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Effects of spatial congruency on saccade and visual discrimination performance in a dual-task paradigm



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ABSTRACT

The present study investigated the coupling of selection-for-perception and selection-for-action during saccadic eye movement planning in three dual-task experiments. We focused on the effects of spatial congruency of saccade target (ST) location and discrimination target (DT) location and the time between ST-cue and Go-signal (SOA) on saccadic eye movement performance. In two experiments, participants performed a visual discrimination task at a cued location while programming a saccadic eye movement to a cued location. In the third experiment, the discrimination task was not cued and appeared at a random location. Spatial congruency of ST-location and DT-location resulted in enhanced perceptual performance irrespective of SOA. Perceptual performance in spatially incongruent trials was above chance, but only when the DT-location was cued. Saccade accuracy and precision were also affected by spatial congruency showing superior performance when the ST- and DT-location coincided. Saccade latency was only affected by spatial congruency when the DT-cue was predictive of the ST-location. Moreover, saccades consistently curved away from the incongruent DT-locations. Importantly, the effects of spatial congruency on saccade parameters only occurred when the DT-location was cued; therefore, results from experiments 1 and 2 are due to the endogenous allocation of attention to the DT-location and not caused by the salience of the probe. The SOA affected saccade latency showing decreasing latencies with increasing SOA. In conclusion, our results demonstrate that visuospatial attention can be voluntarily distributed upon spatially distinct perceptual and motor goals in dual-task situations, resulting in a decline of visual discrimination and saccade performance.

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1. Introduction

We live in a complex environment with a vast amount of different stimuli competing for our attention. Attentional mechanisms must select relevant stimuli and deselect irrelevant stimuli within the visual field (selection-for-perception) in order for our visual system to function efficiently. In addition, attention is required for movement programming and execution, in particular for the selection of movement-relevant visuospatial information which has to be integrated into a movement plan (selection-for-action; Allport, 1987; Neumann, 1987).

Schneider (1995) proposed the visual attention model (VAM) which assumes that visual attention fulfills two main functions: selection-for-action and selection-for-perception. One commonly used paradigm to examine the relationship between these two

functions is the dual-task paradigm by Deubel and Schneider (1996). Participants perform a tachistoscopically presented visual discrimination task at one location while they program a movement towards the same (congruent condition) or a distinct (incongruent condition) location. A wealth of studies demonstrated that prior to saccade onset perceptual processing is obligatorily enhanced at the saccade target location whereas it is poor at non-saccade locations (Deubel, 2008; Deubel & Schneider, 1996, 2003; Hoffman & Subramaniam, 1995; Kowler et al., 1995; Tibber, Grant, & Morgan, 2009; Wilder et al., 2009). Even when the time to program the saccade is extended up to 1200 ms, attention remains locked at the saccade target and cannot be withdrawn from it (Deubel & Schneider, 2003). However, studies on sequential saccades demonstrated that pre-saccadic perceptual facilitation can also occur at multiple saccade targets (Baldauf & Deubel, 2008; Godijn & Theeuwes, 2003). Attention seems to be allocated prior to saccade onset to all locations of the saccade sequence in a parallel, non-contiguous, and gradual manner (Baldauf & Deubel, 2008).

There is converging evidence that during saccade programming at least some attentional resources can be allocated to non-saccade

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locations improving perceptual processing at these locations (Castet et al., 2006; Deubel, 2008; Doré-Mazars, Pouget, & Beauvillain, 2004; Kowler et al., 1995; Montagnini & Castet, 2007). In support, studies on predictive remapping show that visual attention is not only allocated to the saccade target location, but also at predictively remapped locations (Harrison et al., 2013; Jonikaitis et al., 2013; Rolfs et al., 2011). However, the dynamics of attentional allocation during the preparation of eye movements seem to differ between saccade and non-saccade locations. Studies varying the time between the discrimination task and the saccade target cue (=Go-signal) suggest that attentional resources progressively shift to the saccade location with decreasing time to saccade onset, whereas they remain constant at non-saccade locations (Born, Ansorge, & Kerzel, 2013; Deubel, 2008, Exp. 1).

Dual-task studies have primarily focused on the effect of pre-saccadic visual attention on perceptual performance. Following the view that selection-for-perception and selection-for-action share common and capacity-limited attentional resources (Schneider, 1995), one would also expect that movement performance is affected when attention is drawn away from the movement goal. In other words, when one is required to perform a movement to a specific location in space which is not the single locus of attention, movement performance should be poor compared to situations where the movement target location is fully attended. Accordingly, some studies found slower and less accurate saccades in addition to decreased perceptual performance when attention was directed away from the saccade target (Born, Ansorge, & Kerzel, 2013; Deubel, 2008; Hoffman & Subramaniam, 1995; Kowler et al., 1995). In contrast, other studies which also reported effects of visual attention on perceptual performance were unable to find attention-dependent changes in saccade parameters (Deubel & Schneider, 1996, 2003). These inconsistent findings might be explained by the fact that the oculomotor system is hardly affected when drawing little attention away from the saccade target which can already lead to some increase in perceptual performance at non-saccade locations. However, if most of the attentional resources are allocated to the perceptual task during movement programming, costs emerge for the oculomotor system resulting in longer saccade latency and decreased saccade accuracy (Kowler et al., 1995).

Saccade curvature has been identified as one important parameter which is tightly associated with the spatial deployment of attention (Van der Stigchel, 2010; Van der Stigchel, Meeter, & Theeuwes, 2006). Previous studies demonstrated that target-directed saccades curve away from covertly attended locations (Sheliga, Riggio, & Rizzolatti, 1994, 1995; Van der Stigchel & Theeuwes, 2005, 2007). Saccade curvature has often been explained by inhibitory accounts assuming that curvature away is caused by the inhibition of a saccade plan towards the covertly attended location (suppression hypothesis; Sheliga, Riggio, & Rizzolatti, 1994), or on a neuronal level by inhibitory mechanisms acting on neuronal population codes representing competing saccade programs to target and distractor (population coding account; McSorley, Haggard, & Walker, 2004; Tipper, Howard, & Houghton, 2000; for an alternative account see Kruijine, Van der Stigchel, & Meeter, 2014). Explanations of saccade curvature have often been related to the premotor theory of attention which proposes that shifts of covert attention are a by-product of saccade preparation, suggesting that attention and eye movements are tightly linked (Rizzolatti et al., 1987). According to this theory, each shift of covert attention is preceded by an eye movement program to the locus of covert attention. Attention and eye movements usually play in concert, but they are not inextricably interwoven (Awh, Armstrong, & Moore, 2006). Recent studies even claim that “endogenous attentional orienting is entirely independent of motor control” (Smith & Schenk, 2012, p. 1112; see also, Smith, Ball, & Ellison, 2014; Smith, Schenk, & Rorden, 2012).

So far, effects of covert attention on saccade curvature have been revealed in tasks requiring the detection of an imperative signal triggering a saccade (Sheliga, Riggio, & Rizzolatti, 1994, 1995). Previous evidence from a study which applied a dual-task-like paradigm in which participants performed a letter discrimination task before a saccade task found that target-directed saccades curved away from attended non-saccade locations when multiple locations were attended before the saccade was initiated (Van der Stigchel & Theeuwes, 2005). Our study aims to extend their findings on saccade curvature to the classical dual-task paradigm by Deubel and Schneider (1996) where a saccade and a highly demanding discrimination task must be performed simultaneously, facilitating competition between attentional resources.

The present study aims to investigate how spatial congruency and movement preparation time influence different saccade parameters in a modified version of the dual-task paradigm by Deubel and Schneider (2003). We varied the spatial congruency of a primary saccade task and a secondary visual discrimination task. We measured perceptual performance in the visual discrimination task and evaluated different saccade parameters with respect to spatial congruency and movement preparation time. The visual discrimination task was embedded into the saccade task so that it had to be performed during saccade preparation. In order to examine discrimination performance in more detail, we applied a 4 alternative forced choice (4-AFC) task (see also Khan, Song, & McPeck, 2011). Discrimination performance and saccade parameters (latency, accuracy, and precision) were taken as measure of visual attention for perception and action, respectively. Additionally, saccade curvature was used as an oculomotor measure of attentional allocation in space. We hypothesize that discrimination performance in the congruent condition should exceed performance in the incongruent condition and performance in the incongruent condition should be better than chance, as attention can be diverted from the saccade target when subjects are informed about the future DT-location. Based upon the assumption that selection-for-action and selection-for-perception share at least some attentional resources, saccade parameters should deteriorate similarly as perceptual performance deteriorates in spatially incongruent trials. In view of saccade curvature, we expect target-directed saccades to curve away from attended non-saccade locations, i.e. in situations where the DT-location has been specified.

