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The precision of attentional selection is far worse than the precision of the underlying memory representation

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A R T I C L E I N F O

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A B S T R A C T

Voluntary attentional selection requires the match of sensory input to a stored representation of the target features. We compared the precision of attentional selection to the precision of the underlying memory representation of the target. To measure the precision of attentional selection, we used a cue-target paradigm where participants searched for a colored target. Typically, RTs are shorter at the cued compared to uncued locations when the cue has the same color as the target. In contrast, cueing effects are absent or even inverted when cue and target colors are dissimilar. By systematically varying the difference between cue and target color, we calculated a function relating cue color to cueing effects. The width of this function reflects the precision of attentional selection and was compared to the precision of judgments of the target color on a color wheel. The precision of the memory representation was far better than the precision of attentional selection. When the task was made more difficult by increasing the similarity between the target and the nontarget stimuli in the target display, the precision of attentional selection increased, but was still worse than the precision of memory. When the search task was made more difficult, we also observed that for dissimilar cue colors, RTs were slower at cued than at uncued locations (i.e., same location costs), suggesting that improvements in attentional selectivity were achieved by suppressing non-target colors.

1. Introduction

When we look for an object in the environment, search is guided by an internal representation of the object's features, which is referred to as attentional template (e.g., Duncan & Humphreys, 1989). The attentional template is thought to be stored in visual working memory (Bundesen, Habekost, & Kyllingsbaek, 2005; Chelazzi, Miller, Duncan, & Desimone, 1993), but it may be offloaded into long-term memory when the target does not change over successive trials (see Carlisle, Arita, Pardo, & Woodman, 2011). The previous literature has been concerned with the question whether the content of visual working memory automatically guides attentional selection (e.g., Downing & Dodds, 2004; Foerster & Schneider, 2018; Hollingworth & Beck, 2016; Houtkamp & Roelfsema, 2006; Kim & Cho, 2016; Olivers, Meijer, & Theeuwes, 2006; Soto, Heinke, Humphreys, & Blanco, 2005; Woodman & Luck, 2007) or with the question how simultaneous control of attention is achieved when there are multiple attentional templates (Hollingworth, Matsukura, & Luck, 2013; Ort, Fahrenfort, & Olivers, 2017).

In the present study, we investigated how the precision of the attentional template relates to the precision of attentional selection. In case of a one-to-one correspondence between the internal target representation and attentional selection, observers would only select stimuli for further processing that correspond to the stored features of the target. Research on the contingent capture paradigm developed by Folk, Remington, and Johnston (1992) suggests that this may indeed occur. When observers search for an unchanging target color, a different color does not capture attention even when it is equally salient (Eimer, Kiss, Press, & Sauter, 2009; Folk & Remington, 1998; Lien, Ruthruff, Goodin, & Remington, 2008). For instance, during search for a green target, a green cue presented at the target location results in shorter RTs than a green cue presented at a non-target location (i.e., a cueing benefit). In contrast, a red cue of equal saliency does not affect RTs, suggesting that only target-matching colors capture attention. However, attentional selection is somewhat imprecise because target-similar cues that do not completely match the target color also capture attention. For instance, in search for a green target, a greenish cue will capture attention more than a reddish cue (Anderson & Folk, 2010). Thus, similarity between cue and target color increases attentional capture by the cue (Anderson & Folk, 2010; Ansorge & Heumann, 2003; Becker, Folk, & Remington, 2013; Goller, Ditye, & Ansorge, 2016).

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1.1. Precision of attentional selection and the attentional template

The reason for attentional capture by target-similar cues may be that attentional selection is imprecise despite a very precise memory representation of the target. Alternatively, the precision of the memory representation may correspond to the precision of attentional selection. While target and target-similar colors would certainly be discriminable in a perceptual task (e.g., Brady, Konkle, Gill, Oliva, & Alvarez, 2013), little is known about the target representation in memory while the search task is performed. Judgments of the color of a single item stored in visual working memory (VWM) have a standard deviation of ~14° in color space (Zhang & Luck, 2008), which may suggest that it is the poor precision of the attentional template in memory that accounts for the failure to exclude target-similar stimuli from attentional selection. Presently, no data is available to decide whether the precision of attentional selection is worse, better or equal to the precision of memory.

However, data on shared or independent limits of precision would constrain models on the interaction between memory and attentional selection in important ways. If the precision of attentional selection is worse than the precision of the underlying memory representation, it appears unlikely that the capacity of attentional selection is close to the capacity of memory. In the literature, there is an unresolved dispute between proponents of a severe capacity limit for attentional selection who claim that only a single item in VWM can guide attentional selection (reviewed in Olivers, Peters, Houtkamp, & Roelfsema, 2011). Others suggest that attentional selection has a capacity that approaches the capacity of visual working memory, with at least two possible search targets (Beck, Hollingworth, & Luck, 2012; Grubert & Eimer, 2016; Irons, Folk, & Remington, 2012; Moore & Weissman, 2010; Roper & Vecera, 2012). The relation between capacity and precision is straightforward. If the precision of attentional selection is lower than the precision of the underlying memory representation, it is not possible to discriminate between as many search as memory targets. For instance, if colors A and B are close in color space, it may be possible to store them with sufficient precision in memory to allow for successful differentiation of a nontarget color C that is intermediate between A and B. If attentional selection is less precise than the memory representation, it may not be possible to select A or B without also selecting C. Thus, the number of stimuli that can be distinguished and independently selected is reduced. However, the reduced capacity of selective attention will only be evident when the similarity between target and nontargets is high.

The relation between the precision of attentional selection and its underlying memory representation is complicated by the fact that the precision of both may be adapted to task requirements. Geng, DiQuattro, and Helm (2017) showed that the precision of attentional selection increased when target-similar nontargets were more frequent. In their study, two color patches were shown and participants had to identify the shape presented on the patch in the target color. In one group of participants, the target color was frequently presented together with a similar nontarget color, whereas in another group of participants, dissimilar nontarget colors were more frequent. The typical increase in RTs caused by similar nontargets (e.g., Duncan & Humphreys, 1989) was smaller when trials with similar nontargets were more frequent, suggesting that attentional selection was more precise. At the same time, there was some evidence that the memory representation of the target shifted away from the nontarget color, in accordance with the idea that the difference between target and nontargets is exaggerated to increase the signal-to-noise ratio (Navalpakkam & Itti, 2007).

An objection to the conclusions of Geng et al. (2017) is that the smaller increase in RTs with frequent similar nontargets may be unrelated to precision, but may arise from increased top-down control of attention. It has been demonstrated that frequent distractors capture attention less than rare distractors (Folk & Remington, 2015; Müller, Geyer, Zehetleitner, & Krummenacher, 2009; Sayim, Grubert, Herzog, & Krummenacher, 2010; Schönhammer & Kerzel, 2018). Thus, an alternative account of the shorter RTs with similar nontargets may be increased top-down control over stimulus-driven capture in the group that was frequently exposed to similar nontargets. To disentangle contributions of search requirements and nontarget frequency, it may be necessary to separate the target display (used to manipulate search difficulty) from the distractor display (used to measure attentional selectivity). This can be easily achieved in the contingent capture paradigm where the cue display serves to measure effects of attention (i.e., it acts as a distractor) while the target display provides the opportunity to vary target-nontarget similarity (e.g., Gaspelin, Ruthruff, & Lien, 2016; Gaspelin, Ruthruff, Lien, & Jung, 2012).

1.2. Cueing costs

Cueing effects in the present experiments were mostly used as a tool to measure the precision of attentional selectivity. Nonetheless, our experiments allowed us to contribute to a debate on the inversion of cueing effects that sometimes occurs with cue colors that do not match the target color (e.g., a red cue with a green target). Typically, these non-matching cues do not capture attention. That is, RTs were not different between cued and uncued target locations (Folk & Remington, 1998; Folk et al., 1992). However, when the search display was composed of multiple colored nontargets, RTs were found to be longer for targets at the cued compared to the uncued location (Lamy & Egeth, 2003), which represents a cueing cost as opposed to the typical cueing benefit with target-matching cues. Cueing costs with cues that do not match the target were not observed when the target was the only colored stimulus in the target display (i.e., a singleton) or when it was accompanied by only one colored nontarget (see Fig. 1C; Folk & Remington, 1998). The explanation for cueing costs is elusive. Initially, it was proposed that cueing costs reflect attentional suppression of nontarget features (Eimer et al., 2009; Lamy & Egeth, 2003), but cueing costs were found to depend on the duration of the cue. Because cue duration determines the perceived continuity of the display elements, it was suggested that cueing costs may reflect the time it takes to update an object whose features change between the cue and target display (Carmel & Lamy, 2014, 2015). That is, when a non-matching cue is shown at the target location, the color at the target location changes between cue and target display, which may be perceived as an object with changing features. However, object updating is assumed to be a conscious process, yet Schoeberl, Ditye, and Ansorge (2017) found that subliminal cues also result in cueing costs. Thus, the origin of cueing costs remains an open question.

