
Highlights

► We investigated the source of competition in the saccadic Stroop task. ► Response times and errors were similar for words, arrows, and peripheral onsets. ► Saccade trajectory deviations were only found for peripheral onsets. ► The results could pose a challenge for models of oculomotor target selection.



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The site of interference in the saccadic Stroop effect

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ABSTRACT

In two experiments, the source of competition in the saccadic Stroop effect was investigated. Colored strings of letters were presented at fixation with colored patches in the surround. The task of the participants was to make an eye movement to the patch in the same color as the central string of letters. Three types of cues were compared: Either the string of letters composed a word indicating a direction (the saccadic Stroop condition), or it was a set of arrow signs, or a peripheral stimulus appeared. Whereas response times and saccade errors were similarly influenced by the different types of cues, saccade trajectory deviations away from the cue were found only for peripheral onsets. A second experiment demonstrated that the absence of the curvature effects for direction words was not due to insufficient time to process the words. The results raise doubts on whether the saccadic Stroop effect is effectively an oculomotor effect and could pose a challenge to models of saccade target selection.

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1. Introduction

Several studies have demonstrated seemingly automatic effects of linguistic cues on ongoing behavior. For example, it has been found that perceiving a direction word (e.g., 'left', 'right') can speed up or slow down manual (button press) responses to visual targets, depending on the congruency between the direction indicated by the word and the location of the visual target (Hommel et al., 2001). Furthermore, words have been found to influence verbal responses. Possibly the most famous demonstration of this effect is the so-called Stroop task (MacLeod, 1991; Stroop, 1935), in which participants are asked to name the ink color of a set of words. If these words are the names of colors, strong interference is found when the color indicated by the word itself and the color of the ink are incongruent. Recent studies have also suggested that words can influence eye movements. For example, it has been found that when participants are presented with a set of pictures on a computer screen, their eyes tend to move to the pictures related to simultaneously presented verbal input (Cooper, 1974; Hüttig, Rommers, & Meyer, 2011; Tanenhaus et al., 1995).

Further evidence for the influence of linguistic cues on eye movements was found in an oculomotor version (Hodgson et al.,

2009) of the classical Stroop task. The stimulus sequence in this task is illustrated in Fig. 1, 'Word'.² Participants were asked to fixate a centrally presented fixation symbol. After a delay, the fixation symbol was replaced by a word and four colored patches appeared left, right, above and below fixation. Participants were instructed to make an eye movement to the patch of the same color as the print of the word in the center of the screen. For example, when they saw the word 'right' printed in yellow, their task was to make an eye movement to the yellow patch on the left of the screen. In this example the direction of the word ('right') is incongruent with the direction of the required eye movement ('left'), and the direction of the word therefore acts as a distractor for the eye movement (e.g., Bompas & Sumner, 2009; Walker et al., 1997). Two categories of words were used: Either the words were color names ('red', 'green', 'yellow', 'blue') or they indicated a direction ('left', 'right', 'up', 'down'). For both categories, eye movements were found to be initiated more slowly and more errors were made when the direction indicated by the word name was incongruent with the required direction of the saccadic eye movement than when they were congruent. An analysis of the errors demonstrated that incorrect initial saccades were often directed towards the patch indicated by the (conflicting) word name. These incorrect initial saccades were often followed by

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² Note that in the original experiment (Hodgson et al., 2009), the color patches appeared together with the centrally presented word, and not with the fixation point, as was the case in our experiment. This early onset of the color patches in our experiment was introduced to be able to add a black rim around one of the patches to create a new onset. If the patches would appear at the same time as the target word, a simultaneously presented black rim around one of the patches would no longer have the effect of a new onset.

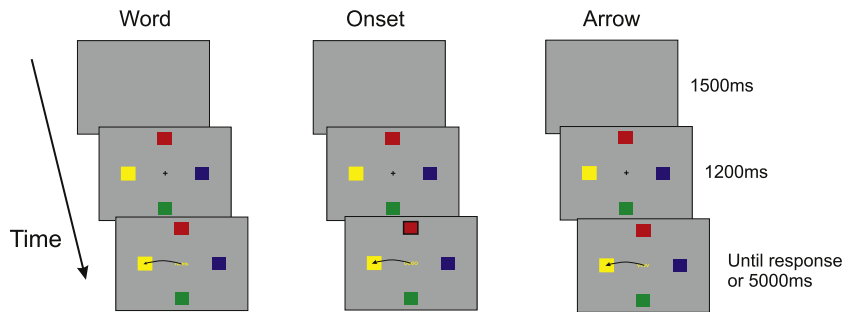


Fig. 1. Stimulus sequence for the 'word', 'onset', and 'arrow' conditions (see Introduction and Methods). Each trial started with a drift correction (not shown) during which participants were asked to fixate a small fixation target in the center of the screen while the experimenter pressed a key to confirm fixation. The drift correction was followed by a blank screen for 1500 ms followed by a fixation screen, showing a fixation cross in the center of the display and four colored patches in the surround. Fixation was followed by the target, consisting of a string of letters whose print color indicated to the participant which colored patch in the periphery to look at. In the 'word' condition, the centrally presented string of letters formed a word indicating a direction (Dutch words for 'left', 'right', 'up', and 'down'), which was either congruent or incongruent with the target direction. In the onset condition, a black ring appeared around one of the colored patches, either congruent with the target color, or around one of the other patches. In the 'arrow' condition, arrow shapes were presented centrally, pointing towards the target patch or towards any of the other patches. In the neutral condition (not shown) a series of Xs appeared in one of the target colors in the center of the screen, providing a situation without conflicting direction information. An example of a correct eye movement response is shown (black curved line) in last frame.

78 fast error correcting saccades with very short (50–150 ms) intersaccadic intervals (the time between the end of the initial incorrect eye
79 movement and the start of the correcting saccade). These intersaccadic intervals were much shorter than the time needed to initiate the
80 initial response, and were often shorter than typical latencies of express saccades (Fischer & Boch, 1983; Fischer & Ramsperger, 1984),
81 the fastest known goal-directed eye movements, suggestive of the parallel programming of the initial and corrective saccade (Godijn
82 & Theeuwes, 2002; McPeck, Skavenski, & Nakayama, 2000; Theeuwes et al., 1998; Walker & McSorley, 2006).