2. Experiment 1

2.1. Methods

2.1.1. Subjects

Ten right-handed human subjects with normal or corrected-to-normal vision participated in the first experiment. They either received course credit or monetary compensation. The participants (4 female) were between 20 and 28 years old ($M = 23.9$, $SD = 2.6$). Written informed consent approved by the local ethics committee was provided by each subject prior to participation. The experiment was performed in accordance with the Declaration of Helsinki (2008).

2.1.2. Apparatus

Participants sat at a table in a dimly-lit room with their head restrained by a chin rest. Stimuli were presented on a 22 in. CRT monitor (Iiyama, MA203DT; refresh rate 85 Hz; screen resolution 1280 × 960 pixels) placed 50 cm in front of the subject. Stimulus delivery was controlled by Presentation[®] (Version 16.3, www.neuro-robots.com). Monocular movements of participants' right eye were recorded via a head mounted video-based EyeLink[®] II (SR Research, Mississauga, ON, Canada) at a sampling rate of 500 Hz. Before each

experimental block the eye tracker was calibrated using a 9 point calibration procedure. Manual choice response to the discrimination task was recorded via an optoelectronic motion tracking system (Optotrak[®] 3020, Northern Digital Inc., Waterloo, ON, Canada) which registered a position marker placed on the right index finger with a sampling rate of 150 Hz.

2.1.3. Stimuli

All visual stimuli were presented on a 50% gray background. The fixation cross ($0.7^\circ \times 0.7^\circ$) and colored arrows (width = 0.4° , height = 1°) were presented at the center of the screen. Saccade targets consisted of three character 8s (width = 0.7° , height = 1°) which were presented at an eccentricity of 7° at 10.30, 12.00, and 13.30 o'clock. Discrimination targets (characters b, d, p, and q) as well as distractors (characters 2 and 5) were similar in size as character 8s. Visually presented response boxes ($8.1^\circ \times 8.1^\circ$) framing enlarged discrimination targets (width = 2.2° , height = 3.2°) were always presented at the same screen locations (upper left and upper right screen and lower left and lower right screen).

2.1.4. Procedure

2.1.4.1. Training. Before the experiment, participants performed two training sessions. *Discrimination training* consisted of at least 3 blocks of 12 trials. Trials started with a fixation screen presenting a fixation cross and three character 8s. After 506 ms of fixation, a drift correction was performed, followed by another 506 ms of fixation (1012 ms fixation period). The fixation cross was replaced for 506 ms by a yellow arrow indicating the location of the future discrimination target (DT-cue) followed by a 106 ms delay presenting the fixation screen. Thereafter, the character 8 at the cued location changed to a character d, b, p, or q and the character 8s at the other locations changed randomly to a character 2 or 5. After 82 ms, DT and distractors changed back to character 8s (mask screen). This screen lasted 1506 ms. Thereafter, the response screen appeared (~1500 ms) and participants had to touch the appropriate DT with their right index finger. Trials were separated by a pause. They had to achieve at least 8 hits out of 12 trials in the 3rd block to continue with the experiment. Otherwise the discrimination training was continued until they succeeded.

Latency training consisted of 24 trials. Subjects were instructed to perform the saccade as fast and precise and accurate as possible. Movement latencies should range between 130 and 600 ms. Each trial started with the presentation of an audio signal, which instructed subjects to pay attention and fixate the center of the screen. Afterwards, the fixation screen (including the drift correction) appeared for 1012 ms followed by a red arrow, indicating the saccade target (ST-cue). The ST-cue was presented until the end of the trial. After a delay of 0, 250, or 500 ms an audio Go-signal prompted participants to execute a saccade from the fixation cross towards the ST-location. The trial ended 1506 ms after the presentation of the Go-signal. Trials were separated by a pause.

2.1.4.2. Saccade-only. The saccade-only task was designed to control for differences in saccade parameters depending on the location of the saccade targets. The stimulus sequence and instructions in the saccade-only task were the same as in the latency training except for the SOA between ST-cue and Go-signal (0, 100, 200, 300, 400, or 500 ms). Each subject received a pseudorandom trial sequence containing 108 trials resulting in 6 repetitions per ST and SOA.

2.1.4.3. Dual-task. To assure correct response classification we examined individual touch locations due to slightly different marker positions on the index finger before each block.

Subjects were instructed that the saccade task was the primary task and the discrimination task was the secondary task. Saccades had to be performed as quickly, precisely, and accurately as possible.

First, subjects performed a training session to assure their understanding of the task. The training consisted of 144 trials containing 3 SOAs (0, 250, and 500 ms). Participants achieved at least a percent correct rate of 45% in the visual discrimination task. The stimulus sequence is depicted in Fig. 1 (please note that size and color of stimuli and background were partially changed for better illustration). Trial start was signaled by a tone which instructed subjects to fixate the forthcoming fixation cross and to pay attention to the task. After the tone, the fixation screen including the drift correction (1012 ms) was presented, followed by the DT-cue (506 ms) and a 506 ms delay (fixation screen). Thereafter, the ST-cue replaced the fixation cross indicating the ST-location. Subjects were instructed to perform a saccade after an audio Go-signal (80 ms) which occurred 0, 100, 200, 300, 400, or 500 ms after the onset of the ST-cue. After the Go-signal the character 8s changed randomly to a distractor (character 2 or 5) except for the DT-cued character 8 which changed into one of the discrimination targets (d, b, p, q) for 82 ms. Afterwards, distractors and DT changed back to character 8s for 1506 ms. Then, a screen asking which discrimination target they saw appeared (1506 ms) followed by a response screen prompting subjects to indicate the DT by touching the appropriate character with their right index finger (~2000 ms). Each participant received a pseudorandom trial sequence. Subjects performed 288 trials divided into three blocks of 96 trials (24 replications per SOA and congruency). Each ST and DT occurred with the same frequency in each SOA. In 50% of the trials, DT and ST were presented at the same location (*congruent trials*) counterbalanced across SOAs. In the other 50%, DT and ST occurred at different locations (*incongruent trials*) with the DT equally often located at one of the other two locations counterbalanced across SOAs.

2.1.5. Data analysis

Data were analyzed using R (R Development Core Team, 2012, www.R-project.org) and MatLab R2013a (The Math Works Inc., Natick, MA). For the parameterization of saccades, custom-made software written in MatLab was used (Koenig, 2010). Eye movements were classified as saccades when their velocity outran $60^\circ/s$. Starting point and endpoint were set at 15% peak velocity.

The first correct saccade within each trial was included into the analyses. Correct saccades were characterized by onset, offset, and timing criteria. The onset error of saccades had to be smaller than 3° (distance from saccade onset to fixation cross). The offset error had to be smaller than 3° (distance from saccade offset to correct saccade target location) and smaller for the correct target location than all other locations. Total movement time (latency plus duration) had to be longer than 160 ms and saccade latency shorter than 600 ms. Minimum total movement time was 168 ms; therefore there was no trial in which the saccade landed at the ST while

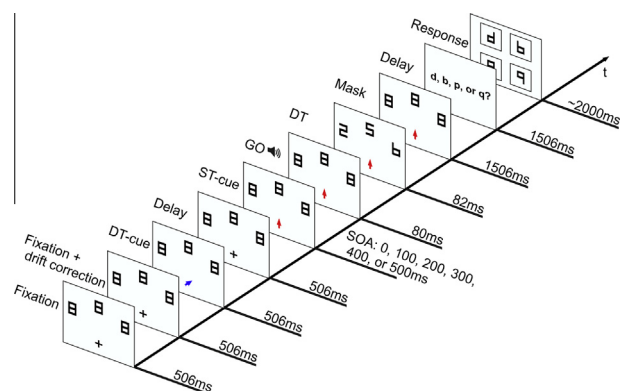


Fig. 1. Stimulus sequence in the dual-task. Times denote the presentation duration of the stimulus events. ST = saccade target. DT = discrimination target.

the DT was still present. Hence, subjects were not able to foveate the discrimination target and thus had to covertly attend its location in order to solve the discrimination task during saccade preparation. In total, 150 trials were excluded across participants (14%) in the saccade-only condition and 655 trials in the dual-task condition (23%). The remaining trials contained 53% congruent trials. For saccade curvature analyses, we additionally excluded outliers which were defined as values which were at least two standard deviations from the mean (113 trials, 5%).

