VISUAL COGNITION
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Target templates in singleton search vs. feature-based search modes

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ABSTRACT

It is well-known that visual attention can be tuned in a top-down controlled manner to various attributes. Amongst other search strategies, previous research has identified a feature search mode in which attention is tuned to the target feature (e.g., colour) vs. a singleton search mode, where all salient items can attract attention. A short review of the literature reveals that singleton search mode is not regularly applied in single-target search, but could play a role in two-target search. Here we critically tested whether results suggesting singleton search could alternatively be due to top-down tuning to different attributes of the targets (e.g., luminance). The results of the first experiment show a mixture of attentional tuning to the target colours (red, green), as well as luminance (darker), and residual singleton capture. A second experiment shows that such mixed results can be obtained in the standard paradigm, with only small changes to the stimuli. These results cannot be coherently described within a single mental representation, and are therefore difficult to reconcile with the notion of a target template. Non-representational theories such as feature map theories seem better equipped to explain mixed search results, which could be a decisive weakness of representational theories.

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Introduction

Visual attention modulates sensory and cognitive processes to select the most relevant objects for further in-depth processing, which gates access to awareness. Given the importance of attention for conscious perception and behaviour, much research has been devoted to identify how we allocate visual attention. It is well-known that early, transient attention is determined by an interplay of two attentional control systems: First, objects with the same features (e.g., colours: all green objects) inhibit each other via lateral inhibitory connections, so that a stimulus with a single deviant feature (*singleton*; e.g., a red object) seems to pop out. This is part of an automatic, hard-wired, bottom-up, stimulus-driven system that prioritises stimuli that have a high local feature contrast (e.g., Itti & Koch, 2000; Theeuwes, 1992). Secondly, attention can be tuned or biased in a top-down controlled manner to the features of items that match our current goals (e.g., Folk & Remington, 1998; Folk, Remington, & Johnston, 1992; Wolfe, 1994). For instance, according to feature similarity views, we have a mental representation of the target (*target template*) that specifies the task-relevant feature (e.g., particular colour, orientation, shape), and limits processing to items that match this feature (e.g., Duncan & Humphreys, 1989; see also Folk & Remington, 1998; Wolfe, 1994).

There has been a lot of debate about which of the two control systems (bottom-up, top-down) dominates the other. Initially, attention was believed to be largely determined by bottom-up processes (e.g., Itti & Koch, 2000; Nothdurft, 2015; Theeuwes, 1992; Treisman & Gelade, 1980; Wolfe, Cave, & Franzel, 1989). For instance, Theeuwes (1992) found that an irrelevant colour singleton (i.e., a red item among green items) can interfere with search for a shape target even when it is completely irrelevant and argued that salient items can automatically and involuntarily attract attention – regardless of whether they are in line with our intentions and goals or not (*singleton capture hypothesis*).

However, later studies used more spatially specific measures of attention, which showed that irrelevant distractors attract attention much more strongly when they are similar to the target, and do not (strongly) attract attention when they do not match the target features (e.g., Folk et al., 1992; Folk & Remington, 1998; Ludwig & Gilchrist, 2002). In addition, Bacon and Egeth (1994) pointed out that most studies

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showing distraction by irrelevant salient items also used a salient target, so that it is possible that observers were actively attending to singletons (or all deviants), because the target had a unique feature (*singleton detection mode*). In this instance, attentional capture by an irrelevant singleton would be due to observers adopting a fairly broad top-down setting for the target: Rather than tuning attention to the specific feature of the target (e.g., target shape or colour; *feature search mode*), search was geared towards singletons, which led to capture by irrelevant singletons. However, as this was the result of a strategic choice, capture by singletons was not purely bottom-up.

Bacon and Egeth (1994) also proposed that singleton search mode may be the preferred or *default* search strategy when the target is salient. However, the majority of studies suggests that attention is by default tuned to the specific target feature (e.g., red), even when the target is salient. For instance, Folk and Remington (1998) asked observers to search for a salient target with a specific colour (e.g., red, among 3 white non-targets), and presented an irrelevant salient pre-cue prior to the target that could either indicate the target location (valid cue) or a non-target location (invalid cue). They found that a salient cue (e.g., red cue) only captured attention when observers were searching for a target with corresponding features (e.g., red target), as reflected by a significant validity effect (with faster responses on valid than invalid trials). The same cue failed to attract attention when observers were searching for a different target (e.g., green target; as reflected in a zero validity effect), demonstrating that attention was tuned to the feature of the salient target, and modulated attentional capture.

In line with the findings of Theeuwes (1992), the same experiment showed that a salient, non-matching pre-cue could elongate response times (RT), even if it did not attract attention (as indicated by the zero validity effect), which led Folk and Remington (1998) to conclude that salient irrelevant items can produce spatially unspecific interference or "*filtering costs*". Unspecific filtering costs may be due to the fact that a salient, irrelevant distractor is still encoded into visual short-term memory (Martin & Becker, 2018; see also object updating cost; object files; Kahneman & Treisman, 1984), or that observers actively inhibit the distractor feature (Becker, 2007; see also Treisman & Sato, 1990).

In line with these findings, several EEG studies later showed that an irrelevant salient distractor that does not match the target also does not produce a significant N2pc, which is a marker of attentional selection (e.g., Eimer, Kiss, Press, & Sauter, 2009). Thus, while irrelevant salient distractors can interfere with search and elongate RT, they do not usually attract attention to their location, but can produce spatially unspecific (filtering) costs.

Becker (2007) examined the conditions that would produce singleton capture vs. filtering costs in visual search for a size target, and found exactly the same result, that irrelevant colour singletons could elongate RT without producing any spatially specific effects (e.g., compatibility effects, distance effects). The irrelevant distractor captured attention only when the features of the distractor and the remaining items switched across trials (e.g., presenting either a red colour singleton among other green items or vice versa, a green singleton among other red items). The irrelevant colour singleton captured attention only on switch trials, reflecting that switching colours impaired top-down selection of the size target (Becker, 2007). Eye tracking studies showed exactly the same result, that a salient distractor is not selected above chance when it does not match the target (Becker, 2010a). Again, capture of the gaze was found only on switch trials, indicating that capture by the distractor depended on intertrial priming effects (Becker, 2010a; Maljkovic & Nakayama, 1994): Selection of the target on a given trial *primes* attention and eye movements towards selecting the same colour on the subsequent trial(s), which leads to selection of the distractor when the colours of target and distractor switch (but more precise target selection if the colours of target and distractor are repeated; Becker, 2007, 2008a, 2008b, 2010a; see also Becker, Ansorge, & Horstmann, 2009; McPeek, Maljkovic, & Nakayama, 1999). Intertrial priming effects directly reflect feature specificity in search for a salient target, and thus do not support the view that attention is biased indiscriminately to select singletons in search for a salient target (i.e., no singleton detection mode, Bacon & Egeth, 1994).

