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Predictability of spatial and non-spatial target properties improves perception in the pre-saccadic interval

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ABSTRACT

In a dual-task paradigm with a perceptual discrimination task and a concurrent saccade task, we examined participants' ability to make use of prior knowledge of a critical property of the perceptual target to improve discrimination. Previous research suggests that during a short time window before a saccade, covert attention is imperatively directed towards the saccade target location. Consequently, discrimination of perceptual targets at the saccade target location is better than at other locations. We asked whether the obligatory pre-saccadic attention shift prevents perceptual benefits arising for perceptual target stimuli with predictable as opposed to non-predictable properties. We compared conditions in which the color or location of the perceptual target was constant to conditions in which those properties varied randomly across trials. In addition to the expected improvements of perception at the saccade target location, we found perception to be better with constant than with random properties of the perceptual target. Thus, color or location information about an upcoming perceptual target facilitates perception even while spatial attention is shifted to the saccade target. The improvement occurred irrespective of the saccade target location, which suggests that the underlying mechanism is independent of the pre-saccadic attention shift, but alternative interpretations are discussed as well.

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1. Introduction

Shifts of visual attention and eye movements both serve the purpose of selection: To explore our surroundings, saccadic eye movements are made 3–4 times a second to consecutively align the fovea, the retinal region of best visual acuity, with new objects of interest. In a similar vein, the attentional "spotlight" selects parts of the available information for further processing. A long-standing debate centers around the question whether attention and eye movements only serve the same purpose, or whether both selection mechanisms draw on the same underlying resources (Klein, 1980; Posner, 1980; Remington, 1980; Reuter-Lorenz & Fendrich, 1992). Some studies suggest a coupling between attention and saccades: covert attention is supposed to imperatively shift towards the saccade target around the time an eye movement is initiated. This has been extensively studied using a dual-task paradigm combining a saccade task with a perceptual discrimination task (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler et al., 1995). In these studies, observers typically had to prepare a saccade to one display element while simulta-

neously performing a perceptual discrimination task either on the item presented at the saccade target location or on another item in the display (see Fig. 1B for an example). When the location of the perceptual target was not known in advance, discrimination was substantially better when it was incidentally presented at the saccade target location compared to when the location of the saccade and the perceptual target did not coincide.

While this manipulation could assert that attention moves toward the saccade target location under conditions of location uncertainty of the perceptual target, subsequent variations of the dual-task paradigm were run, trying to create optimal conditions for a de-coupling of attention and saccade preparation. For instance, Hoffman and Subramaniam (1995; Experiment 2) kept the saccade target location constant across trials, while an arrow cue indicated with 75% validity the likely location of the perceptual target. Thus, participants were encouraged to shift attention according to the arrow cue. Hoffman and Subramaniam observed a spatial congruency effect, that is, better discrimination performance if the perceptual target was presented at the saccade target location, but no advantage of valid over invalid cues. That is, participants were unable to move attention to the cued location while a saccade to another location was prepared. These results suggest that programming an eye movement to one location is imperatively accompanied by a shift of covert attention (see also Deubel,

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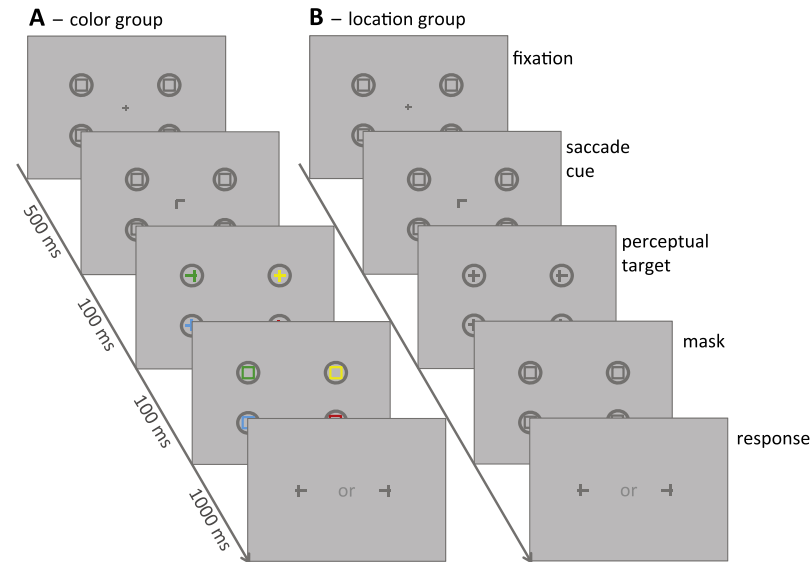E-mail address: sabine.born.fr@gmail.com (S. Born).

Fig. 1. Sequence of events in Experiment 1 (A: color group; B: location group). Participants made saccades to the circle indicated by the central arrow (saccade cue); 100 ms after the arrow cue, one asymmetric cross (=perceptual target) was presented in one of the circles along with three perfectly symmetric distractor crosses in the other circles. Crosses were substituted by masking squares after 100 ms. Saccade and perceptual target locations were always uncorrelated, resulting in 25% same-location trials (A: example of a same-location trial, B: example of a different-location trial). Participants indicated with a button press at the end of each trial whether the vertical bar of the perceptual target was slightly offset to the left or right. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2008; Deubel & Schneider, 1996; Doré-Mazars, Pouget, & Beauvillain, 2004; Kowler et al., 1995; Montagnini & Castet, 2007; Shepherd, Findlay, & Hockey, 1986).