In order to investigate whether discrimination performance depended on spatial congruency and saccade preparation time (SOA), we conducted 2×6 repeated measures analyses of variance (RM-ANOVA) with the factors *congruency* (congruent and incongruent) and SOA (0, 100, 200, 300, 400, and 500 ms). Saccade parameters were also subjected to 2×6 RM-ANOVAs with the factors congruency and SOA. Regarding saccade curvature, we derived specific hypotheses for each ST and DT position. Therefore, we computed RM-ANOVAs with the factor *discrimination location* (left, central, and right) for each saccade target location (left, central, and right).

For the evaluation of effects an alpha of .05 was chosen. Whenever sphericity determined by Mauchly's test (Mauchly, 1940) in ANOVAs was violated, degrees of freedom were corrected using the Huynh–Feldt method (Huynh & Feldt, 1976). The generalized eta-squared was computed (Bakeman, 2005) as measurement for the effect size. We calculated two-sided paired-sample *t*-tests. Unless stated otherwise, whenever multiple *t*-tests were calculated Holm correction (Holm, 1979) was used to control for family-wise error rate.

Dependent variables. We computed several dependent variables to examine effects on selection-for-perception and selection-for-action.

Discrimination performance was calculated as the arcsine square root transformed relative frequency of correct responses (Rao, 1960; Winer, Brown, & Michels, 1971) as these data points are usually not normally distributed and therefore analysis can yield spurious results. The arcsine square root transformation is supposed to yield an approximation of a normally distributed variable. Statistical analyses on discrimination performance were calculated on the transformed data (note that analysis on untransformed data yields similar results). Figures, means, and standard deviations refer to data in percent correct as these values are more intuitive.

Saccade latency was defined as the time in ms between the onset of the imperative Go-signal and saccade onset.

Saccade accuracy was calculated as the mean of the distance between saccade offset and actual target position in degrees of visual angle.

Deviation of **saccade endpoints** on the *x*-axis and *y*-axis were calculated by subtracting saccade endpoints from the actual target location.

Saccade precision was defined as the standard deviation of the distance between saccade offset and target in degrees of visual angle.

Saccade amplitude was measured in degrees of visual angle and computed from gaze resolution data. As the relationship between gaze position and visual angle is not constant for gaze position data, instantaneous angular resolution is recorded at the point of gaze. Gaze resolution data was used to estimate distances between gaze positions, and to compute eye movement velocities (EyeLink® II User Manual, Version 2.14). Amplitude data were converted to mm in order to normalize saccade curvature.

Saccade curvature was determined as the area enclosed by the saccade trajectory and a straight line running from the starting point to the endpoint of the saccade using a trapezoidal method (Ludwig & Gilchrist, 2002). Each saccade was normalized by

dividing the area by the squared amplitude and multiplying this value by 100 (Koenig & Lachnit, 2011). Values indicate the percentage of the area on the squared amplitude with negative and positive values representing leftward and rightward curvature, respectively. Normalization of the area of curvature with amplitude measures has been previously used in several studies investigating saccade curvature (Koenig & Lachnit, 2011; Ludwig & Gilchrist, 2002; McSorley, Haggard, & Walker, 2004; Walker, McSorley, & Haggard, 2006).

2.2. Results

The present work aimed to investigate the coupling of selection-for-perception and selection-for-action during saccadic eye movement planning. In addition to the discrimination performance, we examined saccade parameters and saccade curvature in order to shed more light on how attentional deployment in space affects saccade parameters.

2.2.1. Saccade target location

To rule out an effect of ST-location on saccade parameters, we subjected data from the saccade-only condition to separate ANOVAs with the dependent variables latency, accuracy, precision, and amplitude. The ANOVAs revealed that none of the dependent variables differed between the saccade targets (latency: $F_{(2,18)} = 2.85$, $p = .11$; accuracy: $F_{(2,18)} = 1.03$, $p = .36$; precision: $F_{(2,18)} = 1.37$, $p = .28$; amplitude: $F_{(2,18)} = 1.04$, $p = .37$). As a consequence we collapsed data for saccade targets except for curvature analysis.

2.2.2. Discrimination performance

We analyzed discrimination performance in the visual discrimination task as a function of spatial congruency and SOA. Performance in the visual discrimination task was used as a measure of visual attention for perception.

Fig. 2A illustrates discrimination performance in percent correct averaged across subjects and plotted as a function of spatial congruency and SOA. We found that performance was strongly influenced by spatial congruency of ST and DT ($F_{(1,9)} = 69.93$, $p < .001$, $\eta^2 = .41$). Performance in congruent trials exceeded performance in incongruent trials ($M_{\text{congruent}} = 87.48\%$, $SD_{\text{congruent}} = 9.09$, $M_{\text{incongruent}} = 62.01\%$, $SD_{\text{incongruent}} = 15.74$). Neither the time to prepare the movement ($F_{(5,45)} = 1.34$, $p = .27$) nor the interaction between spatial congruency and SOA ($F_{(5,45)} = 1.07$, $p = .39$) influenced discrimination performance. Separate analyses on the effects of ST- ($F_{(2,18)} < 1$) and DT-location ($F_{(2,18)} = 1.98$, $p = .17$) on discrimination performance revealed no significant results. We also tested if performance in incongruent trials was above chance level (25%). Indeed, a *t*-test showed that discrimination performance was above chance level when ST- and DT-location did not match ($t_{(9)} = 6.97$, $p < .001$).

2.2.3. Saccade parameters

Here, we examined if and how spatial congruency and movement preparation time affected saccade parameters. Therefore, we analyzed latency, accuracy, and precision. Results for saccade parameters are depicted in Fig. 2B–D.

We found that saccade latency was affected by spatial congruency ($F_{(1,9)} = 7.68$, $p < .05$, $\eta^2 = .02$). Latencies were shorter in congruent trials compared to incongruent trials ($M_{\text{congruent}} = 267.51$ ms, $SD_{\text{congruent}} = 27.54$, $M_{\text{incongruent}} = 276.55$ ms, $SD_{\text{incongruent}} = 27.24$). Furthermore, latencies decreased with increasing SOA ($F_{(5,45)} = 23.96$, $p < .001$, $\eta^2 = .28$). The interaction of congruency and SOA did not reach significance ($F_{(5,45)} = 2.02$, $p = .09$).

