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Ideomotor perception modulates visuospatial cueing

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Abstract The ideomotor theory of action posits that the cognitive representation of an action includes the learned perceptual effects of the action. Support for this theory has come from studies demonstrating how perceptual features that match the outcome of a response can facilitate selection of that response. We investigated another, complementary implication of ideomotor theory: would a bias toward selecting a response result in a perceptual bias toward the known effect of the response? In other words, would an action tendency direct attention to the anticipated perceptual features? Through an initial acquisition phase, participants learned that two possible responses (left/right keypress) consistently produced two distinct colors. Next, in a test phase, we manipulated response bias at the beginning of each trial, using an uninformative spatial prime presented at the left or right periphery. We then examined the extent to which color transients that either matched or mismatched the induced response bias can orient participants' visual attention. Results revealed a perceptual bias toward the color effect of the primed response, manifested in a stronger visual orienting toward this color. Thus, biasing response selection can bias perception. These findings extend the scope of the ideomotor theory to visual perceptual processes.

Introduction

Visual perception is highly selective, such that at any moment only a subset of available information can be processed extensively. The process of selection is determined, in part, by the properties of the visual scene (e.g., Itti & Koch, 2001; Pomerantz & Portillo, 2011; Theeuwes, 2010), but also by the goals and intentions of the observer (e.g., Folk, Remington, & Johnston, 1992; Remington & Folk, 2001; Yantis & Egeth, 1999). An additional source of bias in visual selection is the observer's mode of action, that is, the very same visual stimulus can be processed differently depending on what action the observer is performing or planning to perform (e.g., Bekkering & Neggers, 2002; Brown, Moore, & Rosenbaum, 2002; Hommel & Schneider, 2002; Müsseler & Hommel, 1997). The present study is concerned with whether a bias in action selection can influence selection of visual information.

One reason why actions influence visual processing stems from the necessity to prioritize features that are relevant to successful action control; for instance, when reaching for an object, its size, orientation, and distance from the body determine the required reaching length, hand orientation, and grip aperture. Consequently, more processing resources are allocated to these features when grasping, compared to when the object is merely viewed or pointed at (Bekkering & Neggers, 2002; Brown et al., 2002; Craighero, Fadiga, Rizzolatti, & Umiltà, 1999; Wykowska, Schubö, & Hommel, 2009).

Another reason for the influence of actions on vision is attributed to the overlap between the representation of features used in perception and action. Although action and perception involve distinct underlying neural and cognitive processes, they are thought to operate on shared perceptual features (Hommel, 1997; Hommel, Müsseler, Aschersleben,

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& Prinz, 2001; Müsseler, 1999; Prinz, 1990, 1997). Specifically, the representation of an action is thought to include the expected perceptual outcomes of that action; for instance, turning on a light involves planning to bring about the proprioceptive sensation of the arm moving toward the light switch, the tactile sensation of the fingers against the switch, the “click” sound from the switch, and the visual sensation of light turning on. The assumption that action representation and planning involves recruiting perceptual codes provides the foundation for the *ideomotor theory* of action (James, 1890; Shin et al., 2010; Stock & Stock, 2004). This theory proposes that intentional action planning consists of planning to bring about a set of desired perceptual outcomes. Before considering the implication of this account for the influence of action on visual perception, we briefly review the empirical support for the theory.

Support for the main proposal of the ideomotor theory comes from demonstrations that when a perceptual feature consistently results from an action, that particular feature is incorporated into the representation of the action to the extent that its congruency with other features of the action would influence performance efficiency (Ansorge, 2002; Elsner & Hommel, 2001; Hommel, 1993, 1996; Kunde, 2001); for instance, in a visual discrimination task where a single key should be pressed softly or forcefully in response to two color stimuli, performance is more efficient if the soft keypress produces a soft tone and the forceful keypress produces a loud tone, compared to the opposite response–effect mapping (Kunde, 2001). Similarly, in a task where a left or right keypress should be performed in response to the stimuli, performance is more efficient if the keys turn on lights on corresponding locations (e.g., left keypress turning on a light on the left-hand side), compared to when they turn on lights on opposite locations (Ansorge, 2002; Kunde, 2001).

Further empirical support for the ideomotor theory comes from studies in which perceiving an action effect, prior to response selection, biases participants toward selecting the corresponding response (e.g., Elsner & Hommel, 2001; Hommel, 1996; 2004); for instance, participants in a study by Hommel (1996, Experiment 3) learned, in an initial acquisition phase, that each of their two possible responses to visual targets (“X”/“O”) would produce a tone of a distinct pitch (e.g., left key and low tone, right key and high tone). Next, in a test phase, the tones were presented together with target letter appearing at fixation. Thus, although the task only required responding to letter identity, the tone could either be congruent or incongruent with the learned effect of correct response. This was indeed the case, as faster and more accurate performance resulted when the tone matched the known effect of the correct response (i.e., after hearing the low tone, participants were more efficient to select the key

that produced a low tone). Later, experiments by Elsner and Hommel (2001) ruled out the possibility that these findings were due to stimulus–stimulus mapping between target letters and the tones. Therefore, perceiving an action effect feature prior to response selection seems to bias participants toward selecting the corresponding response. This observation supports the ideomotor proposal that selecting (to bring about) a set of perceptual features is essential to action planning.

