

# Feature-based effects in the coupling between attention and saccades

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Previous research has demonstrated that prior to saccade execution visual attention is imperatively shifted towards the saccade target (e.g., Deubel & Schneider, 1996; Kowler, Anderson, Doshier, & Blaser, 1995). Typically, observers had to make a saccade according to an arrow cue and simultaneously perform a perceptual discrimination task either at the saccade endpoint or elsewhere on the screen. Discrimination performance was poor if the location of the saccade target (ST) and the discrimination target (DT) did not coincide. However, those experiments only investigated shifts of spatial attention. In the current experiments, we examined how feature-based attention is deployed before a saccade. In [Experiment 1](#), we randomly varied the colors of the ST and DT. Results showed that discrimination performance was better when the DT was shown in the same color as the ST. This color congruency effect was slightly larger and more reliable when ST color was relevant and constant across trials ([Experiment 2](#)). We conclude that selection of a colored ST can induce display-wide facilitative processing of stimuli sharing this color. Results are discussed in terms of saccade programming and saccade selection, color priming in visual search, color cuing, and color-based top-down contingent attentional capture. We also discuss basic mechanisms of spatial- and feature-based attention and predictive remapping of visual information across saccades.

**Keywords:** feature-based attention, spatial attention, saccades

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## Introduction

Basic vision and conscious visual perception are both capacity-limited: we cannot see and we cannot process all there is in our environment at one single glance. To explore our surroundings, saccadic eye movements are made three to four times a second to consecutively align the fovea—the retinal region of best visual acuity—with new objects of interest. In a similar vein, attention is shifted to successively select parts of the available information for further processing. Because attention shifts and eye movements both serve the purpose of selection, it has been suggested that the two are tightly coupled and may even rely on the same underlying mechanisms. The issue has seen considerable discussion in the 1980s and early 1990s. Repeatedly, the question arose, whether covert shifts of visual attention are accomplished by the preparation of an eye movement that ultimately will be suppressed (Klein, 1980; Klein & Pontefract, 1994; Posner, 1980; Remington, 1980; Reuter-Lorenz & Fendrich, 1992; Rizzo-

latti, Riggio, Dascola, & Umiltà, 1987; Shepherd, Findlay, & Hockey, 1986). Mostly based on spatial cuing studies, it was concluded, however, that although there was a tight functional link between attention and eye movements, not every shift of covert attention necessarily reflects preparation of a saccade that is not executed (see also Belopolsky & Theeuwes, 2009; Hunt & Kingstone, 2003; Juan, Shorter-Jacobi, & Schall, 2004).

In the mid-1990s, the issue has been revived by a series of studies using a dual-task paradigm combining a saccade task with a perceptual discrimination task (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Doshier, & Blaser, 1995). However, the focus was slightly different: the studies examined whether covert attention imperatively shifts towards the saccade target (ST) before an eye movement is initiated. In other words, the question was not whether every covert shift of spatial attention is equivalent to preparing a saccade. Instead the question was whether saccade programming prior to saccade execution automatically entails a shift of covert

attention towards its desired endpoint (saccade target). Typically, observers had to prepare a saccade according to an arrow cue and simultaneously perform a perceptual discrimination task either at the ST location or elsewhere on the screen. The discrimination targets (DTs) were only briefly presented and masked before the saccade was initiated. When the DT location was not known in advance, discrimination performance was good if the DT was incidentally presented at the ST location, but poor if the location of the ST and the DT did not coincide. Masking the DT before saccade initiation ensured that the performance difference could not be explained by postsaccadic perception. That is, performance was not better at the ST location because participants were fixating there after the saccade. It was concluded that a covert shift of attention towards the ST preceded the eye movement. Importantly, presenting the DT at a constant or cued location did not substantially improve discrimination if the saccade had to be made towards a different location (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995), at least not without costs in saccade performance (Kowler et al., 1995). These findings suggested that it is not possible to program an eye movement to one location and at the same time direct covert attention to another location.

The dual-task paradigm has been widely used to investigate the time course, generality, and limits of the obligatory coupling between shifts of covert attention and saccades. In particular, it has been confirmed that (limited amounts of) covert attention can be shifted away from the ST early in the saccade preparation phase (Deubel, 2008; Doré-Mazars, Pouget, & Beauvillain, 2004; Montagnini & Castet, 2007), and that attention may be directed to more than one (eye or hand) movement goal before initiation of the first movement of an action sequence (Baldauf & Deubel, 2008; Gersch, Kowler, & Doshier, 2004; Godijn & Theeuwes, 2003; Jonikaitis & Deubel, 2011; Rolfs, Jonikaitis, Deubel, & Cavanagh, 2010). Further, neurophysiological studies have shown that stimulating saccade motor neurons in the superior colliculi or the frontal eye fields with a pulse train below the threshold of evoking an eye movement improves perceptual performance and modulates neuronal responses in visual area V4. Importantly, these effects were restricted to stimuli presented in the neuron's movement field, that is, at the location the neuron would trigger a saccade to when firing or when stimulated with a suprathreshold pulse train (Armstrong, Fitzgerald, & Moore, 2006; Armstrong & Moore, 2007; Cavanaugh, Alvarez, & Wurtz, 2006; Cavanaugh & Wurtz, 2004; Moore & Armstrong, 2003; Moore & Fallah, 2001, 2004).

In sum, previous studies examined shifts of selective spatial attention prior to saccade execution. However,

it is unclear how feature-based attention is deployed in the context of saccades. As laid out above, selection of an item as a ST has been shown to attract spatial attention towards its location. However, ST selection might not only facilitate processing at its *location*, but also lead to facilitative processing of other ST features, for instance ST color. That is, selection of a location as saccade endpoint facilitates processing of the stimulus presented at the ST location, including all its features. As a result, the stimulus is easier to discriminate. In a similar vein, selection of an item as a ST may bias feature-based attention, facilitating the processing of ST-similar features, irrespective of where these features are presented. It is known that feature-based mechanisms can enhance neuronal responses associated with the attended feature independent of location, that is, across the entire display (e.g., Andersen, Müller, & Hillyard, 2009; Maunsell & Treue, 2006; Saenz, Buracas, & Boynton, 2002; Vierck & Miller, 2008). Feature-based enhancement of neuronal activity in V4 has also been observed for items possessing task-relevant features (e.g., the search target's color) when a saccade is made to another stimulus outside the receptive field of the recorded neuron, that is, when spatial attention is presumably directed to another stimulus (Bichot, Rossi, & Desimone, 2005; Zhou & Desimone, 2011). Moreover, classic behavioral cuing studies have not only demonstrated that selecting a target based on specific features such as color is possible, but also that processing of nontarget items such as cues is modulated depending on whether they share relevant target features or not (cf. Folk & Remington, 1998; Folk, Remington, & Johnston, 1992). For example, if participants search for a red target, highly salient but different colored cues (e.g., a green color singleton) presented shortly before the target are successfully ignored (for a review see Burnham, 2007). In contrast, a cue with a target-similar color happens to attract attention, even though it may not be more salient than other stimuli in the display (Lamy, Leber, & Egeth, 2004). It is assumed that participants search for the target color across the whole area of potential target positions and that a target-similar cue attracts attention to its position because of its match to a top-down search setting for the target color (e.g., Ansorge, Kiss, Worschech, & Eimer, 2011; Eimer & Kiss, 2008; Folk et al., 1992).