Saccade accuracy was also influenced by spatial congruency ($F_{(1,9)} = 13.83$, $p < .01$, $\eta^2 = .04$). Saccades in congruent trials were

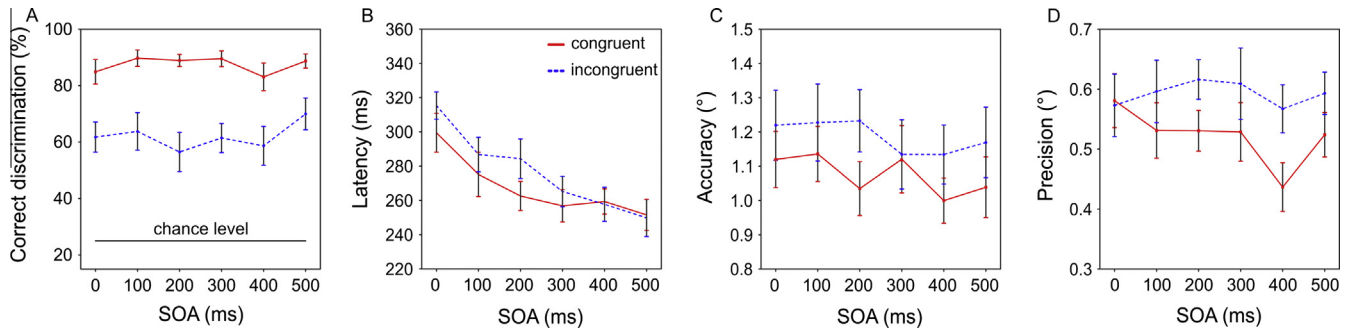


Fig. 2. Discrimination performance and saccade parameters. Mean performance rates in the discrimination task (A), saccade latency (B), accuracy (C), and precision (D) as a function of SOA. Mean data are shown with the standard errors of the mean. Data is plotted for congruent (solid red line) and incongruent trials (dashed blue line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

more accurate compared to incongruent trials ($M_{\text{congruent}} = 1.07^\circ$, $SD_{\text{congruent}} = .24$, $M_{\text{incongruent}} = 1.19^\circ$, $SD_{\text{incongruent}} = .29$). Movement preparation time had no significant effect on accuracy ($F_{(5,45)} = 2.23$, $p = .07$) and did not interact with spatial congruency ($F_{(5,45)} = 1.05$, $p = .40$).

For precision, saccades revealed a main effect of spatial congruency ($F_{(1,9)} = 7.26$, $p < .05$, $\eta^2 = .07$). Saccades in incongruent trials were less precise compared to congruent trials ($M_{\text{congruent}} = .52^\circ$, $SD_{\text{congruent}} = .11$, $M_{\text{incongruent}} = .59^\circ$, $SD_{\text{incongruent}} = .12$). Neither the SOA ($F_{(5,45)} = 1.73$, $p = .15$) nor the interaction of congruency and SOA ($F_{(5,45)} = 1.51$, $p = .22$) were significant.

2.2.4. Saccade curvature

In order to examine effects of spatial congruency on saccade curvature, we analyzed saccade curvature for each ST-location as a function of DT-location. Curvature was analyzed separately for each ST because saccade curvature significantly differed between the three ST-locations ($F_{(2,18)} = 12.93$, $p < .001$, $\eta^2 = .39$; saccades to the left ST were mirrored); thus, data could not be collapsed.

For each ST, DT-location had a significant influence on the normalized area enclosed by the saccade trajectory (ST left: $F_{(2,18)} = 8.67$, $p < .01$, $\eta^2 = .08$; ST central: $F_{(2,18)} = 14.25$, $p < .01$, $\eta^2 = .24$; ST right: $F_{(2,18)} = 10.33$, $p < .01$, $\eta^2 = .05$). To further explore the effects, we performed t -tests to compare the congruent and the incongruent conditions for each ST.

For the left ST, incongruent DTs appeared to the right of the ST; hence, we expected saccades to curve more to the left relative to the congruent condition (Fig. 3, left panel; $M_{\text{congruent}} = -1.60$, $SD_{\text{congruent}} = 2.89$, $M_{\text{DT central}} = -3.35$, $SD_{\text{DT central}} = 2.21$, $M_{\text{DT right}} = -2.67$, $SD_{\text{DT right}} = 2.50$). Indeed, we found that saccades curved away from the incongruent DT-locations compared to the congruent condition (DT central: $t_{(9)} = 4.22$, $p < .01$; DT right: $t_{(9)} = 2.09$, $p = .07$). Please note that one t -test fell short of statistical significance.

For the central ST, we expected saccades to curve to the left when the DT appeared at the right location and to curve to the right when the DT appeared at the left location compared to congruent trials (Fig. 3, central panel; $M_{\text{congruent}} = 1.47$, $SD_{\text{congruent}} = 1.55$, $M_{\text{DT left}} = 2.86$, $SD_{\text{DT left}} = 1.99$, $M_{\text{DT right}} = .71$, $SD_{\text{DT right}} = 1.44$). As expected, saccades curved away from the DT-locations relative to the congruent condition (DT left: $t_{(9)} = -5.83$, $p < .001$; DT right: $t_{(9)} = 2.02$, $p = .07$). Please note that one test (congruent against DT right) fell short of statistical significance.

For the right ST, we expected the mirrored results as we did for the left ST. Therefore, as both incongruent DTs appeared to the left of the ST, saccades were expected to curve away to the right compared the congruent condition (Fig. 3, right panel; $M_{\text{congruent}} = 5.22$, $SD_{\text{congruent}} = 3.49$, $M_{\text{DT left}} = 6.71$, $SD_{\text{DT left}} = 3.41$, $M_{\text{DT central}} = 6.60$,

$SD_{\text{DT central}} = 2.79$). Indeed, saccades curved away more strongly when the DT appeared at an incongruent location compared to when it appeared at the congruent location (DT left: $t_{(9)} = -3.96$, $p < .01$; DT central: $t_{(9)} = -3.76$, $p < .01$).

In sum, saccades consistently curved away from the DT-location in the incongruent compared to the congruent condition irrespective of the location of the saccade target.

2.2.5. Saccade endpoints

Saccade accuracy, precision, and curvature might be related to systematic differences in saccade endpoints depending on spatial congruency. We used t -tests to evaluate this relationship. We found no differences between the horizontal saccade endpoints for the left ST (DT central: $t_{(9)} = -2.05$, $p = .14$; DT right: $t_{(9)} = .64$, $p = .54$), the central ST (DT left: $t_{(9)} = -.59$, $p = .57$, uncorrected p -value; DT right: $t_{(9)} = -.11$, $p = .92$, uncorrected p -value), and the right ST (DT left: $t_{(9)} = -2.33$, $p = .09$; DT central: $t_{(9)} = -.55$, $p = .59$). There was only one trend out of two comparisons for each ST, indicating that saccades to the right ST landed more to the right when the DT appeared at the left location compared to congruent trials. We also found no differences between the vertical saccade endpoints for the left ST (DT central: $t_{(9)} = .28$, $p = .78$; DT right: $t_{(9)} = 2.07$, $p = .14$), the central ST (DT left: $t_{(9)} = -1.11$, $p = .29$; DT right: $t_{(9)} = 2.24$, $p = .10$), and the right ST (DT left: $t_{(9)} = .59$, $p = .57$, uncorrected p -value; DT central: $t_{(9)} = .85$, $p = .41$, uncorrected p -value).

2.3. Summary experiment 1

We found that discrimination performance was enhanced at the saccade target location independent of the SOA. When the saccade and the discrimination task were spatially non-aligned, i.e. in incongruent trials, discrimination performance was worse but clearly above chance. We found similar effects for saccade parameters. When both tasks coincided at the same spatial location, saccades were initiated faster, more accurate, and more precise. Additionally, saccade latencies decreased with increasing SOA. In contrast, SOA had no impact on accuracy and precision. Importantly, saccades curved away from the discrimination target location in the incongruent condition relative to saccades in the congruent condition.