The reviewed research suggests that response selection can be influenced in a stimulus-driven manner. Could such effects on response selection, in turn, have any influence on perception? According to the ideomotor theory, to have a response bias *is* to have a perceptual bias toward the known effects of the response (Schütz-Bosbach & Prinz, 2007; Shin et al., 2010). This important implication of the ideomotor theory, however, remains to be tested. To illustrate the question, let us consider a task in which responses are defined based on two features: location (left/right keypress) *and* auditory effect (low/high-pitched tone). In this example, we could bias response selection in favor of the left keypress, either by presenting the observer with stimulus on the left side, which activates the response via the spatial code, *or* by presenting a low-pitched tone, which activates the response via its known effect. We can then ask whether biasing the response, using the spatial dimension, can have an effect on perception of the tones. Finding that a bias in response selection leads to a perceptual bias for features associated with the response will have two important consequences. First, this finding will strengthen the ideomotor theory by demonstrating the potential for bidirectional activation between perception and action. Second, by considering action selection as a source of perceptual bias, this finding will inform our view of the mechanisms underlying perceptual prioritization.

It is worth emphasizing that we aimed to examine the effect of a response *bias* rather than the effect of a planned or executed response. This is because formation of an action plan involves processes well beyond the ideomotor principle, and these additional processes might mask or reverse any potential ideomotor perceptual facilitation; for instance, planning an action is thought to involve integration of the constituent features into a single event, which results in a temporary unavailability of those features for other concurrent processes (Hommel et al., 2001). Furthermore, representation of an action plan has to be protected from other similar, but independent events, which might also cause a disadvantage for other perceptual processes (Schubö et al., 2004). A third possibility for an action-induced interference may be due to the necessity to protect an action plan from a second activation by a featurally similar stimulus (Müsseler & Hommel, 1997). Indeed, there is a substantive body of research showing that

planning or executing an action can interfere with featurally similar perceptual processes (e.g., Müsseler & Hommel, 1997; Müsseler et al., 2001; for a reviews, see Thomaschke, Hopkins, & Miall, 2012a; Zwickel & Prinz, 2012). Although action-induced interference is, by virtue of being feature-specific, consistent with the view that action representation includes perceptual features, it calls for further explanatory steps concerning action planning that go beyond the ideomotor principle. To minimize the possibility of action-induced interference effects, therefore, we chose a paradigm that employs stimulus-driven response bias, instead of action planning or execution.

A choice reaction task is used in the present study, wherein each response is distinct on two dimensions—location and color. We can take advantage of this dual representation by using one feature (location) to produce a response bias while we examine the possible changes to the perception of the second feature (color). Similar to previous studies, we presented participants with irrelevant perceptual events that overlapped with response features so that these irrelevant events can activate corresponding responses (e.g., activating *left* by presenting an irrelevant stimulus on the left periphery). Critically, we presented the second (color) feature at a later point in time when a response bias was already induced by the first (spatial) event. This allows us to examine the perceptual influence of the response bias; when responses and colors are linked in an action representation, does biasing a response alter the processing of color?

Previous research on stimulus-induced response bias (e.g., Elsner & Hommel, 2001; Hommel, 1996) suggests that presenting a perceptual feature that overlaps with the representation of one response will bias response selection. For our purposes, it was critical to first confirm whether we could induce a measurable response bias using a spatial prime, given the specific task characteristics. First, the possibility that responses might be represented based on colors might weaken the role of location in response representation and, consequently, weaken the effect of an uninformative spatial prime. Second, the delay between the onset of the spatial prime and the onset of the imperative stimulus was relatively long (400 ms), which might render any possible transient bias unobservable. Thus, in Experiment 1, we introduce the basic structure of our task and provide evidence for the effectiveness of spatial primes inducing a response bias. Then, in Experiment 2, we modify the task to address the issue of a color-based perceptual bias induced by a bias in response selection.

Experiment 1

The goal of this experiment was to test whether an uninformative spatial prime can be effective in causing a

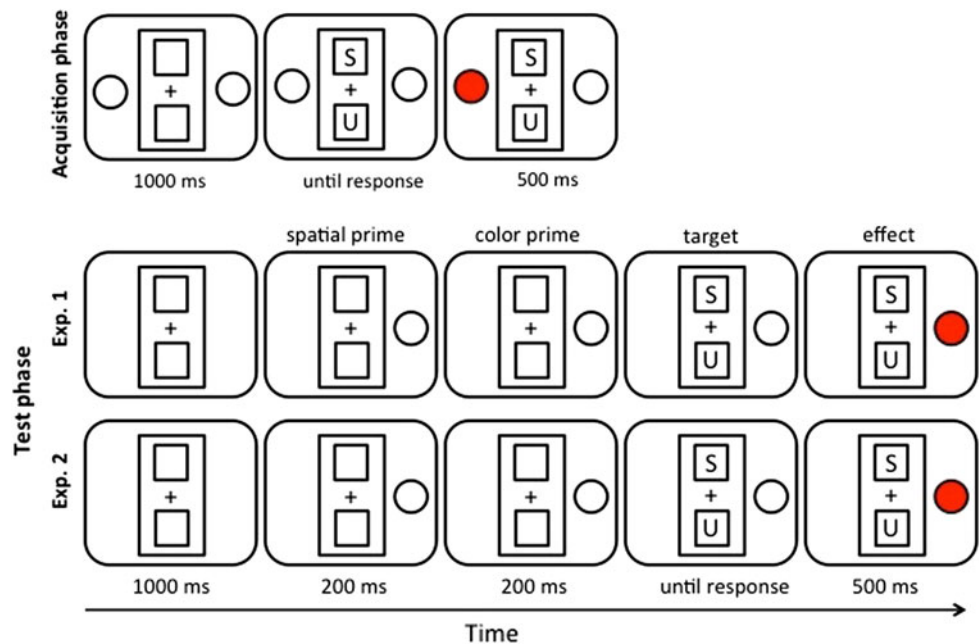
measurable response bias after introducing an association between responses and their color effects? In our pilot experiments, we have found that forming a response–color association can greatly reduce or eliminate response–target spatial compatibility effects, suggesting the dominance of the non-spatial dimension is response coding (cf. Hommel, 1996; 2004). On the other hand, there is also evidence for the possibility of two-feature response coding, such that each response feature could interact with stimulus features. In particular, Kunde and Stöcker (2002) reported persistent spatial compatibility effects when responses were defined on spatial (left/right) and a non-spatial (short/long) dimensions. Finding a similar persistence of the spatial dimension in response coding is important for the present study, since we aim to rely on the spatial dimension to produce response bias.

