



Co-Editors: James W. Tanaka &amp; Christian N.L. Olivers

ISSN: 1350-6285 (Print) 1464-0716 (Online) Journal homepage: <http://www.tandfonline.com/loi/pvis20>

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To cite this article: Josef G. Schönhammer, Stefanie I. Becker & Dirk Kerzel (2017) Which kind of attention is captured by cues with the relative target colour?, *Visual Cognition*, 25:7-8, 703-714, DOI: [10.1080/13506285.2017.1323811](https://doi.org/10.1080/13506285.2017.1323811)

To link to this article: <https://doi.org/10.1080/13506285.2017.1323811>



Published online: 16 May 2017.



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## Which kind of attention is captured by cues with the relative target colour?

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### ABSTRACT

Most theories of visual search maintain that attention is selectively tuned to the attributes of the search target (e.g., orange). Conversely, according to the relational account, attention is biased to the relative feature of the target (e.g., redder). However, previous studies that supported the relational account mainly measured mean response times. Hence, the results might not reflect early, perceptual mechanisms (e.g., signal enhancement) but later, decision-based mechanisms (channel selection). The current study tested the relational account against feature-specific theories in a spatial cueing task, in which the targets were backward-masked, and target identification accuracy was measured. The first experiment corroborated earlier results, demonstrating that relational effects are due to signal enhancement. In the second experiment, we chose highly discriminable colours along the blue–red continuum, and obtained results that were more consistent with broad feature-specific rather than relational tuning. The implications of these findings for current theories of attention are discussed.

### ARTICLE HISTORY

Received 1 January 2017  
Accepted 18 April 2017

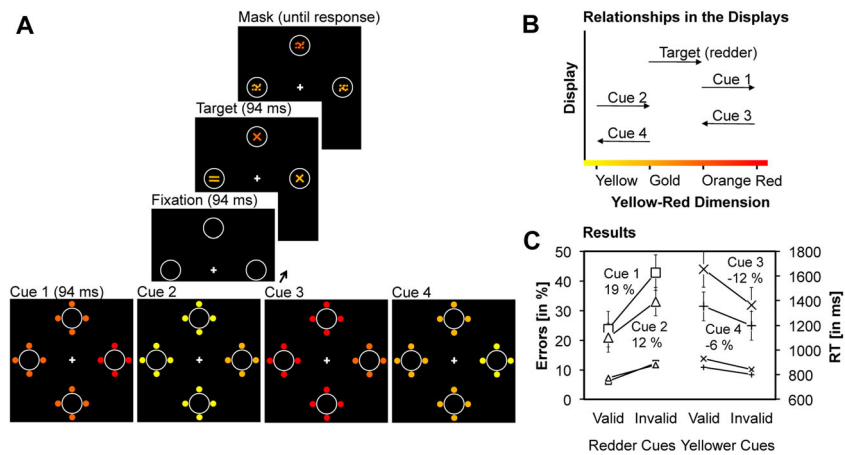
### KEYWORDS

Visual attention; attentional capture; perceptual sensitivity; masking; visual search

How are task-relevant items found in a visual array, when their features are known but not their locations? Theories have been converging on the idea that various control factors can bias visual processing in a spatially global manner and guide focal attention to potential target objects (e.g., Wolfe, 2007). In search for a red target, for instance, attention can be tuned to all red items in the search display, which then receive a processing boost and are more likely to gain focal attention. Multiple attentional control mechanisms have been identified, amongst them bottom-up, stimulus-driven mechanisms and top-down, goal-directed mechanisms. For stimulus-driven control, stimulus features such as the saliency or feature contrast is important, as stimuli with a high feature contrast can be found faster than low-contrast targets, and salient items may even automatically attract attention (e.g., Theeuwes, 2014). Goal-directed attention refers to our ability to actively tune or bias attention to certain attributes (e.g., target colour, orientation, shape), which allows selectively attending to stimuli with those attributes (e.g., Duncan & Humphreys, 1989; Wolfe, 2007). In the current study, we will focus on different goal-directed mechanisms of attentional control, in which attention

is guided to certain locations based on knowledge about the feature (e.g., colour) of a sought-after target stimulus.

The influence of feature-based top-down control on spatial attention has frequently been investigated with spatial cueing tasks (e.g., Folk, Remington, & Johnston, 1992). Folk and Remington (1998), for example, asked participants to search for a red target among three white nontargets and to identify the target symbol (X or =) (see Figure 1). Prior to the target, a cue was presented that either matched the target colour (a red cue among white contextual cue elements) or not (a green cue among white elements). Cue and target locations were spatially uncorrelated so that observers had no incentive to attend to the cue location. Nevertheless, the target-matching, red cue attracted spatial attention, as reflected in a *validity effect*, with faster response times (RTs) when the target was presented at the same location as the cue (valid trial) than when it was presented at a different location (invalid trial). The non-matching green cues failed to produce significant validity effects, indicating that they did not attract attention. Folk and Remington (1998) proposed that the task-requirement to find targets with a known colour made observers adopt a



**Figure 1.** (A) In Experiment 1, only colour defined cues and targets were used. (B) Each arrow represents the feature relationship on a theoretical yellow–red tuning dimension, in the respective display. For example, in cue display 1 the cue context was orange and the cue was red. Hence the cue was relatively redder. This relation is represented by an arrow pointing from orange to red. The relational account predicts attentional capture, when cue and target arrows have the same direction. (C) The upper graphs represent the mean error rates (left scale, large symbols) on valid and invalid cue trials. Error bars show within-subject 95% confidence intervals for the comparison of valid and invalid trials for each cue condition (Franz & Loftus, 2012). The text fields next to the error graphs show the average cueing effects. The bottom graphs depict mean median RTs (right scale, small symbols).

top-down task-set for the target colour that limits attention to select all and only those items with a matching colour.