In experiment 1, the discrimination target cue predicted the saccade target in 50% of all cases; however, there were three possible target locations. Therefore, one could argue that the discrimination target cue becomes relevant to the saccade task. It has been demonstrated that probability manipulations can affect saccade latencies. When the oculomotor system is biased or facilitated to program a saccade to a location which is likely to be the saccade

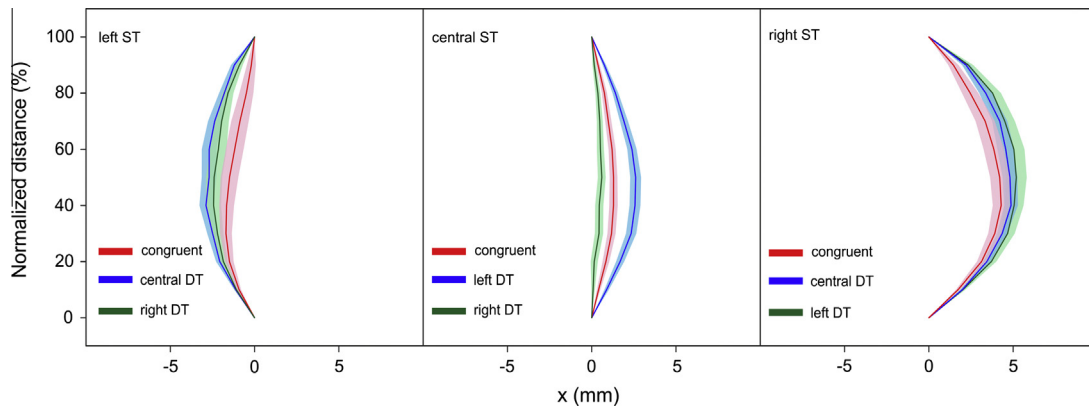


Fig. 3. Normalized saccade trajectories for each ST- and DT-location. Saccade starting point was set to $x = 0$ and $y = 0$. Trajectories were rotated to a final direction of 90° . Colored areas around the mean trajectories indicate 95% confidence intervals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

target, latencies are lower compared to when a location is not likely to be the saccade target and the oculomotor system is suppressed (Belopolsky & Theeuwes, 2009, 2012). In order to control for potential probability effects, we performed a second experiment in which the discrimination target cue exerted maximum uncertainty as the central saccade target was removed and therefore there was no advantage to program a saccade to the cued location of the discrimination target.

3. Experiment 2

3.1. Methods

3.1.1. Subjects

Eleven right-handed human subjects with normal or corrected-to-normal vision participated in the second experiment. Two subjects were excluded as trial dropout in the dual-task exceeded 50%. The remaining nine participants (5 female) were between 20 and 29 years old ($M = 25.4$, $SD = 3.0$). Written informed consent approved by the local ethics committee was provided by each subject prior to participation. The experiment was conducted in accordance with the Declaration of Helsinki (2008).

3.1.2. Apparatus and stimuli

Apparatus and stimuli were the same as in the first experiment. The only difference between the first and the second experiment was the removal of the central target location.

3.1.3. Procedure

Participants performed 48 trials with 3 SOAs (0, 250, and 500) of dual-task training. After training, subjects performed two experimental blocks, each consisting of 96 trials with 5 SOAs (0, 100, 200, 300, 400, and 500). Each ST and DT occurred equally often in each SOA (16 replications per SOA and congruency). There were 50% congruent and 50% incongruent trials. Each subject received a pseudorandom trial sequence. The timing of stimulus events was the same as in experiment 1.

3.1.4. Data analyses

Analyses were the same as in experiment 1. We excluded 288 trials across participants (17%) due to violation of onset, offset, and timing criteria. The remaining 1440 trials contained 51% congruent trials. For saccade curvature analyses, we additionally excluded outliers which were defined as values which were at least two standard deviations from the mean (79 trials, 5%).

3.2. Results

3.2.1. Discrimination performance

We found that performance was strongly influenced by spatial congruency of ST and DT ($F_{(1,8)} = 28.92$, $p < .001$, $\eta^2 = .12$). Performance in congruent trials exceeded performance in incongruent trials ($M_{\text{congruent}} = 73.27\%$, $SD_{\text{congruent}} = 19.38$, $M_{\text{incongruent}} = 58.73\%$, $SD_{\text{incongruent}} = 22.05$). Neither the time to prepare the movement ($F_{(5,40)} = 1.52$, $p = .20$) nor the interaction between spatial congruency and SOA ($F_{(5,40)} = 1.75$, $p = .15$) affected discrimination performance. Fig. 4A illustrates the results on discrimination performance. Separate analyses on the influence of ST- ($F_{(1,8)} < 1$) and DT-location ($F_{(1,8)} < 1$) on discrimination performance revealed no significant results. Additionally, a t -test showed that discrimination performance was significantly above chance when ST and DT did not coincide at the same location ($t_{(8)} = 4.42$, $p < .01$).

3.2.2. Saccade parameters

Results for saccade latency, accuracy, and precision are depicted in Fig. 4B–D. We found that saccade latency decreased with increasing SOA ($F_{(5,40)} = 10.27$, $p < .01$, $\eta^2 = .21$). However, neither spatial congruency ($F_{(1,8)} < 1$; $M_{\text{congruent}} = 279.18$ ms, $SD_{\text{congruent}} = 44.36$, $M_{\text{incongruent}} = 277.74$ ms, $SD_{\text{incongruent}} = 41.53$) nor the interaction of congruency and SOA influenced latencies ($F_{(5,40)} = 1.33$, $p = .29$).

Saccade accuracy was affected by spatial congruency ($F_{(1,8)} = 9.21$, $p < .05$, $\eta^2 = .05$). Saccades in congruent trials were more accurate compared to incongruent trials ($M_{\text{congruent}} = .98^\circ$, $SD_{\text{congruent}} = .21$, $M_{\text{incongruent}} = 1.09^\circ$, $SD_{\text{incongruent}} = .16$). Movement preparation time did not affect saccade accuracy ($F_{(5,40)} < 1$) and did not interact with spatial congruency ($F_{(5,40)} = 1.53$, $p = .20$).

For saccade precision, we found a main effect of spatial congruency ($F_{(1,8)} = 5.55$, $p < .05$, $\eta^2 = .05$) showing less precise saccades in incongruent than congruent trials ($M_{\text{congruent}} = .46^\circ$, $SD_{\text{congruent}} = .04$, $M_{\text{incongruent}} = .51^\circ$, $SD_{\text{incongruent}} = .04$). Neither SOA ($F_{(5,40)} = 1.91$, $p = .11$) nor the interaction of congruency and SOA ($F_{(5,40)} = 1.03$, $p = .41$) affected saccade precision.

3.2.3. Saccade curvature

Based on the results of experiment 1, we expected saccades to curve away from the DT-location when it appeared at a location different from the ST (incongruent) compared to situations where DT and ST shared one location (congruent). We analyzed curvature separately for each ST because saccade curvature differed between the ST-locations ($F_{(1,8)} = 78.97$, $p < .001$, $\eta^2 = .57$; saccades to the left ST were mirrored). Mean saccade trajectories are illustrated

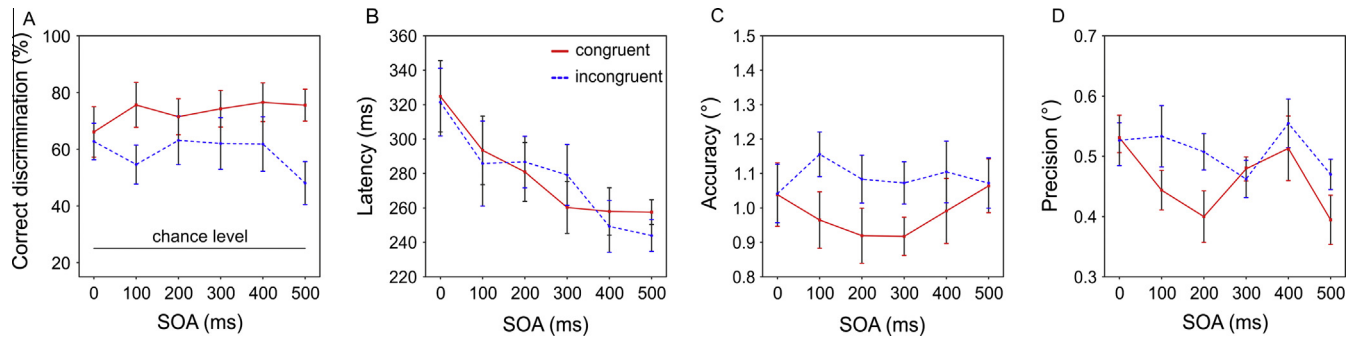


Fig. 4. Discrimination performance and saccade parameters. Mean performance rates in the discrimination task (A), saccade latency (B), accuracy (C), and precision (D) as a function of SOA. Mean data are shown with the standard errors of the mean. Data is plotted for congruent (solid red line) and incongruent trials (dashed blue line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in Fig. 5. Consistent with our hypothesis, we found that saccades directed to the left ST, curved to the left when the DT appeared at the incongruent right location compared to the congruent left location ($t_{(8)} = 3.06$, $p < .05$; $M_{\text{congruent}} = .87$, $SD_{\text{congruent}} = 2.52$, $M_{\text{incongruent}} = -.12$, $SD_{\text{incongruent}} = 2.09$). Saccades that were directed to the right ST showed the opposite pattern; they curved to the right when the DT appeared at the incongruent left location compared to the congruent right location ($t_{(8)} = -3.17$, $p < .05$; $M_{\text{congruent}} = 3.58$, $SD_{\text{congruent}} = 1.88$, $M_{\text{incongruent}} = 4.63$, $SD_{\text{incongruent}} = 1.96$). As in the first experiment, we demonstrated that saccades curve away from the DT-location when DT and ST appeared at different locations.