In sum, there is clear evidence that top-down tuning of attention to a particular feature (i.e., feature search mode) can eliminate bottom-up saliency effects, and neutralise the attention-driving capacity of an irrelevant salient distractor, provided that the conditions allow effective top-down tuning of attention (i.e., when the target and distractor features remain constant). In these instances, the distractor will not attract attention to its location, but may still produce unspecific interference or filtering costs, highlighting the importance of assessing attentional capture with spatially specific measures. There is also a lot of evidence that attention is in fact tuned to the feature of the target and that observers do not engage in singleton detection mode, even when the target is salient and it would in principle be possible to find it in virtue of its saliency alone. That said, the frequent failure to find evidence for "pure" singleton search does not mean that the singleton status is completely irrelevant, even when the results show evidence for feature-specific search. Moreover, singleton search may still be the default search mode in search for *multiple* possible targets.

For instance, Folk and Anderson (2010) found evidence for singleton search in a spatial cueing task where observers had to search for a salient red or green target that was presented among white non-target items. In the study, a blue cue attracted attention to the same extent as a red or green cue, as reflected in significant validity effects (that were also of the same magnitude across all cue conditions). The finding that both the target-matching red and green cues and the non-matching blue cue captured attention to the same extent supports singleton search mode, and indicates that it may be the default search strategy in search for multiple targets (Folk & Anderson, 2010; Bacon & Egeth, 1994; but see Grubert & Eimer, 2016; Irons, Folk, & Remington, 2011). However, a recent study by Harris, Becker, and Remington (2015) indicated that singleton search mode may not entail selection of any singletons but may be specific to the stimulus dimension of the target (e.g., colour dimension). In the study, they replicated Folk and Anderson's (2010) findings, but additionally included an irrelevant motion cue. The results showed equally strong capture by red, green and blue cues, but no capture, or much reduced capture by the motion cue (Harris et al., 2015; Exp. 1 and 2). These results do not support a singleton search mode in which all salient items indiscriminately attract attention in virtue of their bottom-up saliency, but instead suggest that singleton search may still be governed by top-down processes specifying the target dimension. The finding of dimension-specific singleton search implies that singleton search is more under top-down control than originally thought (as singleton search is limited to the task-relevant stimulus dimension). While most current theories of attention do not allow top-down tuning of attention to a particular stimulus dimension (e.g., Becker, 2010b; Duncan & Humphreys, 1989; Navalpakkam & Itti, 2007; Wolfe, 1994), the results are consistent with the *dimension weighting account*, that attention is usually biased to a stimulus dimension (e.g., Found & Müller, 1996; Liesefeld & Müller, 2019; Liesefeld, Liesefeld, Pollmann, & Müller, 2019; Müller, Heller, & Ziegler, 1995; Zehetleitner, Goschy, & Müller, 2012).

Alternatively, it may still be possible to explain previous reports of singleton search by a slightly different feature-based top-down setting. Of note, in the studies above, the red or green target was always embedded among white non-target items, rendering the targets consistently darker than the non-target items. Hence, it is possible that attention was tuned to darker items (e.g., Becker, 2010b; Becker, Folk, & Remington, 2013), or the specific brightness level of the red and green targets (e.g., Navalpakkam & Itti, 2007; Wolfe, 1994), and that the red, green and blue cues attracted attention because they were all darker than the other items and hence, matched the target template. Tuning to dark(er) items can also explain why the motion cue failed to capture attention in the study of Harris and colleagues (2015), as the motion cue was rendered in white, and thus, did not match the target template (of darker; Harris et al., 2015).

Another possible explanation is that attention was tuned to the relative colours of the targets (greenest or reddest item; Becker, 2010b; Becker, Folk, & Remington, 2010; Becker et al., 2013), or the specific colours (red, green; e.g., Duncan & Humphreys, 1989; Navalpakkam & Itti, 2007; Wolfe, 1994), and that other colours were able to attract attention because red and green are on opposite sides of colour feature space (e.g., CIE space), which can co-activate colours that are in-between (e.g., because attention needs to be tuned to different directions in feature space, or to a large area; e.g., Becker, 2010b, Becker et al., 2013; Duncan & Humphreys, 1989), or due to other limitations in top-down tuning (e.g., that we can only tune attention to a single feature within each dimension; e.g., Huang, Treisman, & Pashler, 2007; or to a single channel; e.g., Wolfe, 1994). Such instances of co-activation are difficult to distinguish from a genuine top-down setting to all colours in the colour dimension (dimension weighting; Müller et al., 1995), but would have the added advantage of being able to explain why search for a single feature (e.g., only red) usually results in tuning attention to a specific feature (e.g., red, or the reddest item) rather than the entire colour dimension (e.g., Folk & Remington, 1998; but note that colours can also behave like sub-dimensions; e.g., Found & Müller, 1996; Liesefeld & Müller, 2019). While a co-activation account would be difficult to distinguish from top-down tuning to the colour dimension, it is possible to distinguish these views from top-down tuning to all darker items, or the brightness level of the targets.

In the present study, we critically tested whether previous results suggesting dimension-specific singleton search / singleton capture were due to observers tuning attention to the brightness level of the target or all darker items (Becker, 2010b). To that aim, we conducted two spatial cueing experiments that were similar to the previous studies showing singleton search, and systematically manipulated the brightness of different colours. If the results show feature-based tuning to the brightness of the target, this would establish that feature-based tuning is preferred to singleton search, even in search for two different targets. A corresponding result would also call into question previous findings showing dimension-specific singleton search, and demonstrate that attention can be tuned to the target's brightness when the task requires tuning to two different target colours.

Experiment 1

To test whether attention may have been tuned to darker stimuli, we systematically manipulated the colours in this experiment. As in the original studies (Folk & Anderson, 2010), the targets (red, green) were distinctly darker than the nontargets, which were medium-grey. A first set of cues was designed to mimic the original set of cues, and consisted of dark red, dark green and dark blue cues, whereby the red and green cues matched the target colours and the blue cue was an equiluminant, non-matching cue. In addition, we presented equiluminant light red, light green and light blue cues that were lighter than the grey nontargets (and other cues in the context), while still maintaining similar hues as the original red, blue and green colours (see Figure 1).

In singleton detection mode or dimension-specific search, all of the cues should attract attention equally, regardless of their luminance or colour. On the other hand, if attention is tuned to darker stimuli, only the dark red, green and blue cues should attract attention, whereas the light red, green, and blue cues should not capture.

Attentional capture was assessed as in previous studies, by assessing cue validity effects: If a given cue attracts attention, responses should be faster when the cue is presented at the target location than at a nontarget location. Although the main predictions concerned response times (RT), we also inspected the mean error scores, to check for possible speed-accuracy trade-offs. Moreover, to ensure that the data were not contaminated by eye movements, we monitored fixation with an eye tracker and removed trials with eye movements.

Methods

Participants

Fourteen participants with normal colour vision and normal or corrected-to-normal vision participated in the study for course credit or monetary compensation (\$10/h). The sample size was chosen to match the original study of Folk and Anderson (2010; Exp. 1) very closely, which comprised 13 participants. All methods and procedures of this study were approved by an Ethics Committee of The University of Queensland and were in line with the Declaration of Helsinki.

Apparatus

The participant's head and chin were placed in a headrest and chin-rest of a video-based eye tracker (Eyelink 1000, SR Research, Ontario, Canada) that monitored the participant's eye movements at 500 Hz. Stimuli were displayed on a 19″ CRT colour monitor with a resolution of 1,280 × 1,024, and viewed from a distance of 62 cm. The timing of the experiment was controlled using the software Presentation (Neurobehavioural systems) and responses were collected with a standard USB mouse.