1.3. Goals of study

The current investigation pursued three goals. First, we aimed at a comparison between the precision of attentional selection and the precision of the attentional template. To this end, we measured the width of a function that relates color differences to cueing effects and the width of the distribution of memory errors. We used the typical design of experiments on contingent attentional capture where the target is fixed for each participant and is therefore repeated on each trial (Folk & Remington, 1998; Folk et al., 1992). Target repetition is expected to facilitate attentional selection (e.g., Maljkovic & Nakayama, 1994) and recall from memory (e.g., Besner, Keating, Cake, & Maddigan, 1974). The second goal was to investigate the effect of task requirements on precision. We wondered whether increased target-nontarget similarity would affect the precision of attentional selection and memory performance in the same way. Third, we investigated the effects of task requirements on cueing costs. So far, there are only anecdotal observations (Carmel & Lamy, 2014) suggesting that displays with multiple nontarget colors result in cueing costs, but a systematic investigation is missing.

2. Experiment 1

In Experiment 1, we opposed search for singleton and non-singleton targets, similar to Folk and Remington (1998) Experiment 1. In principle, search for a singleton target only requires a very crude target template because it is not necessary to search for a specific color. Nonetheless, Folk and Remington (1998) found that participants did search for a specific color because only target-matching colors captured attention. If they had searched for any color, cueing effects would be expected for all cue colors. In the feature-search condition, we presented the target together with a colored nontarget so that participants had to search for a specific color. In principle, a more precise target template was required in feature than in singleton search, but the color difference between target and the colored nontarget was large (Witzel & Gegenfurtner, 2013, 2015a).

We probed attentional selection by measuring cueing effects for cue colors that varied systematically around the target color (see Fig. 1A and B). On some trials, we also probed memory for the target color by asking participants to indicate the target color on a color wheel. Then, we fit a model inspired by the mixture model of visual working memory (Ma, Husain, & Bays, 2014) to cueing effects and memory errors. One parameter of the model, the width of the curve, could be directly compared between cueing effects and memory errors, allowing for the joint characterization of the precision of attentional selection and the underlying memory representation (i.e., the attentional template).

The mixture model accounts for performance in experiments where participants retained one or more colors from a memory display and later reproduced these colors on a color wheel. It was proposed that the distribution of the memory error (i.e., the deviation between judged and true stimulus color) is composed of a mixture of high-precision responses to the target and random guesses (Ma et al., 2014). That is, the distribution of color errors shows a peak around the true memory color but does not reach zero because of guessing on trials where the target color could not be retrieved from memory. More technically, the precision of responses corresponds to the width of the peak of the distribution whereas random guesses correspond to a shift of the distribution on the y-axis. Further, there may be a bias in the distribution, which corresponds to a shift of the distribution on the x-axis.

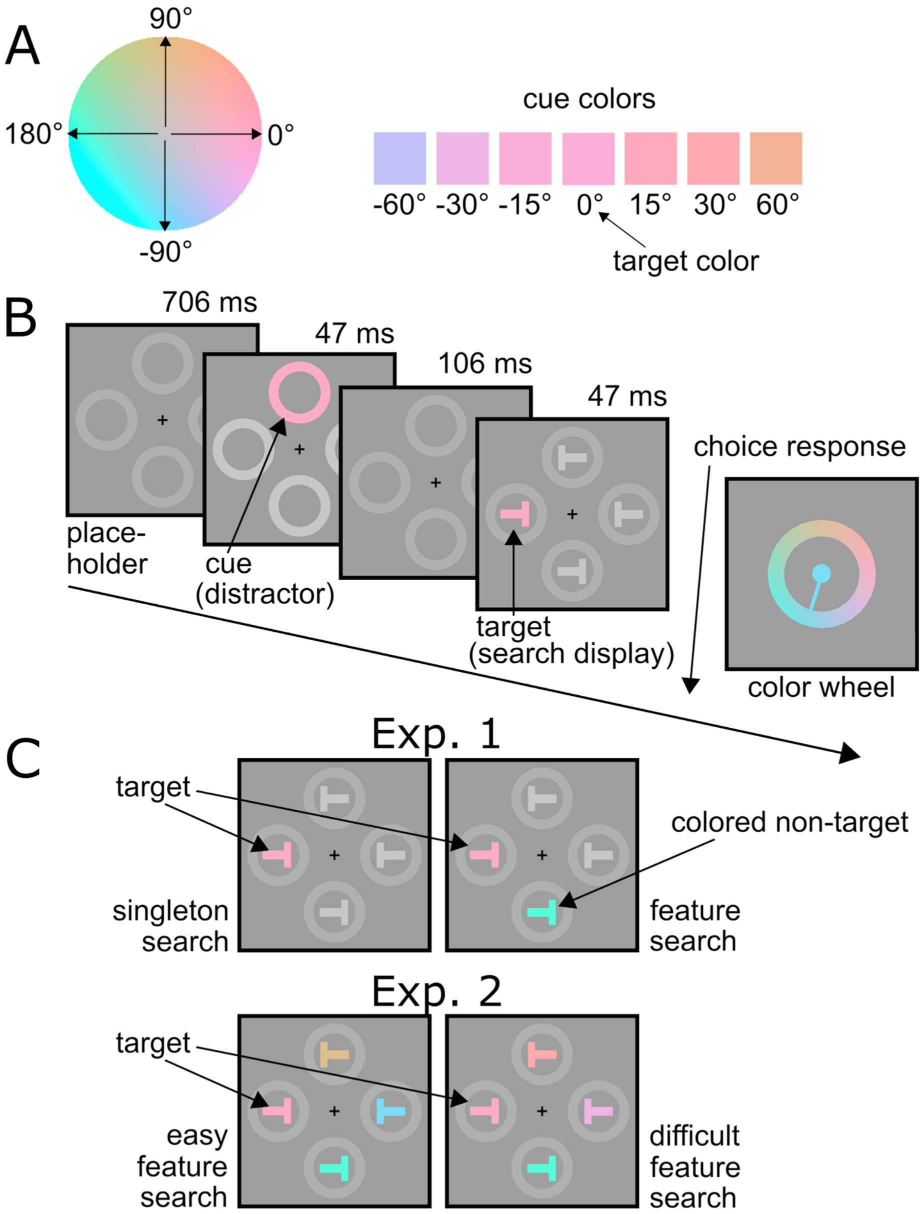

Fig. 1. Illustration of experimental stimuli (not drawn to scale). Panel A illustrates CIELAB color space. Chroma increases from the center to the periphery of the disk. The azimuth corresponds to the hue. Arrows illustrate hue differences of 90° for a red target at 0°. We presented cue colors that varied from −60° to +60° around the target color. Panel B shows the sequence of events in the singleton search condition of Experiment 1. Participants discriminated the orientation of the letter T in the target color by mouse click. They were instructed to ignore the cue display. The cue is also referred to as distractor. On some trials, a color wheel appeared, and participants judged the target color. Panel C shows the target displays in Experiments 1–2. In the example, the target was red. In Experiment 1, the target was shown without colored nontarget in the singleton search group and with one highly discriminable nontarget of 180° color difference in the feature search group. In the easy feature search condition of Experiment 2, the target color was shown with one nontarget at 180° and two nontargets at 90° color difference, all of which were highly discriminable from the target color (lower left). In the difficult feature search condition, the target was shown with two similar nontarget colors of 30° color difference and one dissimilar color at 180° (lower right). Note that placeholders in the experiments were composed of two unfilled circles. The dark gray rings in the figure were used for clarity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The transfer of the mixture model to the function relating cue color and cueing effects is straightforward (see Fig. 3). We expect attentional capture to be maximal for cue colors that are close to the target color in color space. With increasing separation of cue and target color, attentional capture is expected to decrease. The decrease may be slow or rapid, resulting in broad or narrow peaks, respectively. At large separations between cue and target color, the function is expected to reach a plateau. Because large separations correspond to non-matching cues in the previous literature, we expect the plateau to be at zero or below zero. That is, at large separations between cue and target color, cueing benefits should be absent or there may even be cueing costs.