Although strong spatial congruency effects suggest an obligatory coupling between attention shifts and saccades, it remains somewhat unclear whether prior knowledge of the perceptual target's location might nevertheless result in a general improvement in discrimination performance or a modulation in the strength of the congruency effects. Although previous studies included experiments with constant (or validly cued) and random locations of the perceptual target, they often failed to directly compare performance across these conditions (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Shepherd, Findlay, & Hockey, 1986). The data from Hoffman and Subramaniam (1995) suggest that there is no substantial benefit from cuing the perceptual target when a saccade has to be prepared at the same time (see above). In contrast, the manual reaction time data from Shepherd, Findlay, and Hockey (1986) shows some (likewise untested) modulations across cue validity conditions. Kowler et al. (1995; Experiment 2) demonstrated that discrimination performance away from the saccade target location improved substantially when the location of the perceptual target was kept constant across trials, resulting in a reduced spatial congruency effect. However, in accordance with instructions, their participants sacrificed saccade latency (by around 50–75 ms) to optimize discrimination performance, suggesting that they initiated saccade preparation only after completion of the discrimination task. In other words, Kowler and colleagues' findings may not reflect perceptual processing *during* saccade preparation. More recently, Montagnini and Castet (2007) obtained improvements in the perceptual task for validly cued perceptual targets, both when they were coincident with the saccade target and when the saccade and perceptual target were located opposite each other. To complement and further consolidate previous findings, the first aim of the current study is therefore to directly compare random vs. constant location conditions in a classic dual-task setup to see whether and how prior knowledge of the perceptual target's location affects discrimination performance when a saccade has to be prepared simultaneously.

Further, previous studies only investigated effects of fixed or validly cued spatial location of the perceptual target. It is not known whether non-spatial information (e.g., about the color of the perceptual target) may improve discrimination or make it less contingent on saccade target location. The second aim of the current study is therefore to test whether discrimination improves with constant color of the perceptual target. In a previous study (Born, Ansorge, & Kerzel, 2012), we tested the influence of color congruency between saccade and perceptual target on discrimination performance. In these experiments, the saccade target and the perceptual target were both colored and the color of the perceptual target varied randomly, matching the saccade target's color on a subset of trials. We found that perceptual targets incidentally matching the color of the saccade target were slightly easier to discriminate than perceptual targets not matching the color of the saccade target (see also Gersch et al., 2008, 2009). The effect of color congruency did not interact with the effect of spatial congruency, that is, the two effects were additive. These findings are in line with neurophysiological studies demonstrating additive effects of spatial and feature-based attention (Andersen, Fuchs, & Müller, 2010; Hayden & Gallant, 2009; Treue & Martinez Trujillo, 1999) and feature-based modulations of neuronal responses despite concurrent saccade programming (Bichot, Rossi, & Desimone, 2005; Zhou & Desimone, 2011). Accordingly, we might also expect additive effects in the current study. That is, keeping the color of the perceptual target constant might improve discrimination irrespective of spatial congruency between saccade and perceptual target. In statistical terms, we expect a main effect of color predictability of the perceptual target, along with a main effect of spatial congruency between saccade target and perceptual target.

2. Experiment 1: constant vs. random perceptual target properties

In Experiment 1, we examine whether prior knowledge of the location or color of a perceptual target modulates discrimination performance during saccade preparation. To this end, we compared conditions in which the perceptual target's color or location was

held constant for several blocks of trials to conditions in which its properties varied randomly across trials.

2.1. Methods

2.1.1. Participants

Forty-five first-year psychology students (twelve men) between 17 and 39 years of age completed Experiment 1 in three one-hour sessions. All received course credit or 20 Swiss Francs per hour for their participation.

2.1.2. Apparatus

Experiments were programmed in Matlab (The MathWorks Inc., Natick, MA, USA) using the Psychophysics and Eyelink Toolbox extensions (Brainard, 1997; Cornelissen, Peters, & Palmer, 2002; Pelli, 1997). Stimuli were displayed on a 21″ CRT monitor (NEC MultiSync FE2111SB) running at 85 Hz with a resolution of 1280 × 1024 pixels. Eye movements were recorded using an EyeLink1000 desk-mounted eye tracker (SR-Research Ltd., Mississauga, ON, Canada) at a sampling rate of 1000 Hz. Participants were seated in a dimly lit room. Viewing was binocular but only the right eye was monitored. The participant's head was stabilized by a chin and a forehead rest at 67 cm from the monitor.

2.1.3. Stimuli

The fixation cross consisted of two gray bars of 5 × 1 pixels (subtending about 0.13°). The four stimuli were placed on the diagonal axes and presented 5° from central fixation (center-to-center) at 3.5° horizontally and 3.5° vertically. The saccade target circles were drawn with a radius of 1.5° (pen width of 0.25°), the masking squares with a side length of 1.4° (pen width of 0.2°), the bars making up the perceptual target and the distractor crosses were likewise 1.4° long and 0.2° thick. Stimuli were presented on a bright gray background (58 cd/m²) and matched for luminance: 19 cd/m² (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: $x = 0.63$, $y = 0.34$).

2.1.4. Design and procedure

The sequence of events in the color condition is illustrated in Fig. 1A. At the beginning of each trial, the fixation cross and four circles containing masking squares were shown. After 500 ms, an arrow cue was presented that required participants to saccade as fast as possible towards the circle it pointed to (subsequently referred to as the saccade target). Up to this point, all stimuli were gray. During saccade preparation, that is, 100 ms after presentation of the arrow cue, colored crosses appeared within the gray circles. The vertical bar of one cross did not bisect the horizontal bar in the cross center, but was slightly offset either to the left or right. This asymmetric cross served as the perceptual target. The remaining crosses were perfectly symmetric (distractors). The crosses remained on screen for 100 ms and were then masked by squares of the same color. 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 indicating whether the vertical bar of the perceptual target was slightly shifted to the left or right. Upon response, acoustic feedback was provided if participants chose the wrong key. The locations of saccade and perceptual target were fully randomized within and across trials (i.e., 25% were same-location trials). The stimulus colors (i.e., which color appeared at which location) were likewise randomized. The sequence of events in the location condition (see Fig. 1B) was identical, except that all stimuli, including the perceptual target and the distractor crosses, were gray.