Stimuli

All stimuli were presented against a white background. The fixation display consisted of 4 placeholder boxes

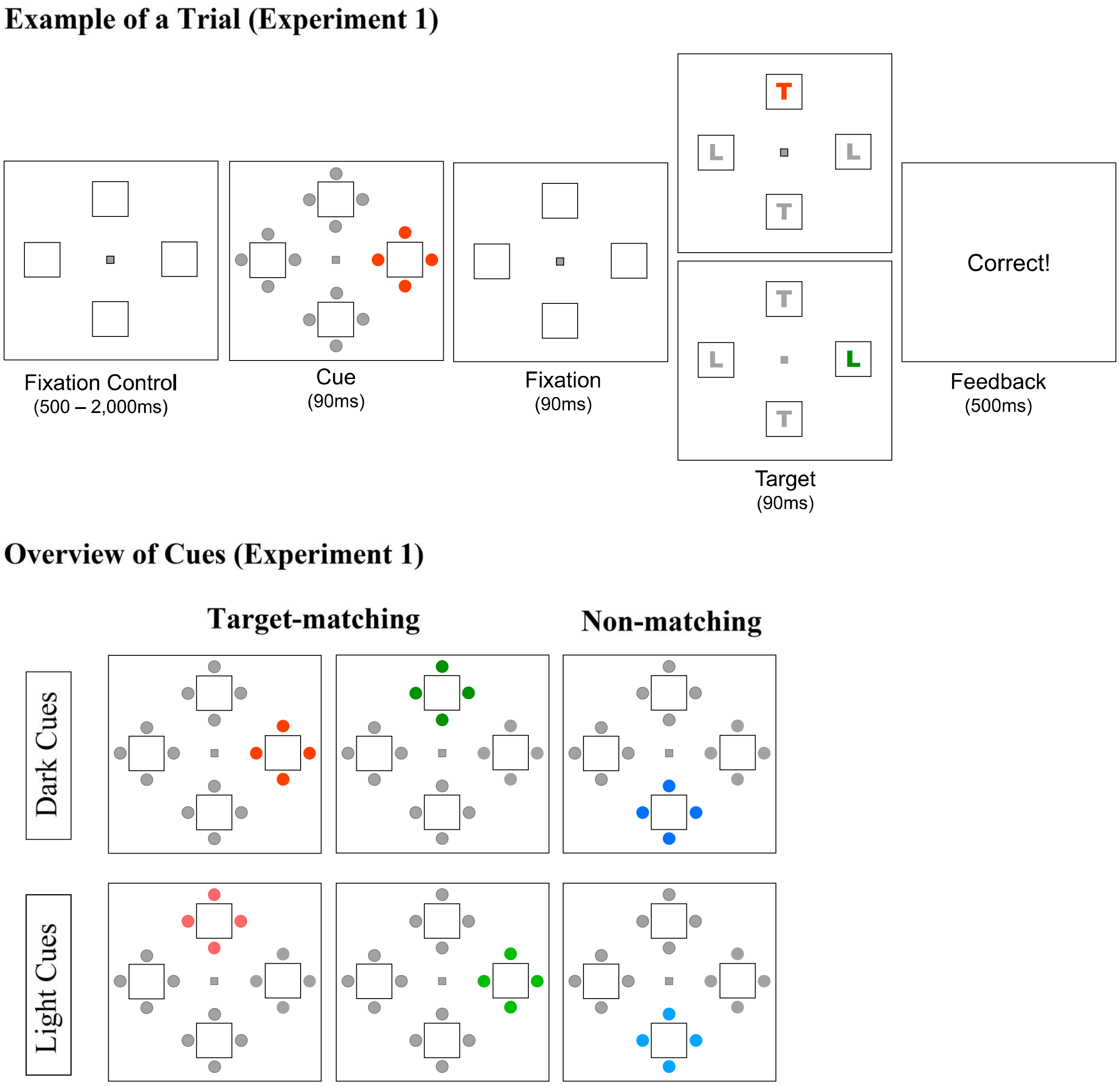

Figure 1. Overview of the stimuli and procedures used in Experiment 1. The target was a dark red or green item, which was darker than the grey non-targets, and observers had to indicate whether the target was a T or L. Prior to the target display, a cue was presented that could be either red, green or blue, and that could be lighter or darker than the grey cues in the context, which had the same colour as the non-targets. The top panel shows an example for a trial; the bottom panel shows the cue colours (target-matching dark red and dark green cue; dark blue cue; light red, light green and light blue cue).

outlined in black that measured 1.48° × 1.48° (degree of visual angle) and were positioned in a diamond configuration 5.1° from a central black fixation square (0.23° × 0.23°; centre-to-centre). Cue displays consisted of the fixation display with the addition of 4 four-dot cues that surrounded each placeholder box (diameter: 0.23°; see Figure 1). Search displays consisted of the fixation display with the addition that each placeholder box contained a T or L (Arial Black 13pt; size: 0.74° × 0.74°; line thickness: 0.28°).

The possible targets in the spatial cueing task were equiluminant red [*Lu′v′*: 14.9, .295, .480], or green [*Lu′v′*: 14.3, .130, .588], and were presented among grey non-targets that were visibly lighter [*Lu′v′*: 28.8, .174, .472], thus allowing locating the targets by tuning attention to darker stimuli. The cues consisted of target-matching dark red and dark green cues that had the same colours as the target, and a non-matching blue cue that had the same luminance [*Lu′v′*: 14.2, .154, .390]. In addition, there was a set of brighter cues that were noticeably brighter than the grey nontargets and could be light red [*Lu′v′*: 40.8, .197, .445], light green [*Lu′v′*: 44.8, .122, .561], or light blue [*Lu′v′*: 46.9, .154, .441]. All cues were presented among 3 other cues that had the same grey value as the nontargets.

Design

The target position (1–4), cue position (1–4), target colour (red, green), cue colour (dark red, dark green, dark blue, light red, light green, light blue) and response-related letter (T, L; right, left button press) were all varied pseudo-randomly within a single block, such that each of the variables was represented an equal number of times in a random sequence. This ensured that the cues were non-predictive of the target location (1/n design; 25% valid trials), and that the targets and cues were presented an equal number of times at all positions, paired with each response. The combination of variables resulted in 384 trials, which were run twice (in a newly generated sequence), resulting in 768 trials per participants.

Procedure

Prior to the experiment, observers were instructed to search for the red or green letter in the target display, and to press the right mouse button if the coloured target was a T, and the left mouse button if it was an L. Moreover, observers were instructed to maintain fixation on the central fixation dot at all times, and to respond as accurately as possible, without delaying their responses. Prior to the experiment, the eye tracker was calibrated with a random 9-point calibration.

Each trial started with the presentation of the fixation display (and the placeholders), which was yoked to a fixation control: The trial only started when observers had been fixating on the centre of the screen (within 100 pixels) for a continuous 200–700 ms (within a time window of 2,000 ms), and otherwise were calibrated anew. After detecting a successful fixation, the fixation display was followed by the cue display (90 ms), followed by another fixation display (90 ms), and the target display (90 ms). The fixation square remained visible until the response, and was immediately followed by the feedback display containing the written words "Correct" or "Incorrect" (in black; Arial Black, 13pt), with the possible addition of the warning "Error EYE" when the eye tracker had detected an eye movement. Feedback about correct responses was presented for 500 ms, whereas feedback about errors or eye movements was presented for 1,500 ms, to discourage trading speed for accuracy. Either feedback was followed by a blank display presented for 250 ms, and the next trial started again with the fixation control.