We established the association between responses and their color effects through an initial acquisition phase (e.g., Elsner & Hommel, 2001; Hommel, 2004). During the acquisition phase, participants identified a target letter that was presented together with a distractor letter along the vertical axis (see Fig. 1). The display also consisted of two circles positioned on the left and right periphery. Immediately after each response, the color that was associated with the response filled one of the two peripheral circles. The location of this color effect was chosen randomly (e.g., after the right-hand keypress, red could appear inside the left or right circle with equal probability) in order to avoid forming an association between colors and the circles.

Since each color effect coincided with both a response and a target letter, formation of color–response and color–letter associations were both possible. Based on previous studies, there is reason to assume some degree of color–response association (Hommel, 2004; Ziessler, 1998), although Experiment 1 cannot discriminate between the two kinds of associations. The question of whether any response–color mapping is formed will be addressed directly in Experiment 2. Here, the question is whether the potential color–response mapping would weaken the location–response mapping to such an extent that the location can no longer be used to prime responses.

After the acquisition phase, participants performed the test phase, which involved a similar visual letter identification task (Fig. 1). In this phase, however, before the presentation of the letter stimuli, two primes were presented in sequence, each corresponding to one of the two response dimensions. The first prime was a *spatial prime* and consisted of the onset of one of the peripheral circles at the left or right side of fixation, which later contained the response (color) effect. Presentation of the spatial prime was expected to bias participants toward selecting the response of the same location (e.g., if the circle appears in the left, then participants would be biased toward selecting

Fig. 1 Sequence of events in one trial of the acquisition phase (*above sequence*) and the test phase (*lower sequences*). During the acquisition phase, the color effect of each response was equally likely to appear inside the *left or right circle*. The color prime, in test phase of Experiment 1, consisted of a change in both placeholders above and below fixation, whereas in Experiment 2, it consisted of a change in a single placeholder and, therefore, also functioned as a visual-attentional cue (this cue was equally likely to appear above or below fixation and it did not predict the target location, which was itself equally likely to be above or below)



the left keypress) for two reasons. First, as an irrelevant visual stimulus that possesses the same binary spatial features as the response (i.e., two positions along the horizontal axis), the circle was thought to activate the compatible response code (Ansorge & Wühr, 2004; Kornblum, Hasbroucq, & Osman, 1990; Lu & Proctor, 1995). Second, the circle also signaled the location of an upcoming color effect, and therefore it is possible that the anticipated location of the response effect would also activate the compatible response code (Ansorge, 2002; Kunde, 2001). We treated these factors (i.e., stimulus–response and response–effect compatibility) together as a single source of response bias. The spatial prime was uninformative and could be either compatible or incompatible with the location of the performed response.

After the presentation of the spatial prime at the left or right periphery, the color prime was presented at both possible locations for the imperative stimulus (placeholders above and below fixation). The color prime is also expected to bias performance by activating the associated response (i.e., the response that would produce the same color as the prime; Hommel, 2004), and by activating the associated target letter (i.e., the target letter that coincides with the color). Thus, each trial of the test phase is characterized by the relationship between the spatial prime and the correct response, and the relationship between the color prime and the correct response. We predicted compatible primes to reduce response times, compared to incompatible primes, for both spatial and color primes. In particular, finding an effect of the spatial prime will justify the next step (Experiment 2), which involves examining the effect of response bias on color processing.

Method

Participants

Twenty University of Toronto undergraduate students gave their informed consent and participated in this experiment in exchange for course credit. All participants reported normal or corrected-to-normal vision and were unaware of the purpose of the study. All experimental protocols were approved by the University of Toronto Research Ethics Board.

Apparatus and stimuli

Participants performed the task in dimly lit data collection rooms. The experimental program was run in Matlab (MathWorks, Natick, MA, USA), using the Psychophysics toolbox (Brainard, 1997; Pelli, 1997; version 3.0.8) on Windows-run PCs. Stimuli were presented on 19" CRT monitors set at $1,024 \times 768$ resolution and 85 Hz refresh rate. Using a head- and chin-rest, participants' distance from the display was fixed at about 45 cm.