To compare the precision of the attentional template and attentional selection, we focussed on the width of the peaks because the width was determined in the same units for both memory error and cueing effect (i.e., degrees of color separation). In contrast, the shift on the y-axis and the height of the functions was determined in milliseconds for the cueing effects and in relative frequency for the memory error. Thus, a comparison of these parameters was not meaningful. Further, a comparison of the bias parameter was not feasible because we had to collapse across positive and negative differences between cue and target colors to achieve reliable fits for the cueing effects.

2.1. Methods

Participants. In a previous study, we found cueing effects in a relevant color to be 87–99 ms larger than cueing effects in a neutral (irrelevant) color (Exp. 2 and Exp. 3 in Barras & Kerzel, 2016). The partial etasquare of the respective interaction was 0.57 and 0.59, respectively. When aiming for a power of 0.8 with a type 1 error rate of 5%, the necessary sample size is 9. Because we had many more conditions in the present experiment, we aimed at a sample size of 16 for the singleton (5 male, age: $M = 22.8$ years, $SD = 5.5$) and feature search groups (2 male, age: $M = 19.4$ years, $SD = 1.5$). First-year psychology students participated for class credit. All reported normal or corrected-to-normal vision. The study was approved by the ethics committee of the Faculty of Psychology and Educational Sciences and was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Informed consent was given before the experiment started.

Apparatus. Stimuli were displayed on a 21-inch CRT monitor with a refresh rate of 85 Hz and a pixel resolution of 1280 × 1024 (horizontal × vertical), driven by an ATI Radeon HD 3450 graphics card with a color resolution of eight bits per channel. CIE1931 chromaticity coordinates and luminance (xyY) of the monitor primaries were R = (0.630, 0.340, 18.5), G = (0.293, 0.610, 60.9), and B = (0.152, 0.069, 9.9). Gamma corrections were applied based on the measured gamma curves of the monitor primaries. Observers viewed the screen at 70 cm. Head position was stabilized with a chin/forehead rest.

Stimuli. There was a placeholder, a cue, and a target display for the RT task and a display with a color wheel for the memory task. The placeholder display was composed of a central fixation cross (0.6° diameter) and four outline rings, all drawn in light gray. The distance from the center of the fixation cross to the center of the outline rings was 3°. The outline rings were composed of an inner and an outer circle with a radius of 1.1° and 1.4°, respectively. The linewidth of the circles was 1 pixel or 0.03°. In the cue display, all rings were filled. Three rings were filled with the same light gray as the circles and one ring with a color. In the target display, the letter T rotated by 90° clockwise or counter-clockwise was shown in each placeholder. The bars making up the rotated T were 1° long and 0.3° thick. Depending on the search group, one or two of the Ts were colored. The remaining letters were achromatic.

CIELAB space was used because distances in CIELAB space approximate perceived color differences (Fairchild, 2005; Witzel & Gegenfurtner, 2015b). CIELAB consists of one achromatic axis (perceived lightness L^*) and two chromatic axes (a green-red dimension a^* and a blue-yellow dimension b^*). The polar coordinates of the chromatic axes (a^* and b^*) correspond to hue (azimuth) and chroma (radius). Hue indicates how reddish, yellowish, greenish and bluish a color is, and chroma is a measure of perceived colorfulness (i.e., difference from gray).

The white-point of CIELAB was xyY = (0.29, 0.30, 89.27), which corresponds to chromatic adaptation and maximum lightness. Stimuli were presented on an achromatic background with the chromaticities of the white-point and a lightness of $L^* = 55$, which corresponds to a luminance of 20.5 cd/m^2. The placeholders, the achromatic cues and letters were light gray ($L^* = 73$ or 40.3 cd/m^2). The colors that served as cue, target and nontarget colors were sampled along an isoluminant hue circle at a lightness of $L^* = 73$ and a chroma of 34.

In singleton search, the target was the only colored item in the target display. In feature search, the target was shown with a nontarget that was at 180° from the target color in CIELAB-space. The cue was a color singleton throughout.

The color wheel represented an isoluminant hue circle with the same lightness and chroma as the cue and target colors. The color wheel was 0.6° thick and the inner edge was 1.2° from fixation. To cancel motor biases and to avoid response repetition, the spatial orientation of the zero hue angle was randomized between trials. By turning the mouse around the initial mouse position on the desk, participants were able to rotate the line cursor. The color pointed to by the line cursor was used to draw the cursor line and a central disk with 0.3° radius shown inside the color wheel. Participants confirmed their judgment with an unspeeded mouse click. The individual median RT for the mouse click was between 2267 and 12,452 ms ($M = 5323$ ms) from the onset of the color wheel. After the click, the static color wheel remained on the screen for another 300 ms before a blank screen was shown for 500 ms.

Design. The 128 combinations of 4 cue positions, 4 target positions, 4 cue colors (0°, ± 15°, ± 30°, ± 60°), and 2 responses (left, right) were presented once in a block of 128 trials. The sign of the cue color was randomly positive or negative (i.e., randomly +15° or −15° from the target color). In the singleton search group, participants completed 5 blocks for a total of 640 trials. In the sixth block, 40 trials were run where participants judged the target color on each trial. The RT data from this block was discarded because it is likely that the memory task directed participants' attention to the specific color of the target. However, the goal of singleton search was to examine cueing effects when participants looked for any color. In the feature search group, participants completed 6 blocks for a total of 768 trials. The color task was run on every 12th trial for 60 color judgments. To counterbalance target color, we selected 16 equally spaced colors from CIELAB color space and assigned a different color to each participant. Thus, we hoped to cancel out possible inhomogeneity in CIELAB space.

Procedure. A trial started with the presentation of the placeholder display for 706 ms. Then, the cue display was shown for 47 ms, followed by the placeholder display for 106 ms and the target display for 47 ms. The resulting cue-target SOA was 153 ms. After target offset, the placeholder display remained visible until a response was registered. On trials with a color judgment, the color wheel was shown after the response to the target letter.

Participants responded to the orientation of the target letter by clicking the corresponding mouse button (T rotated counter-clockwise: left button, T rotated clockwise: right button). They were instructed to respond as rapidly as possible while keeping the error rate below 10%. They were also instructed to ignore the cue display. For the color judgment task, they were told that the target color was always the same and that they should try to be as precise as possible without consideration of time.

In the singleton search group, participants started the experiment by practicing the RT task for at least 30 trials or until t hey felt comfortable with it. After having completed five blocks of the RT task, they were briefly trained on the color judgment task. Finally, they performed the sixth block with the combined RT and color task. In the feature search group, participants were first trained on the color judgment task, then on the RT task, and finally completed six blocks of the combined task.

To avoid biases, the target color was not named during practice.

Visual feedback informed participants about choice errors, anticipations (RTs < 0.2 s, which were extremely rare and will not be reported) and late trials (RTs > 1 s). Every 64 trials, visual feedback about the proportion of correct responses, median RTs and median color error (if applicable) were displayed for 10 s, forcing participants to take a short break.

2.2. Results

One dataset from the singleton search group was removed because the distribution of color errors was centered on −75°, whereas the other participants had biases smaller than ± 25°. We considered trials with RTs longer than 1 s as late and excluded these trials (0.07%) from analysis. Next, the data for each participant and condition were trimmed by removing trials with corrected RTs that were further than 2.5 standard deviations away from the respective condition mean, which amounted to 1.9% of the trials. Cues presented at the target location are referred to as valid cues, whereas cues presented at a non-target location are referred to as invalid cues.

Mean RTs as a function of cue validity and cue color (relative to the target color) are shown in Fig. 2. We subtracted mean RTs on valid trials from mean RTs on invalid trials to obtain cueing effects. Average cueing effects are shown in Fig. 3 together with the distribution of color errors. Fig. 4 shows the precision of attentional selection and memory (i.e., mean width parameters).