We compared two blocked conditions: random-property vs. constant-property blocks. In the **random-property** blocks, color or location of the perceptual target (i.e., the asymmetric cross) varied unpredictably from trial to trial. In the **constant-property** blocks, either the color (red, green, cyan, or yellow; at a random location) or the location (upper left, upper right, lower right, or lower left; no colors in the display) of the perceptual target was kept constant across trials. In all conditions, the saccade arrow cue designated randomly one of the four locations as saccade target, keeping the proportion of same-location trials at 25%.

Additionally, two blocked control conditions were run: the saccade-only and the discrimination-only condition. In the **saccade-only** condition, participants made an eye movement as fast as possible towards the circle indicated by the arrow cue. Although the remaining sequence was presented just as in the other conditions, participants were instructed to ignore the subsequent 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. In the **discrimination-only** task, no arrow cue was presented and participants were asked to keep fixation on the central fixation mark. These discrimination-only blocks were always random-property blocks.

The experiment consisted of 13 blocks of 100 or 128 trials (two saccade-only, three discrimination-only, four random-property, four constant-property blocks). Table 1 illustrates the number of trials per condition. To familiarize participants with the relatively difficult tasks, we always ran the easier single-task conditions first: All participants first completed the two saccade-only blocks. Afterwards, they were tested in the three discrimination-only blocks which also served to adjust overall discrimination difficulty to the individual performance of each participant. In these blocks, the horizontal offset of the vertical bar of the perceptual target cross was controlled by a staircase procedure such that overall, discrimination performance remained at 71% correct for each participant (initial offset at 0.3° from the center; 2-down, 1-up rule; staircase step size of 0.1°, minimum offset fixed at 0.05° if staircase ran down to 0°). The mean horizontal offset in the last 60 trials of the two last discrimination-only blocks was used in the subsequent dual-task blocks. The staircase procedure was run to ensure that all subjects were able to see and discriminate the perceptual target to some degree and to have a good performance value to start with, leaving some room for performance improvements as well as decrements in the dual-task. Twenty-three participants were tested in the color condition and 22 in the location condition. The order of random and constant conditions was counterbalanced. All experiments were approved by the ethics committee of the Faculty of Psychology and Educational Sciences of the University of Geneva.

2.1.5. Eye movement data analyses and feedback

Preliminary eye movement data analyses were performed offline after each trial. A time window of 200 ms before and 800 ms after saccade target onset was specified. Saccade onsets and offsets were detected using the default algorithm of the EyeLink1000 parser (velocity criterion of 30°/s, acceleration criterion of 8000°/s²).

Table 1
Trials per condition in Experiment 1.

Condition	Blocks	Trials/ block	Trials (total)	Saccade/discrimination	
				Same location	Different location
Saccade-only	2	100	200	–	–
Discrimination-only	3	128	384	–	–
Dual-task random properties	4	128	512	128 (25%)	384 (75%)
Dual-task constant properties	4	128	512	128 (25%)	384 (75%)

Only the first saccade in the time window with an amplitude >1° was considered. Trials were followed by a written feedback message on the screen if (1) no saccade was found within the time window, (2) saccades were directed into the wrong quadrant, (3) saccadic latencies were shorter than 80 ms, (4) saccade latencies were longer than 350 ms, (5) gaze deviated by more than 1.5° from the display center at the time of saccade onset (failure to fixate), or (6) 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 if (1) a failure to fixate or (2) a blink was detected from 300 ms before to 300 ms after onset of the perceptual target. 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.

2.2. Results

2.2.1. Discarded data

Trials were excluded if the saccade was not correctly performed or recorded according to the above-mentioned criteria (see Section 2.1.5). In total, 18.4% of all trials were excluded (range between 3.5% and 47.4% across participants). Latencies longer than 350 ms (5.4%), failures to fixate (4.6%), and saccades into the wrong quadrant (4.4%) were the most frequent errors.

Subsequently we split up the saccade trials depending on when the perceptual target was masked with respect to saccade onset (see Table 2). First, it is important to exclude trials in which the perceptual target was still visible after the saccade had landed. Exclusion of those trials rules out that congruency effects reflect foveal vision of the perceptual target on same-location trials. Thus, trials in which the perceptual target was extinguished during or after the saccade were excluded. Second, to ensure that the perceptual target was shown in the critical pre-saccadic interval, we further excluded all trials in which it was extinguished (i.e., masked) more than 100 ms before saccade onset. Previous studies have found the strongest spatial congruency effects in the last 100 ms before saccade onset (e.g. Deubel, 2008; Jonikaitis & Deubel, 2011). Table 2 shows that our stimulus timing was appropriately chosen as on most trials, the perceptual target fell into this time window (0–100 ms before the saccade). Note, however, that we refer here to the interval between the *disappearance* of the perceptual target and saccade onset. As the perceptual target was presented for 100 ms, its *appearance* might have occurred up to 200 ms before the saccade was launched on a given trial.

2.2.2. Discrimination performance

We first compared overall discrimination performance in the discrimination-only blocks. Participants responded correctly on 71.4% of trials. A Mann–Whitney test performed on the percent correct values revealed that there was no significant difference between participants tested in the color and the location condition, $p = .555$. This confirms that our staircase procedure succeeded in keeping the overall performance level around 71% correct in both

experimental groups. Note that comparing this initial value to later dual-task performance is not warranted, as the discrimination-only block was only run at the very beginning of the experiment, followed by eight dual-task blocks during which performance increased steadily across blocks. To determine whether there were any a priori differences in discrimination performance across property conditions (e.g., due to the additional colors in the color condition), we calculated the mean horizontal offset of the perceptual target during the discrimination-only blocks. If a larger horizontal offset of the vertical bar is needed to yield 71% correct responses, the discrimination task may be considered more difficult in the respective condition. The average offset was 0.29°. An independent samples t-test revealed no significant difference between the two property conditions (color vs. location), $t(43) = 0.16$, $p = .877$. Thus, the discrimination task was equally difficult in the color condition and in the location condition.