Generally, such findings were interpreted in support of *feature similarity accounts*, which claim that attention is top-down tuned to the target's feature value (e.g., Bravo & Nakayama, 1992; Duncan & Humphreys, 1989; Folk & Remington, 1998; Treue & Martinez Trujillo, 1999). Duncan and Humphreys (1989, 1992), for instance, proposed that observers form a mental template of the sought-after target, which is similar to the idea of a task-set. Visual objects are then compared to this target template. As a result of the comparison, an object's selection weight increases the more it matches with the template, and the object with the highest selection weight is selected for further processing. Thus, according to this account, cues that match the exact physical target colour should attract attention most strongly, and capture should decrease with decreasing similarity to the target.

By contrast, recent findings suggested that top-down tuning can also pertain to the features of cue and target *relative* to the features present in the context (e.g., redder, larger; Becker, 2010) rather than the specific target feature value. Consistent with this *relational account*, Becker, Folk, and Remington (2013) found validity effects on RTs when the cues had the same relative colour as the target,

independent of the physical colour similarity between cue and target. For instance, in one of their experiments, an orange target was presented among gold nontargets (relatively redder target; see the target in Figure 1A). They then contrasted attentional capture by two target-dissimilar cues that were also redder (i.e., a red cue among orange cue context items, and a gold cue among yellow cue context elements) to capture by a cue that had the same colour as the target but did not match the relative target colour (i.e., an orange cue among red context items). In line with the relational account, the target-dissimilar redder cues both captured attention, despite the fact that one of the cues had the colour of the nontargets. However, the target-similar cue that did not share the target's relative colour (i.e., yellow) failed to capture attention. These results showed that attention was tuned to the context-dependent, relative target colour, rather than to the specific colour of the target.

Critically, proponents of the relational account assume that that validity effects for the relationally matching cues were driven by a single attentional orienting mechanism that results in a temporary *enhancement* in signal processing at the cued location relative to uncued locations (e.g., Becker et al., 2013). However, spatially non-predictive cues can also trigger other processing mechanisms. Prinzmetal and colleagues (Prinzmetal & Landau, 2010; Prinzmetal,

Ha, & Khani, 2010; Prinzmetal, McCool, & Park, 2005; Prinzmetal, Park, & Garrett, 2005; Prinzmetal, Taylor, Myers, Nguyen-Espino, & , 2011; Prinzmetal, Zvinyatskovskiy, Gutierrez, & Dilem, 2009) showed that spatially non-predictive cues can result in the priming of decisional processes, critically, without a concomitant improvement in perceptual processing.

Prinzmetal and coworkers called this mechanism *channel selection* (Prinzmetal et al., 2010; Prinzmetal, McCool, et al., 2005; Prinzmetal, Park, et al., 2005). Channel selection is the decision about which location contains the target. Channels are location-specific evidence counters for target-related activity. On valid cue trials, the cue-generated evidence causes the target-generated evidence to reach a decision-threshold earlier than on invalid trials (in which the cue is presented at a nontarget location). Thus, channel selection can explain faster RTs on valid than invalid trials. However, as this mechanism does not change the processing rate of visual signals (contrary to an attentional enhancement mechanism), the perceptual representation of the target remains unchanged.

Importantly, the two processes make different predictions for speeded tasks, in which RT is the main dependent measure, and perceptual accuracy tasks, in which the proportion of correct responses<sup>1</sup> is the central dependent measure. To measure perceptual accuracy, the perceptibility of the target is typically degraded (e.g., Kerzel, Zarian, & Souto, 2009; Prinzmetal, McCool, et al., 2005), for instance, by presenting the target only briefly and masking it immediately after its offset (Breitmeyer & Ögmen, 2006). If (valid) pre-cues lead to signal enhancement, the perceptual representation of the subsequent target should be improved and, correspondingly, responses to the target should be more accurate on valid than invalid cue trials. For the same reason, RTs should be faster on valid than invalid trials. Conversely, if (valid) pre-cues only speed responses by priming decisional processes, the perceptual representation of the target should remain degraded, and the proportion of errors should not reliably differ on valid and invalid trials. However, mean RTs should still be faster on valid than invalid trials.

As previous studies contrasting feature-specific vs. the relational top-down tuning have never degraded perceptibility of the targets, it is currently unknown whether tuning attention to the relative feature affects attentional mechanism that lead to signal

enhancement or also channel selection mechanisms that prime decisional processes. Thus, to examine the mechanisms elicited by the cues in the modified spatial cueing paradigm of Becker et al. (2013), we presented the targets only briefly, backward masked them immediately afterwards, and used the proportion of errors on valid and invalid cue trials as main dependent measure. If relatively matching cues indeed affect early perceptual processes (i.e., cause signal enhancement), we would expect that relationally matching cues result in validity effects on error rates and RTs. If validity effects by relatively matching cues are however due to the priming of response-decisions, we would expect no validity effects on errors, but only on RTs. Finally, if the cues trigger a combination of decisional and signal enhancement processes, validity effects on errors might occur for the same cues that elicited validity effects in previous RT experiments (Becker et al., 2013, Experiment 1), but potentially also just for a subset of those cues. RTs should nevertheless reveal validity effects for the same cues as in those previous experiments.