Results

Data

Data with anticipatory responses (RT < 200 ms) or delayed responses (RT >1,500 ms) were excluded from all analyses (0.15% of all data), as were data where observers had failed to maintain fixation at the centre (2.50% of all data).

Mean RT

A 2×3 × 2×2 ANOVA with the variables "target colour" (dark red, dark green), "cue colour" (red, green, blue), "cue brightness" (darker, lighter cues) and "cue validity" (valid, invalid) computed over the mean RTs showed significant main effects of the target colour, $F(1,13) = 9.60$, $p = .008$, $\eta_p^2 = .43$, and cue validity, $F(1,13) = 39.05$, $p < .001$, $\eta_p^2 = .75$. Of the interactions, the target colour x cue colour interaction was significant, $F(2,26) = 3.36$, $p = .050$, $\eta_p^2 = .21$, as well as the target colour x validity interaction, $F(1,13) = 36.52$, $p < .001$, $\eta_p^2 = .74$, and the cue brightness x validity interaction, $F(1,13) = 9.27$, $p = .009$, $\eta_p^2 = .42$. As shown in Figure 2A, capture by the target-matching, red and green cues was strongest (64 and 71 ms validity effect), followed by the dark blue cue (48 ms validity effect), and the light red, green and blue cue (validity effect of 28, 36 and 22 ms, respectively). Two-tailed *t*-tests showed that the difference between light and dark target-matching cues was significant, as capture was significantly stronger for the dark red than the light red cue, $t(13) = 2.75$, $p = .017$, and stronger for the dark green than the light green cue, $t(13) = 2.52$, $p = .025$. The difference between the dark blue and light blue cue was not significant, $t(13) = 1.75$, $p = .10$. The differences between the target-matching (dark red or dark green) cues and the dark blue cue were not significant; all $ts < 1.8$, $ps > .098$, *ns*. Similarly, the light red, light green and light blue cues all captured attention to the same extent, and did not differ significantly from each other in their validity effects, all $ts < 1.3$, $ps > .23$.

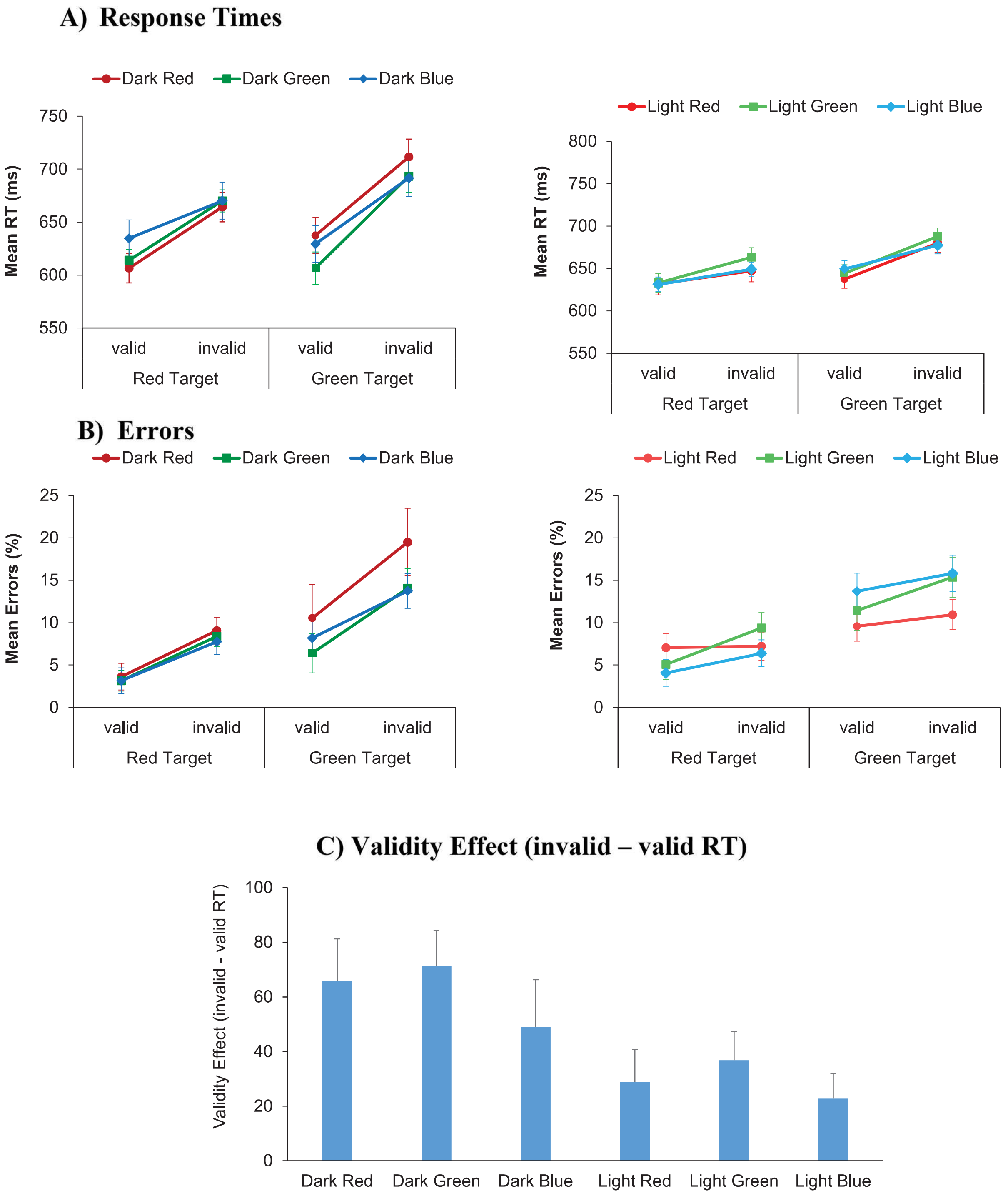

Figure 2. (A) Mean RT and (B) error scores of Experiment 1, depicted separately for the 6 cues. (C) Validity effects (invalid – valid RT) showed most capture by the target-matching red and green cues, followed by the irrelevant blue cue, and generally weaker capture by the light cues than the dark cues. These results suggest a mixture of singleton capture, top-down tuning to the brightness level of the targets, and possibly, also tuning to the target colours (red, green). Error bars depict +/- 1 SEM of the validity effect (Loftus & Masson, 1994).

When pooled across the two target colours, all cues showed significant validity effects; all *ts* > 3.03, *ps* < .011. When the data were analysed separately for the two target colours, the validity effect for the blue cues failed to reach significance with the red target, $t(13) = 2.12$, $p = .054$ for the light blue cue, and $t(13) = 2.05$, $p = .061$ for the dark blue cue. In addition, the light red cue failed to attract attention when the target was red, $t(13) = 1.21$, $p = .25$, while all cues showed significant validity effects with the green target, all $ts > 3.56$, $ps < .005$.