83 The results of the saccadic Stroop task seem to suggest that written words exert a direct influence on the oculomotor system.
84 How such an influence might take place on a neural level, is illustrated in Fig. 2a–d. In these examples, it is assumed that neural
85 interactions take place in the system determining where the eyes go. Some of the effects could also take place at the level of deciding
86 when to move the eyes (for a discussion of the WHEN and WHERE pathways, see Findlay & Walker, 1999). This latter possibility will
87 be elaborated in the general discussion. Fig. 2a–d presents hypothetical oculomotor maps of neural activity, where possible saccade
88 targets (either by instruction or by visual input) are shown as peaks in the topographically organized map. Fig. 2a shows the
89 situation with a congruent target and cue direction (e.g., the word is printed in yellow, requiring a leftward saccade, and the word
90 name is 'left'). Both the print color and the word name induce a response in the oculomotor map at the same location, and activity is
91 expected to reach the required threshold for saccade initiation quickly. When the word print color and the word name indicate
92 different directions, competition is expected between activity at the two locations indicated by the two conflicting sources of information,
93 resulting in longer latencies to initiate the saccade (Fig. 2b). If neurons at the location indicated by the word name accidentally reach
94 threshold first, an incorrect saccade in the word name direction is generated (Fig. 2c). However, some residual activity might remain
95 at the location indicated by the print color (i.e., the required saccade target location; Fig. 2d). This residual activity allows for a fast
96 corrective saccade with a short intersaccadic interval, as less time will be required to reach threshold compared to a situation without
97 residual target activity (e.g., when just the saccade target is presented, without a competing distractor location).

98 The strongest evidence for the above explanation from Hodgson et al. (2009) comes from the fast intersaccadic intervals observed
99 after initially incorrect saccades that follow the direction of the cue, rather than the target. The involvement of residual neural

123 activity in an oculomotor map in such fast corrective saccades is supported by several neurophysiological studies applying single
124 cell recordings in monkey superior colliculus (SC) and the frontal eye fields (FEFs) (McPeck & Keller, 2001; Murthy et al., 2007). For
125 example, McPeck and Keller (2001) found sustained activity in cells coding for the target location for sequences of an initial incorrect
126 saccade to the distractor location followed by an eye movement to the target. This sustained activity was only found for short intersaccadic
127 intervals (less than 125 ms). Similar findings were obtained for movement related cells in the FEF (Murthy et al., 2007), showing
128 target related activity before the initiation of the error correcting saccade from the distractor to the target.

129 Whereas these neurophysiological studies provide evidence for concurrent programming of saccades leading to fast corrective eye
130 movements, they also suggest another prediction if word names in the saccadic Stroop effect automatically generate a peak of activity
131 in the oculomotor map at the location indicated by the name. Several studies in which activity was recorded from monkey SC
132 (Aizawa & Wurtz, 1998; McPeck, 2006; McPeck & Keller, 2002; McPeck, Han, & Keller, 2003; Port & Wurtz, 2003) and FEF cells
133 (McPeck, 2006) have found that concurrent activation of different sites in the oculomotor map is also associated with curved saccade
134 trajectories. The hypothesized curvature and neural mechanism underlying this curvature is illustrated in Fig. 2e and f. Suppose a
135 direction cue (e.g., – the Dutch word for – 'up') is shown in a color requiring an eye movement to the left (Fig. 2e), two peaks of activity
136 are expected in the oculomotor map (Fig. 2f), of which one codes the patch indicated by the cue and the other the saccade target
137 location. Suppose that the neural activity at the target location reaches threshold first, leading to a correct response to the target
138 patch. In this case, it is possible that some residual activity at the location indicated by the cue is still present at saccade onset.
139 Assuming that the eye movement's initial direction is aimed towards the mean vector of activation (an assumption following
140 from neurophysiology, but also often made in models of saccade target selection; Arai & Keller, 2005; Godijn & Theeuwes, 2004;
141 Port & Wurtz, 2003; Trappenberg et al., 2001), it will be directed towards a point in between the target and the cued location
142 (indicated by the white arrow in Fig. 2f). During the saccade a correction takes place, resulting in an eye movement with a
143 curvature towards the cued location. A large body of research points at the involvement of concurrent activity in the oculomotor map
144 in curved eye movements, including studies that used single (and multiple) cell recordings (McPeck, 2006; McPeck, Han, & Keller,
145 2003; Port & Wurtz, 2003), suppression of cell activity with a GABA

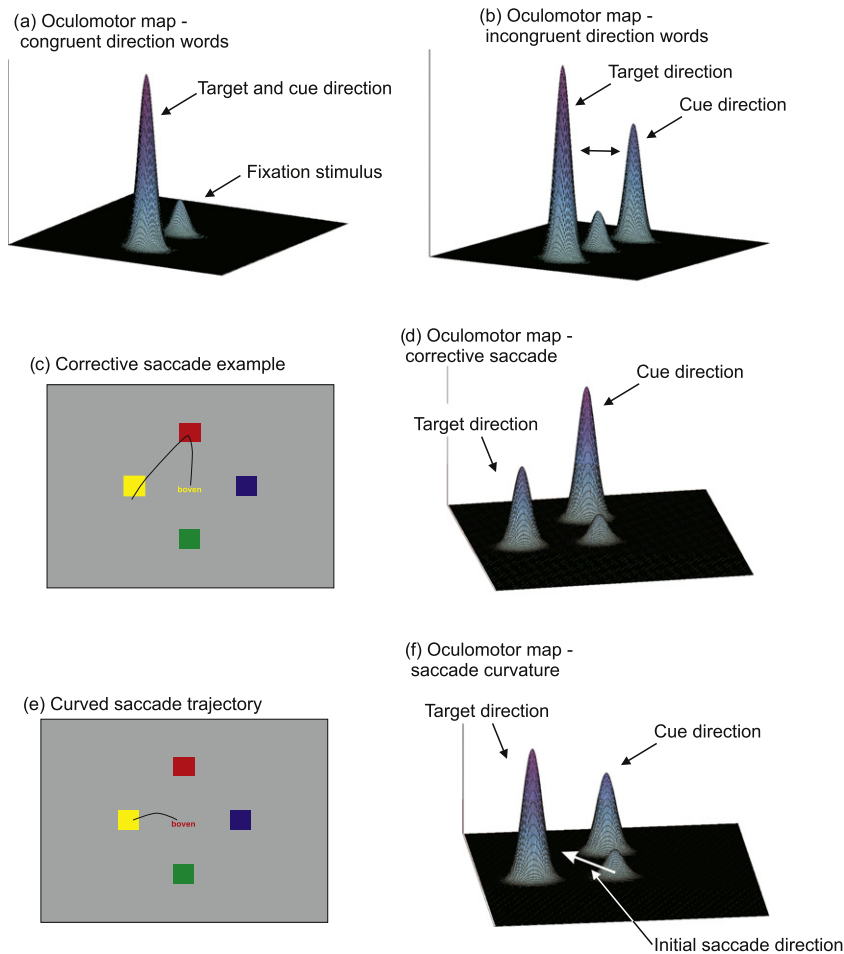


Fig. 2. Examples of hypothetical oculomotor activity that could underlie the different findings in the saccadic Stroop effect. (a) On congruent trials, the target (print color) and the cue (word name) activate the same area of the map and fast response times are expected. (b) On incongruent trials the target and the cue activate different areas. Due to competition, slower response times are predicted. (c) Example of an incorrect response to the location indicated by the cue, followed by a fast corrective saccade. Note that in this particular example, the initial eye movement deviates away from the target. (d) Residual activity at the target location in the map allows for a fast corrective saccade. (e) Example of an eye movement with a trajectory curving towards the direction of the cue. (f) Concurrent activity in the map explains that the initial saccade direction (towards the vector average) is towards the direction of the cue, after which the eye movement is corrected towards the target location, resulting in curvature towards the cue direction.