## Experiment 1

In Experiment 1, we used colours varying along the red–yellow continuum similar to Becker et al. (2013) and measured discrimination accuracy to masked target displays. As in the study of Becker et al. (2013), we presented four different cue displays, in which the singleton cue was either yellower or redder, and either target-similar or target-dissimilar (see Figure 1A), to distinguish between top-down tuning to the exact target feature value versus the relative target feature. The target was an orange item presented among golden nontargets and, hence, was consistently redder than the nontargets.

After the target display, the target symbols were masked immediately. The mask consisted of an overlay of the two possible target characters = and X at each target location and, consequently, could be classified as pattern mask (Breitmeyer & Ögmen, 2006). To prevent ceiling or floor effects, only a certain percentage of the pixels composing the mask was presented. The percentage of pixels was determined in an adaptive staircase procedure in a pilot experiment. It was adapted such that the mean error rate was approximately 29% across all cue conditions. To avoid speed–accuracy trade-off, we explicitly

encouraged observers to be as correct as possible and, as speed was unimportant, to take as much time as needed. Feedback was provided after each trial and, additionally, after blocks of 32 trials. Finally, we monitored saccadic eye-movements to ensure that potential validity effects were attributable to covert attention.

If the pattern of cueing effects observed in RT experiments (Becker et al., 2013, Experiment 1) reflects signal enhancement by relationally matching cues, we would expect that only the relationally matching cues show validity effects on errors and RTs. However, if the pattern of validity effects obtained in previous RT experiments is the result of decision priming, we would expect no cueing effects on errors but only on RTs. If the validity effects in those RT experiments resulted from a combination of signal enhancement and decision priming, all relationally matching cues might elicit validity effects on errors or only a subset of those. RTs, however, should reveal validity effects for the same cues as in previous RT experiments.

## Method

### Participants

In all experiments, students from the University of Geneva took part for class credit. The study was approved by the ethics committee of the Faculty of Psychology and Educational Sciences, and informed consent was provided before the experiment started. All participants reported normal or corrected-to-normal visual acuity, and normal colour vision. Sixteen students accomplished Experiment 1 (16 female, median age of 19 years).

### Apparatus

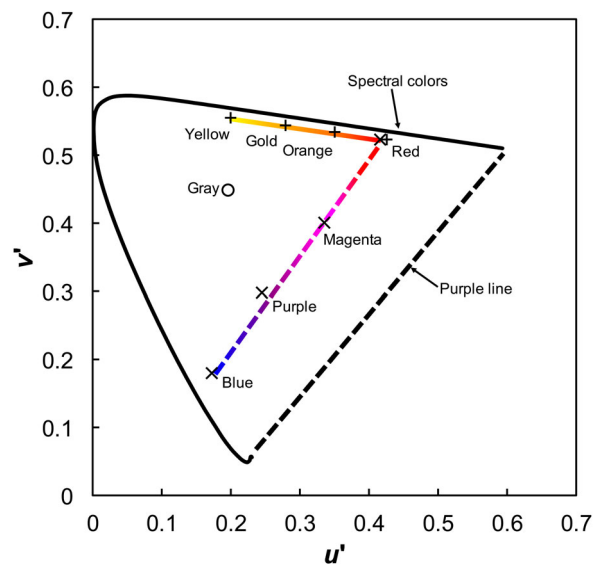
Participants were seated in a dimly lit room, and placed their heads on a chin rest, at a viewing distance of 65 cm from the stimulus monitor (21-inch CRT, 85 Hz, 1280 × 1024 pixels, white point D65). Observers pressed one of two designated response keys on a USB keyboard using the index and middle finger of their preferred hand. Colours were measured with a Cambridge Research Systems ColorCAL MKII colorimeter, and are specified in CIE 1976  $Lu'v'$  coordinates. Eye-movements were recorded at a sampling rate of 1000 Hz using the desktop-mounted EyeLink1000 (SR Research, Ontario, Canada).

### Stimuli

Stimuli were generated using the Psychophysics Toolbox (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997), and were presented on a black background ( $0.30 \text{ cd/m}^2$ ). Four types of displays were presented: fixation, cue, target, and mask display (Figure 1A).

The fixation display consisted of a central, grey ( $L = 23.01$ ,  $u' = 0.191$ ,  $v' = 0.433$ ) fixation cross ( $0.3$  degree of visual angle  $\times 0.3^\circ$ , line width of  $0.03^\circ$  or 1 pixel) and four grey placeholder rings ( $1.2^\circ$  diameter, line width of  $0.03^\circ$ ). The centres of the placeholders were positioned at a distance of  $5^\circ$  above, below, left, or right from the fixation cross.