In the current study, we examine whether selection of an item as ST facilitates processing of ST features (more specifically, ST color), leading to improved discrimination performance for all items sharing these features. To this end, we use the dual-task paradigm previously employed to examine spatial attention shifts prior to saccade execution and vary the colors of STs and DTs independently. If the same principles of feature-based attention described in previous neuro-

physiological or classic behavioral cuing studies apply, one may expect better discrimination performance when the DT is incidentally presented in the ST color. Further, if feature-based attention acts display-wide, performance improvements should occur even when the ST and DT do not spatially coincide. Alternatively, one may expect better performance for color-congruent DTs only when the ST and DT are presented at the same location. It has been shown that color singleton distractors do not capture attention when the attentional window does not encompass the distractor location (Belopolsky, Zwaan, Theeuwes, & Kramer, 2007; Kerzel, Born, & Schönhammer, *in press*). Thus, with spatial attention presumably narrowly focused on the ST location prior to the saccade in the dual-task paradigm, the capacity of feature-based attentional mechanisms to act display-wide could be reduced. Our approach complements previous research by Gersch, Kowler, Schnitzer, and Doshier (2008, 2009) who asked participants to make sequences of saccades along a pathway marked by green items displayed among red background elements. Using a concurrent perceptual or memory task, they demonstrated that some attentional resources can be broadly distributed along the saccade pathway, including previously fixated locations. This broad attentional distribution was only found when the path was marked by color, that is, when all saccade targets shared a critical feature that distinguished them from their surroundings. Thus, they demonstrated an influence of feature-based attentional facilitation remote from the immediate ST. Our study complements these findings by varying the color of the ST and the remote stimuli more systematically. Further, we investigate whether the selection of the ST has to be based on color, that is, whether a top-down search setting for a specific color is critical for facilitative processing of similarly colored items.

## Experiment 1

We examined whether selection of an item as a ST may automatically induce deployment of attentional resources to distinct, but similarly colored stimuli during the saccade preparation interval. To this end, a dual-task paradigm was used that involved a saccade task and a concurrent discrimination task. The sequence of events is depicted in [Figure 1A](#). A central arrow cue indicated the ST, one of four colored circles. The color of the arrow was always identical to the ST color. During the preparation of the eye movement, the circles turned gray and colored crosses were presented inside the four circles. One of the crosses was asymmetric and served as the DT. Color and location of the ST and DT were independently chosen on each trial. The general question was whether discrimination

performance improves when the DT is incidentally presented in the ST color. As laid out in the [Introduction](#), color congruency could affect performance in two ways: if selection of the cued circle as the ST results in display-wide facilitative processing of ST features (i.e., even at locations other than the ST), we would expect better performance for all trials in which the DT is incidentally presented in the same color as the ST, irrespective of spatial location. That is, we would expect a main effect of color congruency. Alternatively, if a narrow focus of spatial attention on the ST reduces the capacity of feature-based attentional mechanisms to act display-wide, one may expect better performance only when the DT is presented at the ST location. In other words, we would expect an interaction between color congruency and spatial congruency. [Experiment 1](#) also included various control conditions to assess the impact of the dual-task assignment (saccade and concurrent discrimination task) and the additional presentation of colors in the DT display (see [Figure 1B](#)).

## Methods

### Participants

Ten participants (five women) between 17 and 31 years of age were tested in [Experiment 1](#). Eight participants were members of the Visual Cognition group of the University of Geneva (students and collaborators, including one of the authors). The remaining two observers were undergraduates. Students received 20 Swiss Francs per hour for their participation. All experiments were approved by the ethics committee of the Faculty of Psychology and Educational Sciences of the University of Geneva.

### Apparatus

Experiments were programmed in Matlab (The MathWorks Inc., Natick, MA), using the Psychophysics and EyeLink Toolbox extensions (Brainard, 1997; Cornelissen, Peters, & Palmer, 2002; Pelli, 1997) and run on a Dell Optiplex 755 personal computer with a processor speed of 1.86 GHz and a 256 MB ATI Radeon X1300PRO graphics card (AMD, Sunnyvale, CA). Stimuli were displayed on a 21" CRT monitor (NEC MultiSync FE2111SB) running at 85 Hz. The screen's resolution was set to 1280 × 1024 pixels. At a viewing distance of 67 cm, about 40 pixels were displayed per degree of visual angle. Eye movements were recorded using an EyeLink1000 desk-mounted eye tracker (SR Research Ltd., Mississauga, Ontario, Canada) at a sampling rate of 1000 Hz (controlled by a second computer). Participants were seated in a dimly lit room. Viewing was binocular but only the right eye



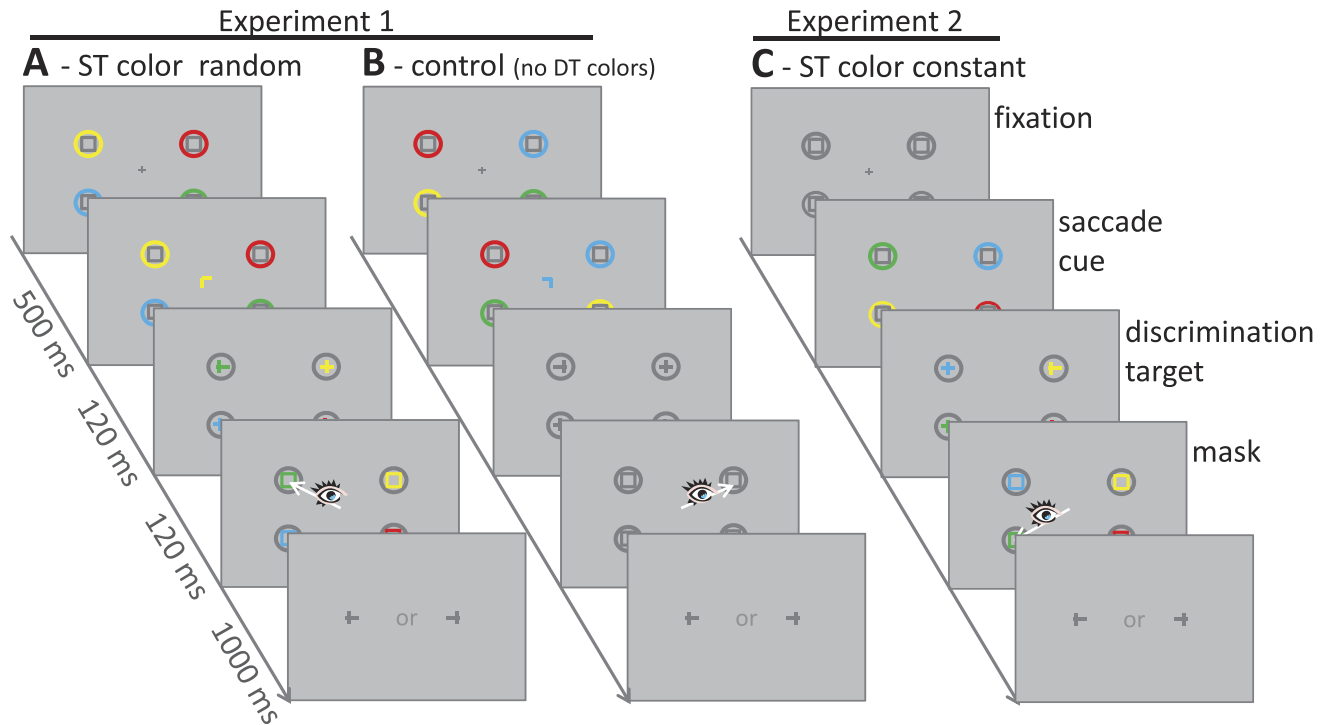


Figure 1. Sequence of events in [Experiment 1](#) (A: color dual-task blocks; B: control conditions, i.e., saccade-only, discrimination-only, and control dual-task blocks) and [Experiment 2](#) (C: only color dual-task blocks). In [Experiment 1](#), participants had to make a saccade to the circle indicated by a colored arrow cue; in [Experiment 2](#), participants had to saccade to the circle of a predefined color (yellow in the example in C); 120 ms after the saccade cue, the DT (one asymmetric cross) was presented in one of the circles along with three perfectly symmetric distractor crosses (A: example of a different-color/same-location trial; B: example of a different-location trial; C: example of a same-color/different-location trial). Crosses were masked by squares after another 120 ms. Participants had to indicate with a button press at the end of each trial whether the vertical bar of the DT was slightly offset to the left or right.

was monitored. The participant's head was stabilized by a chin and a forehead rest.