agonist (Aizawa & Wurtz, 1998) and microstimulation of cells (McPeck, 2006; McPeck, Han, & Keller, 2003). Curvature, however, is not always directed towards the distractor or cued location. Instead, it is also often found to be away from distractors or cued locations (Doyle & Walker, 2001; Godijn & Theeuwes, 2004; Ludwig & Gilchrist, 2003; McSorley, Haggard, & Walker, 2006; Port & Wurtz, 2003; Van der Stigchel & Theeuwes, 2008). Studies using reversible suppression of activity in the oculomotor maps (Aizawa & Wurtz, 1998) and single cell recordings (McPeck, 2006; McPeck, Han, & Keller, 2003; Port & Wurtz, 2003) have suggested that curvature away is found if, near the onset of the saccade, activity in the distractor or cued location is suppressed below baseline, possibly due to top-down inhibition of activity at the distractor site (however, see White, Theeuwes, & Munoz, 2012) or lateral inhibition (Wang, Kruijine, & Theeuwes, 2012).

The present study examines the deviations of saccade trajectories in the saccadic Stroop task (Hodgson et al., 2009) to determine whether they provide evidence for inhibition in the oculomotor system produced by directional words. On the basis of the neurophysiological literature (e.g., McPeck, 2006; McPeck, Han, & Keller, 2003; Port & Wurtz, 2003) and earlier observations of saccade trajectory deviations (e.g., Doyle & Walker, 2001; Godijn & Theeuwes, 2004; Ludwig & Gilchrist, 2003; McSorley, Haggard, & Walker, 2006; Port & Wurtz, 2003; Van der Stigchel & Theeuwes, 2008)

eye movements should deviate away from the direction indicated by incongruent direction words, if direction words automatically activate the oculomotor system (followed by subsequent inhibition). Saccade trajectory deviations have been studied extensively, both in neurophysiological studies (Aizawa & Wurtz, 1998; McPeck, 2006; McPeck, Han, & Keller, 2003; Port & Wurtz, 2003) involving microstimulation, electrical recording and chemical suppression, as well as in behavioral studies (Doyle & Walker, 2001; Godijn & Theeuwes, 2004; McSorley, Haggard, & Walker, 2004, 2005, 2006, 2009; Mulckhuysse, Van der Stigchel, & Theeuwes, 2009a; Nummenmaa & Hietanen, 2006; Sheliga, Riggio, & Rizzolatti, 1994; Sheliga et al., 1995; Van der Stigchel, Meeter, & Theeuwes, 2007; Van der Stigchel, Mulckhuysse, & Theeuwes, 2009; Van der Stigchel, Mills, & Dodd, 2010; Theeuwes & Van der Stigchel, 2009; Van Zoest, Van der Stigchel, & Barton 2008; Walker, McSorley, & Haggard, 2006). It has been shown that direction of saccade deviation is related to patterns of activity and suppression of populations of neurons in the superior colliculus, that code for saccade direction (Aizawa & Wurtz, 1998; McPeck, 2006; McPeck, Han, & Keller, 2003; Port & Wurtz, 2003). Thus, showing that that direction words can influence the deviation of saccade trajectories, in a similar way, would provide further evidence for direction words automatically modulating the activity in the oculomotor map. To test whether deviations away from direction words are indeed

observed, the original experiment by Hodgson et al. (2009) was repeated and deviations of saccade trajectories were examined on trials with orthogonal target and cued locations. Furthermore, two more conditions were added to compare the effects of direction words to two other types of location cues, of which the oculomotor effects are better known (e.g., Hermens & Walker, 2010). These additional conditions are a peripheral onset condition, in which a black ring appeared around one of the colored patches (which were therefore already present during fixation, see Fig. 1, 'onset'). Peripheral onsets have been shown to be powerful distractors in oculomotor preparation (e.g., Bompas & Sumner, 2011; Doyle & Walker, 2001; Hermens & Walker, 2010; Theeuwes et al., 1998) and have been found to reliably produce curvature away from the distractor or cued location under most conditions (however, see McSorley, Haggard, & Walker, 2006; Walker, McSorley, & Haggard, 2006). They have also been associated with exogenous shifts of attention (Müller & Rabbitt, 1989). In the second additional condition, a set of arrows was shown in the center of the screen. Because arrows are generally associated with an endogenous shift of attention and are presented centrally, the effects of arrows might be more comparable to those of the words used in the saccadic Stroop task. A second experiment examined the timing of the Stroop effect by presenting the word in a neutral (black) font, before turning it into the target print color.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Thirteen students from the University of Leuven and the author (three male; average age: 20 years) took part in the experiment. The students received course credits for their participation. Participants all provided informed consent for their participation in the experiment, which was approved by the local ethics committee.

2.1.2. Apparatus

A standard PC presented the stimuli on a 21 in. liyama HM204DT CRT monitor at a refresh rate of 75 Hz and a resolution of 1024 by 768 pixels using the Experiment Builder software Package (SR Research Osgood, ON, Canada). Eye movements were recorded using the Eyelink II system (SR Research Osgood, ON, Canada), controlled by a second PC, sampling the horizontal and vertical gaze positions of both eyes at 500 Hz in pupil-only mode. The viewing distance to the screen was controlled with a chin rest placed at a distance of 60 cm from the computer screen.

2.1.3. Stimuli

Fig. 1 illustrates the stimulus sequence for the three different types of cues ('word', 'onset', 'arrow'), matching the stimulus conditions from Hodgson et al. (2009) as closely as possible. Each trial started with a drift correction (not shown), consisting of a small centrally presented circular target, which participants were asked to fixate, followed by a button press of the experimenter to confirm fixation. After the drift correction a blank screen was presented for 1500 ms, followed by the fixation screen for 1200 ms, in which a fixation cross was flanked by four colored patches. Each of these patches was 3° of visual arc in height and width and was presented at a distance of 7.5° from the center of the display.