The display structure and the sequence of events in the experiment are shown in Fig. 1. Stimuli appeared in white, except when noted otherwise, against a black background. Two vertically aligned squares (size = $2^\circ \times 2^\circ$) acted as placeholders for the letter stimuli ("S", "H", "E", and "U" approximately $.5^\circ \times 1^\circ$ in size, presented in Arial font). The center of each placeholder deviated by 5° of visual angle from fixation. The placeholders were embedded within a larger vertical rectangle ($4^\circ \times 14^\circ$). Outside this rectangle were two horizontally aligned circles

(diameter = 2°), one of which was filled with the color red or green immediately after a response. The center of each circle deviated by 9° of visual angle from fixation. During the acquisition phase, both circles were present throughout the entire block, whereas during the test phase, only one circle appeared after the initiation of each trial, acting as the spatial prime.

Procedure

Each trial of the acquisition phase began with the presentation of empty placeholders. Participants were instructed to begin each trial by fixating at the central cross (1° × 1°). After a 1,000-ms delay, a letter appeared inside each placeholder. On each trial, one target letter (“S” or “H”) and one distractor letter (“U” or “E”) were presented. Participants were instructed to respond as quickly as possible with a right-hand keypress (the “/?” button on the keyboard) when identifying “S” and with a left-hand keypress (the “Z” button on the keyboard) when identifying “H”. Letters remained on the screen until one of the two possible responses was recorded. Participants received visual feedback for anticipation (“TOO QUICK!”) or late responses (“TOO LATE!”), defined as responses earlier than 100 ms and later than 2,000 ms. Immediately after a keypress, one of the two peripheral circles were filled with a color (red and green, for the right- and left-hand keypress, respectively). This color feedback remained on the screen for 500 ms. Note, first, that the location of the color feedback (left or right) had no systematic association with the response location, that is, for instance, the left-hand keypress was equally likely to fill the left or right circle with the color green. This was done to prevent association between colors and location of the peripheral circles. Second, the color effects were produced regardless of the correctness of the response, that is, when participants made an incorrect response (e.g., left-hand keypress to “S”), they received the color feedback associated with their incorrectly performed response, which was then followed by another visual feedback (“MISTAKE!”) remaining on the screen for 2,000 ms.

Each trial of the test phase also began with the presentation of vertically aligned placeholders above and below the central fixation mark. Importantly, the two circles were absent during the initial stage of each trial. After a 1,000-ms delay, one of the two peripheral circles appeared, acting as an exogenous response prime (i.e., the onset of this circle was aimed to bias the participant toward the response that matched the location of the circle and away from the alternative response). After a 200-ms delay, both target placeholders changed color to red or green. After another 200 ms, both placeholders changed back to white and, at the same time, the letter stimuli appeared inside the

placeholders. Similar to the acquisition phase, immediately after a response, the color feedback appeared inside the circle. The mapping between the responses and feedback colors did not change across the two parts of the experiment.

Design

Participants completed one acquisition block of 200 trials and a separate test block of 320 trials. Both the acquisition and the test phase preceded by a separate block of 20 practice trials. During both phases, target letter (“S” or “H”), target location (up or down), and the location of the response effect (left or right) were randomized and equally probable. In addition, during the test phase, the spatial prime and the color prime were both uninformative, predicting response with chance-level validity.

Results

Acquisition phase

After excluding incorrect responses and responses faster than 100 ms and those that fell beyond 2.5 SDs of the total mean (3.7 % of trials), mean response time (RT) was 567 ms (SE = 15). Mean error rate was 2.8 % (SE = .6). Overall, these data suggest good performance during the acquisition phase.

Test phase

Before analyzing the RT data from test trials, incorrect responses (4.2 % of trials) were excluded. Response latencies below 100 ms or latencies beyond 2.5 SD around the total mean were also excluded as outliers¹ (2.2 % of trials). The remaining RT data were submitted to a 3 × 2 repeated measures analysis of variance (ANOVA), with spatial prime (compatible vs. incompatible) and color prime (compatible vs. incompatible) as independent factors ($\alpha = .05$). The data are graphed in Fig. 2. Both main effects reached the significance level: a main effect of spatial prime [$F(1,19) = 5.33, p = .032, \eta_p^2 = .219$] indicated faster responses with compatible ($M \pm SE = 545 \pm 13$ ms) compared to incompatible (551 ± 14 ms) prime. A main effect of color prime [$F(1,19) = 10.70, p = .004, \eta_p^2 = .360$] indicated faster responses with compatible (542 ± 13 ms) compared to incompatible (553 ± 15 ms) color primes. No evidence of a two-way interaction was found ($F < 1$).

¹ Applying this outlier-exclusion criterion to the RT data did not affect the pattern of findings in either of the experiments.

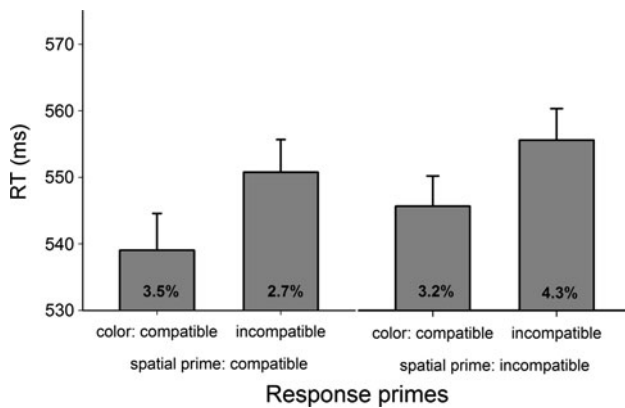


Fig. 2 Response time data from Experiment 1, graphed as a function the first (spatial) and the second (color) primes. Error rates are provided at the base of each bar. Error bars represent within-subjects 95 % confidence intervals (Cousineau, 2007)

Error rate data from the test phase (provided in Fig. 1) were submitted to a similar three-way ANOVA, which revealed no main effect or interaction ($F_s < 1$).