### Stimuli

The fixation cross consisted of two gray bars of  $5 \times 1$  pixels (subtending about  $0.13^\circ$ ). The four stimuli were placed on the diagonal axes and presented  $5^\circ$  from central fixation (center-to-center). The ST circles were drawn with a radius of  $1.5^\circ$  (pen width of  $0.25^\circ$ ) and the masking squares with a side length of  $1.4^\circ$  (pen width  $0.2^\circ$ ); the bars making up the DT and distractor crosses were likewise  $1.4^\circ$  long and  $0.2^\circ$  thick. Stimuli were presented on a bright gray background ( $58 \text{ cd/m}^2$ ) and matched for luminance:  $19 \text{ cd/m}^2$  (gray:  $x = 0.29$ ,  $y = 0.30$ ; green:  $x = 0.29$ ,  $y = 0.61$ ; cyan:  $x = 0.21$ ,  $y = 0.30$ ; yellow:  $x = 0.40$ ,  $y = 0.52$ ; red:  $x = 0.63$ ,  $y = 0.34$ ). The luminance matching of the stimuli was verified with a ColorCAL Colorimeter (Cambridge Research Systems Ltd., Rochester, UK).

### Design and procedure

The sequence of events in the critical *color dual-task* condition is illustrated in [Figure 1A](#). At the beginning

of each trial, the gray fixation cross and four colored circles containing gray masking squares were shown. After 500 ms, an arrow cue was presented that required participants to saccade as fast as possible towards the ST (i.e., the circle it pointed to). Moreover, the arrow cue was always of the same color as the ST—that is, the ST was jointly defined by color and pointing direction. During saccade preparation—that is, 120 ms after presentation of the arrow cue—colored crosses appeared within the now gray circles. The vertical bar of one cross did not bisect the horizontal bar in the center, but was slightly offset either to the left or right. This was the DT. The remaining crosses were perfectly symmetric (distractors). The crosses remained on screen for 120 ms and were then masked again by squares. At the end of each trial (i.e., after participants had executed the eye movement), a manual response display was presented requiring participants to press a key on a standard PC keyboard (QWERTZ layout) indicating whether the vertical bar of the DT was shifted to the left (“y”) or to the right (“m”). The ST and DT locations, as well as their colors, were fully randomized across trials (i.e., 25% same-location trials, 25% same-color trials). Thus, trials in which ST and

DT were presented at the same location *and* in the same color made up 6.25% of trials.

Additionally, three blocked control conditions were run in which only the circles were initially colored, whereas the crosses and masks remained gray (Figure 1B):

*Saccade-only task:* The task was to make an eye movement as fast as possible towards the circle indicated by the arrow cue. Although the remaining sequence was presented just as in any other condition, participants were instructed to ignore all other stimuli and to fully concentrate on the saccade task. On presentation of the response display, participants pressed the space bar to proceed to the next trial.

*Discrimination-only task:* Participants were asked to keep fixation at the center throughout the trial. Although the arrow cue was presented, they were asked to ignore it and to solely concentrate on the discrimination task. As in the dual tasks, the direction of the arrow cue and the position of the DT were uncorrelated—that is, the arrow pointed in the direction of the DT in only 25% of trials.

*Control dual-task:* Participants were asked to execute an eye movement as fast as possible towards the ST circle indicated by the arrow cue while simultaneously performing the discrimination task. The only difference to the color dual-task was that crosses in the DT and mask display were gray.

The experiment was run in blocks of 256 trials (about 20 min per block). Participants were encouraged to take breaks within a block by delaying the key press. In each block, the horizontal offset of the vertical DT bar was controlled by a staircase procedure such that over all conditions, discrimination performance remained at 71% correct for each participant (initial offset at  $0.3^\circ$  from the center; 2-down, 1-up rule; staircase step size of  $0.1^\circ$ , minimum offset fixed at  $0.05^\circ$  if staircase ran down to  $0^\circ$ ). Acoustic feedback (Matlab “beep”) was provided if participants chose the wrong key in a block with the discrimination task. Each participant first completed a practice session consisting of one full block in each control condition: saccade-only, discrimination-only, and control dual-task (always in this sequence to allow participants to get practice in the single tasks before facing the more challenging dual tasks). At the beginning of the data collection phase, first another set of one block in each control condition was run. Afterwards, participants completed eight blocks in the color dual-task. Finally, the experiment concluded with one last block in each control task to get an estimate of performance after extensive practice. Including practice trials, the experiment thus consisted of 17 blocks (amounting to 4,352 trials per participant), which were typically run in sessions of two blocks at a time, over several days. The experimental design is illustrated in Table 1. Two blocks were sufficient in the control conditions because the relation between ST and DT color did not have to be taken into account as the DT was always gray.

### Eye movement data analyses and feedback

Preliminary eye movement data analyses were performed off-line after each trial. A time window of 200 ms before and 800 ms after the ST onset was specified. Saccade onsets and offsets were detected using the default algorithm of the EyeLink1000 parser (velocity criterion of  $30^\circ/\text{s}$ , acceleration criterion of  $8,000^\circ/\text{s}^2$ ). Only the first saccade in the time window with an amplitude  $>1^\circ$  was considered. Trials were followed by a written feedback message on the screen if (a) no saccade was found within the time window, (b) saccades were directed into the wrong quadrant, (c) saccades were anticipatory (latency  $<80$  ms), (d) saccade latencies were longer than 350 ms, (e) gaze deviated by more than  $1.5^\circ$  from the display center at the time of saccade onset (failure to fixate), or (f) a blink was detected between the beginning of the time window and the end of the saccade. In discrimination-only trials, a fixation control was performed and an error message was shown when (a) gaze deviated by more than  $1.5^\circ$  from the display center during a predefined time window of 300 ms before to 300 ms after onset of the discrimination target (failure to fixate), or (b) a blink was detected during that time window. After the experiment, saccade onset and offset criteria were manually checked with the help of a graphical visualization for at least some exemplary trials for each participant, and median saccade reaction times in the various conditions were computed.

### Results

Trials were excluded if the saccade was not correctly performed or not correctly recorded according to the above-mentioned criteria (see previous section) with the exception of the latency criterion. To encourage fast saccade execution, an error message was shown on screen when saccadic reaction time was above 350 ms. However, we allowed saccade reaction times up to 450 ms to be included in the analyses. Note that exclusion of trials with saccade reaction times above 350 ms did not change the pattern of results. In total, 11.5% of all trials were excluded (range between 3.8% and 24% across participants). Saccades directed into the wrong quadrant (4.9%), failures to fixate at the beginning of a trial or during the discrimination-only blocks (2.5%), and latencies longer than 450 ms (1.1%) were the most frequent errors. Subsequently we split up the saccade trials depending on when the DT was turned off with respect to saccade onset. This is important to exclude trials in which the DT was still present after the saccade—that is, to rule out that differences in DT discrimination performance, in particular better performance on same-location trials, reflect fixating the DT after the saccade had been completed. On most

Task	Blocks	Trials/block	Trials (total)	Same color		Different color	
				Same location	Different location	Same location	Different location
Experiment 1							
Saccade only	2	256	512	—	—	128 (25%)	384 (75%)
Discrimination only	2	256	512	—	—	128 (25%)	384 (75%)
Control dual	2	256	512	—	—	128 (25%)	384 (75%)
Color dual	8	256	2,048	128 (6.25%)	384 (18.75%)	384 (18.75%)	1,152 (56.25%)
Experiment 2							
Color dual	14	128	1,792	112 (6.25%)	336 (18.75%)	336 (18.75%)	1,008 (56.25%)

Table 1. Trials per condition for [Experiment 1](#) and [Experiment 2](#). Note: Practice trials not included.

trials, the DT was extinguished in the last 100 ms before saccade onset (see [Table 2](#)). Thus, our stimulus timing was appropriate because the shift in spatial attention is supposed to occur in the last 100 ms before saccade execution (e.g., Deubel, 2008; Jonikaitis & Deubel, 2011). However, there were also a large number of trials with DT offset during the saccade. Although these trials may already be influenced by the change in fixation, we nevertheless included them in our analyses in order to ensure a sufficient number of trials on which the performance for every participant could be assessed. Trials in which the DT was turned off after the saccade were excluded.