After fixation, the target screen was shown in which the fixation cross was replaced by a colored word or string of letters. The color of the central string of letters indicated the target patch for the participant's required eye movement response. Letter strings were shown (Arial font, 18 points) in one of the four colors of the patches around fixation (yellow, green, red, or blue). In the 'words' condi-

tion, the centrally presented strings of letters made up Dutch words for the four cardinal directions ('links' for 'left', 'rechts' for 'right', 'boven' for 'up' and 'onder' for 'down'). In the onset condition, four 'O's were presented centrally and a black rim (5 pixels wide) appeared around one of the colored patches. In the arrow condition, the centrally presented strings of letters consisted of four 'larger than', 'smaller than', capital letter 'V' or '^' symbols. In the fourth, control condition (not shown), four capital letters 'X' were presented. The target screen was shown until the participant's recorded gaze position was inside a virtual box surrounding the position of the colored patch corresponding to the correct response, after which a short sound was produced by the computer speakers and the next trial was started.³ Stimuli (including the drift correction target) were all presented on a gray background.

2.1.4. Design

On each trial, participants received one of four possible conditions: 'word' in which a word indicating a direction was presented at fixation (72 trials), 'onset', in which a black rim appeared around one of the colored patches together with a set of 'O's at fixation (72 trials), 'arrow', in which four arrow-like symbols were presented at fixation (72 trials) and a control condition, in which a sequence of 'X's were presented at fixation (36 trials). For the 'word', 'onset' and 'arrow' conditions, half of the trials used a congruent cue and required response direction, whereas in the other half of the trials, the cue and required response direction were incongruent. On the incongruent trials, the cue direction was equally distributed among the patches not indicated by the color of the string of letters at fixation. The order of the trials, which were all presented in one long block (with short breaks after each 60th trial), was randomized for each participant.

2.1.5. Procedure

At the beginning of the experiment, participants were told that they would be taking part in an eye movement experiment investigating how people deal with conflicting information. Their task would be to make an eye movement to a colored patch indicated by the print color of the centrally presented string of letters (see Fig. 1). Participants were told that the identity of the word at fixation, as well as any onset in the periphery were irrelevant to the task and did not contain any information about which patch to move the eyes to.⁴ They also received the instruction to shift gaze to the patch corresponding to the correct response as quickly as possible, avoiding to look elsewhere first as much as possible. Once they fixated the correct patch a sound would be played and the next trial would be started.

The instruction was followed by fitting the headband of the eye tracker, after which the participant were seated looking at the computer screen with their head position restrained by means of a chin rest. The eye tracking system was then calibrated by presenting participants with a sequence of 10 calibration targets, positioned on a three by three grid. Calibration was considered successful if the recorded eye positions were aligned with the grid and the first and last recorded position were superimposed, associated with an approximate 0.5° accuracy and 0.01° RMS resolution.

³ This way of providing auditory and visual feedback was chosen to match the procedure by Hodgson et al. (2009) as closely as possible. A pilot experiment in which no visual feedback was used yielded the same pattern of results, suggesting that the feedback was not critical to the findings.

⁴ Note that this latter part of our instruction might not have been entirely correct, depending on how it is interpreted. Because the target was equally often presented in the direction of the cue as it was presented elsewhere, the statement is only correct if one assumes that it means that the cue was equally often valid as invalid. Because the cue appeared equally often in the three uncued positions when it was invalid, participants might have used the cue direction as it more likely indicated the target direction than any of the other directions.

After a set of practice trials (around 10 for each participant), the experiment was started. Each trial began with a drift correction, followed by the trial sequence consisting of a blank screen for 1500 ms, a fixation screen for 1200 ms and a target screen until eye gaze landed in the correct colored patch on the screen. The experiment was run as a single block, but participants were offered the opportunity to take a break after each 60th trial. The experiment took about 25 min to complete.

2.1.6. Data analysis

Eye movements of the left eye were analyzed. Saccades were detected using the Eyelink's algorithm, using a 22 deg/s velocity and 8000 deg/s² acceleration criterion. Trials were filtered for incorrect and slow responses as well as blinks occurring during the first saccade after target onset. For the computation of response times and saccade trajectory deviations, trials in which the first saccade after target onset was in the wrong direction (outside an angular region of 30° around the target patch), was of insufficient amplitude (less than 2°), was initiated too quickly (latency of less than 80 ms) or too slowly (latencies of more than 2.5 standard errors above the mean), or contained a blink were removed from the analysis. We also excluded trials with saccade trajectory deviations larger than 50% of the saccade amplitude (turn-around saccades), to avoid exceptionally large deviations towards or away to influence the mean results. These exclusion criteria led to the exclusion of the data of one participant (>30% of trials excluded), and on average, 14.4% of the trials for the remaining participants.

Response times were defined as the time from the onset of the letter string indicating the target color to the onset of the eye movement to the color patch. Saccade trajectory deviations were computed for incongruent target and cued location trials in which the cued direction was at an 90° angle (both clockwise and counterclockwise) from the target direction. Saccade trajectory deviations were calculated as the peak deviation of the saccade trajectory from the straight line connecting the start and the end of the saccade, as a percentage of the amplitude of the saccade. Trajectory deviations were then compared to the deviations observed in the control condition ('XXXX', serving as the baseline trajectory deviation) for the same target direction (Ludwig & Gilchrist, 2002; Van der Stigchel, Meeter, & Theeuwes, 2006). Average trajectory deviations for clockwise and counterclockwise directions were pooled into a single measure indicating the average trajectory deviation away from the distract location. Except for the histograms of intersaccadic intervals, all measures were computed for each participant separately before they were pooled into one mean, or analyzed in a statistical analysis.

2.2. Results

2.2.1. Response latencies

Fig. 3a shows the latencies across the congruent, neutral, and incongruent conditions, for directions indicated by a word, an onset, or an arrow. Note that, in this plot, the neutral condition is plotted three times (once for every direction cue type), whereas it was measured only once. The largest congruency effect seems to be present for the centrally presented arrows, compared to the word and onset conditions. This congruency effect was evaluated in a repeated measures analysis of variance (ANOVA) testing the effects of congruency (congruent versus incongruent; the neutral condition was not included in this comparison, as it did not differ across cue types) and the type of direction cue (word, onset, or arrow). Significant main effects of the type of direction cue ($F(2,24) = 3.87, p = 0.035$) and congruency ($F(1,12) = 99.0, p < 0.001$) were found, as well as a significant interaction between the two factors ($F(2,24) = 14.6, p < 0.001$). Pairwise comparisons between congruent and incongruent cues showed significant

congruency effects for words ($t(12) = 5.13, p < 0.001$), onsets ($t(12) = 2.65, p = 0.021$) and arrows ($t(12) = 12.68, p < 0.001$). Pairwise comparisons with the neutral condition demonstrated that the congruency effects were mainly due to facilitation by congruent cues (p -values smaller than 0.024 for all three types of cues), and less so due to inhibition by incongruent cues (only for the arrow cue a significant difference between neutral and incongruent cues was found: $t(12) = 7.47, p < 0.001$).