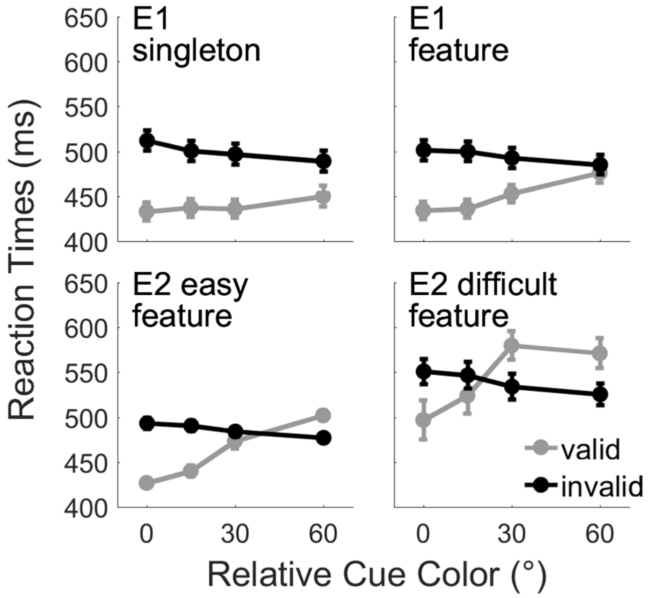

Fig. 2. Mean reaction times as a function of cue validity and cue color (relative to the target color) in Experiments 1 and 2. Singleton and feature search was manipulated between participants in Experiment 1 (upper panels), whereas easy and difficult feature search was compared within participants in Experiment 2 (lower panels). Error bars show the standard error of the mean.

RTs. We collapsed across negative and positive deviations of the cue color to have enough trials in the valid conditions. With four possible cue and target positions, only 25% of the trials are valid, resulting in 40 valid trials per collapsed cue color in singleton search and 48 in feature search. Thus, the color differences in the following text refer to absolute values. We conducted a 2 (group: singleton search, feature search) × 4 (cue color relative to target color: difference of 0°, 15°, 30°, 60°) × 2 (cue validity: valid, invalid) mixed ANOVA on individual mean RTs. The effect of cue validity, $F(1, 29) = 280.6$, $p < .001$, $\eta_p^2 = .906$, showed that responses were faster on valid than invalid trials (445 vs. 497 ms, corresponding to a cueing effect of 53 ms). The interaction of cue validity and search group, $F(1, 29) = 6.23$, $p = .019$, $\eta_p^2 = .177$, showed that the cueing effect was larger in singleton than in feature search (61 vs. 45 ms). The interaction of cue color and cue validity reached significance, $F(3, 87) = 42.11$, $p < .001$, $\eta_p^2 = .592$, confirming the well-known effect of color similarity on attentional capture. The cueing benefit decreased with increasing angular separation between cue and target color (73, 64, 50, and 24 ms for separations of 0°, 15°, 30°, and 60°, respectively). Inspection of the upper panels of Figs. 2 and 3 suggests that cueing effects decreased more rapidly in the group performing feature search than in the group performing singleton search. This impression was confirmed by the three-way interaction of search type, cue color, and cue validity, $F(3, 87) = 3.95$, $p = .011$, $\eta_p^2 = .12$. To examine the origin of the interaction in more detail, we compared the cueing effects between singleton and feature search for each cue color. The critical p-value was adjusted to 0.0125 to correct for four tests. By paired *t*-test, the cueing effect was comparable between singleton and feature search for the 0° cue color (79 vs. 67 ms), $p = .07$, and the 15° cue color (63 vs. 64 ms), $p = .959$. In contrast, it was significantly larger for singleton than feature search for the 60° cue color (39 vs. 9 ms), $t(22.43) = 2.75$, $p = .012$, Cohen's $d = 1$. The difference approached significance for the 30° cue color (61 vs. 40 ms), $t(29) = 2.59$, $p = .015$, Cohen's $d = 0.93$. To examine whether cueing effects were reliable, we conducted one-sample t-tests against zero with an adjusted *p*-value of 0.0063 to correct for eight tests (2 search groups × 4 cue colors). All cueing effects were significantly different from zero, $ts > 4.1$, $ps < .002$, Cohen's $ds > 1.06$, except for the 60° cue color in feature search, $p = .124$. Finally, there were some less interesting results. The interaction of search group and cue color, $F(3, 87) = 5.49$, $p = .002$, $\eta_p^2 = .159$, modulated the main effect of cue color, $F(3, 87) = 3.79$, $p = .013$, $\eta_p^2 = .115$, showing that RTs did not change with increasing angular separation between cue and target color in singleton search (472, 469, 466, 470 ms), whereas they increased slightly in feature search (468, 468, 473, 481 ms),

Choice Errors. Individual percentage of choice errors was submitted to the same ANOVA as above to rule out speed-accuracy tradeoff. The main effect of cue validity, $F(1, 29) = 32.15$, $p < .001$, $\eta_p^2 = .526$, was modulated by the interaction of cue color and cue validity, $F(3, 87) = 13.48$, $p < .001$, $\eta_p^2 = .316$, showing that the difference between valid and invalid trials decreased with increasing angular separation of cue and target colors (differences of 5.1%, 4.4%, 1.9%, 1.1%). The average percentage of choice errors was 4.2%.

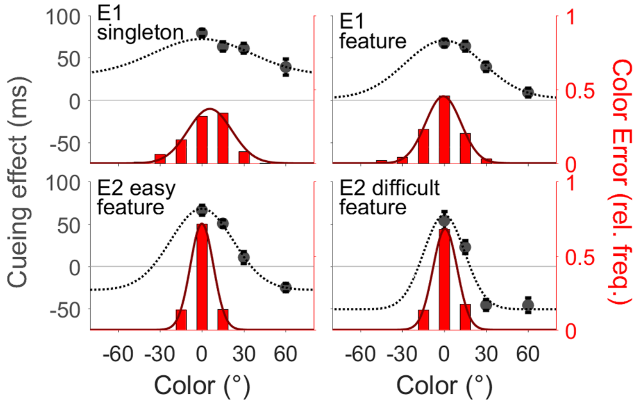

Fig. 3. Cueing effects and color errors in Experiments 1 and 2. The black filled circles show the mean cueing effects (invalid minus valid, left axis) as a function of angular difference between cue and target color (relative cue color). The red histograms show the mean relative frequencies of the color error in 15° bins (right axis). Error bars show the standard error of the mean. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Gaussian fits of color errors. All color judgments were included in the following analysis (40 per participant in singleton search, 60 in feature search). We calculated the relative frequency of color errors in bins of 15° for each participant. The bin size was chosen to match the differences in cue color of 0°, 15°, and 30°. We then fit the relative frequencies with a Gaussian function.

$$Y = a * \exp(-((X - b)/c)^2) + d$$

where Y is the relative frequency of color errors and X is the color error of the respective bin. The parameter a estimates the scaling of the function, which corresponds to its height and describes its range. The parameter b estimates the position of the function on the x-axis, which corresponds to a bias in the color judgements (e.g., a participant may consistently judge a red target to be orange-red). The parameter c estimates the width of the function, which corresponds to the precision of color judgments where small width values correspond to high precision. The parameter d estimates the position of the function on the y axis, which corresponds to the guess rate for color judgments. Only the width parameter was of theoretical relevance, but all parameters will be briefly presented.

We compared the four parameters between groups with singleton and feature search, but none of the independent-samples t-tests was significant, *ps* > .245. Across all participants, the precision was 12 (*SD* = 4), the estimated height was 0.9 (*SD* = 0.8), the bias was 1 (*SD* = 13), and the guess rate was 0.0004 (*SD* = 0.001). The low guess rate shows that only few judgments badly missed the target color, which may compensate for the rather small number of trials used to perform the fit (40–60 trials, compared to 150–160 trials per condition in studies using mixture modeling, see Bays, Catalao, & Husain, 2009; Wilken & Ma, 2004; Zhang & Luck, 2008). To corroborate results from the Gaussian fits, we calculated the means and standard deviations of the color judgments because these are expected to be robust measures. To remove guesses, we excluded color judgments that were beyond 2.5 *SD* from the individual mean (1.8% of the color judgments). By independent-samples *t*-test, the variability of the color judgments did not differ between singleton and feature search (9 vs. 8), *p* = .466. Similarly, the mean was not significantly different (2° vs. −2°), *p* = .395. Further, one characteristic of this sample of participants was the rather large between-subjects variability of the bias parameter, which led to a discrepancy between the fit to the average relative frequencies depicted in Fig. 3 (singleton search: width of 22, feature search: width of 18) and the mean individual precision (12). The reason is that shifts of the distribution from one participant to another broaden the average distribution. The large between-subjects variability of the bias parameter was not replicated in Experiment 2 and is probably a chance finding.