The cue display consisted of the fixation display and an additional set of four disks ( $0.3^\circ$  diameter, line width of  $0.03^\circ$ ) around each of the four placeholders. The disks were centred on an imaginary circle of  $0.9^\circ$  around a placeholder, at the left, right, top, and bottom. The possible colours were red ( $L = 15.59$ ,  $u' = 0.426$ ,  $v' = 0.523$ ), orange ( $L' = 16.00$ ,  $u' = 0.350$ ,  $v' = 0.534$ ), gold ( $L' = 16.10$ ,  $u' = 0.280$ ,  $v' = 0.544$ ), and yellow ( $L' = 16.04$ ,  $u' = 0.200$ ,  $v' = 0.555$ ). The particular colour assignments of the cues and search items in the target displays are specified in Figure 1B. The colours were approximately equiluminant and



**Figure 2.** Colour coordinates in the 1976 CIE  $Lu'v'$  Chromaticity Diagram. The solid black line marks the spectral colours. The crosses (+) represent the colours used in Experiment 1, and the solid coloured line displays the theoretical yellow-red tuning dimension. The crosses (x) represent the colours in Experiment 2, and the dashed coloured line shows the blue-red tuning dimension.

equidistant in the CIE 1976  $Lu'v'$  chromaticity diagram (Figure 2).

The target display consisted of the fixation display and a coloured equals sign (=) or the character X (line length of  $0.6^\circ$ ) in each of the four placeholders. The identity of the items (= or X) was chosen randomly (equal probability for each of the two events) with the constraint that each display contained two = signs and two X characters.

The mask display consisted of the fixation display and a mask at each of the four placeholders. The mask was an overlay of the two possible target characters = and X and had the same colour as the preceding symbol in the target display. To avoid ceiling or floor effects, only a certain percentage of the pixels composing the mask was presented. To determine the percentage of pixels for the mask, six observers worked through an adaptive staircase procedure (two up, one down) in a pilot experiment. The percentage of pixels was adapted such that the mean accuracy was approximately 71% across all cue conditions. Based on the pilot experiment, 236 pixels or 65% of the pixels of each =/X overlay were presented. The positions of the pixels were randomly chosen on each trial and for each mask.

### Design

The 128 conditions resulting from the Cartesian Product of *cue type* (Cue 1, 2, 3, 4), *cue position* (placeholder 1, 2, 3, 4), *target position* (placeholder 1, 2, 3, 4), and *target identity* (=, X) varied across trials, and appeared in random order within an experimental block. Each subject completed four experimental blocks, resulting in 512 trials. For each cue type, there were 32 valid and 96 invalid trials.

### Procedure

Participants were instructed to search for the odd-coloured target and to report the character. Furthermore, participants were informed that the cue was non-predictive of the target location, and instructed to ignore the cue. After the initial instruction, participants worked through approximately 32 trials to familiarize themselves with the task.

A trial started with the presentation of the fixation display for 700 ms. The fixation cross then blinked off for 100 ms and the fixation display was presented for a randomly chosen time ranging from 600 to 1000 ms. Next, the cue display appeared for 94 ms. After an inter-stimulus interval of 94 ms, the target

was presented for 94 ms. The target display was immediately replaced with a mask display, which was presented until response.

Participants reported the target character (= or X) by pressing a designated key on the keyboard (left or right arrow key, respectively). If a response was too early ( $RT < 100$  ms) or incorrect, or an eye-movement or blink was registered, feedback was given by a beep along with a written word detailing the type of error. The right eye was monitored in the time interval starting at the end of the fixation blink-off and ending with the onset of the mask. A saccade was registered if the eye left an imaginary square of  $2^\circ$ , centred at the fixation cross. Participants were instructed to respond as accurately as possible, without consideration of response time.

### Results

An alpha level of .05 (two-sided) was used for determining statistical significance.

### Exclusions

Trials with anticipatory responses ( $< 1\%$  of all trials) and trials with eye-movements and blinks (median proportion of 6.7%, ranging from 2% to 15%) were excluded from further analyses. Three of the original 16 participants were replaced because of high proportions of saccades and blinks ( $> 15\%$ ).

### Errors

The averages of the proportions of errors appear in Figure 1C. A  $2 \times 2$  ANOVA comprising the factors *cue type* and *cue validity* computed over the mean errors revealed significant main effects of *cue type*,  $F(3, 45) = 10.5$ ,  $p < .001$ ,  $\eta_p^2 = 0.41$ , and *cue validity*,  $F(1, 15) = 17.7$ ,  $p = .001$ ,  $\eta_p^2 = 0.54$ . These main effects were qualified by a significant two-way interaction,  $F(3, 45) = 19.5$ ,  $p < .001$ ,  $\eta_p^2 = 0.57$ , indicating that cueing effects differed between different cue types. Consistent with the hypothesis that redder objects would capture attention, redder cues elicited significant validity effects: Cue 1, red among orange, 19%,  $t(15) = 5.5$ ,  $p < .001$ ; Cue 2, gold among yellow, 12%,  $t(15) = 5.3$ ,  $p < .001$ . In contrast, yellower cues resulted in significant inverse validity effects, with fewer errors on invalid trials than valid trials: Cue 3, orange among red,  $-12\%$ ,  $t(15) = -3.3$ ,  $p = .005$ ; Cue 4, yellow among gold,  $-6\%$ ,  $t(15) = -2.8$ ,  $p = .013$ .<sup>2</sup>