Mean errors

The same $2 \times 3 \times 2 \times 2$ ANOVA computed over the mean error scores showed significant main effects of the target colour, $F(1,13) = 27.61$, $p < .001$, $\eta_p^2 = .68$, and cue validity, $F(1,13) = 19.95$, $p < .001$, $\eta_p^2 = .61$. In addition, there was a significant cue colour x cue brightness interaction, $F(2,26) = 6.40$, $p = .006$, $\eta_p^2 = .33$, as well as the target colour x cue colour x cue brightness interaction, $F(2,26) = 6.16$, $p = .006$, $\eta_p^2 = .32$, and a cue brightness x validity interaction, $F(1,13) = 9.40$, $p = .009$, $\eta_p^2 = .42$. As shown in Figure 2B, in line with the view that attention is tuned to darker stimuli, the validity effect was again stronger for the dark cues. The dark red, green and blue cue all produced significant validity effects, both with the red target, all $ts > 3.44$, $ps < .005$, and with the green target: all $ts > 2.24$, $ps < .044$. Conversely, the light coloured cues mostly failed to attract attention, with the exception of the light green cue on red target trials, $t(13) = 2.39$, $p = .033$ (all other $ts < 1.66$, $ps > .12$).

However, when comparing the validity effects directly to each other (errors in invalid – valid trials), capture was not significantly stronger for the dark cues than for the light cues, except for the red cue, $t(13) = 2.72$, $p = .017$ (all other $ts < 1.7$, $ps > .11$). Moreover, capture effects did not differ between the dark red, green and blue cues (not even when the data were pooled across the two targets, all $ts < 1$).

Discussion

The results of Experiment 1 were mixed: In line with previous results (Folk & Anderson, 2010; Harris et al., 2015), the mean RT showed that all coloured cues produced significant validity effects, in line with a singleton search mode. However, at the same time, we found some evidence that capture was modulated by brightness, as reflected by stronger capture effects by the dark cues than the light cues. In addition, there was a trend for colour-specific modulation of capture, as capture was stronger for the target-matching cues than the non-matching blue cue. These results are inconsistent with a "pure" singleton search mode and instead provide tentative evidence for a more specific search setting, in which attention is tuned to darker stimuli (or stimuli of a particular brightness), as well as (potentially) to the particular target colours.

It may be tempting to attribute weaker capture by the light coloured cues to a lack of saliency, as they had a lower feature contrast against the white background than the darker cues (e.g., Nothdurft, 2015). However, as the light coloured cues all produced significant capture effects, it is difficult to argue that they were not salient enough (or not visible enough). By contrast, top-down tuning to darker or lighter stimuli has been shown to have large effects in the spatial cueing paradigm (as well as other attentional paradigms; Becker, Harris, York, & Choi, 2017; Becker, 2010a), rendering it more likely that the results are due to top-down tuning to brightness rather than bottom-up saliency effects.

Regardless of whether weaker capture of the lighter cues is due to top-down or bottom-up processes – the crux of the present set of results is that they do not converge on a single search strategy or tuning mode (or combination of top-down and bottom-up processes). As it stands, the results cannot be clearly attributed to either (dimension-specific) singleton search, tuning to brightness levels, or top-down tuning to colours. Rather, the results seem to reflect a mixture of multiple top-down tuning modes.

Experiment 2 was designed to test whether the same results of mixed search strategies or top-down tuning modes would be obtained if we use the more standardly used displays and conditions (e.g., Folk & Anderson, 2010; Harris et al., 2015)

Experiment 2

The results of Experiment 1 are intuitively plausible, but suggest a mixture of search modes that were originally thought to be mutually exclusive (e.g., singleton vs. feature search mode; Bacon & Egeth, 1994). Moreover, the findings are not in line with previous results that showed very clear evidence for "pure" singleton search mode (in the dimension of colour; Folk & Anderson, 2010; Harris et al., 2015).

The perhaps most notable difference between Experiment 1 and previous studies was that we used equiluminant target and cue colours in Experiment 1, whereas previous studies used full red, green and blue (Folk & Anderson, 2010), or highly saturated colours that differed largely in luminance (Harris et al., 2015). In addition, Experiment 1 differed from previous studies in the background colour, and the use of multiple cues that additionally varied in their luminance. Experiment 2 was designed to test whether we would obtain evidence for "pure" singleton search in the colour dimension if we render all other aspects of the experiment more similar to the original studies (e.g., Folk & Anderson, 2010; Harris et al., 2015), while still using equiluminant colours.

To test whether participants would adopt a singleton search mode in search for an equiluminant red or green target, we designed all other aspects of the experiment such that they were maximally similar to previous studies showing singleton search (e.g., Folk & Anderson, 2010). Specifically, the background colour was changed to black, and the placeholders and fixation dot were rendered in white. The target was red or green, and was presented among 3 white nontargets. Only red, blue and green cues were used, which were always presented among 3 other white cues. With this, the experiment was very similar to previously conducted studies (Folk & Anderson, 2010; Harris et al., 2015), and the only salient difference to previous studies was that the red, green and blue colours of the targets and cues were equiluminant.

If previous results about two-target search producing singleton search mode generalise to equiluminant colours, we would expect the results to show clear evidence for singleton search, with equally large capture effects for red, green and blue cues. If, on the other hand, equiluminant colours encourage or facilitate top-down tuning to the specific target colours, we would expect a feature-specific modulation on capture, such that the target-matching (red and green) cues capture attention more strongly than the non-matching blue cue. (As the experiment did not include any cues that varied in luminance, it was not possible to test whether attention is tuned to luminance differences.)

Methods

Participants

A new set of 12 observers participated in Experiment 2 in exchange for course credit or monetary compensation ($10/hour). All observers had normal or corrected-to-normal vision, and were naïve with regard to the purpose of the experiment.

Apparatus

This was the same as in Experiment 1.

Stimuli

The experiment used the same stimuli as Experiment 1, with the following exceptions: First, all stimuli were presented against a black background, and the placeholder boxes, fixation square, feedback, etc. were all rendered in white. The red or green targets were presented among 3 white nontargets, and we adjusted the colours to be easily discriminable against the black background while still being equiluminant (Red: *Lu′v′*: 19.9, .290, .504; Green: *Lu′v′*: 20.5, .125, .559; Blue: *Lu′v′*: 20.3, .147, .338). As in previous studies, the red, green and blue cues were also presented among 3 white cues (see Figure 3 for an illustration of the colours and displays).

Procedure

The procedure was the same as in Experiment 1, except that the cue display, fixation display and target display were presented for 70 ms each, and the error feedback contained the written word "Wrong!" (rather than "Incorrect!").

Results

Data

Data with anticipatory responses (RT < 200 ms) or delayed responses (RT >1,500 ms) were excluded from all analyses (0.45% of all data), as were data where observers had failed to maintain fixation at the centre (7.50% of all data).