The size of the congruency effect across cues was compared by examining the interaction between the type of cues and target-cue congruency for pairwise comparisons between the different cues. Significantly stronger congruency effects were found for arrows than for onsets ($F(1,12) = 15.9, p < 0.001$), or words ($F(1,12) = 47.6, p < 0.001$). The congruency effects were no different for words and onsets ($F(1,12) = 0.096, p = 0.76$).

2.2.2. Saccade direction errors

Fig. 3b shows the percentage of trials in which participants made an eye movement with an amplitude of at least 2° of visual angle (i.e., excluding small saccades, such as those arising from hesitations), which were not in the direction of the saccade target (i.e., outside an angular region of 30° around the target). Errors were more frequent on incongruent trials than on congruent and neutral trials. There also appears to be a trend for words to induce fewer direction errors in the incongruent condition. The statistical significance of these effects of congruency (congruent versus incongruent) and cue type (word, onset, or arrow) on these direction errors were examined using a two-way ANOVA. Significant main effects were found of congruency ($F(1,12) = 12.10, p = 0.0046$) and the cue type ($F(2,24) = 6.78, p = 0.0047$) in the absence of a significant interaction effect ($F(2,24) = 1.49, p = 0.25$). The direction errors for the incongruent condition were compared using a one-way repeated measures ANOVA, demonstrating that the apparent trend for fewer errors on the word condition failed to reach significance ($F(1,12) = 4.06, p = 0.067$; difference contrast simultaneously comparing the word against the onset and arrow conditions).

Fig. 3c examines the percentage of trials in which the first saccade was erroneously aimed in the cued direction in the incongruent condition, showing that most direction errors were indeed made in the direction of the cue (compare Fig. 3b and c). The apparent trend towards fewer saccades in the cued direction for the word condition was not found to be statistically significant ($F(1,12) = 2.29, p = 0.156$; difference contrast simultaneously comparing the word against the onset and arrow conditions).

2.2.3. Intersaccadic intervals

Fig. 3d compares the distribution of intersaccadic intervals across the different cue types. Plotted here are the durations of the fixations on the incorrect target patch (indicated by the cue) before making a corrective saccade to the target (i.e., only the saccades in the direction of the cue are included in the histograms). Because saccades in the direction of the cue were relatively infrequent, the distribution across observations from all participants are shown (see also Hodgson et al., 2009). To superimpose the histograms for the three types of cues, a line plot is used in which the frequency of the observations at the bin centers are shown (for example, the data points at 50 ms show the frequency for the interval from 25 ms to 75 ms). Similar distributions across the different cue types are found, which all peaked at 100 ms (i.e., in the interval between 75 ms and 125 ms). One-sample Kolmogorov-Smirnov tests comparing the distributions, however, demonstrated a marginally significant difference between the onset and the arrow ($k = 0.42, p = 0.052$), and significant differences between the arrow and the word ($k = 0.43, p = 0.049$) and the onset and the word