## RTs

The same two-way ANOVA computed over the median RTs revealed significant main effects of *cue validity*,  $F(1, 15) = 5.9$ ,  $p = .028$ ,  $\eta_p^2 = 0.28$ , and *cue condition*,  $F(3, 45) = 2.9$ ,  $p = .047$ ,  $\eta_p^2 = 0.161$ , as well as a significant interaction between these variables,  $F(3, 45) = 12.0$ ,  $p < .001$ ,  $\eta_p^2 = 0.44$ . Pairwise comparisons showed that the RT validity effect mirrored the validity effects on the error scores. The redder cues resulted in significant validity effects: Cue 1, red among orange, 147 ms,  $t(15) = 4.2$ ,  $p = .001$ ; Cue 2, gold among yellow, 103 ms,  $t(15) = 3.2$ ,  $p = .006$ . Conversely, the yellower cues resulted in inverse validity effects, with longer RT on valid trials: Cue 3, orange among red,  $-89$  ms,  $t(15) = -2.7$ ,  $p = .017$ ; Cue 4, yellow among gold,  $-58$  ms,  $t(15) = -2.81$ ,  $p = .023$ . Because validity effects on RTs were in the same directions as on errors, it is unlikely that the effects were due to speed-accuracy trade-off.

## Discussion

Validity effects on errors were only obtained with redder cues, that is, the cues that had the same relative colour as the target. This suggests that the mechanisms that tune attention to the relative target colour involve channel enhancement. As validity effects on accuracy were obtained in the same conditions as the RT effects of Becker et al. (2013), our accuracy data completely validate the findings obtained with RT experiments.

When cue and target displays had different relative colours, Becker et al. (2013) reported no reliable effects, whereas the current experiment yielded inverse validity effects. Inverse validity effects might indicate that the context items attracted attention, because they matched the search setting for redder (Harris, Remington, & Becker, 2013). Alternatively, inverse validity effects might indicate that cues with a relative colour opposite to that of the target were suppressed (Eimer, Kiss, Press, & Sauter, 2009; Lamy, Leber, & Egeth, 2004).

## Experiment 2

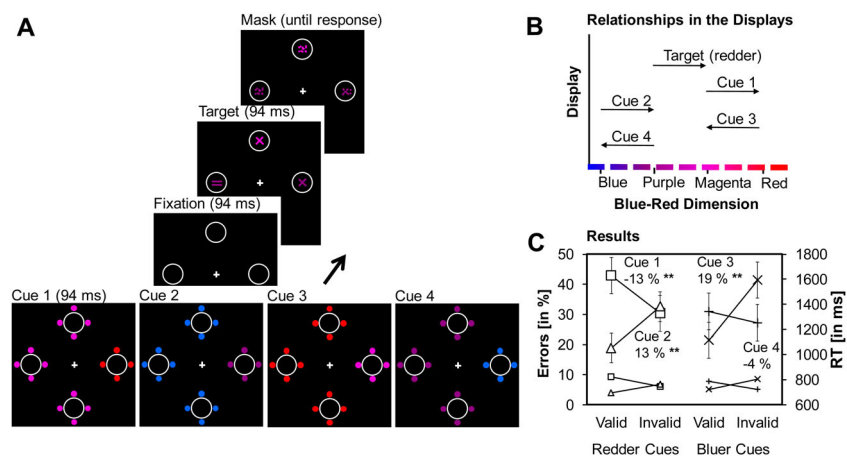
In principle, the relational theory claims that attention can be tuned to any arbitrary feature relation in a colour, shape, or size space. For the colour domain, the working hypothesis was that relations can be

formally described in the CIE  $Lu'v'$  colour space (Becker, 2010). So far, attentional capture by relatively matching cues was frequently reported with colours on the yellow-red continuum (Becker et al., 2013; Becker, Folk, & Remington, 2010; Harris et al., 2013) and rarely with other colours (e.g., hybrid green and red colours, Becker et al., 2013; colours on the green-blue continuum, Becker, Harris, York, & Choi, in press).

The CIE  $Lu'v'$  colour space, however, is based on the perceived match of colours. However, the mental mechanisms that mediate perceived colour might be different from the mechanisms that govern attentional colour tuning. For example, according to the CIE  $Lu'v'$  colour space, an orange target among gold nontargets is relatively redder, and also a magenta target among blue nontargets would be redder. However, the sensory mechanisms that process long-wavelength, yellow-red light compositions are different from the sensory mechanisms that analyse short-wavelength, blue-violet light compositions (Nathans, 1999; Neitz & Neitz, 2008). Hence, it is unclear whether colours between red and blue actually form a continuum of inter-related colours as the yellow-red continuum and, hence, whether it is possible to tune attention to relatively bluer or redder when a magenta target is consistently presented among all-red or all-purple nontarget items.

In Experiment 2, we addressed this question, using the design and procedures from Experiment 1 to test whether possible cueing effects are due to signal enhancement or decision priming. In Experiment 2, we presented four different cue displays, in which the singleton cue was either bluer or redder, and either target-similar or target-dissimilar (Figure 3A). Observers searched for a magenta target among purple nontargets.

Since the target was redder, the relational account predicts that the redder cues should capture attention (i.e., a red cue in magenta context, and a purple cue in blue context), but not the relatively bluer cues (i.e., a magenta cue in red context, and a blue cue in purple context). A feature similarity account would predict instead that target-similar cues should capture attention most strongly (i.e., the magenta cue in red context), whereas the remaining cues should fail to capture. Accordingly, either only the relatively or the physically matching cues should elicit validity effects on errors and RTs.