Gaussian fits of cueing effects. We fit the same Gaussian function as above to cueing effects instead of relative frequencies. Because we had collapsed across positive and negative color differences for the RT data, the cueing effects were mirrored from positive to negative before fitting the Gaussian function. For cueing effects, the shift of the function on the y-axis estimates the asymptotic cueing effect, and not the guess rate as for color judgments. To improve fits, we restricted the height parameter to the difference between the smallest and the largest cueing effect, which corresponds to the observed range of cueing effects. Even so, some functions could not be fit. For singleton search, three functions showed a dip and not the expected peak, which resulted in a negative height parameter (values of −1, −21, and −41). For three further functions, the width parameter was implausibly small (values of 1, 3, 9). Visual inspection revealed that the fit resulted from a single peak at the 0° cue difference, but an otherwise flat function. For another participant, the fit was poor (r^2 = 0.35 compared to a range of 0.58–0.99 for the remaining participants). Thus, the data from seven participants could not be fit in the singleton search group. In the feature search group, the width of one Gaussian was implausibly large (value of 104 compared to a range of 23–52 for the remaining participants). In sum, fits could not be performed for 7 out of 15 participants in the singleton search group, and for 1 out of 16 participants in the feature search group. A Chi-square test showed that the success of our fitting procedure depended significantly on search group, $\chi^2(1) = 6.61$, *p* = .015.

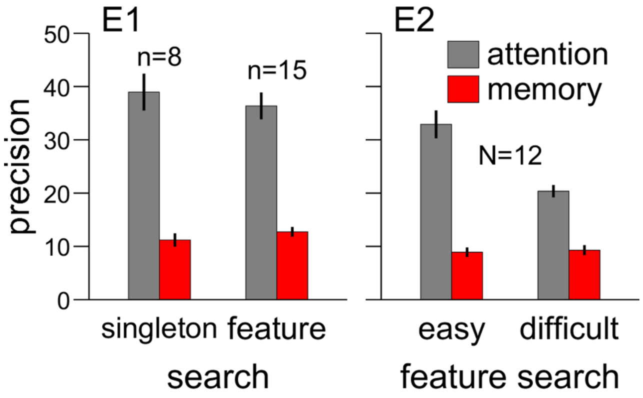

Fig. 4. Mean precision of attentional selection and memory in Experiments 1 and 2. The precision corresponds to the width of Gaussian functions fit to cueing effects (attention) and color errors (memory). Wide functions (high values) correspond to low precision. Singleton and feature search were compared between participants in Experiment 1. Because it was not always possible to fit a Gaussian function, the indicated number of participants was lower than the size of the complete sample. Error bars show the standard error of the mean.

For the 23 participants with successful fits, we compared the height, width, and asymptotic cueing effect between the singleton (*n* = 8) and feature (*n* = 15) search groups, but none of the independent-samples t-tests was significant, *ps* > .419. Collapsed across search groups, the precision was 37 (*SD* = 10), the estimated height was 67 (*SD* = 22), and the asymptotic cueing effect 6 ms (*SD* = 22). By one-sample *t*-test against zero, the asymptotic cueing effect was not significantly different from zero, *p* = .184, suggesting that dissimilar cue colors resulted neither in cueing benefits nor suppression.

Comparison of the precision of attention and memory. Only the 23 participants with successful fits were analyzed. Individual width parameters were entered into a mixed 2 (group: singleton search, feature search) × 2 (dependent variable: cueing effect, color error) ANOVA. The mean width parameters are shown in Fig. 4. The width of the Gaussian functions was larger for cueing effects than for the color error (38 vs. 12), *F*(1, 21) = 139.97, *p* < .001, η_p^2 = .87. None of the other effects were significant, *p* > .354. Because the sample size varied between the singleton and feature search groups, we compared the precision of cueing effects to the precision of color judgments for each group separately. The larger width of the functions fit to the cueing effects were confirmed for singleton search (39 vs. 11), *t*(7) = 6.28, *p* < .001, Cohen's *d* = 2.22, and feature search (36 vs. 13), *t*(14) = 10.97, *p* < .001, Cohen's *d* = 2.8.

We believe that the comparison of precision is conservative because participants with the least precise cueing effect functions (which could not be fit) were excluded from analysis. The comparison is also conservative because cueing effects are difference values, whereas color judgments were absolute values. Therefore, some variability from motor and perceptual processes was removed from cueing effects, whereas this variability contributed directly to the width of the distribution of color errors.

2.3. Discussion

We measured cueing effects to cue colors that differed between 0° and 60° from the color target. Consistent with the previous literature, cueing effects decreased with increasing color difference (Anderson & Folk, 2010; Ansorge & Heumann, 2003; Becker et al., 2013). Further, we had reasoned that singleton search would be less precise than feature search, and the results provide partial support for this conclusion.

The cueing effects with 30° and 60° cue colors were larger in singleton than in feature search. However, evidence for improved precision in feature search was limited to results from the ANOVA. The Gaussian fits to the cueing effects showed no improvements with feature search. Possibly, the difficulty of fitting Gaussian functions to the participants in the singleton search group contributed to the lack of difference.

The central finding of the current experiment was that the precision of attentional selection was far worse than the precision of the memory representation underlying attentional selection. Concretely, the function fit to the cueing effects was much broader than the function fit to the memory error. As a matter of fact, some individual cueing functions were essentially flat, suggesting that there was no attentional selectivity in the range of tested color differences at all. Because we excluded these functions from analysis, the precision of attentional selection may be overestimated. With respect to our original question, we conclude that cueing effects by similar colors are only to some degree caused by an imprecise representation of the target color in memory. Rather, attentional selection is broadly tuned despite a precise memory representation. This point is best illustrated by the 30° color difference. Fig. 3 shows that the relative frequency of a 30° color error is close to zero, suggesting that the memory representation was sufficiently precise to reject the 30° color separation as different. In contrast, there was a solid 50 ms cueing benefit with a 30° cue color, providing evidence for attentional selection by these cues. With respect to the question whether the capacity of attentional selection is equal or inferior to the capacity of VWM, the present results suggest that the lower resolution of attentional selectivity decreases the capacity of attentional selectivity, at least when the target is similar to the nontargets.

However, conclusions regarding differences or similarities between singleton and feature search are limited by the fact that the comparison was run between-subjects. To some degree, this was necessary because previous studies demonstrated that participants keep on using the same search mode even after changes of the search requirements. For instance, participants who performed feature search also applied feature search to stimuli that allowed for singleton search (Kerzel & Barras, 2016; Leber & Egeth, 2006; Zehetleitner, Goschy, & Müller, 2012). Therefore, carry-over from one search type to another may compromise findings of within-subjects designs. Nonetheless, the procedural differences between singleton and feature groups make the comparison of the color judgments unconvincing. In singleton search, the color judgments were blocked at the end to avoid inadvertent induction of feature search in the first part of the experiment. In the final block, however, it is likely that observers switched to feature search because they had to focus on the target color to perform the color judgments. Therefore, the lack of difference between singleton and feature groups regarding memory performance may result from the blocking of memory judgments in the singleton group.

Finally, it should be noted that dissimilar cues at the largest separation between cue and target color (60°) did not result in cueing costs, but in a significant cueing benefit (singleton search) or no cueing effect (feature search). This result is consistent with previous studies using highly dissimilar cue colors, which found cueing benefits (Ansorge & Becker, 2014) or no cueing effects (Ansorge & Becker, 2014; Folk & Remington, 1998; Folk et al., 1992). In these studies, the target was either a singleton or it was accompanied by a single colored nontarget. Possibly, cueing costs may be induced by showing more than a single nontarget color (Carmel & Lamy, 2014, 2015; Lamy & Egeth, 2003). With more colors in the target display, the nontarget colors would necessarily be more similar to the target color. Somewhat trivially, only a single color can be maximally dissimilar in CIELAB-space (i.e., at 180°). Therefore, the similarity between target and nontargets increases when the number of colored nontargets is increased.

3. Experiment 2

To avoid the caveats of comparisons between singleton and feature search, Experiment 2 manipulated precision requirements in feature search with a fixed number of colored nontargets. In easy feature search, two nontarget colors were separated by 90° from the target and the third nontarget was separated by 180°, so that the four colors in the target display were equally distributed in CIELAB-space (see Fig. 1A). Because the colors were highly discriminable and belonged to different color categories (Witzel & Gegenfurtner, 2013, 2015a), precision requirements were low, and the task was easy. In difficult feature search, two nontarget colors were separated by only 30° from the target color, while the third nontarget color was at 180°. Because two nontarget colors were similar to the target color, precision requirements were high, and the task was difficult. The cue colors were the same as in the previous experiment. Precision requirements were manipulated within participants in separate sessions. In both conditions, the target color was judged every twelve trials.