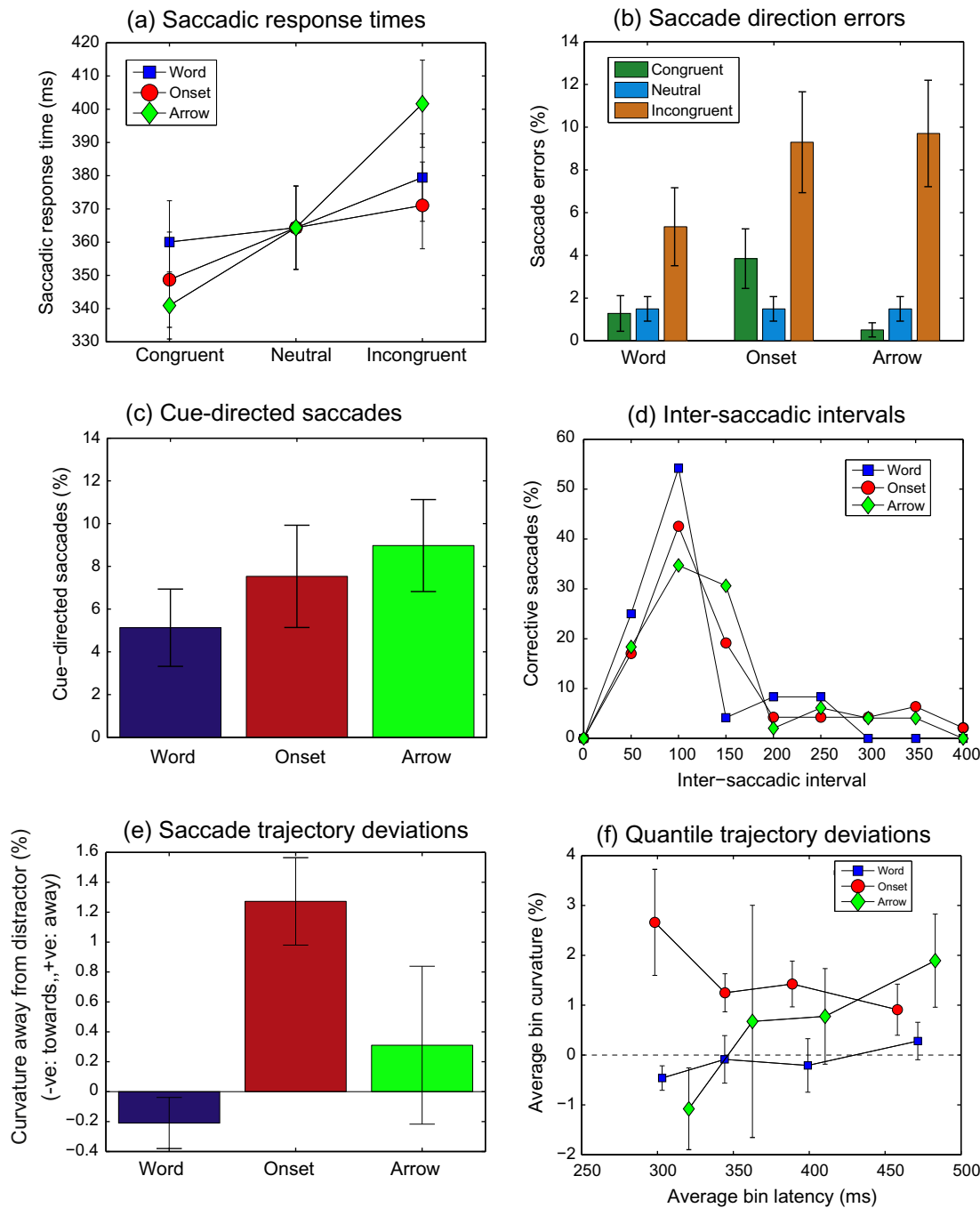


Fig. 3. Results from Experiment 1. (a) Saccadic response latencies for correct responses for the different types of cues (onset, arrows, words) and the different congruency conditions (congruent, incongruent, neutral), showing an advantage for congruent target–cue pairings. (b) Saccade direction errors, defined as the proportion of trials with a saccade of sufficient amplitude ($>2^\circ$) in a direction other than the target patch, showing more errors for incongruent target–cue pairings. (c) The percentage of trials with an initial eye movement towards the direction of the cue. (d) Distributions of intersaccadic intervals, defined as the time spent fixating the cued location before making a corrective saccade towards the target. (e) Average saccade trajectory deviations away from the direction of the cue for situations in which the cued location was orthogonal to the target location, relative to the neutral cue condition ('XXXX') for the corresponding target direction, showing significant deviations away from peripheral onsets, but not from the centrally presented arrows and direction words. (f) Average saccade trajectory deviations (positive values representing deviations away from the cue) as a function of the response time (1st until the 4th quantile), showing curvature away across almost the entire range of response times for peripheral onsets, but no significant deviations for the arrow or direction word cues. Error bars in all data plots show the standard error of the mean across participants.

conditions ($k = 0.44, p = 0.039$), possibly reflecting differences in the 125 ms to 175 ms time bin.

2.2.4. Saccade trajectory deviations

The results so far are in agreement with an interpretation in which the direction indicated by the word, the arrow, and the peripheral onset led to the automatic preparation of a saccade in

that direction. Fig. 3e examines the trajectory deviations of saccade trajectories for the three different conditions. The numbers in this plot are based on trials in which the direction of the cue was orthogonal to the required saccade direction. Saccade trajectory deviations were computed as the peak deviation of the saccade trajectory from the straight path connecting the start and the end of the saccade, relative to the average peak deviation for saccades

with a neutral cue ('XXXX') with the same saccade target (see also the [Methods](#) section). Peak deviations for clockwise and counterclockwise arrangements of target and cue directions were pooled into one number (as similar results were obtained for these two arrangements), such that the resulting number indicated the curvature away from the cue direction, as a percentage of the amplitude of the saccade with respect to baseline (the neutral cue condition with the same target). Whereas onsets show reliable saccade trajectory deviations away from the direction of the cue ($t(12) = 4.36, p < 0.001$), no such deviation away was found for the centrally presented arrow ($t(12) = 0.59, p = 0.57$) and word conditions ($t(12) = -1.23, p = 0.24$).

The direction and size of trajectory deviations have been found to depend on saccade latency (McSorley, Haggard, & Walker, 2006, 2009; Mulckhuysen, Van der Stigchel, & Theeuwes, 2009b; Van der Stigchel & Theeuwes, 2007; Van Zoest, Van der Stigchel, & Barton 2008). Deviations towards are more often found for eye movements with short latency, whereas deviations away from a cue or a distractor are found for those with longer latencies. Such effects might have played a role in the absent effects for words and arrows, if fast deviations towards would have been averaged with slow deviations away. To investigate this possibility, we split our curvature data into four equal bins, each representing one quartile of the response times of that participant. Data for clockwise and counterclockwise configurations were pooled in this analysis, correcting for the direction of the cue by always coding the size of the deviation away from the cue's direction. The bin averages (response times and trajectory deviations) for each participant were then pooled, and the result plotted in Fig. 3f. Although for peripheral onsets there appears to be a slight downward trend towards a decrease of trajectory deviations for longer latencies, the linear contrast of this trend was not statistically significant ($F(1, 12) = 2.03, p = 0.18$). Deviations in this condition were always away from the location of the onset (with p -values in t -tests testing whether the deviation was significantly different from zero of 0.028, 0.0067, 0.0092 and 0.101 for the first, second, third and fourth bin, respectively, of which the second two comparisons survive a Bonferroni correction for multiple comparisons). For arrow cues, the time-dependent trajectory deviations appear to show a positive trend. However, neither this trend ($F(1, 12) = 2.75, p = 0.13$), nor any of the average deviations away or towards per time bin (all p -values larger than 0.066) are statistically significant. For words, the time-bin analysis does not suggest a trend, and within each bin, trajectory deviations were no different from zero (all p -values larger than 0.084).

2.3. Discussion

Experiment 1 compared eye movements towards a target patch indicated by the color of the string of letters presented at fixation in the presence of different types of cues. Strongest influences on response times were found for a string of letters making up a set of arrows, while weaker but significant effects were found for onset cues and directions indicated by direction words. Error trials, in which a large eye movement was made into another direction than the target as the first response were very similar across the different types of cues. The same was found for the time needed to correct an initial incorrect saccade in the direction of the cue (arrow direction, peripheral onset location or word direction), rather than the target (the patch with the correct color). Substantial differences across cues, however, were found when the curvature of saccade trajectories were considered. Clear deviations away from the direction of the cue were found for peripheral onsets, but not for the centrally presented arrows and direction words. These absent deviations for arrows and direction words could not be explained from the pooling of trajectory deviations across different response times.

In our experiment (in agreement with the experiment by Hodgson et al. (2009)), we used cues with an overall validity of 50%, meaning that the cue equally often pointed in the direction of the target as in any of the other locations. This also meant that the cue could possibly contain some information about the likely location of the target, as it pointed in 50% of the cued trials in the direction of the target and only in 16.7% of the cued trials in each of the other three positions (together making up the remaining 50%). As a consequence, participants could have adopted a strategy of paying more attention to the cued direction than to the other three directions. Whereas such increased attention could have increased the benefit on response times, and increased the error rates on incongruent trials, it cannot explain why no deviations of saccade directories away from the cue location were found for the word (and arrow) condition. If direction words have an effect on the oculomotor system, the additional attention should have increased their influence on saccade trajectory deviations, which was not what was observed.

Because Experiment 1 compared several different conditions, it was necessary to pool data across the different directions in which the eye movements were made in order to obtain sufficient data per condition to reliably estimate the size and direction of saccade trajectory deviations. This pooling across different saccade directions might be a problem when saccade curvature is considered, as deviations in saccade trajectories have been found to depend on the direction of the saccade. For example, larger deviations towards and away from distractors have been reported for vertical than for horizontal saccades (Laidlaw & Kingstone, 2010; Van der Stigchel & Theeuwes, 2008; Walker, McSorley, & Haggard, 2006). To examine whether differences in the saccade direction can explain the absence of saccade curvature for direction words, data across 12 more participants were collected only testing the word condition (i.e., no variations in the type of cue). Consequently, each combination of target direction and target and cue congruency could be presented more often, allowing for reliable estimates of saccade trajectory deviations for each saccade target direction. Response times showed significant main effects of the congruency of target and cue direction ($F(2, 22) = 7.26, p = 0.0040$), replicating the results of Experiment 1 and those by Hodgson et al. (2009). In addition, a main effect of saccade direction ($F(3, 33) = 13.70, p < 0.001$) was found, in the absence of an interaction between the two factors ($F(6, 66) = 1.62, p = 0.16$), with slowest response times for incongruent target and cue combinations and for downward eye movements. Saccade trajectory deviations, in contrast, were not affected by saccade direction ($F(3, 33) = 1.59, p = 0.21$) and were not significantly different from zero for either saccade direction (left: $t(11) = -1.70, p = 0.12$; right: $t(11) = -0.21, p = 0.84$; downward: $t(11) = 0.21, p = 0.83$; upward: $t(11) = 1.01, p = 0.34$), indicating that the absent curvature effects for direction words were not due to pooling data across different saccade directions.