### Discrimination performance

Participants responded correctly to the DT in 73.2% of trials. A one-way ANOVA on the arcsine-transformed percent correct values revealed that there were no significant differences across tasks (discrimination-only, control dual-, color dual-task),  $F(2, 18) = 1.75$ ,  $p = 0.202$ , confirming that our staircase procedure succeeded in keeping the overall performance level around 71% correct in all three conditions. To determine whether the conditions differed in discrimination difficulty, we next calculated the mean offset of the vertical DT bar. If a condition needs a larger horizontal offset of the vertical DT bar to yield 71% correct responses, the respective task can be considered more difficult. The vertical bar had to be presented on average with an offset of 0.25°, 0.26°, and 0.24° to the left or right for performance to be kept at around 71% correct in discrimination-only, control dual-, and color dual-task, respectively. A one-way ANOVA revealed that there were no significant differences across conditions,  $F(2, 18) = 0.51$ ,  $p = 0.610$ . To further exclude that any effects in discrimination performance across spatial or color congruency conditions were due to a priori differences produced by the staircase procedure, we next ran a series of Wilcoxon signed rank tests on the mean horizontal offset in each condition. A priori there should be no differences as the horizontal offset on a given trial depends solely on

the response in the preceding trial. As spatial and color congruency conditions are randomly interleaved, none of them should follow more often after a correct or incorrect trial, and therefore, offsets should be the same. Indeed, neither in the discrimination-only condition, nor in the control dual- or the color dual-task, did the offsets of the vertical bar presented in the spatially congruent conditions differ significantly from the incongruent conditions,  $ps > 0.185$ . The same was true for color congruent versus incongruent trials in the color dual-task,  $p = 0.109$ . [Supplementary Figure S1A](#) further shows that the distributions across conditions (averaged across participants) were very similar.

Next we compared the effect of spatial congruency between ST and DT location across tasks. To minimize effects of the current fixation after the saccade, we only included those trials in which the DT was extinguished before or during the saccade (see above). Individual performance values of the participants are based on a minimum of 81 trials per condition. [Figure 2A](#) illustrates that the discrimination-only block only showed a small effect of spatial congruency, whereas both dual-task conditions showed markedly better performance on same-location compared to different-location trials. A 3 (task: discrimination-only, control dual, color dual)  $\times$  2 (spatial congruency: same vs. different location) repeated-measures ANOVA on the arcsine-transformed percentages confirmed significant main effects of task,  $F(2, 18) = 11.46$ ,  $p = 0.001$ , of spatial congruency,  $F(1, 9) = 36.47$ ,  $p < 0.001$ , and a significant interaction of task and spatial congruency,  $F(2, 18) = 8.73$ ,  $p = 0.002$ . Subsequent pairwise Wilcoxon signed rank tests revealed that the spatial congruency effects were only significant in the control dual-task,  $p = 0.005$ , and the color dual-task,  $p = 0.005$ , but not in the discrimination-only condition,  $p = 0.203$ . Further, there was no significant difference between the spatial congruency effects (i.e., the difference between same-location and different-location trials) in the control dual-task and the color dual-task,  $p = 0.386$ .

Finally we compared the discrimination performance across conditions in the critical color dual-task. Again, trials were excluded if the DT was extinguished only

Interval DT offset to saccade onset:

	>100 ms	0–100 ms	During saccade	After saccade
Experiment 1	6.0% (0.0–25.1)	49.8% (21.7–85.2)	38.1% (2.2–63.5)	6.2% (0.1–19.3)
Experiment 2	5.3% (1.5–15.5)	52.8% (18.6–78.1)	25.4% (10.4–40.9)	16.5% (0.9–49.3)

Table 2. Percentage of trials as a function of time between DT offset and saccade onset. *Note:* Range across participants in parentheses.

after saccade completion. The performance values are based on a minimum of 90 trials per condition and participant. **Figure 3A.1** illustrates that discrimination performance was better in the same-location (83.7%) compared to the different-location (71.0%) condition. Participants were in general also slightly better when the ST and DT had the same color (78.4%) compared to different colors (76.6%). A 2 (spatial congruency: same vs. different location) × 2 (color congruency: same vs. different color) repeated-measures ANOVA on the arcsine-transformed values confirmed significant main effects of spatial congruency,  $F(1, 9) = 22.38, p = 0.001$ , and color congruency,  $F(1, 9) = 5.98, p = 0.037$ . The interaction between the two factors did not reach significance,  $F(1, 9) = 0.44, p = 0.522$ . To consolidate the effect of color congruency, we also ran a Wilcoxon signed rank test on color congruent versus incongruent trials (collapsed across spatial congruency condition). This analysis revealed only a marginally significant difference,  $p = 0.074$ . We further repeated the ANOVA including only trials in which the DT offset occurred in the last 100 ms before saccade onset. This is supposed to be the interval in which attention shifts towards the ST. Individual performance values for this analysis are based on a minimum of 33 trials per condition (range between 33 and 100 trials across participants for the least frequent same-location/same-color condition). **Figure 3A.2** illustrates that results are very similar to the original analysis. The ANOVA on the arcsine-

transformed values revealed a significant main effect of spatial congruency (same vs. different location: 84.3% vs. 71.0%),  $F(1, 9) = 29.72, p < 0.001$ . However, the main effect of color congruency did no longer reach significance (same vs. different color: 78.5% vs. 76.6%),  $F(1, 9) = 3.10, p = 0.112$ . The interaction between spatial and color congruency was not significant,  $F(1, 9) = 0.10, p = 0.754$ . A subsequent Wilcoxon signed rank test comparing color congruent to incongruent trials likewise failed to reach significance,  $p = 0.169$ .

**Saccade performance**

To exclude trade-offs between performance in the discrimination and the saccade task, we also analyzed saccade latencies and saccade landing position error. The analyses are based on the same exclusion criteria as the corresponding analyses of discrimination performance. Overall, saccade latencies were very similar across tasks and conditions. A 3 (task: saccade-only, control dual-, color dual-task) × 2 (spatial congruency: same vs. different location) repeated-measures ANOVA revealed that there were no significant main

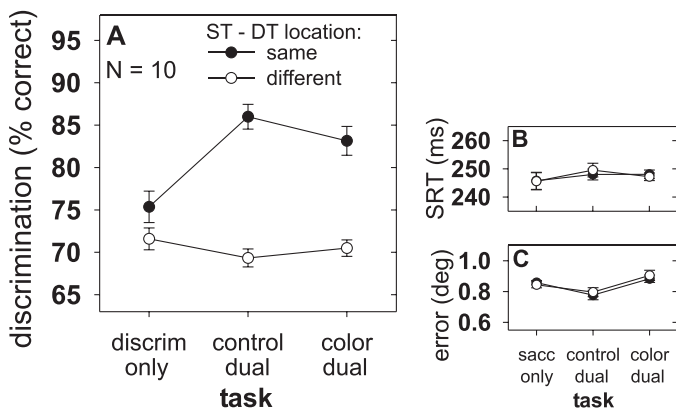


Figure 2. Discrimination performance (in % correct, panel A), saccadic reaction time (SRT, panel B), and saccade landing position error (panel C) as a function of task and spatial congruency between ST and DT locations. Error bars represent within-subject standard errors (Bakeman & McArthur, 1996).