**Figure 3.** (A) Schematic of the displays used in Experiment 2. (B) Feature relationships represented as arrows on a theoretical blue–red tuning dimension. (C) The upper graphs represent the means choice error rates (left scale, large symbols) on valid and invalid cue trials. The text fields next to the error graphs show the average cueing effects. The bottom graphs depict mean median RTs (right scale, small symbols).

### Participants

Sixteen new students (15 female, median age of 20 years) participated in Experiment 2.

### Apparatus, stimuli, design, and procedure

The methodological details were the same as in Experiment 2, except that colours ranged from red to blue. The colours were red ( $L = 9.44$ ,  $u' = 0.417$ ,  $v' = 0.523$ ), magenta ( $L = 9.41$ ,  $u' = 0.335$ ,  $v' = 0.400$ ), purple ( $L = 9.40$ ,  $u' = 0.245$ ,  $v' = 0.298$ ), blue ( $L = 9.49$ ,  $u' = 0.172$ ,  $v' = 0.180$ ), and grey ( $L = 9.51$ ,  $u' = 0.196$ ,  $v' = 0.449$ ). The particular colour assignments in the cue and target displays are specified in Figure 3B. These colours were equiluminant and equidistant in the 1976 CIE  $u'v'$  space (Figure 2). A pilot experiment ( $n = 3$ ) was run to determine the percentage of pixels for the overlay mask (65%).

### Results

#### Data

Trials with anticipatory responses ( $RT < 100$  ms) were removed ( $< 1\%$  of all trials). Trials with eye-movements and blinks were excluded from further analyses (median proportion of 5.6% of all trials, ranging from 2% to 15%).

#### Errors

The results of Experiment 2 are presented in Figure 3C. The same ANOVA as in Experiment 1 showed

significant main effects of *cue validity*,  $F(1, 15) = 25.5$ ,  $p < .001$ ,  $\eta_p^2 = 0.62$ , and *cue type*,  $F(3, 45) = 13.8$ ,  $p < .001$ ,  $\eta_p^2 = 0.49$ , as well as a significant two-way interaction,  $F(3, 45) = 14.4$ ,  $p < .001$ ,  $\eta_p^2 = 0.49$ , implying that cueing effects differed depending on the cue type. Cues resulted in validity effects when their colour was more similar to the target colour: Specifically, Cue 2, purple among blue, 13%,  $t(15) = 6.0$ ,  $p < .001$ , and Cue 3, magenta among red, 19%,  $t(15) = 4.8$ ,  $p < .001$ , both produced significant validity effects that are consistent with signal enhancement of the target. In contrast, cues failed to elicit validity effects on errors when the contextual cues were similar to the target colour. Specifically, both the relationally matching cue, Cue 1, red among magenta,  $-13\%$ ,  $t(15) = -2.8$ ,  $p = .013$ , and Cue 4, blue among purple,  $-4\%$ ,  $t(15) = -1.3$ ,  $p = .199$ , failed to capture attention, and the red cue even showed an inverse cueing effect.

#### RTs

The same ANOVA as above was performed on RTs. It showed a significant main effect of *cue type*,  $F(3, 45) = 4.95$ ,  $p = .005$ ,  $\eta_p^2 = 0.25$ , that was qualified by a significant two-way interaction,  $F(3, 45) = 3.23$ ,  $p = .031$ ,  $\eta_p^2 = 0.17$ . Pairwise comparisons showed that the RT cueing effect mirrored the accuracy effects. The target-similar cues, Cue 2, purple among blue, 53 ms,  $t(15) = 2.72$ ,  $p = .016$ , and Cue 3, magenta among red, 89 ms,  $t(15) = 2.35$ ,  $p = .033$ , both showed significant validity effects. In contrast, the target-dissimilar cues, Cue 1, red among magenta,



–49 ms,  $t(15) = -0.90$ ,  $p = .381$ , and Cue 4, blue among purple, –57 ms,  $t(15) = -2.60$ ,  $p = .020$ , produced no or inverse validity effect. As in Experiment 1, validity effects on RTs were in the same directions as on errors. Hence, we can exclude that the effects on errors were due to speed–accuracy trade-off.

## Discussion

As in Experiment 1, we obtained significant cue validity effects on target identification accuracy, indicating that the validity effects were due to early perceptual processes (signal enhancement) rather than decisional priming (channel selection). However, the results of Experiment 2 contrast with the assumption that attention can be tuned to arbitrary relative colours that form a continuum in CIE  $Lu'v'$  space. In this case, only the cues with the same relative colour as the target should have elicited validity effects (Cue 1 and 2). Instead, we observed validity effects by the purple (redder) cue among blue other cues (Cue 2) and the magenta (bluer) cue among red cues (Cue 3). With this, the results are also deviating from a tuning account that assumes that attention is narrowly tuned to a particular feature value because capture was also observed for a purple cue that had a different colour from the target (magenta). Instead, the results would be consistent with broader tuning accounts that assume that attention is tuned rather broadly to colours such that the width of the tuning function includes a range of similar colours (e.g., Wolfe, 1994; see also Hodsoll & Humphreys, 2001; Hodsoll, Humphreys, & Braithwaite, 2006).