Mean RT

A 2 × 3 × 2 ANOVA with the variables "target colour" (red, green), "cue colour" (red, green, blue), and "cue validity" (valid, invalid) did not reveal a main effect of target colour, nor any interactions with any of the other variables. Hence, we pooled over target colour to increase the power and computed a 3 × 2 ANOVA with the variables "cue colour" (red, green, blue) and "cue validity" (valid, invalid) over the mean RTs. The results showed significant main effects of cue colour, $F(2,22) = 4.82$, $p = .018$, $\eta_p^2 = .31$, and cue validity, $F(1,11) = 53.97$, $p < .001$, $\eta_p^2 = .83$, as well as a significant interaction, $F(2,22) = 7.97$, $p = .002$, $\eta_p^2 = .42$. Two-tailed *t*-tests comparing mean RT on valid vs. invalid trials showed a significant validity effect for the target-

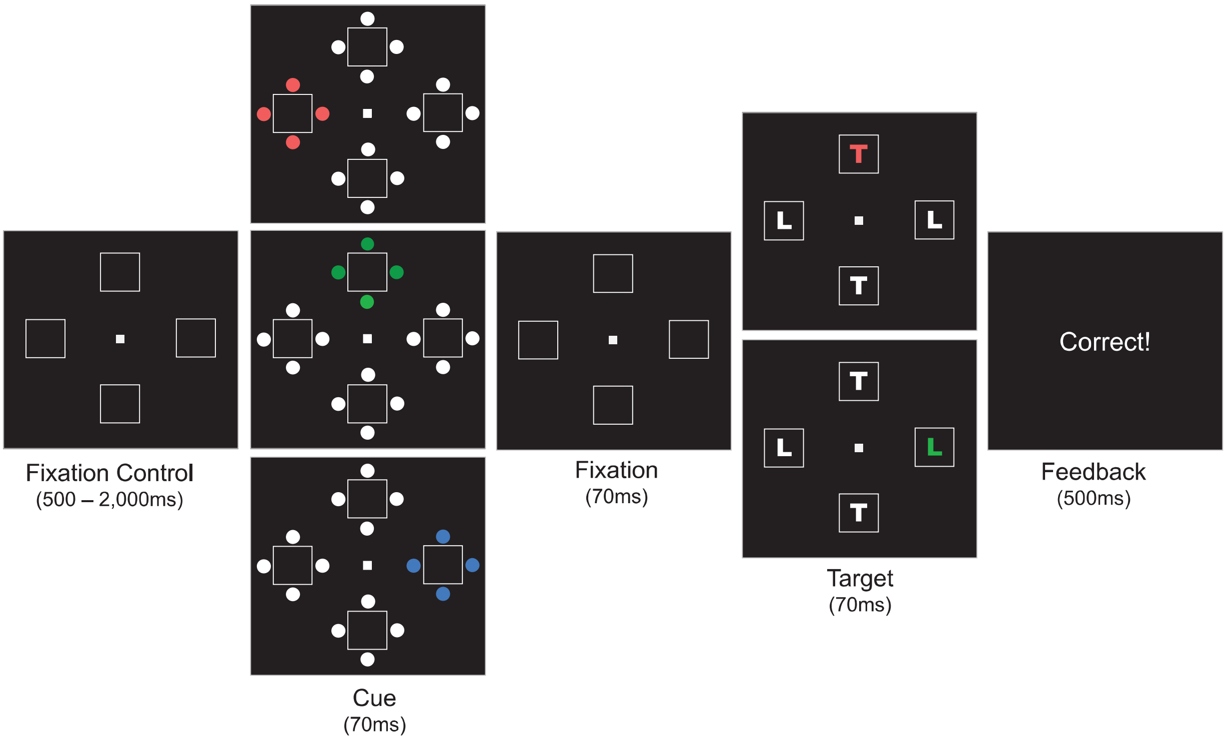

Figure 3. Overview of Experiment 2, in which the red, green and blue colours were equiluminant. As in previous experiments reported in the literature, all stimuli were presented against a black background, and the participant's task was to report the red or green letter (T or L) while ignoring the irrelevant cues.

matching red and green cues ($t(11) = 5.10$, $p < .001$ and $t(11) = 9.13$, $p < .001$, respectively), and also for the non-matching blue cue, $t(11) = 4.09$, $p = .002$. These results indicate that all cues significantly attracted attention, in line with singleton search mode. The validity effects also did not differ between the red and green cue, $t < 1$, indicating that they attracted attention equally strongly. However, the validity effects for the red and green cues were larger than for the blue cue ($t(11) = 2.49$, $p = .030$, $t(11) = 4.22$, $p = .001$), indicating that the target-matching cues attracted attention more strongly than the non-matching blue cue. This result is inconsistent with a "pure" singleton search mode and supports a feature-based search mode, in which attention is at least in part tuned to the target colours.

Mean errors

An omnibus 2 × 3 × 2 ANOVA involving target colour again showed no differences between red and green targets, nor any interactions, so that the data were pooled over target colour. The same 3 × 2 ANOVA computed over the mean error scores showed no significant differences between the cues, $F < 1$, but a significant cue validity effect, $F(1,11) = 13.77$, $p = .003$, $\eta_p^2 = .56$, which did not interact with the different cue types, $F < 1$. However, paired, two-tailed *t*-tests showed significant cue validity effects only for the red cue, $t(11) = 3.41$, $p = .006$, and the green cue, $t(11) = 2.43$, $p = .033$, not for the blue cue, $t(11) = 1.89$, $p = .086$. These differences in the validity effects across the 3 cues however did not reach significance, when we compared the difference values across the different cues (all *t*s < 1). With this, the results of the mean errors mimic the results of the mean RT and cannot be attributed to a speed-accuracy trade-off.

Collectively, the results indicate that attention was attracted to salient cues, but even stronger to singleton cues with the target colours, suggesting that observers both engaged in a singleton search mode and feature search mode. However, it is also possible that the red and green cues attracted attention more strongly due to *priming effects* (e.g., Becker, 2007, 2008b, 2010a, 2010b; Maljkovic & Nakayama, 1994), that is, that the red and green cues captured more strongly because observers had selected a target with the corresponding colour (red or green) on the immediately preceding trial. This could have produced a bias, or primed attention, to select the cue with the corresponding colour on the next trial, thus mimicking a feature-specific top-down bias (e.g., Becker, 2007). To address this possibility, we next analysed the data for possible priming effects.

Priming effects

To assess whether stronger capture by red and green cues may have been due to priming effects, we analysed the data separately according to whether the target on the previous trial had been red or green (see Figure 4, bottom panel). If stronger capture by the target-matching cues is due to priming effects, the stronger capture effect should be limited to trials in which the cue matched the previous target colour, whereas it should be at the same level as for the blue cue when the previous target mismatched the cue colour.

Figure 5 provides an overview of the capture effects (mean RT on invalid – valid trials) when the previous target had been red or green. As shown in the Figure, differences between the previous target conditions were rather small and did not follow the predicted pattern.

A 3 × 2 ANOVA with the variables "cue colour" (red, green, blue) and "previous target" (previous target red vs. green) computed over the validity effects (mean RT on invalid – valid trials) showed a significant main effect of cue colour, $F(2,22) = 7.76$, $p = .003$, $\eta_p^2 = .41$, but not the previous target colour, $F(1,11) = 2.06$, $p = .16$, *ns*, and no significant interaction between the variables, $F < 1$. Two-tailed *t*-tests comparing the validity effects across the two target conditions showed no significant modulation of capture by the previous target colour, neither for the red cue, $t < 1$, the green cue, $t(11) = 1.07$, $p = .31$, *ns*, or the blue cue, $t(11) = 1.01$, $p = .33$, *ns*. Thus, we could find no evidence for stronger capture by red cue when the target on the previous trial had been red rather than green (and analogously for the green cue).