Next we analyzed discrimination performance in the dual-task blocks (saccade and concurrent perceptual discrimination task). The individual performance values for every participant are based on a minimum of 28 trials per condition (average of 88 and 247 trials for congruent vs. incongruent conditions, respectively). Fig. 2 illustrates the results. A mixed-factors ANOVA (2 properties: color vs. location × 2 predictability: random vs. constant × 2 spatial congruency: same vs. different location) on the arcsine-transformed percent correct values revealed a significant main effect of predictability, $F(1,43) = 39.32$, $p < .001$. Figs. 2A and B illustrate that performance was better with constant as compared to random properties. Further, there was a significant main effect of spatial congruency, $F(1,43) = 25.78$, $p < .001$, and a significant two-way interaction between property and spatial congruency, $F(1,43) = 4.11$, $p = .049$. In general, performance was better when the perceptual target was presented at the saccade target location. The interaction suggests that the effect of spatial congruency was overall weaker in the color condition compared to the location condition. Nevertheless, subsequent Wilcoxon signed rank tests on the non-transformed percent correct values revealed that there was a significant difference between same and different location trials
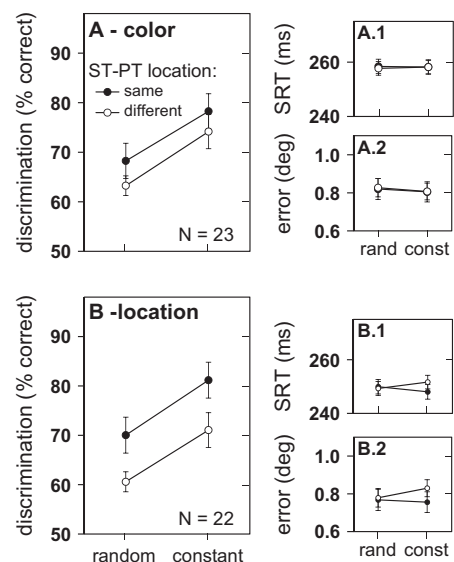
Table 2
Distribution of trials in Experiment 1 depending on the time between onset of the mask following the perceptual target and saccade onset (range across participants in parentheses).

	Interval from mask onset to saccade onset:		
>100 ms	0–100 ms	During saccade	After saccade
9.2%	84.2%	5.6%	1.0%
(0.5–44.3%)	(55.7–94.9%)	(0.0–34.0%)	(0.0–5.5%)

Fig. 2. Results for the color (A) and the location (B) condition in Experiment 1: discrimination performance (main panels A and B), saccadic reaction time (SRT, panels A.1 and B.1) and saccade landing position error (panels A.2 and B.2) as a function of the predictability of the perceptual target's property (random vs. constant), and spatial congruency between saccade target (ST) and perceptual target (PT; same location vs. different location). Error bars represent the standard error of the mean.

for both groups, color: $p = .013$, location: $p = .002$. No other effects or interactions reached significance, $Fs < 1.09$, $ps > .302$.

2.2.3. Saccade performance

An independent samples t-test on saccadic reaction times in the saccade-only conditions revealed significantly shorter SRTs in the location than in the color group (263 vs. 273 ms), $t(43) = 1.84$, $p = .031$. Saccadic reaction times in the dual-task blocks are shown in Figs. 2A.1 and B.1. A mixed-factors ANOVA (2 properties: color vs. location × 2 predictability: random vs. constant × 2 spatial congruency: same vs. different location) on the dual task conditions confirmed shorter latencies in the location than in the color group (250 vs. 258 ms), $F(1,43) = 6.81$, $p = .012$. No further effects or interactions reached significance ($Fs < 2.39$, $ps > .130$).

Finally, the same analyses of the saccade landing position error revealed no significant difference across property groups in the saccade-only blocks (0.81 vs. 0.89 deg), $t(43) = 1.27$, $p = .210$. The ANOVA on the dual-task blocks (Fig. 2A.2 and B.2) did not reveal any significant effects or interactions (all $Fs < 2.59$, $ps > .115$).

2.3. Discussion

First, the results of Experiment 1 reveal better discrimination performance in constant- compared to random-property blocks. Thus, prior knowledge of a critical target property, such as its color or location, can improve perception even while programming a concurrent saccade. Previous research has reported somewhat mixed data on this issue: While some observations (e.g. Hoffman & Subramaniam, 1995) suggested that such a benefit may be prevented by the obligatory shift of spatial attention towards the saccade target, other work suggested that improvements are possible (Montagnini & Castet, 2007).[1] Further, no general effect of predictability was evident in saccadic latencies or accuracy. Therefore, perception did not benefit at the expense of slower or less accurate saccades and a speed-accuracy tradeoff can be ruled out.

Second, spatial congruency effects were larger in the location than in the color condition. In other words, we found a reduced influence of saccade direction on discrimination performance with colored target displays. However, this effect was not replicated in Experiment 2 and we therefore refrain from interpreting it any further.

Third, while we found improvements in the discrimination task in the constant- compared to the random-property blocks, it is interesting to note that they were of similar magnitude in the color and the location groups. Further, improvements due to constant properties were equivalent in trials in which saccade target and perceptual target were presented in the same or different locations. Constant properties did not modulate the impact of saccade preparation on the discrimination task, for instance by improving performance more strongly on incongruent trials. Such an additive pattern may well be explained by assuming an underlying mechanism that acts independently from the facilitative effect of spatial attention at the saccade target location. We will elaborate on this point and alternative interpretations in the General Discussion. However, we would like to address one particular alternative right away: In fact, an account in terms of serial allocation of attention can also explain the two observed main effects. This may become evident when looking at discrimination performance over time.