3.1. Methods

The methods were as in the previous experiment with the following exceptions. Participants completed two sessions with 768 trials on different days for a total of 1536 trials. There were 120 trials with color judgment, with individual median RTs between 3248 and 12,999 ms ($M = 6248$ ms). Between days, the target-nontarget similarity changed. The order of conditions was initially counterbalanced across participants.

We noticed that the difficult feature search led to high error rates in some subjects. To reduce noise in the data, we fixed an exclusion criterion of maximally 25% choice errors (see Luck, 2005). Above 25% choice errors, performance is closer to chance performance (i.e., 50% choice errors) than to optimal performance (i.e., 0% choice errors). Because we initially tried to replace lost subjects, we increased the number of participants from 16 to 19 students. However, five failed the 25% criterion in the difficult feature search condition and one had a large bias in the color judgments, leaving only 13 participants in the final sample (1 male, age: $M = 20.2$ years, $SD = 1.1$). Possibly, some target colors were more difficult than others, pointing to inhomogeneity in CIELAB space (Allred & Flombaum, 2014). Two participants failed with the 11° target (reddish), and another two failed with the 236° target (green-yellow).

3.2. Results

RTs. Late trials (0.07%) and outliers (2%) were removed from analysis. We conducted a 2 (search difficulty: easy, difficult) × 4 (cue color relative to target color: difference of 0°, 15°, 30°, 60°) × 2 (cue validity: valid, invalid) repeated-measures ANOVA on the individual mean RTs. The effect of cue validity, $F(1, 12) = 15.11$, $p = .002$, $\eta_p^2 = .557$, was modulated by search difficulty, $F(1, 12) = 24.02$, $p < .001$, $\eta_p^2 = .667$, showing that the cueing effect was larger with easy than difficult search (26 vs. 4 ms). The interaction of cue color and cue validity, $F(3, 36) = 73.67$, $p < .001$, $\eta_p^2 = .86$, showed that the cueing effects decreased with decreasing cue-target similarity (60, 37, −18, −35 ms for 0°, 15°, 30° and 60° cue colors). Inspection of the lower panels of Figs. 2 and 3 shows that cueing effects decreased more rapidly with increasing separation of cue and target color when the search task was difficult than when it was easy. This observation was substantiated by a three-way interaction of search difficulty, cue color, and cue validity, $F(3, 36) = 4.63$, $p = .008$, $\eta_p^2 = .278$. To examine the origin of the interaction in more detail, we compared the cueing effects between easy and difficult search for each cue color. The critical p-value was adjusted to 0.0125 to correct for four tests. By paired t-test, the cueing effect was comparable between easy and difficult search for the 0° cue color (66 vs. 54 ms), $p = .269$. In contrast, it was significantly larger for easy than difficult search with the 15° cue color (51 vs. 23 ms) and the 30° cue color (11 vs. −46 ms), $ts(12) > 3.87$, $ps < .001$, Cohen's $ds > 1.08$. Finally, the difference between easy and difficult search only approached significance with the 60° cue color (−25 vs. −46 ms), $t(12) = 2.24$, $p = .045$.

Further, the ANOVA confirmed shorter RTs with easy than difficult search (473 vs. 541 ms), $F(1, 12) = 19.56$, p = .001, $\eta_p^2 = .62$. Of lesser interest, there was an effect of cue color, $F(3, 36) = 25.82$, $p < .001$, $\eta_p^2 = .683$, that was modulated by search difficulty, $F(3, 36) = 3.74$, $p = .02$, $\eta_p^2 = .237$. RTs increased with larger cue-target color separation, but this increase was less pronounced with easy (460, 465, 479, 489 ms) than with difficult search (524, 535, 557 548 ms).

It is noteworthy that cueing effects did not always result from shorter RTs to targets at the cued compared to the uncued position (cueing benefit), but sometimes resulted from shorter RTs at the uncued position (cueing cost). To provide evidence for cueing costs, we conducted one-sample t-tests against zero with an adjusted p-value of 0.0063 to correct for eight tests (2 search difficulty × 4 cue color). For easy search, there were significant cueing benefits with the 0° and 15° cue color (66 and 51 ms), $ts(12) > 11.36$, $ps < .001$, Cohen's $ds > 3.1$, and significant cueing costs with the 60° cue color (−25 ms), $t(12) = 5.08$, $p < .001$, Cohen's $d = 1.41$. For difficult search, there was a significant cueing benefit with the 0° cue color (54 ms), $t(12) = 4.94$, $p < .001$, Cohen's $d = 1.37$, and cueing costs with the 30° and 60° colors (both −46 ms), $ts(12) > 5.33$, $ps < .001$, Cohen's $ds > 1.47$.

Choice errors. The same ANOVA as above was conducted on choice errors to rule out speed-accuracy tradeoff. Fewer errors occurred with easy compared to difficult search (3.1% vs. 9%), $F(1, 12) = 11.78$, $p = .005$, $\eta_p^2 = .495$. The interaction of search difficulty and cue validity, $F(1, 12) = 22.29$, $p < .001$, $\eta_p^2 = .65$, showed that fewer errors occurred with valid than invalid cues when search was easy (2.5% vs. 3.6%), but the opposite was true when search was difficult (10.5% vs. 7.5%), which is probably due to the dominance of cueing costs when search was difficult. Further, the interaction of cue color and cue validity, $F(3, 36) = 15.98$, $p < .001$, $\eta_p^2 = .571$, showed that cueing benefits turned into cueing costs with increasing separation of cue and target color (cueing effects of 3.4%, 0.3%, −3.6%, and −4% for cue colors of 0°, 15°, 30°, and 60°, respectively). To rule out speed-accuracy tradeoff, we calculated inverse efficiency scores (IES). IES were calculated as RT / (1-PE), where PE is the proportion of choice errors (Townsend & Ashby, 1978). Running the above ANOVA on IES yielded the same pattern of results as the analysis of RTs.

Gaussian fits to color errors. We fit the color error with the Gaussian function described above. Paired t-tests did not reveal any significant differences in the height, bias, and width parameters between easy and difficult search, $ps > .31$. Averaged over easy and difficult search, the estimated precision was 9 ($SD = 3$), the height was 1.4 ($SD = 0.8$), the bias was 0 ($SD = 4$), and the guess rate was 0.0003 ($SD = 0.0005$).

Gaussian fits to cueing effects. For one participant, it was not possible to fit the cueing effects in the difficult search condition because the function showed a dip and not the expected peak. Thus, 12 out of 13 subjects were retained in this analysis. The mean width of individual Gaussians was smaller with difficult than easy search (20 vs. 33), $t(11) = 4.57$, $p = .001$, Cohen's $d = 1.32$, showing that the precision of attentional selectivity was improved with difficult search. The height of the Gaussian was larger with difficult than easy feature search (119 vs. 92), $t(11) = 3.27$, $p = .008$, Cohen's $d = 0.94$, showing that the range of cueing effects was larger in difficult than in easy feature search. Finally, the asymptotic cueing effect was more negative in difficult than easy feature search (−52 vs. −24), $t(11) = 3.5$, $p = .005$, Cohen's $d = 1.01$, showing a larger downward shift of the functions with difficult compared to easy search that is consistent with the occurrence of stronger cueing costs. By one-sample *t*-test against zero, the asymptotic cueing effect was significantly different from zero in both conditions, $ts(11) > 4.92$, $ps < .001$, Cohen's $ds > 3.61$, suggesting that dissimilar cue colors were suppressed in both conditions.