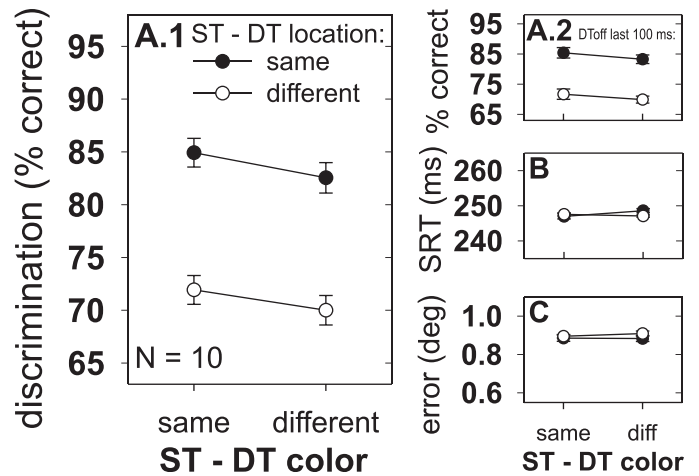


Figure 3. Discrimination performance (in % correct, panel A.1: for all trials with DT offset before or during the saccade; panel A.2: only for trials with DT offset within the last 100 ms before saccade initiation), saccadic reaction time (SRT, panel B), and saccade landing position error (panel C) as a function of spatial congruency and color congruency between ST and DT in the color dual-task of Experiment 1. Error bars represent within-subject standard errors (Bakeman & McArthur, 1996; if not visible, they are occluded by the symbols).



effects of task,  $F(2, 18) = 0.32$ ,  $p = 0.732$ , or spatial congruency,  $F(1, 9) = 0.13$ ,  $p = 0.727$ , and no significant interaction between the two factors,  $F(2, 18) = 1.81$ ,  $p = 0.193$  (see [Figure 2B](#)). An ANOVA across the different conditions in the color dual-task (spatial and color congruency; see [Figure 3B](#)) did not reveal any significant main effects, spatial congruency:  $F(1, 9) = 0.85$ ,  $p = 0.381$ , and color congruency:  $F(1, 9) = 0.45$ ,  $p = 0.518$ . The interaction was marginally significant,  $F(1, 9) = 4.46$ ,  $p = 0.064$ .

The saccade error was estimated by calculating the mean Euclidian distance between saccade endpoint and the center of the saccade target circle. A repeated-measures ANOVA including the factors task and spatial congruency (see [Figure 2C](#)) revealed a marginally significant main effect of task,  $F(1, 9) = 3.30$ ,  $p = 0.060$ , corresponding to less accurate saccades in the color dual- compared to the saccade-only and the control dual-task. The main effect of spatial congruency,  $F(1, 9) = 0.96$ ,  $p = 0.353$ , as well as the interaction between task and spatial congruency,  $F(2, 18) = 1.25$ ,  $p = 0.310$ , did not reach significance. The ANOVA across the different conditions in the color dual-task (see [Figure 3C](#)) did not reveal any significant effects or interactions, spatial congruency:  $F(1, 9) = 1.50$ ,  $p = 0.252$ , color congruency:  $F(1, 9) = 0.11$ ,  $p = 0.744$ , and spatial by color congruency:  $F(1, 9) = 0.26$ ,  $p = 0.623$ .

## Discussion

Results of [Experiment 1](#) can be summarized as follows. First, the mean offset of the vertical DT bar, which was adjusted for every participant by a staircase procedure, did not vary across discrimination-only, control dual- and color dual-task. Hence, the dual-task assignment and the addition of further colors to the DT display did not hamper discrimination performance significantly. Further, we could replicate previous findings of large spatial congruency effects in the dual tasks: discrimination performance was better when the ST and DT were presented at the same location. Importantly, the spatial congruency effect was not significant in the discrimination-only condition, confirming that the spatial effects are a consequence of the preparation of an eye movement towards the ST and not simply the result of an involuntary attention shift triggered by the arrow cue ([Hermens & Walker, 2010](#); [Hommel, Pratt, Colzato, & Godijn, 2001](#); [Tipples, 2002](#)). Critical for the question whether selection of an item as a ST may automatically enhance processing of stimuli sharing ST features either locally (i.e., at the ST location) or globally (i.e., display-wide) are the comparisons across conditions within the color dual-task. We found slightly better performance when the DT was incidentally presented in the same color as the

ST. The finding of a main effect of color congruency and no interaction with spatial congruency speaks for display-wide enhancement of the target color: performance improved for same-location and different-location DTs alike. Analyses of saccade parameters revealed no trade-offs between saccade and discrimination performance. In particular, there were no effects of spatial or color congruency (neither for saccade latencies, nor saccade landing position error). Although significant in the ANOVA, it has to be noted that the effect of color congruency was only small: the improvement of performance amounted to 2%, compared to 13% for spatially congruent DTs. Also, the effect of color congruency was not very reliable because there was no significant effect in subsequent nonparametrical tests and for trials with a DT offset within the last 100 ms, which may be caused by the smaller number of trials and the resulting reduction of statistical power. However, it could also indicate that at least close to saccade execution, location clearly dominated the distribution of attention (as compared to the influences of nonspatial features).

One reason for the relatively weak effects of color could be that color was not necessarily a relevant feature in [Experiment 1](#). As we wanted to look at largely automatic effects of the ST selection process on the deployment of color-based attentional resources, it was made relatively easy for participants to ignore all colors. Similar to previous dual-task studies, the ST was indicated by a central arrow cue. Although the arrow was always presented in the same color as the ST, participants could have relied exclusively on the pointing direction of the arrow for successful ST selection. Also, trial-by-trial changes of the target colors (ST and DT) may have mitigated the participants' ability to make use of the arrow's color for selecting the target and ignoring the distractors ([Belopolsky, Schreij, & Theeuwes, 2010](#); [Folk & Anderson, 2010](#)). In the next step, [Experiment 2](#) examines whether stronger effects of color congruency emerge when color is made relevant for ST selection. That is, we examine how a search set or feature-based attentional bias for a specific color held constant across trials affects performance. In other words, rather than testing whether any instance of ST selection (i.e., based on whichever criterion) involuntarily produces biases in the deployment of feature-based attention (favoring the processing of stimuli sharing ST features), we now examine color-congruency effects when the ST has to be selected according to its color. Although there is already plenty of literature showing influences of feature-based search sets on the processing of nontarget stimuli (just to give one example: the vast literature on contingent capture by nonpredictive spatial cues that incidentally match the color of a subsequent color-defined target; e.g., [Folk & Remington, 1998](#)), strong



effects may be precluded in our paradigm by the concurrent saccade task. Having a concurrent saccade task is in a way special as saccade planning is supposed to draw on spatial attention. Thus, the question becomes: given spatial attention is directed towards the ST (as is nicely confirmed in our spatial congruency effects), can a feature-based attentional bias produce substantial improvements in discrimination performance at other display locations or does the ultimate selection of one stimulus as the ST prevent strong feature-based facilitative effects?

## Experiment 2

### Methods

In [Experiment 2](#), the ST had to be selected according to a constant color that was balanced across participants (red, green, cyan, or yellow). The sequence of events is illustrated in [Figure 1C](#). Circles remained gray during the initial 500 ms fixation period. Afterwards, circles were presented in color for 120 ms, and participants had to saccade as fast as possible towards the circle of their assigned color. Critically, no central arrow cue was presented—that is, participants had to select the ST on the basis of its color alone. The remaining sequence was as in the color dual-task of [Experiment 1](#). Importantly, the DT color was again randomly chosen on each trial—that is, the ST and DT color were uncorrelated (25% same-color trials). For most participants, the experiment was run in three one-hour sessions, which resulted in 12–15 blocks of 128 trials each. For others, the experiment was split up into shorter sessions (five to seven sessions). Nine participants (four men) between 19 and 32 years of age completed [Experiment 2](#). Four participants were members of the Visual Cognition group of the University of Geneva (students and collaborators) who had already participated in [Experiment 1](#). The remaining five observers were undergraduates who received course credit for their participation. None of these five participants had been tested in [Experiment 1](#).