According to such a broad tuning account, the attention-driving capacity could have been largest for cues that perfectly matched the target colour (magenta), intermediate for the similar colours such as purple and red, and smallest for the dissimilar colour (i.e., blue). According to this ordering, magenta cues would have won the competition against red context cues, and purple cues would have dominated over blue other cues, explaining why the magenta and purple cues improved perceptual accuracy in Experiment 2.

This account further predicts that magenta context cues might have won the competition against a red cue, which could also explain the inverse validity effect for red cue in the magenta context (Cue 1). Finally, purple context cues might have attracted

attention more than a blue cue but, because the attention-driving capacity of purple was intermediate, we only obtained a non-significant inverse validity effect (Cue 4).

Although a broad attentional tuning account could potentially explain the results of Experiment 2, none of the cited accounts currently assumes these particular parameters for top-down control. According to the Guided Search model, the maxima of tuning functions are fixed (to red, green, yellow, and blue; Wolfe, 1994), so that the red cue among magenta contextual elements (Cue 1) should have captured instead of the magenta cue among red elements (Cue 3). Other accounts assume that the nontarget features would be suppressed in search for the target (Navalpakkam & Itti, 2007) and, accordingly, the purple cue in the blue cue context (Cue 2) should not have captured attention, as it had the same colour as the nontargets. The results of Experiment 2, in turn, demonstrate that attention can be maximally tuned to an intermediate colour (i.e., magenta), and that even cues with the features of the nontargets can increase perceptual sensitivity for the target.

## General discussion

The present study provided two central insights. First, observers were more accurate to identify masked targets on valid than invalid cue trials in several cue conditions, even though the cues were spatially non-predictive. This finding suggests that those cues enhanced the target signal and, thus, modulated early perceptual processes. This result is noteworthy, given the numerous previous experiments in which non-predictive cues only exerted validity effects in experiments designed to measure RT experiments, but not in accuracy experiments, which suggested that non-predictive cues cause decision priming rather than signal enhancement (Kerzel et al., 2009; Prinzmetal, McCool, et al., 2005). The present study clearly showed that non-predictive spatial cues can improve perception of the target, presumably via top-down tuning of attention to the relative (Experiment 1) or the specific colour of the target (Experiment 2), which led to signal enhancement by cues with target-matching properties (see Prinzmetal et al., 2011, for predictions pointing to this possibility).

The second significant finding is that, in Experiment 1, cue validity effects on error rates were observed

when the cues matched the relative target colour. With this, Experiment 1 is the first demonstration that cues that are dissimilar to the target (and/or similar to the nontargets) can enhance the target representation, via top-down tuning to the relative attributes of the target. By contrast, Experiment 2 revealed cueing effects only for cues that were similar to the specific target colour. This finding is exceptional, not only against the background of Experiment 1, in which attention was tuned to redder, but also against the background of studies where attention was tuned to other relative colours (Becker et al., 2010, 2013), to relative size (Becker, 2010; Harris et al., 2013) or the relative shape of the target (Becker, 2013).

As mentioned above, the results of Experiment 2 were also atypical in that they reflected a broad attentional tuning to the target colour, which is not predicted by any of the extant feature-specific accounts. Why was attention rather broadly tuned to the physical target colour in Experiment 2? One possibility is that attentional tuning depends on where in the spectrum the colours are drawn from. Another possibility is that attentional tuning depends on the target–nontarget similarity. More specifically, one explanation for the failure to observe relative tuning to redder in search for a magenta target could be that non-spectral colours on the purple line of the CIE space are processed by the mechanisms that usually process short-wavelength violet (Neitz & Neitz, 2008), and that relative tuning simply does not occur between colours on opposite sides of the visible spectrum, but only between neighbouring spectral colours along the CIE “horseshoe” (see Figure 2).

Another explanation could potentially be derived from alternative, feature-based attentional tuning accounts. In the Discussion of Experiment 2, we mentioned that the current results cannot be accommodated by an account that assumes narrow tuning functions. A tuning function specifies how much each particular feature value is enhanced by a given top-down bias and, hence, how much attention-capturing capacity an item with the respective feature value will have (salience calculations not considered). If attention had been *narrowly* tuned to the target feature (magenta) in Experiment 2, only the target-coloured magenta cue (Cue 3) should have resulted in a cueing effect because the attention-driving capacity would have been larger for the magenta

cue than for the red contextual cue elements. If attention was tuned *broadly* to the target feature, also purple items would have gained attention-driving capacity, but blue items would have received only little gain. Hence, a broad tuning account is consistent with the results of Experiment 2.

In Experiment 1, attention might have been tuned in a similarly broad manner to red, away from the actual target colour orange, to optimize differentiation between target and nontargets signals (e.g., Navalpakkam & Itti, 2007). A broad attentional set for red would be able to account for the results, if we assume that the peak of the tuning function was closer to red than orange, and that the tuning function was wide enough to still encompass the nontarget colour (yellow–orange). In this scenario, all redder cues should attract attention as long as they are presented in a cue context that is yellower (i.e., further away from the peak), which would explain the findings of Experiment 1.