Comparison of the precision of memory and attention. Only the 12 participants with successful fits were analyzed. The mean width parameters are shown in Fig. 4. Individual width parameters were entered into a 2 (dependent variable: cueing effect, color error) × 2 (search difficulty: easy, difficult) ANOVA. The width of the Gaussian functions was smaller for the color error than for cueing effects (9 vs. 27), $F(1, 11) = 88.88$, $p < .001$, $\eta_p^2 = .89$. The effect of search difficulty, $F(1, 11) = 15.07$, $p = .003$, $\eta_p^2 = .578$, was modified by the interaction of dependent variable and search difficulty, $F(1, 11) = 25.44$, $p < .001$, $\eta_p^2 = .698$, showing that the search difficulty affected the width of the functions fit to cueing effects, but not the width of the functions fit to the color error. By paired *t*-test, the width was smaller with difficult than easy search for cueing effects (20 vs. 33), $t(11) = 4.57$, $p = .001$, Cohen's $d = 1.32$, but not for color errors (9 in both conditions), $p = .646$. Importantly, the width of the function was smaller for color error than for cueing effects with easy (9 vs. 33), $t(11) = 8.42$, $p < .001$, Cohen's $d = 2.43$, and difficult search (9 vs. 20), $t(11) = 7.68$, $p < .001$, Cohen's $d = 2.32$.

3.3. Discussion

We compared feature search with low and high precision requirements. Unlike in Experiment 1, the search displays were balanced between conditions because there were always four colors in the target display. We observed that cueing effects decreased with decreasing similarity of cue and target color, but that the decrease occurred faster with difficult search. Accordingly, fits to the cueing effects showed that the precision of attentional selection was better with difficult than easy search. At the same time, the precision of the attentional template (i.e., the memory error) was not different between difficult and easy search. Consistent with Experiment 1, attentional selection was overall less precise than the attentional template even when the precision of attentional selection was much improved. That is, even the high precision of attentional selection with difficult search was far worse than the precision of the attentional template.

Further, cueing costs emerged for the 60° cue color in easy search and for the 30° and 60° cue colors in difficult search. In Experiment 1, cueing costs were not observed with these cue colors, suggesting that the emergence of cueing costs followed the precision requirements of the search task. In search tasks that imposed only minimal precision requirements (Experiment 1), cueing costs were absent. In search tasks that imposed moderate precision requirements (feature search with dissimilar colors), cueing costs were observed for dissimilar colors at a color separation of 60°, whereas with high precision requirements (feature search with similar colors), cueing costs also emerged for similar colors at a color separation of only 30°.

Finally, the between-subject variability of the bias parameter was much reduced in the current compared to the previous experiment (*SD* of 4 vs. 13). We do not have a good explanation for the difference between the two samples. Possibly, participants were more motivated to respond accurately when they were invited to two experimental sessions (Experiment 2) instead of just one (Experiment 1).

4. General discussion

Voluntary attentional selection is the process by which sensory input is matched to an internal template of the search goal (Duncan & Humphreys, 1989), but both attentional selection and the internal target representation are subject to variability. The first goal of the present study was to compare the precision of attentional selection to the precision of the underlying memory representation (i.e., the attentional template). To this end, we measured effects of cue validity across a range of cue colors from identical up to 60° of separation from the target in CIELAB space. Further, we measured participants' memory for the target color on a color wheel. To estimate precision, the same Gaussian function was fit to cueing effects and memory errors. The results showed that the precision of the memory representation was far better than the precision of attentional selectivity. In other words, the internal representation of the search target was very precise, whereas attentional selection was not. Thus, the cause of attentional capture by target-similar stimuli is only to some degree a poor underlying memory representation, but mostly poor attentional selectivity. Our results favor models that propose that the capacity of attentional selection is lower than the capacity of memory (reviewed in Olivers et al., 2011) because limited resolution in attentional selectivity will pool stimuli that can be differentiated in VWM.

So far, our assumption has been that color errors in the memory task reflect the same representation that is used in the visual search task. However, it is also possible that there are two sources of information with independent representations. Possibly, the representation related to color judgments is more explicit than the representation related to visual search. Depending on the task at hand, the appropriate representation would be selected to optimally meet the task requirements. Alternatively, the same representation is involved in both tasks, but used differently. Presently, we cannot decide between these two accounts, but because the assumption of a unitary memory representation is more parsimonious, we hold on to it for now.

Further, the results showed that the precision of attentional selection increased with increasing task demands, whereas the precision of the attentional template (i.e., the memory error) did not. In contrast, previous research suggests that the precision of the attentional template determines the efficiency of attentional selection. For instance, the attentional template is less precise when participants are asked to search for an object category compared to when they are asked to search for a particular object. Accordingly, search for an object category is slower than search for an exemplar of the category (e.g., Jenkins, Grubert, & Eimer, 2018; Malcolm & Henderson, 2009). In our current study, however, we did not find that the precision of the attentional template determined the precision of attentional selectivity. Rather, the precision of the attentional template was invariable across conditions, whereas the precision of attentional selection varied with task demands.

Improvements of attentional selectivity through increased target-nontarget similarity are consistent with results by Geng and collaborators (Geng et al., 2017; Won & Geng, 2018) who found that the increase in RTs with similar nontargets was reduced for participants who were more frequently exposed to these nontargets. The present study took a different methodological approach by probing attentional selection with a cueing procedure. The cueing procedure has the advantage that characteristics of the search display can be separated from the cue display. Thus, the same cue colors were used throughout, while the target display varied in the number of colored nontargets and target-nontarget similarity. For the precision of the memory representation, we did not find a modulation by task requirements. Consistent with this conclusion, Geng et al. (2017) provided no evidence to suggest that the width of the distribution of memory errors changed between groups of participants who were frequently or rarely exposed to highly similar nontargets. However, Geng et al. (2017) found a change in the bias of the distribution, which was more pronounced for participants frequently exposed to similar nontargets. In particular, the distribution of the memory error was shifted away from the nontarget colors, in support of optimal tuning theory (Navalpakkam & Itti, 2007).

4.1. Visual long-term memory vs. visual working memory

In Geng et al. (2017) and the current study, the search target was fixed for each participant, which may explain why neither the search mode nor target-nontarget similarity affected the precision of the memory representation. Possibly, there was a ceiling effect because the target representation was transferred into long-term memory (see Carlisle et al., 2011). Contribution from long-term memory are likely because the precision in the present study was better than for a single color stored in VWM, but similar to the precision in perceptual color matching tasks. For comparison, we fit the standard mixture model with added bias parameter to the color judgments (Suchow, Brady, Fougnie, & Alvarez, 2013) and found the average *SD* of color judgments to be 9° in Experiment 1 and 5.5° in Experiment 2, which is close to the 5–7° observed for perceptual matching tasks (Brady et al., 2013). Thus, the repeated exposure and recall of an unchanging target certainly improved performance compared to VWM tasks where the memory target changed from trial to trial and where the precision for a single target was found to be around 14° (Zhang & Luck, 2008). Possibly, effects of tasks requirements on memory performance may emerge in VWM tasks with variable targets. For instance, Rajsic, Sun, Huxtable, Pratt, and Ferber (2016) reported that memorized targets were recalled with higher precision when they had to be searched for, and Rajsic, Zhao, and Woodman (2018) found that targets in difficult search were better remembered than targets in easy search. Thus, tasks that tax working memory more strongly may bring effects of search requirements on the precision of memory to the fore.

4.2. Mechanisms underlying the lower precision of attentional selection

The results demonstrated that the precision of attentional selection was far worse than the precision of the memory for the target (i.e., the attentional template). What caused the loss in precision? This question is difficult because it is generally accepted that attentional selection involves the match of sensory information to an internal target representation (Eimer, 2014; Olivers et al., 2011), but little is known about how the stored target features are recoded to match the perceptual input. After all, the stored features are in memory, whereas the incoming information is in the visual system. To find an answer to this question, it may be useful to distinguish between attentional guidance and selection. Cueing effects in the present study arise from the processing advantage resulting from attentional selection of stimuli at the cued location. Therefore, cueing effects result from spatially selective processes. However, there is agreement that attention is guided to spatial locations based on features of the target in a display-wide manner (Wolfe, Cave, & Franzel, 1989), which is commonly referred to as feature attention. Feature-based attention is believed to enhance the processing of the selected feature across the visual field (reviewed in Maunsell & Treue, 2006). Necessarily, the display-wide enhancement involves neurons with large receptive fields (reviewed in Eimer, 2014) and possibly, this loss of spatial precision is accompanied by a loss in featural precision. In other words, it may be that the difference between the precision of the attentional template and attentional selection arises at the stage where the stored target features are transformed into display-wide enhancement of the target feature. However, this idea is speculative and requires further research.