Rather, capture by the target-matching red and green cues remained stronger than for the blue cue, both when the previous target had been red, ($t(11)$

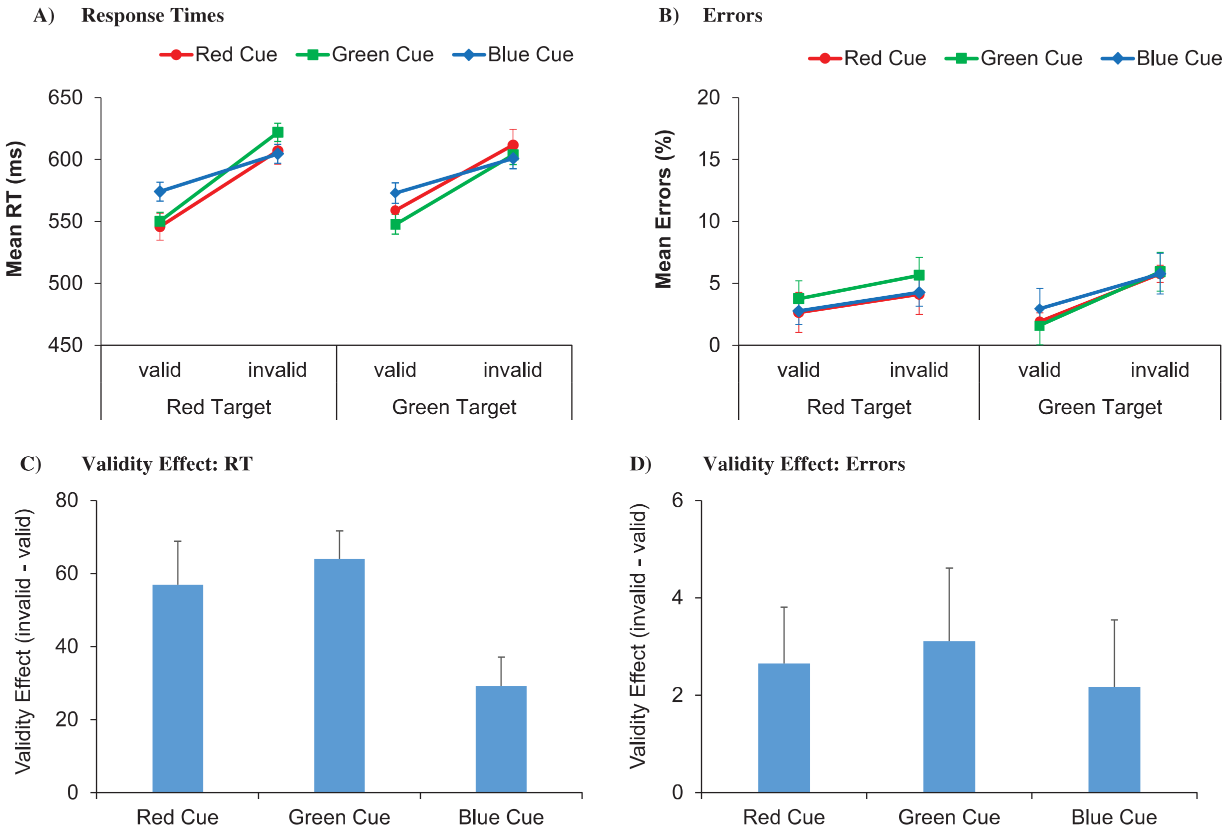

Figure 4. (A) Mean RT and (B) errors in Experiment 2, separately for each cue and target colour. (C, D) The validity effect in the (C) mean RT and (D) errors showed stronger capture for the target-matching red and green cues than for the blue cue, which still had a significant capture effect, suggesting a mixture for feature-based tuning and singleton search mode. Error bars indicate 1 SEM of the validity effect.

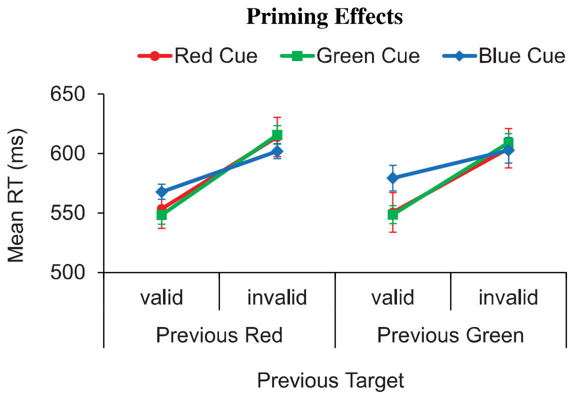

Figure 5. Results of Experiment 2, depicted separately for trials in which the target on the previous trial was red vs. green. Evidence for feature-specific tuning, as reflected in larger validity effects for the target-matching red and green cues, was independent of the previous target colour. Error bars depict ± 1 SEM.

= 2.27, $p = .044$, and $t(11) = 5.02$, $p < .001$, respectively), and when the previous target had been green ($t(11) = 2.18$, $p = .052$, and $t(11) = 2.94$, $p = .013$, respectively), whereas the red and green cues did not differ, $ts < 1$. Thus, stronger capture by the target-matching cues than the blue cue cannot be attributed to priming, but probably reflects top-down tuning to the target colours.

Discussion

Deviating from previous studies (e.g., Folk & Anderson, 2010; Harris et al., 2015), Experiment 2 did not show evidence for "pure" singleton search mode, but a mixture of singleton search and feature-specific tuning to the target colours (red, green), as reflected in the stronger capture effect for these colours. The analysis of intertrial effects moreover indicated that stronger capture by the target-matching cues was not due to automatic priming effects, but to top-down tuning of attention to the relevant colours (e.g., Becker et al., 2009; Folk & Remington, 2008; Leonard & Egeth, 2008).

We can only speculate as to why previous experiments showed singleton search, whereas the present one showed a mixture of singleton search and feature-specific modulations. Possibly, rendering the colours of the targets and cues equiluminant made the colours more similar to each other. In the study of Harris et al. (2015) that showed evidence for dimension-specific singleton detection mode, red and blue were quite dark (9.71cd/m^2 and 5.43cd/m^2), whereas green was quite bright (35.9 cd/m^2), and the colours had about twice the distance in CIE feature space compared to the current study and thus, were more dissimilar to each other. Possibly, rendering the colours equiluminant discouraged singleton search mode to some extent, or rendered the experiment more sensitive to detecting small differences in capture between the cues.

More importantly, it should be noted that the results cannot be interpreted as clear evidence for singleton search mode or feature search mode (Bacon & Egeth, 1994): In singleton search mode, all cues should have shown validity effects of the same magnitude, contrary to the observed results. In feature search mode, the blue cue should not have shown a significant validity effect at all, also contrary to the observed effects. Instead, the finding of significant validity effects for all cues, and stronger validity effects for the target-matching red and green cues suggests a mixture of different search modes. As will be discussed in more detail below, the results of Experiments 1 and 2 are difficult to reconcile with the notion of mutually exclusive search modes, or any higher-order search strategy that is based on a mental representation of the target ("target template", e.g., Duncan & Humphreys, 1989).

