatially corresponding location (e.g., far-left key generating a visual onset at the far-left placeholder, etc.) compared to when the keys generate spatially non-corresponding visual outcomes (see also, Ansorge, 2002; Elsner & Hommel, 2001, 2004; Gozli et al., 2013; Hommel, 1993, 2004; Pfister, Janczyk, Gressmann, Fournier, & Kunde, 2014; Pfister, Kiesel, & Hoffmann, 2011; Pfister, Kiesel, & Melcher, 2010; Pfister, Pfeuffer, & Kunde, 2014).

Similarly, Koch and Kunde (2002) found faster verbal colour-naming responses (e.g., “blue”) when the response generated the same colour, compared to when it generated an incompatible colour. In addition, Kunde, Koch, and Hoffmann (2004) found faster responses when the intensity of the response was compatible with the intensity of the sensory outcome. Therefore, response selection is facilitated when the anticipated sensory outcomes are compatible with the to-be-performed responses, which strongly supports the notion that outcome anticipation has an essential role in action selection. The complementary question, for attention researchers, is how selection of features and objects is guided by the action system.

Recent studies have begun asking how actions that are associated with a sensory outcome impact attention to that outcome, compared to the more commonly employed condition in which participants passively view visual events. Kumar et al. (2015, Experiment 1) used a visual search task with two separate conditions. In the “action condition” participants pressed a key to unmask the search items. In addition to revealing the search items, the keypress also caused the appearance of a feature singleton (e.g., one red item among homogeneously grey items). By contrast, in the “no-action condition” participants simply waited until the search items and the singleton appeared on the display. The authors argued that the singletons in the action condition were regarded as self-caused by the visual system, while in the no-action conditions they were regarded as externally caused. The results showed an increased attentional benefit for the singleton in the action condition. The authors explained their findings by reference to action-driven sensory preactivation (Hughes et al., 2013; Roussel et al., 2013; Waszak et al., 2012), arguing that performing the action activated the representation of the visual singleton prior to seeing the display. As a consequence of this internal preactivation, the singleton was selected faster in the action condition. Consistent with the role of learned action-outcome associations, no difference between the action condition and a no-action condition was found when actions inconsistently (50% of trials) resulted in feature singletons (Kumar et al., 2015, Experiment 2).

The attentional advantage for the self-caused features over passively viewed features reported by Kumar et al. (2015) appears, at first glance, inconsistent with findings of reduced sensitivity and weaker neural responses to self-caused perceptual events (e.g., BäB, Widmann, Roye, Schröger, & Jacobsen, 2009; Blakemore, Wolpert, & Frith, 1998; Bompas & O’Regan, 2006a, 2006b; Cardoso-Leite et al., 2010; Kimura & Takeda, 2014; Roussel et al., 2013, 2014). One empirical demonstration of reduced sensitivity to learned action outcomes was reported by Cardoso-Leite et al. (2010), who measured visual detection sensitivity ( $d'$ ) for near-threshold events that were compatible or incompatible with the learned action outcome. The reduced sensitivity for action outcomes could, in principle, be reconciled with the attentional advantage (Kumar et al., 2015), based on an account proposed by Waszak et al.

(2012; see also Hughes et al., 2013; Roussel et al., 2013). According to this account, an action preactivates the internal representation of the sensory action-outcome, prior to encountering the actual stimulus. This preactivation, on the one hand, reduces the relative contribution of the external stimulus to the total activation of the feature representation, which explains the reduced sensitivity (cf., Miall & Wolpert, 1996). On the other hand, preactivation gives the representation a temporal head-start, which could explain why a sensory action-outcome, compared to an externally caused stimulus, is perceived closer in time to the action (e.g., Haggard, Clark, & Kalogeras, 2002).

The faster selection of the action-outcome, therefore, could be explained with the same logic that explains reduced sensitivity to the action-outcome. To examine whether reduced sensitivity and faster selection of action outcomes could be observed in the same experimental setup, Gozli et al. (2016) compared the impact of learned action-outcomes that were either (a) always at the target location (“valid” condition) or (b) singletons that were always at a distractor location (“invalid” condition). Both conditions began with the same acquisition phase, in which participants learned that their keypress actions would immediately result in the appearance of a visual singleton (red or green, among homogeneously white items). In the test phase, the keys continued to produce colour singletons, but now each key could result in a compatible (red singleton after pressing the “red” key) or incompatible colour (red singleton after pressing the “green” key). When the singleton always indicated the target location, the compatible colour was selected faster than the incompatible colour, consistent with the findings of Kumar et al. (2015), and consistent with the temporal benefit given by the preactivation (Hughes et al., 2013). Moreover, when the singleton always indicated a distractor location, the compatible singletons were less costly than the incompatible singletons, consistent with the reduced sensitivity findings (Cardoso-Leite et al., 2010) and the preactivation (Waszak et al., 2012). In short, evidence for reduced sensitivity and faster selection of learned action-outcomes were observed within the same experimental setting, lending

support to the preactivation account of action-driven influence on visual processing.