3.2.4. Saccade endpoints

We calculated t -tests to test for differences in saccade endpoints depending on spatial congruency. We did not find differences for either the horizontal saccade endpoints for the left ST (DT right: $t_{(8)} = 1.21$, $p = .26$) and the right ST (DT left: $t_{(8)} = -2.29$, $p = .05$) or for the vertical saccade endpoints for the left ST (DT right: $t_{(8)} = -.62$, $p = .55$) and the right ST (DT left: $t_{(8)} = .60$, $p = .57$). There was a similar trend as in the first experiment indicating that saccades to the right ST land more to the right when the DT appeared at the left location compared to congruent trials.

3.3. Summary experiment 2

In line with experiment 1, we found that discrimination performance in the spatially congruent condition was superior to

performance in the spatially incongruent condition. Again, discrimination performance in incongruent trials was better than chance. Perceptual performance was independent of the SOA. Regarding saccade parameters, results from the second experiment largely matched the results of the first experiment. Saccades were more accurate and more precise in the congruent condition irrespective of SOA. Saccade latency decreased with increasing SOA. Saccade curvature was again influenced by spatial congruency with saccades curving away from the discrimination target location in the incongruent condition compared to saccades in the congruent condition. The only result that differed between both experiments was whether or not saccade latencies were affected by spatial congruency. In the second experiment, we found no difference in saccade latency between congruent and incongruent trials due to the removal of the predictive bias.

4. Experiment 3

In order to test whether the differences in discrimination performance and saccade parameters found in experiments 1 and 2 were caused by the voluntary deployment of attentional resources to the non-ST-location or by the salience of the probe itself, we performed a third experiment. We adopted the design of the second experiment, but omitted the discrimination target cue and presented the discrimination target randomly at the saccade target and the non-ST-location. Similar findings as in experiments 1 and 2 would suggest that it is not the voluntary allocation of covert

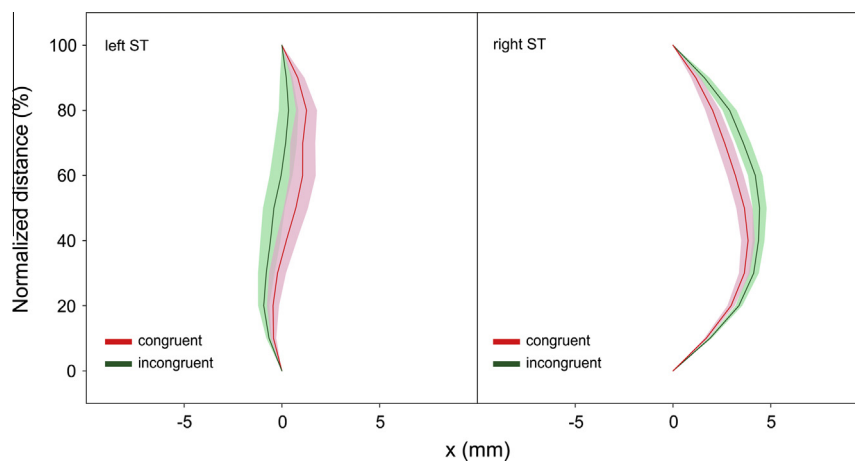


Fig. 5. Normalized saccade trajectories for each ST- and DT-location. Saccade starting point was set to $x = 0$ and $y = 0$. Trajectories were rotated to a final direction of 90° . Colored areas around the mean trajectories indicate 95% confidence intervals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

attention to the discrimination target location, but rather the salience of the probe itself which caused our results.

4.1. Methods

4.1.1. Subjects

Ten right-handed human subjects with normal or corrected-to-normal vision participated in the third experiment. One subject was excluded as trial dropout in the dual-task exceeded 50%. The remaining nine participants (5 female) were between 21 and 27 years old ($M = 24.1$, $SD = 2.1$). Written informed consent approved by the local ethics committee was provided by each subject prior to participation. The experiment was carried out in accordance with the Declaration of Helsinki (2008).

4.1.2. Apparatus and stimuli

Apparatus and stimuli were the same as in experiments 1 and 2 except that the DT-cue which informed subjects about the location of the discrimination task together with the subsequent delay of 506 ms was omitted. The discrimination task appeared randomly either at the ST-location or at the non-ST-location.

4.1.3. Procedure

Participants performed 48 trials with 3 SOAs (0, 200, and 400) of dual-task training. Afterwards, they performed 240 trials with the same 3 SOAs. Each ST and DT occurred equally often in each SOA (40 replications per SOA and congruency). Each subject received a pseudorandom trial sequence with 50% congruent and 50% incongruent trials.

4.1.4. Data analyses

Data analyses were the same as in experiments 1 and 2. We excluded 453 trials across participants (21%) due to violation of inclusion criteria. The remaining 1707 trials contained 50% congruent trials. Additionally, we excluded 84 trials (5%) from the analyses on saccade curvature as values were at least two standard deviations from the mean.

4.2. Results

4.2.1. Discrimination performance

Spatial congruency of ST and DT strongly affected discrimination performance ($F_{(1,8)} = 19.19$, $p < .01$, $\eta^2 = .38$). When ST and DT coincided at the same location in the congruent condition, perceptual performance was superior compared to the incongruent condition when ST and DT appeared at distinct locations ($M_{\text{congruent}} = 66.95\%$, $SD_{\text{congruent}} = 23.42$, $M_{\text{incongruent}} = 34.76\%$, $SD_{\text{incongruent}} = 16.58$). Neither movement preparation time ($F_{(2,16)} < 1$), nor the interaction between spatial congruency and movement preparation time ($F_{(2,16)} = 2.82$, $p = .09$) had an influence on discrimination performance (Fig. 6A). Separate analysis on the influence of ST- ($F_{(1,8)} < 1$) and DT-location ($F_{(1,8)} = 3.55$, $p = .10$) revealed no significant effects. A *t*-test comparing discrimination performance in the incongruent condition against chance level was not significant ($t_{(8)} = 1.71$, $p = .13$).

4.2.2. Saccade parameters

Results for saccade latency, accuracy, and precision are depicted in Fig. 6B–D. As in experiments 1 and 2, saccade latency declined with increasing movement preparation time ($F_{(2,16)} = 14.55$, $p < .001$, $\eta^2 = .37$). Neither spatial congruency ($F_{(1,8)} < 1$), nor the interaction between spatial congruency and movement preparation time ($F_{(2,16)} = 2.47$, $p = .12$) had an influence on saccade latency.

Saccade accuracy was also affected by movement preparation time ($F_{(2,16)} = 5.41$, $p < .05$, $\eta^2 = .09$) but not by spatial congruency

($F_{(1,8)} < 1$) or the interaction of both factors ($F_{(2,16)} < 1$). With increasing SOA, saccades became more accurate ($M_0 = .92^\circ$, $SD_0 = .07$; $M_{200} = .89^\circ$, $SD_{200} = .12$; $M_{400} = .84^\circ$, $SD_{400} = .11$).

We did not find a significant influence of spatial congruency ($F_{(1,8)} < 1$), movement preparation time ($F_{(2,16)} = 2.03$, $p = .16$), or their interaction ($F_{(2,16)} < 1$) on saccade precision.