By presenting the perceptual target at different times before the saccade, previous research has established a typical time course: Discrimination steadily improves at the saccade target location the closer in time the perceptual target is presented to saccade onset, while discrimination at distant locations stays constant over time (see Fig. 3A for a schematic illustration). This pattern is thought to reflect the spatial attention shift towards the saccade target (e.g. Deubel, 2008; Harrison, Mattingley, & Remington, 2013; Jonikaitis & Deubel, 2011; Montagnini & Castet, 2007; Rolfs & Carrasco, 2012; Rolfs et al., 2010). However, there is also evidence that it is possible to allocate some attentional resources away from the saccade target location early in the saccade latency period when exogenously drawn towards the location of the perceptual target (Deubel, 2008; Doré-Mazars, Pouget, & Beauvillain, 2004). Similarly, better discrimination performance in constant property conditions may be explained by assuming that attention is initially directed to the perceptual target (time permitting) and only later on shifted towards the saccade target. For such a serial account, we predict a time-course as schematically depicted in Fig. 3B: on same-location trials, discrimination performance remains stable over time as attention goes initially towards the perceptual target and the saccade never causes it to shift away. In contrast, on different-location trials, discrimination should be best early in the saccade latency period and decrease the closer the perceptual target is presented to saccade onset as attention is imperatively drawn towards the saccade target prior to the saccade (see Deubel, 2008; Experiment 2 for results that follow such a pattern). Note that when averaging over the different time points (see small panels to the side of Figs. 3A and B), spatial congruency effects emerge in both time course scenarios and overall performance is better in the constant property conditions. Note further, that the onset of the perceptual target up to 200 ms before saccade onset in our Experiment 1 may have allowed for a serial shift if one assumes very rapid allocation of attention. Previous research has already shown that constant or validly cued *location* conditions show a pattern similar to the one in Fig. 3A (Deubel, 2008; Montagnini & Castet, 2007). However, White, Rolfs, and Carrasco (2013) found some evidence that feature-based attention can exert some early influence away from the saccade target. Thus, even though serial allocation of attention may seem an unlikely explanation for the location-based effect given previous research, it may still hold for the color-based effect. To further elucidate the nature of the predictability effect, we introduced a variable stimulus onset asynchrony (SOA) between onset of the saccade arrow cue and presentation of the perceptual target in Experiment 2. Comparing performance in the constant color and constant location conditions over time may give insights into whether the same or different mechanisms are responsible for the performance improvements with the two properties.

3. Experiment 2: time-course of effects in constant property conditions

3.1. Methods

Experiment 2 was similar to Experiment 1, with the following exceptions. There were no saccade-only blocks and participants only completed two instead of three discrimination-only blocks. The 71%-correct discrimination threshold of the second block was then used as fixed offset of the perceptual target in the subsequent dual-task blocks. Only the constant property conditions were run. Again, the saccade target location was fully randomized (i.e., 25% were spatially congruent trials). In contrast to the previous experiment, the SOA between saccade cue onset and presentation of the perceptual target was randomly varied across trials
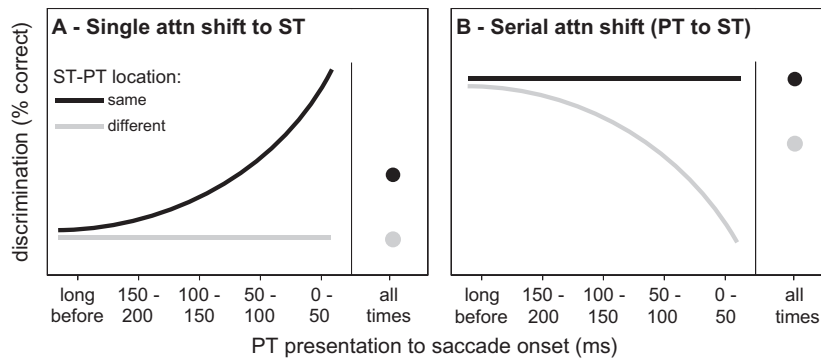
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[1] Note that Montagnini and Castet (2007) report decreasing congruency effects across three blocked conditions with varying validity (i.e., informativeness for the target location) of a spatial cue. These congruency effects, however, are made up of both improvements at validly cued locations and performance decreases on the rare invalid cue trials; if one only takes into account the improvements at validly cued locations (equivalent to our constant condition), results suggest similar improvements at the saccade target location or away from it when the cue is informative compared to a non-informative condition.

Fig. 3. Two alternative hypothetical time course scenarios of spatial congruency effects in discrimination performance as a function of time between presentation of the perceptual target (PT) and saccade onset. Panel A: Schematic time course reflecting a single attention (attn) shift toward the saccade target (ST). We assume this time course to underlie the random-property conditions. Panel B: Schematic time course reflecting serial allocation of attention (time permitting) from the perceptual target to the saccade target (see Deubel, 2008). Such a serial attention shift could potentially explain the advantage with constant properties observed in Experiment 1. This is illustrated by the single data points to the right of each panel, reflecting mean discrimination performance averaged over all presentation times and mimicking the results obtained in Experiment 1.

between −100 ms and 200 ms (possible SOAs: −100, −80, −60, −40, −20, 0, 20, 40, 60, 80, 100, 120, 140, 160, 180 or 200 ms; negative values denoting presentation of the perceptual target before saccade cue onset). This was done to create a broad range of intervals between perceptual target presentation and saccade onset. Only the presentation of the perceptual target was variable in time, the saccade cue was always presented after a constant fixation period of 500 ms. Participants completed between 10 and 13 blocks of 128 trials in the constant-property dual-task. Seven first-year psychology students (all women) between 18 and 25 years of age completed the constant-color condition in three one-hour sessions. Eight (five women) students between 18 and 22 years completed the constant-location task. All students received course credit for their participation.