### Results

In total, 21.2% of all trials were excluded (range between 1.7% and 34.2% across participants). Direction errors (15.8%), late responses (4.2%), and failures to fixate at the beginning of a trial (2.8%) were the most frequent errors. Among the direction error trials, the percentage of saccades directed towards the cross (instead of the circle) of the predefined color was only slightly elevated (30% of trials; chance level: 25%),

indicating that participants were overall well able to select the ST based on the color of the circles and to ignore the color of the crosses. As in [Experiment 1](#), we determined in which time epoch before saccade initiation the DT was extinguished ([Table 2](#)). Again, on most trials the DT was turned off in the last 100 ms before saccade onset, but there was also a relatively high percentage of trials with a DT offset during the saccade.

### Discrimination performance

Overall discrimination performance was 72.9% correct. The vertical DT bar had to be presented on average  $0.32^\circ$  away from the horizontal midline to achieve this level of performance. To exclude the possibility that any effects in discrimination performance across spatial or color congruency conditions were due to a priori differences produced by the staircase procedure, we compared the mean horizontal offset of the vertical DT bar in spatial congruent versus incongruent conditions and color congruent versus incongruent conditions using Wilcoxon signed rank tests. The horizontal offset of the vertical bar presented in the spatially congruent conditions did not differ significantly from the incongruent conditions,  $p > 0.635$ . However, there was a marginally significant difference for color congruent versus incongruent trials,  $p = 0.083$ . The mean horizontal offset was slightly smaller in the color congruent trials than incongruent trials ( $0.315^\circ$  vs.  $0.319^\circ$ ). Note that this difference may not explain a potential increase in discrimination performance for color congruent trials, as a smaller offset renders the discrimination task more difficult. Further, [Supplementary Figure S1B](#) shows that the distributions of offsets (averaged across participants) were again very similar across conditions.

Similar to [Experiment 1](#), we first analyzed discrimination performance for trials in which the DT was extinguished before or during the saccade. The performance values are based on a minimum of 41 trials per condition and participant (range between 41 and 94 across participants for the least frequent condition, i.e., same-color/same-location condition). [Figure 4A.1](#) illustrates that there were strong congruency effects. A  $2$  (spatial congruency: same vs. different location)  $\times$   $2$  (color congruency: same vs. different color) repeated-measures ANOVA on the arcsine-transformed percentages confirmed that participants' performance was significantly better when the ST and DT spatially coincided ( $83.3\%$  vs.  $71.7\%$ ),  $F(1, 8) = 50.40$ ,  $p < 0.001$ , and when they were incidentally presented in the same color ( $80.9\%$  vs.  $74.1\%$ ),  $F(1, 8) = 5.97$ ,  $p = 0.040$ . The interaction between spatial and color congruency did not reach significance,  $F(1, 8) = 0.01$ ,  $p = 0.924$ . The effects of spatial as well as color

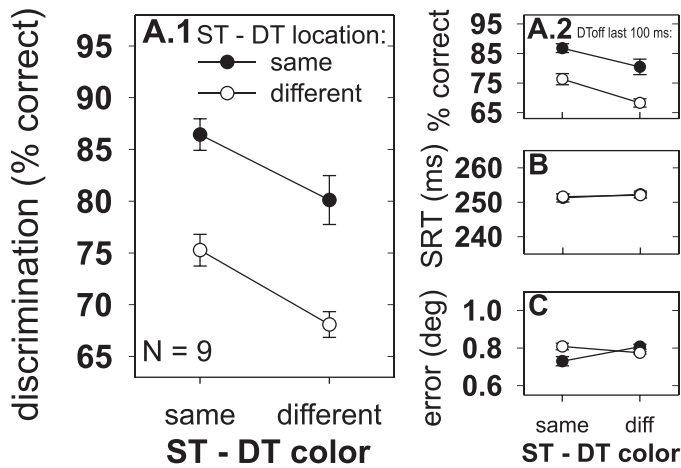


Figure 4. Results of Experiment 2. Conventions are as in Figure 3.

congruency were confirmed by subsequent Wilcoxon signed rank tests,  $p = 0.008$  and  $p = 0.021$ , respectively. We further repeated the analysis including only trials with a DT offset in the last 100 ms before saccade onset. Individual performance values are based on a minimum of 17 trials per condition (range between 17 and 69 across participants in the same-location/same-color condition). Figure 4A.2 illustrates the results. The ANOVA on the arcsine-transformed values revealed again significant main effects of spatial congruency (83.6% vs. 72.3%),  $F(1, 8) = 34.09$ ,  $p < 0.001$ , and color congruency (81.5% vs. 74.4%),  $F(1, 8) = 5.40$ ,  $p = 0.049$ . The interaction between spatial and color congruency did not reach significance,  $F(1, 8) = 0.06$ ,  $p = 0.804$ .

Next, to assess whether results differed across experiments, we repeated the 2 (spatial congruency: same vs. different location)  $\times$  2 (color congruency: same vs. different color) repeated-measures ANOVA (arcsine-transformed percentages), including the factor experiment (color dual-task of Experiment 1 vs. Experiment 2) as between-subjects factor. The main effects of spatial congruency (83.5% same vs. 71.3% different location),  $F(1, 17) = 56.59$ ,  $p < 0.001$ , and color congruency (79.6% same vs. 75.2% different color),  $F(1, 17) = 10.46$ ,  $p = 0.005$ , were again significant. Neither the main effect of experiment nor any interaction including this factor approached significance,  $F_s < 2.55$ ,  $p_s > 0.129$ .

Finally, to assess the influence of the blocked design (i.e., ST color repetition) on the color congruency effect, we re-examined results of Experiment 1 based on whether the ST on a given trial  $n$  had the same color as in the preceding trial  $n - 1$ . As ST color varied randomly in Experiment 1, this was the case for 25% of trials. Data for these comparisons were collapsed across spatial congruency conditions. Color congruency effects (percent correct in congruent minus incongruent conditions) were slightly larger for ST color

repetitions than nonrepetitions (4.6% vs. 1.3%, respectively). A Wilcoxon signed rank test based on the arcsine-transformed percentage values revealed a marginally significant difference,  $p = 0.093$ . Subsequent Mann-Whitney tests comparing these effects to the overall color congruency effect of Experiment 2 revealed a marginally significant difference to the nonrepetitive trials of Experiment 1 (7.1% vs. 1.3%),  $p = 0.072$ , and no significant difference to repetition trials (7.1% vs. 4.6%),  $p = 0.568$ .

### Saccade performance

Figure 4B illustrates the saccade latencies in Experiment 2. An ANOVA across the different conditions (spatial and color congruency) did not reveal any significant main effects or interactions, spatial congruency:  $F(1, 8) = 0.01$ ,  $p = 0.943$ ; color congruency:  $F(1, 8) = 0.39$ ,  $p = 0.548$ ; and interaction spatial by color congruency:  $F(1, 10) = 0.05$ ,  $p = 0.834$ .

Similarly, the ANOVA on the saccade error data (Figure 4C) did not reveal any significant main effects, spatial congruency:  $F(1, 8) = 1.20$ ,  $p = 0.305$ , and color congruency:  $F(1, 8) = 1.89$ ,  $p = 0.206$ , but a significant interaction between spatial and color congruency,  $F(1, 8) = 7.31$ ,  $p = 0.027$ . In same-color trials, the saccade landing position error was slightly less pronounced for spatially congruent compared to incongruent trials; the opposite was true in different-color trials.