4.2.3. Saccade curvature

Curvature was analyzed separately for each ST as saccade curvature differed between the ST-locations ($F_{(1,8)} = 20.20$, $p < .01$, $\eta^2 = .32$; saccades to the left ST were mirrored). When the DT appeared randomly at the ST or the non-ST-location (without prior cueing), saccade curvature was unaffected by spatial congruency (Fig. 7). Curvature in the congruent and the incongruent condition did not differ for the left saccade target ($t_{(8)} = -.13$, $p = .90$; $M_{\text{congruent}} = .74$, $SD_{\text{congruent}} = 2.27$, $M_{\text{incongruent}} = .75$, $SD_{\text{incongruent}} = 2.28$) or for the right saccade target ($t_{(8)} = -.19$, $p = .86$; $M_{\text{congruent}} = 2.14$, $SD_{\text{congruent}} = 2.27$, $M_{\text{incongruent}} = 2.16$, $SD_{\text{incongruent}} = 2.22$).

4.2.4. Saccade endpoints

We did not find differences for either the horizontal saccade endpoints depending on spatial congruency for the left ST (DT right: $t_{(8)} = -1.39$, $p = .20$) and the right ST (DT left: $t_{(8)} = -1.66$, $p = .14$) or for the vertical saccade endpoints for the left ST (DT right: $t_{(8)} = -.20$, $p = .84$) and the right ST (DT left: $t_{(8)} = -.80$, $p = .44$).

4.3. Summary experiment 3

In line with the first and second experiment, we found improved discrimination performance in the spatially congruent condition compared to the spatially incongruent condition independent of the SOA. However, when the discrimination target location was not cued (and the discrimination target appeared randomly at saccade target and non-saccade target location), discrimination performance in incongruent trials was at chance. Regarding saccade parameters, we expected that spatial congruency should not affect saccade parameters, as covert attention has not been voluntarily allocated to the discrimination target location due to the missing discrimination target cue. In support with our hypothesis, we did not find any effect of spatial congruency on saccade latency, accuracy, precision, or curvature. Hence, the findings of experiment 3 rule out the possibility that the results from experiments 1 and 2 are caused by the salience of the probe. As in the previous experiments, latency decreased with increasing SOA. Additionally, we found that accuracy increased with increasing SOA; however, this effect was rather small.

5. Discussion

In the present study we investigated the coupling of selection-for-action and selection-for-perception during the preparation of saccadic eye movements using a modified version of the dual-task paradigm by Deubel and Schneider (2003). We measured the effects of spatial congruency of saccade target (ST) and discrimination target (DT) location and of movement preparation time on discrimination performance as a measure of visual attention for perception, on saccade parameters as a measure of visual attention for action, and on saccade curvature as an oculomotor measure of attentional allocation in space. The 3 experiments consistently showed that discrimination performance was better at the ST-location compared to the non-ST-location. Discrimination performance at the non-ST-location was above chance, but only if this location was cued (Exp. 1 and 2) compared to a non-cued situation (Exp. 3). In line with previous findings, movement preparation

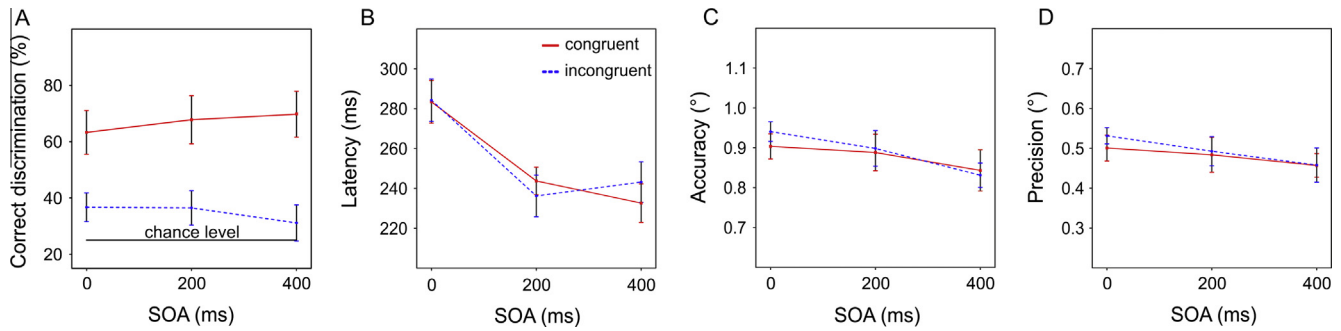


Fig. 6. Discrimination performance and saccade parameters. Mean performance rates in the discrimination task (A), saccade latency (B), accuracy (C), and precision (D) as a function of SOA. Mean data are shown with the standard errors of the mean. Data is plotted for congruent (solid red line) and incongruent trials (dashed blue line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

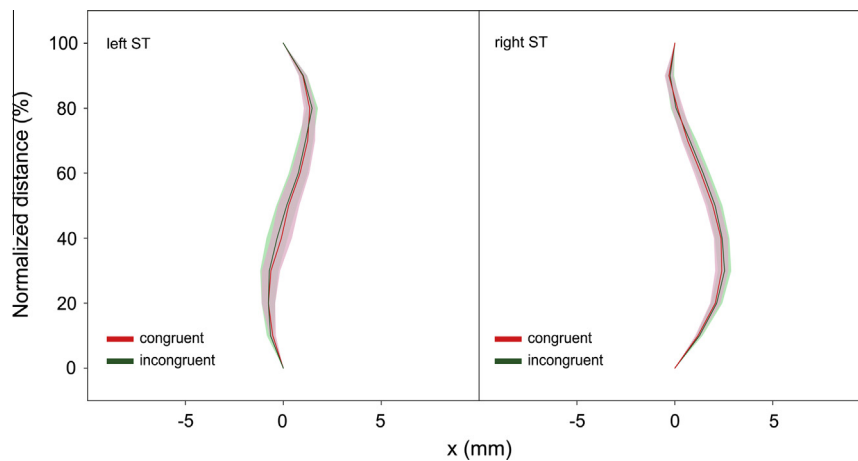


Fig. 7. Normalized saccade trajectories for each ST- and DT-location. Saccade starting point was set to $x = 0$ and $y = 0$. Trajectories were rotated to a final direction of 90° . Colored areas around the mean trajectories indicate 95% confidence intervals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

time had no influence on discrimination performance (Deubel & Schneider, 2003). For saccade performance, we consistently found that accuracy and precision were impaired in spatially incongruent compared to spatially congruent trials when the DT-location was cued (Exp. 1 and 2), but there was no effect of spatial congruency when the DT-location appeared randomly and the DT-cue was omitted (Exp. 3). Saccade latency was only affected by spatial congruency when the DT-cue predicted the ST-location to a higher degree than each of the remaining locations (Exp. 1). When the predictive bias was removed, spatial congruency no longer influenced saccade latency (Exp. 2 and 3). In all 3 experiments, saccade latency declined with increasing movement preparation time while accuracy and precision were largely unaffected by the SOA. Saccade curvature varied as a function of spatial congruency. Target-directed saccades curved away from the cued DT-location in spatially incongruent compared to spatially congruent trials (Exp. 1 and 2). In contrast, when the DT-cue was omitted, saccade curvature was unaffected by spatial congruency ruling out a potential effect of the salience of the probe itself (Exp. 3).

5.1. Discrimination performance

Discrimination performance was best when the location of the discrimination target and the location of the saccade target coincided. This implies that programming a saccade enhances visual processing at the saccade target location, as has been shown by numerous studies (Deubel, 2008; Deubel & Schneider, 1996, 2003; Hoffman & Subramaniam, 1995; Kowler et al., 1995;

Tibber, Grant, & Morgan, 2009; Wilder et al., 2009). We also observed that discrimination performance at the non-ST-target location was above chance when the DT-location was cued. This finding supports the results of a recent dual-task study (Born, Ansoerge, & Kerzel, 2013) indicating that subjects used prior knowledge of the perceptual target location in order to voluntarily direct attentional resources to the non-saccade location. In accordance with previous findings (Born, Ansoerge, & Kerzel, 2013; Castet et al., 2006; Doré-Mazars, Pouget, & Beauvillain, 2004; Kowler et al., 1995; Montagnini & Castet, 2007), our results suggest that attention is not locked at the saccade target but can be allocated to non-saccade locations during saccade programming.