3.2. Results

In the location group, one participant was excluded from analysis because of too many errors (58.2%). For the remaining participants, exclusion criteria were as in Experiment 1, with the following exception. To encourage fast execution of saccades, an error message was shown when saccadic reaction times were longer than 350 ms. However, to cover a large range of stimulus timings for our time course analysis, we allowed saccade reaction times up to 450 ms to be included in the analyses. 18.8% of all trials (range between 4% and 42% across participants) were excluded. Direction errors (6.1%), failures to fixate (4.5%) and late responses (3.1%) were the most frequent errors.

3.2.1. Discrimination performance

We first compared overall discrimination performance in the discrimination-only blocks. Participants responded correctly in 70.0% of trials. A Mann–Whitney test revealed no significant difference between the color and the location group, $p = .249$. To determine whether discrimination performance differed between the two groups, we calculated the mean horizontal offset of the vertical target bar during the discrimination-only blocks. The vertical bar had to be presented on average 0.31° away from the center and an independent samples t-test revealed no significant difference between the color and the location condition, $t(12) = 0.36$, $p = .725$.

Following the convention to present data time-locked to saccade onset (e.g. Deubel, 2008; Doré-Mazars, Pouget, & Beauvillain, 2004; Rolfs et al., 2010), we first collapsed data from the dual task over all SOAs and then recoded them according to the time elapsed between masking of the perceptual target and saccade onset. We

created seven bins: masking occurred longer than 200 ms before saccade onset, 200–150 ms before saccade onset, 150–100 ms before saccade onset, 100–50 ms before saccade onset, within the last 50 ms before saccade onset, during the saccade and after the saccade. Table 3 illustrates the percentages of trials falling into each bin for the color and the location group. As we were only interested in pre-saccadic attention, trials in which masking occurred during or after the saccade were excluded from further analysis.

Fig. 4 illustrates discrimination performance across the five remaining bins. Data is based on at least 20 trials per participant and condition (average of 57 and 156 trials for congruent vs. incongruent conditions, respectively). We ran a mixed-factor ANOVA (2 properties: color vs. location × 5 bins × 2 spatial congruency: same vs. different location) on the arcsine-transformed percent correct values. The analysis revealed significant main effects of bin, $F(4, 48) = 26.77$, $p < .001$, and congruency, $F(1, 12) = 44.50$, $p < .001$, and a significant interaction of bin and congruency, $F(4, 48) = 10.10$, $p < .001$. Figs. 4A and B demonstrate that congruency effects steadily increased the closer in time the perceptual target was presented to saccade onset. Importantly, this stemmed from increasing performance on same-location trials. There was no indication of discrimination on different-location trials being best with perceptual target presentation early before saccade onset and declining with temporal proximity to saccade onset. No further effect or interaction reached significance, $Fs < 1.59$, $ps > .231$. In particular, there was no interaction of property and spatial congruency, $F(4, 48) = 0.51$, $p = .488$. In contrast to Experiment 1, effects of spatial congruency did not depend on property.

3.2.2. Saccade performance

SRTs as a function of time are illustrated in Figs. 4A.1 and B.1. The mixed-factors ANOVA (2 properties × 5 bins × 2 congruency) on saccade latencies revealed a significant main effect of bin, $F(4, 48) = 13.63$, $p < .001$, and a significant two-way interaction of bin and congruency, $F(4, 48) = 5.34$, $p = .001$ (all other effects or interactions: $Fs < 1.63$, $ps > .226$). Congruency effects emerged when the perceptual target was presented long before the saccade for both the color and the location condition. Thus, congruency effects in SRTs were strongest where the weakest congruency effects in discrimination performance were observed.
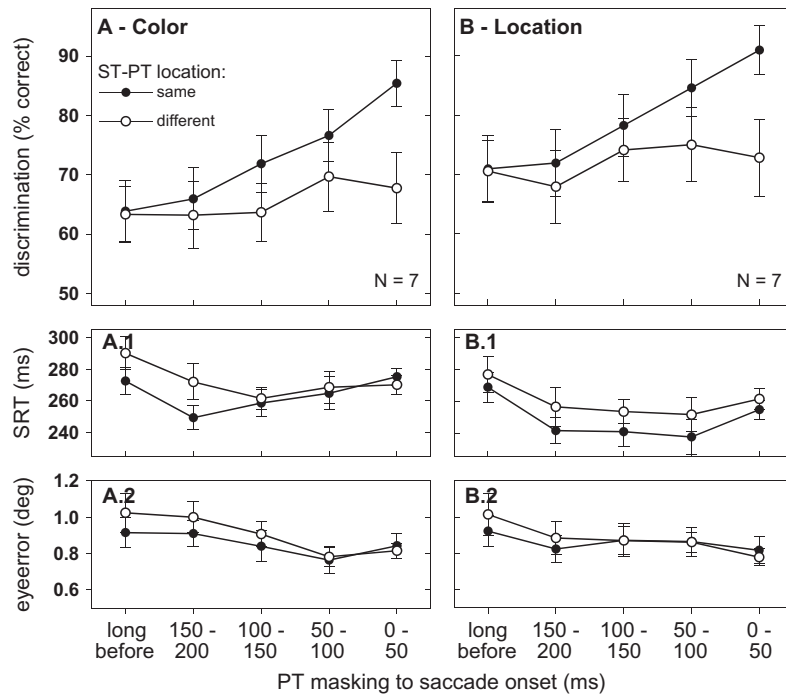
The same ANOVA on saccade landing position error (Figs. 4A.2 and B.2) revealed a significant main effect of bin, $F(4, 48) = 9.67$, $p < .001$, and significant two-way interactions of property and bin, $F(4, 48) = 3.13$, $p = .023$, and bin and congruency, $F(4, 48) = 2.72$, $p = .040$ (all other effects or interactions: $Fs < 0.47$, $ps > .505$). Fig. 4 illustrates that saccade error decreased across

Table 3
Distribution of trials (in %) in Experiment 2 depending on time between mask and saccade onset. The range across participants is given in parentheses.