An *optimal tuning* account predicts that attention is tuned to the extreme colour when target–nontarget discriminability is low, but not when it is high (Navalpakkam & Itti, 2007; Scolarì & Serences, 2010). As the colour coordinates in Figure 2 suggest, the colours in Experiment 1 were indeed more similar than in Experiment 2, so that the present set of results could also be consistent with an optimal tuning account. A similar explanation can be derived from the *attentional engagement* theory of Duncan and Humphreys (1989, 1992). They proposed that attentional templates can be formed more easily for endpoints than intermediate values of feature dimensions, so that attentional weights are therefore larger for extreme (endpoint) features than for intermediate features. Accordingly, in Experiment 1, in which target–nontarget similarity was relatively high, it might have been relatively difficult to form a template for the intermediate orange target and, hence, participants instead adopted a template for red. In Experiment 2, in which the distance between the target and nontarget colours in feature space was higher, it might have been easier to bias attention to the magenta target (i.e., configure a template for the magenta target). In this sense, the different results in Experiment 1 and Experiment 2 might reflect the flexibility of attentional control, which adopts the control strategy that guarantees target detection with highest efficiency (see Scolarì & Serences, 2010).

A third noteworthy finding of the present study was that discrimination accuracy was even lower on valid compared to invalid trials when cues and targets did not match the relational (Experiment 1) or the specific target colour (Experiment 2). Becker et al. (2013) had observed no effects at all in the corresponding conditions, whereas Harris et al. (2013) also reported inverse validity effects on RTs. Since the stimuli in the previous and the current study were very similar, it is unclear what causes the presence or absence of inverse cue validity effects. However, the present study shows that those effects can involve signal enhancement processes. There are at least two possible explanations how cues with target non-matching properties could produce inverse validity effects.

One possibility is that inverse effects are caused by selection of one or more of the cue context items, which matched the respective top-down settings. In Experiment 1, for instance, when participants searched for the redder (orange) target, the golden context elements were redder compared to the yellow singleton cue, and therefore matched the search setting for the redder target. This account of the reversed effects would be in line with the relational view. In Experiment 2, in which attention was probably tuned to the target colour magenta, the cue display with the magenta contextual cues also resulted in an inverse validity effect, similarly suggesting that task-set matching contextual cues captured attention.

Results from the study of Lien, Ruthruff, and Cornett (2010) support this possibility. In their study, the target had a particular colour (e.g., red) and appeared among heterogeneous nontargets. The cues were pop-out stimuli, as in the present study, and there were no inverse cueing effects in one cue condition, in which neither the cue singleton nor the cue context items had the target colour (e.g., a green singleton among three blue context items). However, Lien et al. (2010) observed inverse cueing effects in a second cue condition, in which the cue singleton had an unrelated colour (e.g., green) and the cue context elements contained the target colour (e.g., red). As inverse cueing effect only appeared when the cue context items had the target colour, the authors proposed that the inverse cueing effects were attributable to selection of the cue context items.

A second possibility is that the inverse cueing effects on discrimination accuracy reflect spatially

specific inhibition of the cue singleton. Certainly, accounts that link inverse RT cue validity effects to inhibition are usually formulated to propose inhibition of specific feature values or other specific object characteristics rather than the relative features of target and cue (Anderson & Folk, 2012; Belopolsky, Schreij, & Theeuwes, 2010; Gaspelin, Leonard, & Luck, 2015, 2017; Sawaki & Luck, 2010, 2013a, 2013b). Nevertheless, in theory, it is also possible that target dissimilar relative features are suppressed and that corresponding items are inhibited. However, inverse cueing effects have frequently been reported to occur, and further experiments are necessary to identify the underlying causes, specifically with regard to relationally mismatching cues (Harris et al., 2013).

In sum, the present study provides clear evidence that cues that match the current task-set for relative or specific colours result in signal enhancement at the cued location. Even though Experiment 1 supported the idea that signal enhancement can be brought about by top-down tuning of attention to relative colours, Experiment 2 showed that attention can also be tuned broadly to a specific feature value, indicating that tuning to relative colours may not be possible for all colours in CIE colour space, specifically not for those falling on the purple line of CIE colour space.

## Notes

1. We display the percentage of errors instead of the usual percentage of correct responses to make the results more easily comparable to those from RTs experiments.
2. The validity effect for the cue with the more extreme colour (Cue 1) tended to be larger than that for the less extreme cue (Cue 2),  $F(1, 18) = 3.8$ ,  $p = .064$ ,  $\eta_p^2 = 0.17$ . It is currently unclear why these validity effects differed in size; however, these differences in the magnitude of validity effects appear to be unreliable across studies. In studies that measured validity effects on mean RTs, no such differences occurred (Becker et al., 2013; Harris et al., 2013), or the validity effects for the more extreme cues were smaller than for the less extreme cues (Schönhammer, Grubert, Kerzel, & Becker, 2016). Moreover, inverse validity effects tended to be larger for Cue 3 than Cue 4,  $F(1, 15) = 3.4$ ,  $p = .073$ ,  $\eta_p^2 = 0.16$ , but also this difference was unreliable across studies.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

## Funding

DK and JGS were supported by the Swiss National Foundation grants PDFMP1-129459 and 100014\_162750. SIB was supported by an Australian Research Council Future Fellowship (FT130101282); Schweizerischer Nationalfonds zur Förderung der Wissenschaftlichen Forschung.

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