Discussion

Both the spatial prime and the color prime successfully biased the selection of the compatible response, consistent with the assumption that location and color were included in response representation. Most important, for our purpose, the uninformative spatial prime produced a measurable bias in response selection, despite the 400-ms delay between the onset of the prime and the onset of the target, and despite the onset of a color prime during this delay period.

The effect of the color prime, however, is somewhat less clear. On the one hand, this effect can be interpreted as evidence for the inclusion of color codes in response representation, consistent with previous work (Hommel, 2004; Koch & Kunde, 2002). On the other hand, color primes could also bias participants toward their corresponding target, due to the formation of target–color associations during the acquisition phase. Of course, these two possibilities are not mutually exclusive. In light of the findings of the next experiment, however, we reason that there is some degree of response–color mapping underlying the main effect of the color prime.

The absence of an interaction between the two sources of response bias is often taken to indicate the distributed nature of response representation over cortically separate feature maps, enabling each feature to form a separate association with the motor command (e.g., Colzato, Warrens, & Hommel, 2006; Hommel, 1998; Hommel & Colzato, 2004). This means that each feature can function

independently as a source of response bias. Importantly, the location–color mapping was successfully prevented through our random localization of the response effects.

After establishing that both features could be incorporated into the representation of the responses, we next modify the task used in Experiment 1, such that possible changes to perceptual sensitivity for colors, resulting from the induced response bias, could be measured.

Experiment 2

In this experiment, we directly test perceptual bias for colors, by employing the visual-attentional cueing paradigm (Posner, 1980; Posner & Cohen, 1984). In this paradigm, participants detect or identify a target (e.g., a letter) that could appear in one of multiple possible locations. Prior to the appearance of the target, a cue appears at one of the possible target locations (e.g., an increase in brightness, a sudden motion, and a change in color). Even when the cue is uninformative (i.e., signaling target location with chance-level validity), it benefits performance when it coincides with the target location (valid cue) relative to when it appears at a nontarget location (invalid cue), indicative of an automatic shift of attention to the cued location (e.g., Abrams & Christ, 2003; von Mühlhens, Rempel & Enns, 2005).

The task used in Experiment 1 could be successfully modified into a variant of the visual cueing paradigm, by presenting the color prime at only one target placeholder. By spatially confining the color transient, we could expect to observe a typical visual-attentional cueing effect, manifested in faster responses when the cue is valid compared to when it is invalid. Before presenting the hypothesis, a note on the use of the terms “prime” and “cue” seems necessary. Although these terms could be used in very similar senses, in the present text, we reserve the term “cue” and “cueing effect” only for the role of the color transient in orienting visual attention to a possible target location. Thus, we reserve the term “priming” when referring to the activation of a response (e.g., left key press) or possibly a target identity (e.g., letter “H”).

In the present experiment, the color event is expected to have two roles: in addition to priming a response, the color event also acts as a visuospatial cue. This cue should draw the participants’ attention to one the target locations, resulting in faster performance when the target letter would coincide with the color prime location (Posner, 1980; Posner & Cohen, 1984). Most importantly, the color prime was presented when participants had already acquired a response bias, due to the previously presented spatial prime. We hypothesize that the response bias, caused by the spatial

prime, would lead to a perceptual bias toward the matching color, resulting in a stronger visual-attentional cueing effect by the matching color prime. On the other hand, the induced response tendency would bias participants against the color associated with the alternative response, resulting in a weaker visual-attentional cueing effect by the mismatching color prime.

Method

Participants

Twenty-two University of Toronto undergraduate students gave their informed consent and participated in this experiment in exchange for course credit. All participants reported normal or corrected-to-normal vision and were unaware of the purpose of the study. All experimental protocols were approved by the University of Toronto Research Ethics Board.

Apparatus, stimuli, and procedure

These were identical to Experiment 1. The only modification made was to the color prime of the test phase; instead of both target placeholders changing color, only one of the placeholders changed color before the target onset.

Design

Participants completed one acquisition block of 200 trials and a separate test block of 320 trials. Both the acquisition and the test phase preceded by a separate block of 20 practice trials. The spatial prime and the color prime were uninformative, that is, they predicted response and target location with chance-level validity. Trials of the test phase were coded based on the relationships between the spatial prime and the correct response (compatible vs. incompatible), the relationship between the color prime and the response effect (compatible vs. incompatible), and the validity of the color prime, as an attention cue, in predicting the location of the visual target (valid vs. invalid).

Note that the two primes matched whenever they were both either compatible or incompatible with the correct response. Therefore, we expected stronger attentional cueing by color when both response primes were compatible or incompatible. By contrast, the two primes mismatched whenever only one of them was compatible with the response. Therefore, we expected a weaker attentional cueing by color when only one of the two primes was compatible with the correct response.