General discussion

The present study yielded several interesting results. The first experiment tested whether observers would tune attention to the luminance level of the targets or adopt a singleton detection mode in two-target search. The results showed a mixture of singleton search, feature-based tuning to the luminance level of the targets, and possibly also feature-based tuning to the colours of the targets (red, green). In the second experiment, we rendered the target and cue colours equiluminant, and presented them again among white non-targets. In line with previous results (Folk & Anderson, 2010; Harris et al., 2015), we found that the non-matching blue cue still captured attention, but we also found evidence for feature-specific tuning to red and green, as the red and green cues captured even more strongly. In a nutshell, both experiments showed mixed results patterns that cannot be clearly classified as instances of either singleton search mode, dimension weighting, feature-based tuning, or luminance-based search.

The individual data also did not reveal any systematic differences between the observers, which would indicate that they followed individually different search strategies. For instance, in Experiment 2, 8 out of the 12 observers showed stronger capture by red and green cues than the blue cue, and of the 4 observers that showed stronger capture by the blue cue, 3 showed stronger capture by blue than red, and one showed stronger capture by blue than green. Thus, there is no indication that a subset of observers engages in pure singleton search and others in strictly feature-based search. It is still possible that these two search strategies are applied on different trials. However, this possibility is unlikely, given the often-reported finding that observers tend to apply a search strategy continuously, even after it has outlived its usefulness (e.g., Becker, Harris, Venini, & Retell, 2014; Irons & Leber, 2016, 2018). More importantly, other studies have reported mixed results that are not consistent with a single search strategy, but point to observers using multiple search strategies that are conceptually inconsistent (e.g., Becker et al., 2014).

Rather than trying to find solutions that would render a given set of results consistent with the concept of these different search modes, it may be time to accept that such mixed results exist and to interpret them realistically. Possibly, the different search modes exist only as extreme points on a continuum of possible ways to tune attention to the target, and the visual system can use multiple of these search strategies to varying degrees to ensure successful target selection. One implication of this realistic interpretation is that the contents of the target template cannot always be characterised straightforwardly. The concept of a target template (or a mental representation guiding attention) has its limitations, which are especially noticeable whenever we observe an apparent mixture of different search modes that cannot be readily combined into a single representation that is free of contradictions.

The way in which attention is tuned to the target is perhaps better understood by assuming that attention can be top-down tuned to objects via different channels (e.g., Wolfe, 1994), or sensory neurons that respond to specific features (i.e., feature maps or dimension-specific maps), which can be up- or down-modulated in accord with the task demands (e.g., Chawla, Rees, & Friston, 1999; Treisman & Sato, 1990; see also Müller et al., 1995; Zehetleitner et al., 2012). Compared to the target template, the view that attention is tuned via channels or feature maps does not require a mental representation, because the underlying models are essentially "*analytical models*", and allow attention to be tuned to different attributes, without requiring that the combination of activated channels or feature maps would result in a coherent mental representation of an object. Moreover, these theories would allow neurons with different response characteristics to be simultaneously active, thus explaining the emergence of mixed search modes that cannot be coherently described by a single mental representation.

This should not be taken to mean that observers do not have a mental representation of the target or a target template. Observers are clearly capable of reporting the remembered attributes of the target and it is reasonable to suppose that the observer's knowledge could be grounded in a conscious mental representation of the target. However, we should consider the possibility that this mental representation of the target does not guide attention (e.g., Becker, 2010a). Rather, attention seems to be top-down tuned to the attributes of the target in a manner that can be radically different from the contents of our mental representation of the target. Specifically, the visual system seems to tune attention to a sought-after object by up- or down-modulating the gain of multiple feature maps or sensory neurons, and fine-tune these top-down settings in response to on-line feedback, in a largely automatic fashion (Becker, Atalla, & Folk, in press).

It is perhaps even worth considering abandoning the notion of a target template or representational theories in the future (at least for the purpose of explaining attentional guidance / attentional capture), as the competing analytical theories that operate on sensory neurons (feature maps or channels) seem to have several advantages over representational theories: (1) analytical theories provide a framework that specifies which attributes can guide attention (and which cannot), by positing corresponding sensory neurons, whereas the notion of a target template requires positing extraneous mechanisms that allow predicting whether the target can be found quickly or requires effortful search. (2) Analytical theories can provide simple explanations of intertrial priming effects and other history-based effects, by positing that weight settings or the configuration from the previous trial remains in place for next trial (e.g., Becker & Horstmann, 2009; Maljkovic & Nakayama, 1994; Müller et al., 1995). By contrast, views based on memory representations often posit a rather sophisticated process that involves actively retrieving memory representations, and/or activating them, which does not seem very parsimonious (e.g., Hillstrom, 2000; Huang, Holcombe, & Pashler, 2004; see also Becker, 2008b). (3) Analytical theories can accommodate gradual changes in search, as for instance, the tendency to select a given location more frequently when it is more likely to contain the target (e.g., via statistical learning), simply by positing gradual changes in weight settings (e.g., Geyer & Müller, 2009). There is a plausible biological principle underlying these gradual changes in weight settings, too, as synapses between neurons become gradually stronger the more frequently the respective neurons fire in unison (Hebb, 1949). Gradual changes in attentional allocation are more difficult to explain in representational theories, which would have to posit that target templates gradually gain in saliency or strength, or that the target template gradually changes to contain additional information (e.g., location information). These possibilities are difficult to reconcile with the notion of a target template or a mental representation guiding attention.

Despite these difficulties, we should ask whether target templates and the corresponding representational theories do not have some advantages over the more analytical, feature-based theories, especially in explaining guidance by higher-order information. For instance, Wyble, Folk, and Potter (2013) showed that attention can also be guided towards complex visual scenes such as dinner or picnic scenes, in response to a word cue. Here it is difficult to imagine how word cues would translate into a particular configuration of filters or channels, or differentiated weight settings acting on sensory neurons (e.g., because it is unclear how we would "know" which channels to address, and how to weight them). More generally speaking, the entire process of adjusting weight settings on 100 or more channels may often seem too involved to justify the possible explanatory gains; so here, thinking that attention could be "simply" guided by a mental representation of the target may seem more parsimonious.

However, we should maybe also ask how much explanatory work the target template can really do. An explanation of guidance in this situation would probably entail a causal chain, such that (a) hearing or reading a word evokes a certain mental representation, which (b) then guides attention to those regions in the visual field that match the target template (perhaps first selecting items that match the target template most closely, with descending orders for less well-matching items; Duncan & Humphreys, 1989).

Even though this explanation is intuitive, elegant, and short, we should ask whether this is a complete explanation. Does it still make sense to ask *how* words evoke mental representations? And how it is determined which items in the visual field actually match this representation? Or, who or which instance would decide which visual inputs match the mental representation and which do not? – It seems completely legitimate to ask these questions. The fact that these questions are still left open indicates that intuitively plausible explanations do not always provide a very thorough or informative explanation. At a minimum, the notion of a target template would probably profit from a neuronal implementation that explains what factors and mechanisms cause mental representations, and how neurons can detect a match between the representation and visual inputs.

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