	Interval from mask onset to saccade onset (ms)						
	>200	150–200	100–150	50–100	0–50	During s	After s
Color	22.1% (11.3–37.1)	13.6% (9.6–16.1)	18.0% (15.2–22.1)	14.8% (11.6–19.6)	19.1% (11.7–24.2)	4.8% (3.7–6.0)	7.6% (2.6–11.5)
Location	19.6% (16.8–32.1)	14.9% (12.3–17.2)	16.2% (13.7–19.2)	14.0% (11.0–16.8)	17.9% (13.3–24.6)	7.7% (2.5–11.3)	9.9% (4.5–12.6)

During s: mask onset during saccade, after s: mask onset after saccade had landed.

Fig. 4. Results of Experiment 2 in the constant color (panel A) and constant location (panel B) dual-task as a function of spatial congruency between saccade target (ST) and perceptual target (PT; same location vs. different location) and time elapsed between PT presentation (time of masking) and saccade onset: discrimination performance (main panels A and B), saccadic reaction time (SRT, panels A.1 and B.1) and saccade landing position error (panels A.2 and B.2). Error bars represent the standard error of the mean.

the five bins included in the analysis and that this decrease seemed to be slightly more pronounced in the color group. Further, congruency effects emerged for the early, but not for the late bins.

3.3. Discussion

In agreement with previous studies, we found congruency effects to increase the closer in time the perceptual target was presented to saccade initiation. The pattern was largely due to a performance increase on same-location trials, reflecting the time course of the progressive allocation of attention towards the saccade target location (see Fig. 3A; Deubel, 2008; Harrison, Mattingley, & Remington, 2013; Jonikaitis & Deubel, 2011; Montagnini & Castet, 2007; Rolfs & Carrasco, 2012; Rolfs et al., 2010). There was no sign of a performance decrease on different-location trials the closer in time the perceptual target was presented to saccade onset, neither in the location nor in the color condition. Thus, we are confident that (time permitting) attention was not first allocated to the perceptual target and subsequently to the saccade target in our experiments. While previous studies have already established the observed time course for location manipulations (Deubel, 2008; Montagnini & Castet, 2007), our results complement these studies by showing that a constant color likewise does not elicit perceptual benefits away from the saccade target exclusively in early epochs.

One could argue that participants in Experiment 2 might not have tried to process the perceptual target as soon as it was pre-

sented, precluding early facilitation effects at locations away from the saccade target. However, our saccade performance data indicates that there was nevertheless some allocation of resources towards the perceptual target when it was presented long before the saccade: Saccades were initiated faster and landed more accurately on congruent trials.

Finally, we note that we could not replicate the smaller spatial congruency effect in the color compared to the location condition that was found in Experiment 1, justifying our decision not to discuss it any further.

4. General discussion

In a dual-task paradigm involving a saccade task and a concurrent perceptual discrimination task, we examined whether participants can make use of prior knowledge of a critical property of the perceptual target to improve perception. To this end, we compared blocks in which the color or location of the perceptual target was kept constant to blocks in which those properties varied randomly from trial to trial. Previous research has already studied similar conditions (Deubel, 2008; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler et al., 1995; Montagnini & Castet, 2007; Shepherd, Findlay, & Hockey, 1986). However, these studies only investigated the *location* condition and mainly focused on the question whether the influence of the saccade task (a spatial congruency effect, i.e., better discrimination when the saccade has to be directed towards the perceptual target) persisted when the

location of the perceptual target was fixed; they did not compare performance in constant vs. random location conditions directly. Results of Experiment 1 replicate and complement these previous studies by showing that despite persisting congruency effects, a constant property indeed improves performance, that the improvement is independent of where the saccade has to be directed on a given trial (i.e., it occurs for spatially congruent trials as well as incongruent trials), and that it also occurs when the perceptual target's *color* is kept constant instead of its location. Further, the improvement was not accompanied by large trade-offs with saccade performance (see Kowler et al., 1995, Experiment 2 for an example of such a trade-off). A time-course analysis of the constant property conditions (Experiment 2) further revealed that the effect is unlikely to be due to serial allocation of attention.

The performance increase with constant properties (color or location) is reminiscent of our recent finding of a color congruency effect in the dual-task paradigm: Discrimination performance improves when the perceptual target is presented in the same color as the saccade target, irrespective of its location (Born, Ansorge, & Kerzel, 2012). The color congruency effect in our previous study was more reliable when *saccade target* color was constant across trials and therefore relevant for the saccade task. We concluded that strong modulations by color may only emerge with a strong attentional bias in favor of one particular color. In a similar vein, the improvements in discrimination performance with constant *perceptual target* color in the current study could be explained by an attentional color bias: Stimuli presented in the favored color benefit from enhanced attentional processing. Given that color was task-relevant, the attentional color bias may have been adopted voluntarily by the participant (e.g. Folk & Remington, 1998) or it may have resulted more passively from mere repetition of the color participants have to respond to (e.g. Belopolsky, Schreij, & Theeuwes, 2010). We argued previously (Born, Ansorge, & Kerzel, 2012) that the lack of interaction of color effects with the spatial congruency effect (i.e., the signature effect for a pre-saccadic spatial attention shift) speaks for the independent nature of spatial and feature-based attentional mechanisms. It is therefore rather surprising that similar performance improvements result when the *location* of the perceptual target was kept constant, which, following our logic, would indicate that there may also be a spatial attentional mechanism acting independently of the saccade-related (presumably likewise spatial) attention shift.