Results

Acquisition phase

After excluding incorrect responses and response latencies below 100 ms and those that fell beyond 2.5 SD of the total mean (3.6 % of trials), mean RT was 594 ms (SE = 16). Mean error was 4.3 % (SE = .7). Overall, these data suggest good performance during the acquisition phase.

Test phase

Before analyzing the RT data from test trials, incorrect responses (3.4 % of trials) were excluded. Response latencies below 100 ms or latencies beyond 2.5 SD around the total mean were also excluded as outliers (3.7 % of trials). The rest of the RT data were submitted to a $2 \times 2 \times 2$ repeated measures ANOVA, with spatial response prime (compatible vs. incompatible), color–response prime (compatible vs. incompatible), color prime location (valid vs. invalid), as independent factors ($\alpha = .05$). The data are graphed in Fig. 3. All main effects reached significance level: a main effect of the spatial prime [$F(1,21) = 5.08$, $p = .035$, $\eta_p^2 = .19$], indicated that compatible spatial primes (M \pm SE = 546 \pm 14 ms) led to faster responses compared to incompatible spatial primes (552 \pm 15 ms); a main effect of the color prime [$F(1,21) = 9.36$, $p = .006$, $\eta_p^2 = .31$], indicated that compatible color primes (544 \pm 15 ms) led to faster responses compared to incompatible color primes (554 \pm 15 ms); a main effect of the color prime location [$F(1,21) = 7.56$, $p = .012$, $\eta_p^2 = .26$], indicated that when the color validly cued the target location (544 \pm 14 ms), it led to faster responses compared to when

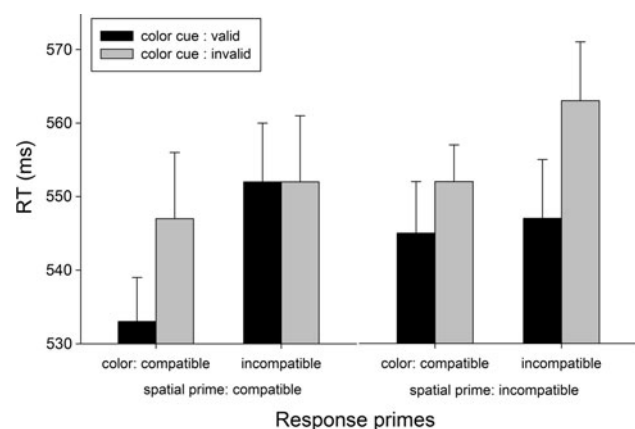


Fig. 3 Response time data from Experiment 2, graphed as a function of the relationship between the first (spatial) response prime and the performed response, the second (color) response prime and the performed response, and the validity of the color cue in signaling the location of the imperative stimulus. Error bars represent within-subjects 95 % confidence intervals

Table 1 Percentage of errors (SE) in Experiment 2, as a function of spatial prime, the color prime, and location of the color prime (valid vs. invalid)

	Spatial prime: compatible		Spatial prime: incompatible	
	Color prime: compatible	Incompatible	Color prime: compatible	Incompatible
Valid cue	3.3 (.6)	2.3 (.7)	3.8 (.9)	3.1 (.8)
Invalid cue	3.4 (.8)	4.9 (.9)	3.0 (.6)	3.8 (.7)

it was an invalid cue (554 ± 15 ms). None of the two-way interactions reached significance ($F_s < 1$). Most importantly, a three-way interaction was found [$F(1,21) = 6.75$, $p = .017$, $\eta_p^2 = .24$], consistent with the prediction that cueing strength should depend on the relationship between the two primes.

As Fig. 3 shows, when the color of the cue was consistent with the spatial response prime (i.e., when both were either compatible or incompatible with the correct response), it caused an attentional cueing effect of 15 ms ($SE = 4$) that was significantly greater than zero [$t(21) = 4.37$, $SE = 3.46$, $p < .001$]. Importantly, the consistency between the two primes caused a significant cueing effect, both when the target letter was compatible with both [leftmost cluster in Fig. 3; $t(21) = 2.34$, $SE = 6.00$, $p = .029$] and when the target letter was incompatible with both [rightmost cluster in Fig. 3; $t(21) = 3.42$, $SE = 4.74$, $p = .003$]. By contrast, when the color of the cue was inconsistent with the spatial response cue, its effectiveness was not significantly different from zero (cueing effect = 3 ± 5 ms, $p > .4$). More specifically, no attentional cueing was observed when the spatial prime alone ($p > .9$), or when the color prime alone ($p > .3$) was compatible.

Error rate data (Table 1) from the test phase were submitted to a similar three-way ANOVA. This analysis only revealed a significant two-way interaction between color prime and location cue validity [$F(1,21) = 5.00$, $p = .036$, $\eta_p^2 = .192$]. Specifically, when the color prime was compatible with the correct response, location validity did not reduce error rates [3.7 and 3.3 % error, for valid and invalid conditions, $t(21) < 1$]. This was not surprising in light of the fact that, during these trials, the color of the prime would already have biased participants to select the correct response. On the other hand, when the color prime was incompatible with the response, location validity reduced error rates [2.8 and 4.6 % error, for valid and invalid conditions, $t(21) = 2.21$, $SE = .008$, $p = .038$]. In short, the effect of cue validity on accuracy became noticeable when the correct response was not primed by the color. No other main effect or interaction in the error rate data suggests that the RT findings were not produced by a speed-accuracy tradeoff.