### Discussion

Results of Experiment 2 confirm those of Experiment 1. Along with the well-documented spatial congruency effect, we found a main effect of color congruency: discrimination performance was better when the ST and DT were of the same color. Those effects were not accompanied by variations in saccade performance. The results speak for display-wide facilitative processing of ST features, improving likewise the processing of DTs sharing those features, regardless of where the DT is presented. Further, the effect of color congruency was numerically slightly larger and more reliable (i.e., we found significant effects in nonparametrical tests and when analyzing only trials with DT offset within the last 100 ms before saccade onset) than in Experiment 1. Thus, repeatedly selecting the ST according to a prespecified color consolidates the influence of color congruency. This demonstrates that a search set or feature-based attentional bias established before saccade programming influences discrimination performance irrespective of the immediate requirement to make a saccade and independently of the corresponding *spatial* allocation of attention. In other words, the programming of

the saccade did not cancel the feature-based biases in the distribution of attention. In contrast, saccade programming is known to interfere with the spatial distribution of attention: knowing the DT location in advance does not improve discrimination performance or abolish spatial congruency effects, suggesting that spatial attention cannot be maintained at a location in space when a saccade is directed elsewhere (e.g., Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995). In this context, recall that the DT was always presented 120 ms after the ST in our experiments. That is, it was shown at a time when the ST selection process based on color was already completed on most trials. This is corroborated by the fact that error saccades were only slightly more often directed to the circle containing the cross of the searched-for color than to other elements. Thus, at the time of DT presentation, the spatial programming of the saccade towards the selected item was probably already in progress (as evident in the strong spatial congruency effects). Nevertheless, the colored DT display gave rise to a new distribution of color-based attention with yet another bias towards the DT having the same color as the ST.

What remains somewhat unclear in [Experiment 2](#) is whether the more reliable color congruency effect resulted from the mere repetition of the ST color (i.e., the blocked design), or whether it reflects the influence of a true top-down search set. The intertrial analysis of the color congruency effect in [Experiment 1](#) gives tentative evidence that there may indeed be some intertrial priming: having saccaded to an element of a specific color in the preceding trial biases feature-based attention in the current trial towards that color. In this sense, the small color congruency effect in [Experiment 1](#) could be explained by assuming that automatic activation of target features upon ST selection was simply too slow to already affect perception during the saccade programming phase, but created an anticipatory feature-based attentional bias in the next trial. Note, however, that the intertrial analysis only showed tendencies and is therefore not entirely conclusive. We speculate that the more reliable color congruency effects may be a mixture of automatic repetition effects and a top-down search set. Irrespective of the exact nature of the effect, however, our experiments show that it acts independently of the spatial facilitation effect at the ST location.

## General discussion

We examined the allocation of feature-based attention prior to the execution of saccadic eye movements. We used a dual-task paradigm in which participants had to make a saccade while simultaneously performing a perceptual discrimination task. In line with

previous research, we found spatial congruency effects in the perceptual task: discrimination was better when the DT was presented at the ST location. Further, a DT that incidentally shared color with the ST was likewise better discriminated. Performance improved irrespective of the spatial congruency between the ST and DT—that is, we found similar improvements in discrimination performance for DTs presented at the ST location or at another location. [Experiment 2](#) showed a tendency for the color-based performance increase to be more reliable when the ST had to be selected according to a predefined constant color. In contrast, when color information was not necessary to correctly select the ST (selection could have been based on the directional information of a central arrow cue) and the ST color changed from trial to trial, slightly weaker and less reliable color congruency effects were observed ([Experiment 1](#)). The latter finding suggests that during the saccade programming phase, there may be only little, if any, effect of automatic feature-based enhancement of irrelevant ST features evoked by the mere selection of a stimulus as the target for a saccadic eye movement. However, an intertrial analysis suggested that such a process may evolve over a larger time scale, biasing the attentional distribution in the subsequent trial. In any case, whether originating from automatic enhancement or a top-down search set, results from [Experiment 2](#) show that a pre-established feature-based attentional bias for a specific color can reliably improve discrimination performance for a stimulus of the corresponding color during the preparation of a saccadic eye movement. Previous studies have already demonstrated feature-based facilitation effects away from the immediate saccade goal (Gersch et al., 2008, 2009). In a task requiring sequences of saccades, perceptual performance at previously fixated items was improved only when the saccade path to follow was marked by color (i.e., by green elements among red distractors), but not in a memory-guided saccade sequence. Our results complement this research in various respects. First, we show that feature-based facilitation away from the saccade target is possible even for items never inspected by an eye movement. Second, we found that the facilitation of items presented in a relevant compared to irrelevant color is of similar magnitude at the ST location or elsewhere, confirming independence (additivity) of spatial- and feature-based attentional mechanisms in the task.

## Color priming and saccade target selection processes

The underlying mechanisms for our color congruency effect could be related to color cuing or color priming. It is known that a color cue can facilitate



processing of an upcoming target of the corresponding color. The effect may be purely stimulus-driven as it can even be observed when the color cue is completely uninformative about the target color (i.e., when the proportion of color congruent trials is at chance level; Ansorge & Becker, 2012; Theeuwes & Van der Burg, 2007). Taking this idea to the extreme, the small color congruency effect that we observed in [Experiment 1](#) could even be exclusively driven by the color of the central arrow cue. In other words, the simple fact that participants were fixating a colored item could have triggered facilitative processing of subsequent color-congruent DTs (and the small intertrial modulations). Thus, the effect may not necessarily be dependent on the requirement to make a saccade, but may be purely visual in nature. Note, however, that the case is different for [Experiment 2](#). No cues were presented in [Experiment 2](#) to define the ST on a given trial, but participants chose the ST solely based on the color instruction. The ST color was not even foveated more often than the other colors: The circle colors defining the ST were presented only for 120 ms; the subsequent cross colors were uncorrelated to the circle colors. Thus, at the time the saccade landed, the foveated color could have been any of the four colors with equal probability, which rules out the possibility that the color congruency effect in [Experiment 2](#) was due to a simple overrepresentation of the ST color in the display, at the fovea, or an uneven distribution across the visual field. The color congruency effect must therefore stem from the requirement to act on the target stimulus, in our case by directing a saccade towards it.

As argued above, ST color repetition might have been a prerequisite for strong color effects to emerge. In visual search tasks, it is well established that observers react faster to a target of the same color as in the preceding trial than to a target of a different color. Different accounts have been proposed to explain this priming effect, including attentional, perceptual, episodic memory and response-related mechanisms, and it is likely that more than one stage of visual processing is affected by feature repetition (see Kristjánsson & Campana, 2010 for a recent review). To relate our findings to the large body of literature on feature repetition priming, we think it is important to discuss several aspects of our paradigm: First, unlike some visual search studies in which participants have to respond to a color oddball, our effects cannot be due to the repetition of a stimulus-driven saliency signal (priming of pop-out; Maljkovic & Nakayama, 1994). In [Experiment 2](#), our targets were never more salient than the nontargets. On any given target display, no matter if a ST or DT display, four colored circles or crosses of equal luminance were presented. Note, however, that according to some

authors (Lamy, Zivony, & Yashar, 2011; Meeter & Olivers, 2006), feature priming is even fostered when the target is less salient. Second, unlike many other studies on feature repetition priming, the effect of color repetition was not assessed in the same task in which the target feature was repeated (i.e., in our case, the saccade task). Instead, we observed an influence of (repetitive) selection of a colored circle as target for a saccadic eye movement on discrimination performance in an interleaved perceptual task in which the target color varied from trial to trial. In other words, the (repeated) ST color produced an effect on the response to a target of a different shape (DT = cross vs. ST = circle) in a different task, which required a different response (unspeeded key press vs. speeded saccade). This setup rules out some of the simpler repetition priming accounts, especially those proposing the involvement of a joint response representation. In fact, our paradigm may be more closely related to studies on contingent attentional capture, in which the influence of an irrelevant (singleton or nonsingleton) color cue on the response time to a subsequently presented (repeated) color target is examined (Folk & Remington, 1998; Lamy et al., 2004). Similar to those cuing effects, we suggest that our color congruency effects, especially in [Experiment 2](#), are best accounted for by a feature-based attentional bias for the ST color established in anticipation of the upcoming target. Note that similar to our discussion above, it has been suggested that the attentional bias in contingent capture studies result to a large part from involuntary intertrial color priming effects (Belopolsky et al., 2010). In contrast to contingent capture (and, for that matter, feature repetition priming according to attentional accounts; see e.g., Becker & Horstmann, 2009; Kristjánsson & Campana, 2010; Maljkovic & Nakayama, 1994; Müller, Reimann, & Krummenacher, 2003), our color congruency effects are not necessarily mediated by the allocation of spatial attention (see next paragraph).