Other than originating from two distinct mechanisms or components of attention, one alternative is that the performance improvements with constant color and location are both ultimately mediated by one single spatial attention process. With serial allocation being unlikely (Experiment 2), the constant color or location may have induced a split of spatial attention with one focus at the saccade target and another at the location of the perceptual target. Additive effects when the two foci coincide are also conceivable. The possibility of multiple attentional foci has previously been discussed in studies in which sequences of eye movements or simultaneous eye and hand movements had to be performed (Baldauf & Deubel, 2008; Gersch et al., 2008, 2009; Godijn & Theeuwes, 2003; Jonikaitis & Deubel, 2011; Rolfs et al., 2010). In those studies, better discrimination has been observed at all movement goal locations in a sequence (not just the immediate saccade target; but see Gersch, Kowler, & Dosher, 2004), compared to locations that were never targeted by any movement. However, even though a split of spatial attention may explain the improvement with constant properties, the time window for allocating one of the foci towards the location of the perceptual target was very different for constant color and constant location. With constant location, participants may have focused attention on the known location even prior to stimulus onset. However, in the constant *color* condition, participants could not focus spatial

attentional resources prior to the onset of the colors in the display. Thus, if the performance improvements were due to the allocation of spatial attention, there should have been much less improvement in the constant color condition than in the constant location condition simply because participants could shift attention earlier in the constant location than color condition. To explain similar improvements for constant color and location, one needs to assume faster attentional allocation in the color task. Thus, although we cannot fully exclude that spatial attention is ultimately responsible for the improvements with constant location *and* constant color, it is likely that the exact mechanism by which these are achieved is different, with the color manipulation presumably even eliciting faster attentional allocation.

Assuming an attentional account for the effects, how fast was attentional allocation (spatial or non-spatial) in the color condition? As the perceptual target was only presented for 100 ms before it was masked, attention needed to exert its facilitative influence on perception within these 100 ms. There is some tentative evidence suggesting that voluntary allocation of attention based on a predefined color can indeed operate that fast, with modulations in discrimination performance already visible after 50 ms (Laarni, Koski, & Nyman, 1996). Further, in a recent dual-task paradigm very similar to ours (White, Rolfs, & Carrasco, 2013), it has been observed that motion congruency between saccade and perceptual target can improve sensitivity to a contrast increment within the saccade latency period, emphasizing the plausibility of rapid feature-based attentional modulations.

Another mechanism by which improved performance in both constant property conditions may be explained is the reduction of location uncertainty for the perceptual target (Prinzmetal, McCool, & Park, 2005). Discrimination in the constant property conditions may not have been better than in the random conditions because of a more accurate percept. Instead, performance may have been better because the predefined property allows the decision on each trial to be based on one single stimulus, reducing the overall rate of false responses by precluding errors caused by mistaking one of the distractors for the perceptual target. In the location condition, the critical stimulus was known in advance; in the color condition, the fact that the masking squares were presented in the same colors as the preceding stimuli made it easy to determine which of the four stimuli must have been the PT, if not already during, then at least after stimulus presentation. However, as we have previously argued for color congruency effects (Born, Ansorge, & Kerzel, 2012), such an account predicts an interaction between predictability and spatial congruency. Even in the random condition, uncertainty about the perceptual target's location should have been low on spatially congruent trials: The shift of pre-saccadic attention should have made it easy to ascertain that the saccade target also contains the perceptual target. In contrast, the perceptual target was shown at three possible locations on incongruent trials. Thus, the benefit of reducing location uncertainty by keeping one of the properties constant should have been larger in the spatially *incongruent* condition, but there was no interaction of predictability and spatial congruency.

A similar argument can be made for memory processes. Keeping properties constant reduces the number of relevant items that have to be held in memory until the response is made (i.e., after the intervening saccade). It has been found that only a limited number of three to four items can be retained in memory across saccades (see Irwin, 1996; Mathôt & Theeuwes, 2011 for reviews). Moreover, the item at the saccade target seems to have priority in trans-saccadic memory (Currie et al., 2000; Zhao et al., 2012). Similar as for location uncertainty, improvements in the constant property conditions should therefore be less strong on spatially congruent trials. If an item has already been selected for memory because it is presented at the saccade target location, there should

be no additional benefit because it is likewise selected for memory based on its property. Indeed, a strong reduction in spatial congruency effects due to better performance on incongruent trials has been reported previously in a memory task when the to be remembered stimulus was cued in advance (Gersch et al., 2008), albeit at a cost in saccade performance.

Finally, do our additive effects necessarily speak for two independent attentional processes? As we did not measure attentional allocation simultaneously at multiple locations on each trial, our results may also be caused by averaging: Subjects may have attended to the saccade target only on some trials while focusing on one of the other locations on other trials. Choosing to attend to the saccade target more often than to one of the other three locations on random trials may cause a congruency effect. In constant property blocks, the relevant locations were restricted to the saccade target and the perceptual target location, causing an overall performance increase. However, assuming that participants did not attend the saccade target location on some trials is in conflict with previous research claiming that attentional allocation towards the saccade target is obligatory (Deubel, 2008; Deubel & Schneider, 1996; Doré-Mazars, Pouget, & Beauvillain, 2004; Hoffman & Subramaniam, 1995; Kowler et al., 1995; Montagnini & Castet, 2007; Shepherd, Findlay, & Hockey, 1986). This interpretation should therefore be viewed with caution. Future research may investigate attention at multiple locations on each trial, for instance, by using a match/mismatch task (e.g. Godijn & Theeuwes, 2003), in which two briefly presented discrimination targets have to be compared with each other.

Acknowledgments

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