An interesting question is whether visual bias that is driven by action selection is similar to other types of visual bias by memory content, including biases driven by feature repetition (e.g., Kristjánsson, 2006; Logan, 1990), working memory (e.g., Olivers, 2009; Soto, Heinke, Humphreys, & Blanco, 2005), recent response history (e.g., Buttaccio & Hahn, 2011; Rothermund, Wentura, & De Houwer, 2005), or semantic processing (e.g., Ansorge & Becker, 2012; Ansorge, Kiefer, Khalid, Grassl, & Koenig, 2010; Goodhew, Kendall, Ferber, & Pratt, 2014; Sun, Shen, Shaw, Cant, & Ferber, 2015). In considering this question, it is necessary to distinguish the antecedent causes of bias from the bias itself. Different factors might cause visual biases of essentially the same kind, all of which could be described in terms of feature preactivation (Waszak et al., 2012). Preactivation could be direct, via repetition or selecting the feature for another task (Olivers, 2009), or it could be indirect, via selection of an associated feature (Ansorge et al., 2010; Ansorge & Becker, 2012; Gozli, Moskowitz, & Pratt, 2014; Sun et al., 2015). At present, it is reasonable to assume action-driven visual bias relies on the general principle of associative learning (Hebb, 1949), which translates action selection to preactivation of anticipated sensory outcomes. Whether this preactivation has similar strength, reliability, and time-course as the preactivation caused by other factors is a question that warrants further investigation.

The negative compatibility effect we observed at SOA = 100 ms seems anomalous, although a similar, but statistically non-significant pattern was found by Ziessler et al. (2012, Experiment 2). In that experiment, the action-compatible visual stimulus received faster responses at SOA = 200 ms, but slower responses at SOA = 100 ms, compared to the action-incompatible stimulus. The authors found this pattern only when action-outcomes were no longer presented in the test phase. In the present experiment, by contrast, action outcomes were presented in both acquisition and test phases of the experiment and, thus, the presentation of action outcomes cannot explain the similarity of findings. At present, we can only speculate regarding this negative compatibility effect,<sup>3</sup> on the

<sup>3</sup>The negative compatibility effect is unlikely to reflect an inhibition of return (Klein, 2000), because inhibition of return tends to emerge later in time, and it tends to be relatively more stable than our negative effect. The fact that the present negative effect (a) was observed at SOA of 100 ms and (b) reversed within 100 ms both point against an inhibition of return explanation.

basis of another experimental phenomenon known as *action-induced blindness* (Müsseler & Hommel, 1997a, 1997b). This phenomenon is currently understood as a feature-specific interference effect, driven by feature integration (Hommel, Müsseler, Aschersleben, & Prinz, 2001). Representation of each event, according to this account, goes through three phases: (1) initial activation of features, (2) integration of features, and (3) gradual decay of activated features. Accordingly, feature overlap between two concurrent events should result in facilitation in phases (1) and (3). During phase (2), however, when features of an event are occupied as components of a unified representation, feature overlap is expected to result in interference. This account fits the present findings (i. e., facilitation at SOAs of 0 and 200 ms, but interference at SOA = 100 ms).

Describing the present finding of a negative compatibility effect (at SOA = 100 ms) as action-induced blindness would not be unproblematic, however, mainly because action-induced blindness has been found to be temporally more stable, beginning with response selection and persisting until response execution (e.g., Müsseler, Wühr, & Prinz, 2000; Pfister, Heinemann, Kiesel, Thomaschke, & Janczyk, 2012; Wühr & Müsseler, 2001). It is possible that action-induced effects are more stable when the feature is an integral part of the action plan (e.g., signifying movement location, movement duration, etc.) as it was the case in prior studies but more transient when the feature is less integral to the action plan (e.g., when it concerns a visual colour outcome) as it was the case in the current study. This distinction is related to what Ziessler and Nattkemper (2011) referred to, respectively, as the *desired* and the *anticipated* outcomes of an action. Namely, the desired action-outcomes might be more robustly integrated in the action plan, whereas anticipated outcomes might be more transiently integrated in the action plan (cf., Hommel, 2010; Thomaschke, Hopkins, & Miall, 2012). This issue certainly merits further investigation.

An alternative explanation of the time course of the compatibility effect can be derived from the preactivation theory (Waszak et al., 2012; see also, Hughes et al., 2013; Roussel et al., 2013), and more specifically based on how the strength of preactivation changes with time. At the onset of action selection, and after enough delay (relatively early and relatively late

phases of preactivation), the activation of anticipated sensory outcome is presumably weak and the cells' activity are far from satiation level. At these phases, the action-compatible stimulus will be at an advantage because the benefit of preactivation is not counterbalanced by satiation. At peak levels of preactivation, by contrast, the cells are close to satiation and thus relatively insensitive to external stimulation. Consequently, the incompatible stimulus will be at an advantage. This explanation, importantly, does not rely on the assumption of feature-integration and code occupation (Hommel et al., 2001).

The present study confirms that the interplay between action and visual attention is not limited to the time *after* action execution, but begins *before* execution. The two types of modulations likely differ in important ways, because the effects that follow action execution presumably involve *evaluation* of an already-performed action, whereas the effects that precede action execution involve selection of to-be-performed action (Hommel, 2013; Kimura & Takeda, 2014). In the present study, we explored the guidance of visual attention by action selection, finding a visual bias in favour of stimuli that resemble the corresponding action-outcome immediately after selecting an action. Importantly, this effect was transient and did not persist at longer delays between action selection and its execution. The transient nature of this bias is important, because it suggests that the effect is driven by action selection processes, instead of strategic attentional control.

To conclude, the present findings suggest that action selection plays a role in the guidance of visual attention because of the learned associations between observer's movements and the known sensory outcomes of the movements. Thus, visual attention should be considered as a capacity of active agents that interact with their visual environment and are capable of skilfully changing and anticipating such changes in their own visual input.

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