## Location- and feature-based attentional mechanisms

A tremendous amount of research on location- and feature-based attention has accumulated up to date, describing their effects, comparing the underlying mechanism, and examining their interactions (see e.g., Carrasco, 2011 for a recent review). A comprehensive discussion of all relevant literature is beyond the scope of the current paper, and we can therefore only focus on a few issues. For instance, a striking characteristic of the current results is that color-congruency effects were observed irrespective of the spatial congruency between the ST and DT. The lack of interaction is reminiscent

of neurophysiological studies demonstrating additive effects of spatial- and feature-based attention on neuronal responses (Andersen, Fuchs, & Müller, 2010; Hayden & Gallant, 2009; Treue & Martinez Trujillo, 1999). Moreover, feature-based enhancement of neuronal activity in area V4 has also been demonstrated when a saccade is made outside of the receptive field of the recorded neuron, confirming that feature-based modulations are not affected by the programming of a concurrent saccade (Bichot et al., 2005; Zhou & Desimone, 2011). Similar to modulations by spatial attentional mechanisms, these effects seem to reach V4 via the frontal eye fields (Zhou & Desimone, 2011). Our behavioral results indicate that the feature-based enhancement of V4 activity may go along with improved perceptual discrimination of the corresponding stimuli. To our knowledge, this has only been demonstrated for spatial attentional modulations (Armstrong & Moore, 2007).

The interplay between location- and feature-based attention has also been studied in conditions in which a target is jointly defined by color and location (e.g., Hillyard & Münte, 1984; Humphreys, 1981). Results demonstrated that the two attentional mechanisms contribute to a variable degree, depending on which system provides better or faster information. Others have argued for a dominant or special role of spatial attention (e.g., Lamy & Tsal, 2001), an idea that is in line with our finding that the spatial congruency effects were always larger than the color congruency effects. Some research has focused on *how* exactly spatial- and feature-based attention affect stimulus processing. There are now a number of studies suggesting that only spatial attention can enhance the perceptual representation of a target stimulus, allowing for improved target identification and discrimination. In contrast, feature-based attention may only highlight relevant items to subsequently guide spatial attention to their locations (Andersen et al., 2010; Hamker, 2004; Moore & Egeth, 1998; Nissen, 1985; Theeuwes & Van der Burg, 2007; Tsal & Lavie, 1988). In other words, feature-based attention does not enhance the sensory quality of a stimulus, but is thought to prioritize the (serial) allocation of spatial attention. This idea is also at the core of prominent visual search models (e.g., Müller et al., 2003; Wolfe, Cave, & Franzel, 1989). Indicative for the improvement of the perceptual representation of a stimulus are experiments in which stimuli are presented only briefly, masked, and in which the dependent measure is an accuracy measure (Moore & Egeth, 1998; Prinzmetal, McCool, & Park, 2005). Note that all this is true for our experiments. Assuming that spatial attention is thought to be allocated to the ST location in our paradigm, it is thus somewhat surprising that we were able to demonstrate feature-based modulations in perceptual discrimination performance, contradicting

previous studies that found such effects only for manipulations of spatial attention (e.g., Moore & Egeth, 1998; Theeuwes & Van der Burg, 2007).

Prinzmetal et al. (2005) specify that prioritizing a stimulus for response selection can nevertheless affect perceptual accuracy measures in conditions of location uncertainty—that is, when observers are unsure not only *which* target was presented (in our case: left or right offset of the vertical bar), but also *where* the target was presented. Location uncertainty was indeed at play in our experiments as the DT location varied randomly from trial to trial. Hence, it is possible that, although not informative, feature-based highlighting of the color-congruent cross in the DT display induced a post-sensory response bias. In other words, the percept of the color-congruent cross may not have been better than the percept of the other stimuli, but stronger reliance on stimuli sharing ST features during response selection could have improved performance when the DT shared the features of the ST (Prinzmetal et al., 2005). Two things speak against a response bias interpretation of our color congruency effects, though. First, a response bias account makes the wrong predictions with respect to discrimination performance. In the spatially congruent conditions, due to the allocation of spatial attention to the DT at the saccade endpoint, uncertainty about the DT's location should have been low. In contrast, in the spatially incongruent condition, participants shifted spatial attention to a distractor cross, leaving three possible locations for the DT. Thus, if color congruency effects were due to a response bias because of DT location uncertainty, they should have been larger in the spatially *incongruent* condition. In other words, the response bias account would have predicted an interaction, whereas we found additive effects of location and color congruency. Second, previous research failed to show differences in saccade-related attention shifts between conditions with or without uncertainty about the DT location (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler et al., 1995). These studies used a constant or a cued DT location. Fixing the DT location should likewise have induced a strong response bias and thus, similar modulations as our color manipulation. However, no improvements in discrimination performance compared to a random DT location condition were found.

Yet another possibility could be that feature-based attention allowed for spatial attention to be split in our paradigm. As briefly mentioned in the [Introduction](#), attention may be directed to more than one (eye or hand) movement goal before initiation of the first movement of an action sequence. As a consequence, improved discrimination performance has been observed at more than one (eye or hand) movement goal when the task involves a sequence of eye movements or simultaneous execution of eye and hand movements,

suggesting a split of spatial attention (Baldauf & Deubel, 2008; Gersch et al., 2004; Godijn & Theeuwes, 2003; Jonikaitis & Deubel, 2011; Rolfs et al., 2010). If and how exactly an attentional focus on a specific color may provoke a split of spatial attention remains speculative, however. Future research will be needed to make a stronger claim about the exact nature of the color-congruency effect.

Finally, our results could also be of importance for studies on predictive remapping of visual information across saccades. Recent behavioral work suggests a strong link between attentional shifts towards ST locations and attentional allocation related to predictive remapping: both show a similar time course of spatial facilitation effects prior to saccade execution (Rolfs et al., 2010). Further, some neurophysiological studies suggest that receptive fields in some areas (V4, frontal eye fields) do not shift parallel to the saccade vector prior to an eye movement as suggested by the seminal work of Duhamel, Colby, and Goldberg (1992). Instead, receptive fields seem to shift towards the saccade endpoint (Hamker, Zirnsak, Calow, & Lappe, 2008; Tolia et al., 2001; Zirnsak, Lappe, & Hamker, 2010), which may also explain the improved discrimination performance at the ST location observed in behavioral studies. It has been suggested that predictive remapping relies purely on spatial attentional mechanisms (Cavanagh, Hunt, Afraz, & Rolfs, 2010). Future research may elucidate how the current findings of feature-based facilitation effects prior to saccade execution relate to predictive remapping—whether they present a challenge to the proposal of purely spatial remapping mechanisms or simply imply that not all facilitation effects found during the saccade preparation interval are a result of remapping.

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