There are at least two explanations why perceptual performance is above chance at the cued non-ST-location. On the one hand, common attentional resources for action and perception might be divided upon ST- and DT-location in the incongruent condition (Born, Ansoerge, & Kerzel, 2013). Studies on sequential saccades suggest that attention can be split upon multiple saccade locations with different attentional weights in a parallel and non-contiguous fashion (Baldauf & Deubel, 2008; Godijn & Theeuwes, 2003). However, there is evidence for very fast shifts of attention prior to saccades (Rolfs & Carrasco, 2012) suggesting that attention can be serially deployed to DT- and ST-location. On the other hand, partially distinguishable attentional components might exist for perception and action resulting in improved performance at both saccade and non-saccade locations (Blangero et al., 2010; Montagnini & Castet, 2007; Wolfe & Whitney, 2014).

In our 3 experiments and in support with the findings by Deubel and Schneider (2003), we observed that perceptual performance was independent of the SOA between ST-cue and Go-signal. This suggests that saccade programming continuously requires attentional resources at the ST-location. Importantly, the study by Deubel and Schneider (2003) and our study manipulated the time between the ST-cue and the Go-signal, while the time between Go-signal and discrimination task was constant. Other studies which varied the SOA between the discrimination task and the ST-cue (=Go-signal) showed that the deployment of attention to the ST-location increased when saccade onset was shifted closer to the discrimination task, while attention at non-ST-locations remained unaffected (Born, Ansorge, & Kerzel, 2013; Deubel, 2008, Exp. 1). These results indicate that attentional deployment to the saccade target can change over time during saccade preparation.

5.2. Saccade parameters

Previous research primarily focused on perceptual performance in dual-task situations. This study emphasized saccade performance by examining different movement parameters as a function of spatial congruency and movement preparation time. Movement planning requires a selection process to transform the visuospatial target information into a movement plan (Allport, 1987; Neumann, 1987). This selection process for motor preparation shares the same capacity-limited attentional resources required for perceptual selection processes (Schneider, 1995). Therefore, allocating attention away from the ST-location during movement preparation (i.e., both processes are competing for the same resources) should result in deteriorated movement performance. Indeed, we consistently found saccades to be less accurate and less precise when the discrimination task was performed at the cued non-ST-location. However, there was no systematic directional bias of saccade endpoints in the horizontal or the vertical direction depending on spatial congruency. Previous evidence suggests that a decrease in saccade accuracy occurs when saccade and perceptual task are spatially non-aligned (Born, Ansorge, & Kerzel, 2013; Kowler et al., 1995). For reach-to-grasp movements it has been demonstrated that orienting covert attention away from the movement goal before movement onset (i.e., during movement preparation), but not at or after movement onset, affects a variety of movement parameters (Castiello, 1996). Here, we present complementary evidence demonstrating that accuracy and precision of saccadic eye movements are also affected by spatial congruency and that this effect occurs independently of movement preparation time. However, saccade accuracy and precision did not vary with spatial congruency when the DT-location was not cued. This suggests that saccade accuracy and precision deteriorate when attention is voluntarily allocated away from the saccade target location.

In our first experiment, saccades were initiated faster in the congruent than in the incongruent condition. This effect was absent in experiments 2 and 3. This difference can be explained by the unbalanced predictive values of the DT-cue in experiment 1 where the DT-cue predicted the ST-location to 50% but each of the remaining two locations only to 25%. One could argue that it was therefore advantageous to program a saccade to the cued DT-location. This is in line with recent evidence suggesting that the oculomotor system is facilitated when the probability to execute an eye movement to a location where attention is maintained is high, whereas it is suppressed when this probability is low (Belopolsky & Theeuwes, 2009, 2012). Hence, removing the predictive bias in the subsequent experiments eliminated the difference in latencies depending on spatial congruency. Please note that only the effect on latency was affected, while discrimination performance, saccade accuracy, precision, and curvature remained unchanged (comparison between Exp. 1 and 2). Our results are in

line with studies by Deubel and Schneider (1996, 2003) who also found that saccade latencies did not differ for spatially congruent and incongruent conditions, in contrast to other studies (Born, Ansorge, & Kerzel, 2013; Deubel, 2008; Hoffman & Subramaniam, 1995; Kowler et al., 1995). These ambiguous results are probably caused by differences in the experimental design. As in our study, Deubel and Schneider (2003) manipulated the time between ST-cue and Go-signal while other studies manipulated the time between discrimination task and ST-cue (Born, Ansorge, & Kerzel, 2013; Deubel, 2008). As mentioned above, these timing differences are crucial to explain variations in perceptual performance and might also be responsible for differences in saccade latencies.

Following the premotor theory of attention (Rizzolatti et al., 1987), the allocation of attention to the cued non-ST-location in incongruent trials goes in line with a saccade plan to the covertly attended location which interferes with the saccade plan to the movement target because both saccade plans compete for selection. This competition results in inferior accuracy and precision of the executed saccade. Since saccade accuracy and precision did not improve with longer movement preparation time our results further imply that attentional resources remain at the cued non-ST-location. This is supported by our observation that discrimination performance was also unaffected by SOA.

5.3. Saccade curvature

In humans, it has been shown that saccades curve away from the locus of covert attention (Sheliga, Riggio, & Rizzolatti, 1994, 1995; Van der Stigchel & Theeuwes, 2005, 2007). However, it has not yet been demonstrated if the same phenomenon also occurs in more complex dual-task situations when an attention demanding perceptual task has to be performed during saccade preparation. Here, we consistently found saccades curving away from the spatially incongruent location where a cued discrimination task was performed relative to saccades in the congruent condition. Importantly, these effects only occurred when participants were able to voluntarily allocate covert attention to the location of the discrimination task due to prior cueing of that location. Hence, the current effects on saccade curvature can be attributed to the voluntary deployment of covert attention and not to the salience of the probe itself.

Similar results have been reported by Van der Stigchel and Theeuwes (2005) who also applied a dual-task-like paradigm but presented the perceptual task *before* the saccade goal was indicated in contrast to our study where the perceptual task was performed *after* the saccade target was specified. Moreover, subjects performed both tasks in a serial fashion and not simultaneously as in the present study. In addition, the perceptual task applied by Van der Stigchel and Theeuwes (2005) was less demanding compared to ours because discrimination had to be performed with less time pressure (750 ms vs. 82 ms) and required less response alternatives (2-AFC vs 4-AFC). Besides these conceptual and methodical differences, their findings match our results on saccade curvature showing that saccades curve away from attended non-saccade locations. Van der Stigchel and Theeuwes (2005) concluded that the prepared saccade to the non-saccade location could only be inhibited just before the saccade was executed because subjects did not know where to move their eyes until the actual ST was indicated unequivocally. We assume a comparable process in our dual-task but instead of the uncertainty of the ST, the simultaneous performance of the discrimination task requires the maintenance of attention at the non-ST-location. Based on this assumption, differences in saccade curvature would probably emerge by inserting a delay between ST-cue and Go-signal in the experiment by Van der Stigchel and Theeuwes (2005). As their discrimination task was performed before the

Go-signal, there is no need to maintain attention at the non-saccade location; hence, inhibition fades away and saccade curvature away from the previously attended non-saccade location declines as a function of the delay period. With respect to our experiments 1 and 2, we would expect no variation of saccade curvature as a function of SOA as attention needs to be maintained at the non-ST-location until the discrimination task is accomplished. Indeed, we did not find that curvature for each ST in the incongruent condition was affected by early (combined SOAs: 0, 100, 200 ms) or late (combined SOAs: 300, 400, 500 ms) SOAs (all $F_s < 3.36$, all $p_s > .10$, data not shown; analysis for experiments 1 and 2).

6. Conclusions

Our results suggest that visual attention can be voluntarily deployed to multiple locations serving as spatial goals for perceptual and motor tasks. However, this is accompanied by impaired perceptual and saccade performance (saccade accuracy and precision), due to two interfering saccade plans to the perceptual and the motor goal in the dual-task. Saccade latency, however, only seems to be affected by spatial congruency if a predictive target-selection bias is present. Our results further extend previous findings on saccade curvature to dual-task situations and suggest similar underlying mechanisms causing saccades to curve away from the covertly attended perceptual target location.

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