The results of Experiment 1 are difficult to interpret in terms of the predictions made on the basis of single cell recordings in monkeys (Aizawa & Wurtz, 1998; McPeck, 2006; McPeck & Keller, 2002; McPeck, Han, & Keller, 2003; Port & Wurtz, 2003). The facilitation of saccade initiation by congruent cues and the fast corrective saccades suggest the automatic preparation of an oculomotor response in the direction indicated by the central or peripheral cues. Saccade trajectory deviations, on the other hand, are only consistent with such automatic response preparation (and subsequent inhibition) for peripheral onsets, but not for direction words or arrows.

A possible difference between the centrally presented cues on the one hand and the peripheral onset on the other, might lie in time needed to interpret the cues and to use this information in saccade preparation. Such an interpretation would fit with earlier observations, showing that, for example, gaze cues and arrows

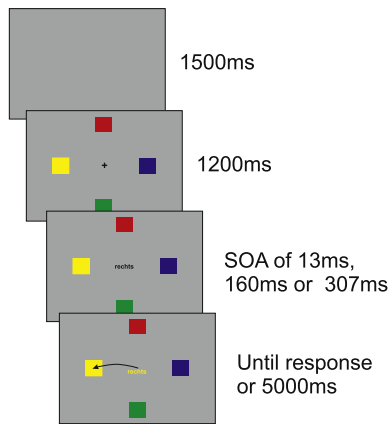


Fig. 4. Stimulus sequence in Experiment 2. As in Experiment 1, a drift correction (not shown) was followed by a fixation screen. After fixation, a preview of the target word was shown by means of presenting the word in a black font. Following an SOA of 13 ms, 160 ms, or 307 ms, the target word turned into the target color indicating the colored patch that participants had to make an eye movement to. Once the target patch was fixated, a sound was played and the next trial was started.

take more time to influence saccade trajectories than peripheral onsets (Hermens & Walker, 2010). The influence of gaze cues and arrow cues increased in this study when the cues were presented ahead of the peripheral saccade target. In Experiment 2, a similar manipulation will be used to investigate whether such delayed curvature effects also occur for direction words. To this end, the direction word is first presented in a neutral color (black). After one of three stimulus onset asynchronies (SOAs) its color switched to the target color (Fig. 4). The SOA manipulation introduced in this way should allow for more time to process the direction indicated by the word.

3. Experiment 2

Experiment 2 investigates whether the lack of an effect of direction words on saccade trajectory deviations could have been due to insufficient time to process the cue, previously found for gaze and arrow cues (Hermens & Walker, 2010). After a variable SOA the font color of the word was therefore changed from the neutral color (black) into the target color. Three SOAs were used, corresponding to 1 refresh of the CRT screen (13 ms), 12 refreshes (160 ms), or 23 refreshes (307 ms).

3.1. Methods

3.1.1. Participants and apparatus

Fifteen students from the University of Leuven and the author took part in the experiment, resulting in a total of 16 participants (seven male; average age 19.5 years). The same apparatus as in Experiment 1 was used.

3.1.2. Stimuli and procedure

The stimulus sequence is illustrated in Fig. 4. As in Experiment 1, drift correction was followed by a fixation screen, consisting of a fixation target (in the center) and four colored patches. After a delay of 1200 ms, the fixation target was replaced by a preview of the word, shown in a black font. After a delay of 13, 160, or 307 ms, the preview word turned into the target color, indicating the color of the patch the participant had to make an eye movement to. Once the recorded eye gaze was within the target patch, a sound was played and the next trial was initiated after a short blank.

3.1.3. Design

Each SOA (13, 160, and 307 ms) was presented 72 times. In half of the trials, the direction indicated by the word name was congruent with the direction indicated by the color of the word, whereas in the other half of the trials word meaning and color direction were incongruent. On incongruent trials, the cued direction was distributed equally among the three directions not indicated by the target color. As in Experiment 1, the target word was the Dutch word for one of the cardinal directions (left, right, up, down). In addition, 36 neutral trials were included, in which the centrally presented letter string consisted of four times the letter 'X'. These were presented in four different colors (corresponding to the patches) and with three different SOAs (just like the congruent and incongruent target words). As in Experiment 1, all trials were presented in one block. After each 60 trials, participants were presented with a screen indicating their progress within the block and the request to press a key on the computer keyboard to continue the experiment. For each participant, the order of the trials was randomized.

3.1.4. Data filtering

The task of Experiment 2 proved to be more difficult than that of Experiment 1. Data of one participant had to be removed for having an error rate higher than the set threshold of 30%. After removal of the data of this subject, it was found that participants made an incorrect initial saccadic response at 17.5% of the trials, which included saccades that did not land inside the target patch (15.9%), responses that were too fast or too slow (4.1%), blinks during saccades (1.2%) and turn-around saccades (0.8%; categories not mutually exclusive). These trials were excluded from the response times and saccade curvature analysis.

3.2. Results

3.2.1. Response times

Fig. 5a plots the average saccadic latency from the onset of the colored word until the onset of the saccade to the target patch across different SOAs and for congruent, neutral ('XXXX'), and incongruent direction words. Increases in the SOA led to faster response times. As in Experiment 1, faster responses were found for congruent direction words than for neutral or incongruent words. The statistical significance of these differences was tested using a repeated measures ANOVA, with two factors: SOA (three levels) and congruency (three levels). Significant main effects were found for the SOA ($F(2,28) = 41.19, p < 0.001$) and congruency ($F(2,28) = 25.09, p < 0.001$). These factors did not interact significantly ($F(4,56) = 1.14, p = 0.35$). Posthoc two by three factor repeated measures ANOVAs comparing each of the congruency conditions across SOAs showed significant differences between the congruent and the neutral conditions ($F(1,14) = 27.51, p < 0.001$, in the presence of a main effect of SOA, $F(2,28) = 32.11, p < 0.001$, and the absence of an interaction with SOA, $F(2,28) = 1.65, p = 0.21$), but not between the neutral and incongruent condition ($F(1,14) = 1.26, p = 0.28$; in the presence of a main effect of SOA, $F(2,28) = 26.51, p < 0.001$ and the absence of an interaction with SOA, $F(2,28) = 0.59, p = 0.56$).