Discussion

The key finding of Experiment 2 was that the response bias induced by the spatial prime affected subsequent color processing. Because participants encountered the colors after already acquiring a modest but measurable response bias, we reason that this response bias involved activating the anticipated perceptual effects of the response, including the learned color effect. Therefore, when participants subsequently encountered a color that matched this bias, their attention was reliably drawn to the location of that color. Similar to the findings of Experiment 1, the present findings showed that both the spatial prime and the color prime biased performance. The absence of a two-way interaction between the effects of the two primes supports the assumption that, although both features might have been included in response representation, they were not directly associated with each other.

Although we propose that the main effect of cue validity reveals a visual-attentional orienting, it should be demonstrated that this effect is not due to any potential stimulus–response compatibility effect. In particular, attentional orienting should be independent of any spatial compatibility effect between the visual events and the response. From previous work, we know that spatial compatibility effects can emerge that enhance processing efficiency for *left-down* and *right-up* combinations (Cho & Proctor, 2003; Proctor & Cho, 2006). If so, the combination of a *right* spatial prime, an *up* color prime, and an *up* target may have resulted in what seems like an attentional cueing effect.² Thus, to test the independence of our proposed attentional cueing from this orthogonal spatial compatibility, we re-analyzed the data, in a 2×2 ANOVA with target–response orthogonal compatibility (compatible vs. incompatible) and cue validity (valid vs. invalid) as factors. We found no orthogonal compatibility effect ($p > .94$). Instead, we found a cueing effect [$F(1,21) = 7.43$, $p = .013$, $\eta_p^2 = .261$], which did not interact with the potential orthogonal spatial compatibility. Therefore, the attentional cueing effect seems genuine and cannot be accounted for by a spatial stimulus–response compatibility ($p > .98$).

² We thank Ulrich Ansorge for suggesting this possibility.

In discussing the findings of Experiment 1, we pointed out how the main effect of color prime could not discriminate between letter–color and response–color associations. In view of the results of Experiment 2, however, we argue that some degree of response–color association must have been formed, that is, because the spatial prime, by activating its corresponding response, also caused a processing advantage for the color associated with the response. Importantly, the effect of spatial primes on processing colors was mediated by response activation because there is no evidence that the two features were directly associated (i.e., in both experiments, we failed to obtain a two-way interaction between the two primes). In fact, we minimized the possibility of forming a direct association between the location of the spatial prime and the colors by presenting each color at both locations equally frequently.

Furthermore, the results strongly suggest that the perceptual bias for color did not depend on target letter identity, but instead depended on the induced response bias. If target identity was critical in obtaining the perceptual bias for color, then attentional cueing should not be observed when the spatial prime and the color prime were consistent with each other but both incompatible with the target letter (i.e., the rightmost cluster of bars in Fig. 3). Contrary to this expectation, we found a reliable attentional cueing ($p = .003$) when both primes were incompatible, that is, the spatial prime led to a perceptual bias for color even when the observer ultimately performed the incompatible response. Therefore, the perceptual bias for color seems to have been due to a bias in response selection, instead of being mediated by a bias toward forming a consistent target–response–effect episode (Hommel, 1998; Logan, 1988).

The observation that target letters did not modulate the perceptual bias for color is also inconsistent with an account based on accumulated response activation by multiple features (e.g., Fournier, Eriksen, & Bowd, 1998). According to such an account, the observed RT benefits are due to the presence of visual features that are all associated with one response (e.g., right spatial prime + red + "S"). Since this account is based on response activation, it does not predict any change in the effect of color prime based on where the prime appears, that is, it does not predict the observed attentional cueing effect. Therefore, the most parsimonious explanation of the present finding seems to require a perceptual bias toward color (induced by response bias) and not merely accumulated response activation.

Why was the attentional cueing effect non-significant when the color cue did not match the concurrent response bias? A plausible account for this observation is based on rapid disengagement of attention from the location of the color transient (Theeuwes, Atchley, & Kramer, 2000).

Disengaging from the location of the color cue would have been a useful strategy, since the color cues were uninformative regarding the location of the upcoming letter target. It is generally thought that when target presentation does not follow the cue onset within 150 ms, disengagement from the cued location becomes increasingly probable (Posner & Cohen, 1984; Theeuwes et al., 2000). It is, however, less efficient to disengage from the cued location when participants are biased toward the cue feature (e.g., Folk et al., 1992; Remington & Folk, 2001). In the present experiment, the different visual-attentional cueing effect by color transients that matched and mismatched the concurrent response bias might have been due to a difference in efficiency of disengagement from the cued location.

Another possibility for the ineffectiveness of the color cues that mismatched the concurrent response bias is that the induced response bias may have caused inhibition of the color associated with the alternative response. Top-down feature inhibition has been shown to play a role in modulating stimulus-driven attentional orienting (e.g., Gozli & Pratt, 2012; Treisman & Sato, 1990). Such feature inhibition may have further facilitated the rapid disengagement from the location of the color cues in the present experiment. In short, consistent with our hypothesis, employing the attentional orienting paradigm successfully revealed the perceptual bias caused by a bias in response selection.