Another – equally speculative – idea is that the same neuronal representation is used for attentional selection and memory judgments, but in different ways. Possibly, attentional selection relies on individual neurons whereas memory judgments rely on the average of the same population of neurons. One may assume that the representation of the target color is distributed across a population of color-tuned neurons where each neuron has a distribution of responses to color (Gegenfurtner, 2003; Witzel & Gegenfurtner, 2018). For instance, a neuron tuned optimally to red would be best stimulated by red, but would still respond sub-optimally to yellow. At the population level, the average response of color-tuned neurons may reliably code the stimulus color (Wachtler, Sejnowski, & Albright, 2003). The population of neurons may be accessed in two different ways: at the level of the average and at the level of individual neurons. The probability of finding an activated neuron for a given stimulus increases with increasing similarity to the average population response. For instance, with a red target stimulus, it is more probable to find activated neurons tuned to red than activated neurons tuned to yellow. Based on the assumption that sensory areas are recruited to maintain representations in VWM (Kamitani & Tong, 2005), we also expect a population of color-tuned neurons to underlie the storage of the target color in VWM. Possibly, the match of stimulus color to memorized target color is achieved by matching the activity of sensory neurons to the activity of memory-related neurons. Because this match relies on individual neurons, the precision of the match will mirror the population of activated neurons. That is, it will be easier to find matching neurons close to the population average, but a match may also occur for other activated neurons, which makes selection imprecise. For instance, a yellow stimulus may be occasionally selected when the memorized target stimulus is red, even if selection of red is more probable. In contrast, color judgments may rely on the population average, and not on individual neurons. The reason for the different access to the same population may be that visual search must operate rapidly, whereas memory judgments are performed without time constraints, leaving sufficient time for calculation of the average. As a result, the observed memory errors reflect the errors in the calculation of the average, which will be much closer to the true average than individual neurons drawn from the same population of neurons.

4.3. Cueing costs and suppression

Further, our results shed some new light on the potential causes of cueing costs. As outlined in the introduction, feature suppression (Lamy & Egeth, 2003) or object updating (Carmel & Lamy, 2014; Schoeberl et al., 2017) have been discussed as potential explanations. The emergence of cueing costs in search displays with multiple nontarget colors (Experiment 2) confirms the anecdotal observation that heterogeneous color displays lead to cueing costs (Carmel & Lamy, 2014). Experiment 2 suggests that the causal factor for cueing effects was not the number of colored nontargets per se, but the increased precision requirements. In Experiment 2, the number of colored nontargets was always three, but cueing costs were more pronounced with difficult than easy search. In particular, the 30° cue color separation produced no cueing effect with easy feature search, but a significant cueing cost with difficult feature search. To provide further evidence for the idea that it was the required precision in the search task, and not the number of colored nontargets in the search display that was responsible for cueing costs, we ran a supplementary experiment. In this experiment, there was only a single colored nontarget (as in the feature search group of Experiment 1), but with a smaller color separation from the target (randomly 30° or 60°). By one-sample *t*-test, we observed significant cueing benefits with cues matching the target color (41 ms), $t(15) = 9.83$, $p < .001$, Cohen's $d = 2.46$, and significant cueing costs with non-matching cues of 30° and 60° separation (−25 and −29 ms), $ts(15) > 4.5$, $ps < .001$, Cohen's $d > 1.12$. In contrast, there were no cueing costs in the feature search group of Experiment 1 where there was also a single colored nontarget, but at a large color separation (180° from the target). Thus, it is not the number of colored nontargets, but their similarity to the target color that promotes cueing costs.

Another way of looking at the switch from cueing benefits to cueing costs is as an increase in suppression of non-target features. Along these lines, Lamy and Egeth (2003) proposed that participants suppressed the known feature of the cue, rather than salient stimuli per se. There is research to support the idea that known distractors, but not unknown or variable distractors, can be suppressed. For instance, interference from a distractor is large in the first trials of an experiment, but decreases as participants become familiar with the distractor's features (Gaspelin & Luck, 2017; Vatterott & Vecera, 2012; Zehetleitner et al., 2012). Further, the number of distractors that can be effectively suppressed may be severely limited. Possibly, only a single known distractor can be entirely suppressed so that it does not interfere with search (Graves & Egeth, 2016; Kerzel & Barras, 2016). In the current study, however, there were six different cue colors (±15°, ±30°, ±60° relative to the target color) and therefore, it seems unlikely that suppression was directed to only a single known color. Rather, the current results suggest that there was suppression of any color that differed from the target color.

Further, suppressive effects in the current study are fully in line with electrophysiological research that considered suppression as a top-down process counteracting capture by salient stimuli (reviews in Gaspelin & Luck, 2018b; Geng, 2014). In this context, a contralateral positivity at posterior electrodes about 200–300 ms after stimulus onset, the P_D component, has been used as an index of attentional suppression (Hickey, Di Lollo, & McDonald, 2009; Sawaki, Geng, & Luck, 2012). However, most of the research on the P_D has used Theeuwes (1991) additional singleton paradigm where distractor and target are simultaneously present (Burra & Kerzel, 2013; Gaspar & McDonald, 2014; Gaspelin & Luck, 2018a; Hilimire & Corballis, 2014; Jannati, Gaspar, & McDonald, 2013). To our knowledge, there is no existing evidence for the P_D component in the contingent capture paradigm. Nonetheless, clear predictions can be derived. For instance, the 30° cue color condition would be expected to result in a P_D in the difficult search condition (similar to Experiment 2), whereas an index of attentional selection, the N2pc (Eimer & Kiss, 2008; Lien et al., 2008), would be expected to the same color in singleton search (similar to Experiment 1).

4.4. Alternatives to suppression

Measurements of the electrophysiological response to the cue may also be necessary to rule out alternative accounts of the cueing costs. Possibly, RTs depend on the evidence in favor of the target color that is observed at the target location. Short RTs are expected when there is a lot of evidence in favor of the target color and long RTs are expected when there is little evidence. When cue and target are presented at the same location on valid trials, there is more evidence in favor of the target color when cue and target color match than when they are dissimilar, which may explain the shorter RTs with matching than with non-matching cues. Conversely, when cue and target are presented at different locations on invalid trials, there will be evidence in favor of the target at a non-target location with matching cue colors, which may explain the longer RTs with matching than non-matching cues. Further, the accumulated evidence may result in a tie between target and non-target locations when similarity is high. Let us assume that the evidence in favor of the target color corresponds to the average of cue and target color at a given location. For a 60° cue and a 0° target, the average would be 30°. When the nontargets are 90° away from the target color (i.e., easy feature search in Experiment 2), the average on valid trials would still favor the target location. However, when nontargets are only 30° away from the target color (i.e., difficult feature search), the average may result in a tie between target and nontarget locations, which may underlie cueing costs. This alternative account would be invalidated by electrophysiological indices of attentional suppression to the cue because the accumulator account does not rely on attentional processes, but rather on decision making.

4.5. Feature-based attention

The cueing costs observed in Experiment 2 provide evidence for feature-based suppression, which fits nicely with studies on feature-based attention. For instance, Störmer and Alvarez (2014) asked participants to attend to identical or different colors on opposite sides of fixation. The target dots were accompanied by nontarget dots and participants reported brief intervals of coherent motion in dots of the attended colors. Unsurprisingly, performance was best when the same color was attended on both sides of fixation. More interestingly, performance decreased with increasing color separation between the two attended colors. The decrease reached a minimum at a color difference of 30°. Between 30° and 60°, however, performance improved again. This pattern of results suggests surround suppression in feature space that is centered on 30° of color separation. However, using a different methodological approach, Wang, Miller, and Liu (2015) found no evidence for a “rebound” of performance, but rather a continuous decrease. In the current study, we did not observe a “rebound” of cueing effects between 0° and 60° as in Störmer and Alvarez (2014). Rather, we observed a floor effect that occurred earlier with difficult feature search (at 30°) and later with singleton or easy feature search (at 60°). Nonetheless, our results are broadly in line with the suppression of non-attended features, even if suppression in the present study occurred only with feature search and displays with multiple nontarget colors (Experiment 2).

4.6. Conclusions

We compared the precision of attentional selection and its underlying memory representation. We observed that the precision of attentional selection is far worse than the precision of the attentional template. Thus, attentional capture by target-similar stimuli is explained by poor attentional selectivity and not by poor memory. Further, the precision of attentional selection improved with increasing task demands, but there was no change in the precision of the attentional template. Possibly, the invariable precision of the attentional template was due to contributions from long-term memory. Further, we observed that the cueing benefit with cues similar to the target turned into a cueing cost when task requirements were high, suggesting that increases in precision are achieved by suppressive mechanisms.

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