General discussion

According to the ideomotor theory of action, the cognitive representation of an action involves the known perceptual outcomes of the action. In the present study, we investigated a consequence of this proposal: would a bias toward selecting a response result in a perceptual bias toward the known effect of the response? In particular, in the context of a choice–response task, where each response produced a distinct color effect, we tested whether a response bias would induce a perceptual bias for the associated color. After establishing that a measurable response bias could be induced with an uninformative spatial prime, we examined the influence of this response bias on processing color transient that appeared at possible target locations. The results revealed a reliable attentional cueing effect caused by the color transient when it matched the induced response bias, but no such cueing effect when the color mismatched the response bias. This observation is consistent with the ideomotor proposal that action selection involves selecting a set of known perceptual outcomes, and that processes underlying action and perception operate on common feature representations (Hommel, 1996, 1997; Hommel et al., 2001; Prinz, 1990; 1997).

Inducing a response bias prior to response selection is not commonly used as a manipulation in studying the influence of action on perception. It is, therefore, important to contrast our response-bias manipulation from the frequently used response selection or execution manipulation (e.g., Gozli & Pratt, 2011; Kunde & Wühr, 2004; Müsseler & Hommel, 1997; Schubö et al., 2001, 2004; Thomaschke, Hopkins, & Miall, 2012b; Wühr & Müsseler, 2001; Zwickel, Grosjean, & Prinz, 2007, 2010). Interestingly, selecting or executing an action often interferes with perceiving visual events that share a feature with the observer's action; for instance, a leftward keypress response can interfere with visual perception of a briefly presented leftward arrow (Kunde & Wühr, 2004; Müsseler & Hommel, 1997; Wühr & Müsseler, 2001). On the one hand, since this type of action-induced interference with perception is feature-specific, it supports the proposal that action and perception operate on common features (Hommel et al., 2001). On the other hand, by addressing the impact of action *after* action selection, these studies perhaps bypassed the intervals in which ideomotor perception (i.e., perceptual bias toward action outcomes) could be revealed.

The interference of action with perceiving a featurally similar visual stimulus is interpreted to be due to the integration of the feature into the action plan, which renders it temporarily unavailable for other concurrent perceptual processing (Gozli & Pratt, 2011; Hommel et al., 2001; Thomaschke et al., 2012b; Zwickel et al., 2007, 2010; Zwickel & Prinz, 2012). An important additional assumption proposed by Stoet and Hommel (1999) is that the time interval in which the feature code is integrated into (or occupied by) an action plan is a subset of the interval in which the feature has above-baseline activation, that is, a feature can be activated without being bound to a response, during brief time intervals preceding and following the response. In the present study, for instance, the color cues were presented prior to response selection, presumably during a time interval when the color codes were not integrated into any response plan, but were activated due to response bias. If we consider the present response-bias manipulation to have caused feature activation, without integration, then the present findings would be consistent with previous work on action-induced interference with perception.

Therefore, we propose that a response bias, prior to response selection, results in the activation of response features without the integration of the features into an action. Examining perceptual processes during this time window can reveal characteristics of ideomotor perception, which may be masked or reversed by feature integration after response selection. Similarly, Zwickel and Prinz (2012) pointed out that ambiguity regarding the upcoming

perceptual and response features may increase sensitivity to features that are consistent with concurrent bias (before selection). By contrast, certainty regarding response features may reverse the effect of bias on perception. It is possible that this ambiguity-certainty distinction of Zwickel and Prinz (2012) is similar to the distinction made between bound or unbound features (Hommel et al., 2001; Treisman & Schmidt, 1982).

Consistent with the ideomotor proposal, it was previously shown that selecting a left/right keypress response can produce a greater disadvantage for items presented on the visual hemifield contralateral for the response location (Hommel & Schneider, 2002; Müsseler et al., 2005; Thomaschke et al., 2012b). Hommel and Schneider (2002) used a dual task experiment, in which a low- or high-pitched tone (S1) indicated the first keypress response (R1: left vs. right). Shortly after the onset of S1, an array of four letters, including one target letter (S2) was briefly presented and masked. Results revealed a relative advantage for S2 when it appeared on the same side as R1. Importantly, this was observed only when the onset of S1 was followed by S2 onset by no later than 300 ms. In a similar paradigm, Müsseler et al. (2005) found the same pattern of results when S2 followed S1 by no later than 200 ms. As Hommel and Schneider noted, it is unlikely that this time window solely represents post-selection stage of action. Indeed, it is possible that the activation of location code, prior to integration into an action plan, gave the unrelated visual stimuli that shared this code a selective advantage. This advantage was not observed when the temporal distance of S1 and S2 was increased. Compared to those studies, our task presented the stimulus of interest within a time interval which was unambiguously before response selection. Furthermore, we showed that the response-induced advantage is not limited to location, but could also be observed for other response features.

Beyond ideomotor theory, the present findings have several implications for theories of visual attention. Although most theories assume a role for top-down modulation of feature salience, the primary sources of top-down bias are considered to be either perceptual goals of the observer or knowledge of the visual context (Bundesen et al., 2005; Chun et al., 2011; Knudsen, 2007; Yantis, 2000; although see Allport, 1993; Hommel, 2010). Here, we demonstrated that the participants' tendency to select an action can also modulate visual-attentional processing, due to the knowledge of the outcome of the action, in a manner so as to increase the effective salience of visual events that are consistent with the behavioral tendency. Moreover, top-down modulations are often considered to enhance performance efficiency and guard against salient distractors. As we showed, however, action-induced modulations in perception can also be the by-product of how actions are

represented via their perceptual associations. Taking such action-based sources of perceptual bias into account can expand our understanding of the nature of visual perception as processes situated within the demands of action systems.

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