3.2.2. Saccade direction errors

The number of saccade direction errors, defined as trials with a first large saccade (more than 2° in amplitude) in any direction other than the saccade target, is plotted in Fig. 5b for the different SOAs and congruency conditions. More saccade direction errors are found for the longer SOA and the incongruent condition. A three by three two-factor repeated measures ANOVA (testing the effects of congruency and SOA) revealed a significant interaction between cue-target congruency and SOA ($F(4,56) = 6.42, p < 0.001$). By testing the effects of congruency within each SOA, it was found that congruency

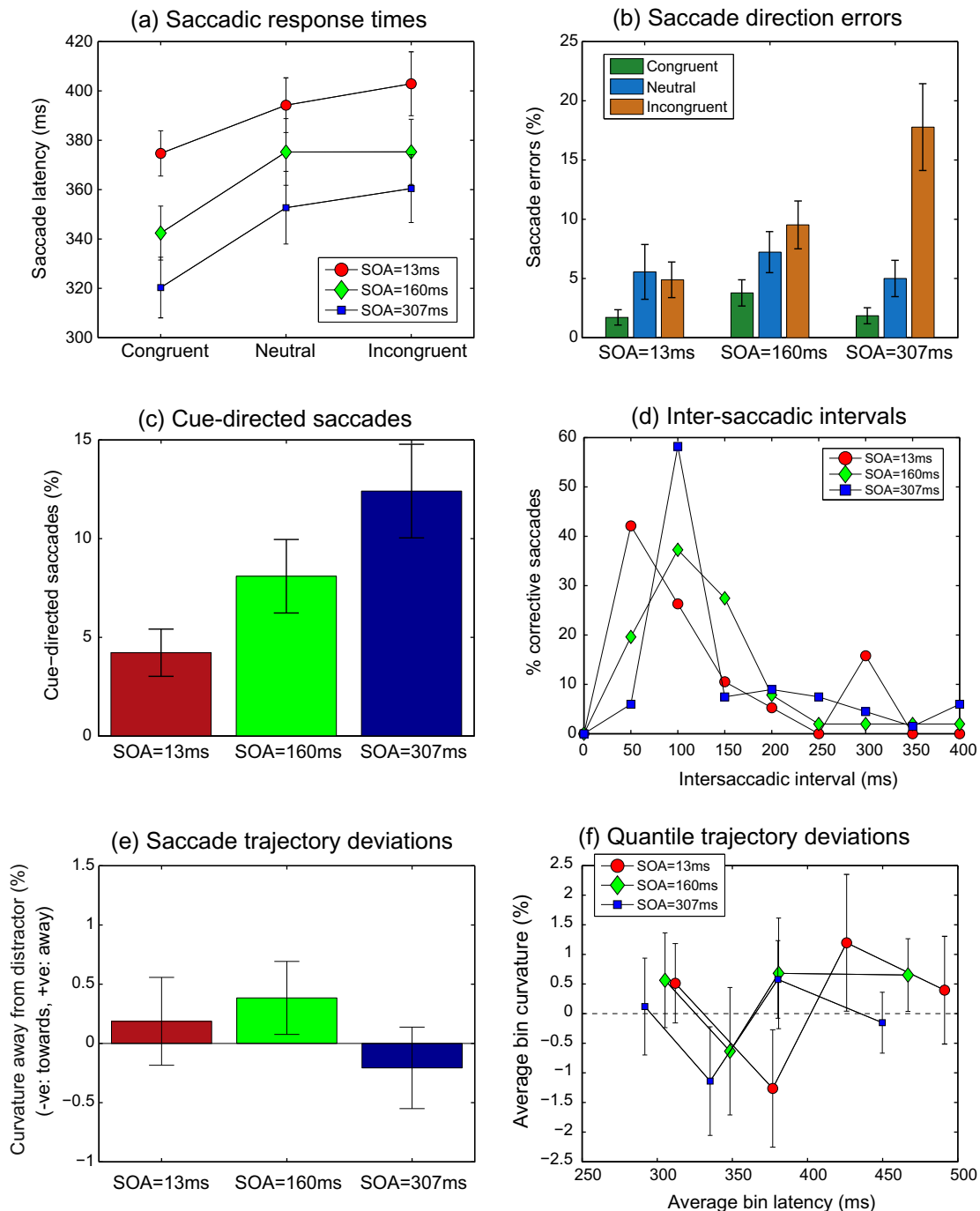


Fig. 5. Results of Experiment 2. (a) Saccadic latencies, defined as the time from the onset of the target color at fixation to the onset of a correct first saccade towards the target patch, showing shorter latencies for the longer SOA. (b) Saccade direction errors, defined as the percentage of trials with an incorrect initial saccade with an amplitude of at least 2°, showing more errors for the long SOA. (c) Percentage of trials in which the first saccade was directed towards the cued location, showing slightly faster corrections for the shorter SOA. (d) Intersaccadic intervals for error correcting saccades after an initial incorrect saccade towards the cued location, showing that the percentage of error correcting saccades depended on the SOA. (e) Saccade trajectory deviations away from the cued direction on trials in which the cue direction was orthogonal to the target direction, as a percentage of the amplitude of the saccade and relative to the neutral cue condition ('XXXX') for the corresponding SOA and target direction, showing no significant saccade trajectory deviations for the SOAs tested. (f) Saccade trajectory deviations as a function of saccadic latency, showing that the absence of deviations away for each of the SOAs was not due to pooling deviations towards or away across different latency bins. In each of the plots, error bars denote the standard error of the mean across the 15 participants in the analysis.

696 affected the saccade error rates only significantly at the longest
 697 SOAs (SOA = 13 ms: $F(2,28) = 2.60$, $p = 0.092$; SOA = 160 ms:
 698 $F(2,28) = 0.45$, $p = 0.64$; SOA = 307 ms: $F(2,28) = 8.29$, $p = 0.0010$).
 699 Testing the effects of SOA within congruent ($F(2,28) = 2.09$,
 700 $p = 0.14$), neutral ($F(2,28) = 5.83$, $p = 0.0076$) and incongruent trials
 701 ($F(2,28) = 16.3$, $p < 0.001$) showed significant differences across
 702 SOAs for neutral and incongruent trials.

Most of the saccade direction errors in the incongruent condi-
 tion were in the direction of the cue, as shown by Fig. 5c. As
 for the saccade direction errors in general, the percentage of cue direc-
 ted error saccades depended on the SOA ($F(2,28) = 7.62$, $p = 0.002$).
 Posthoc comparisons, showing significant differences between the
 SOA = 13 ms and the SOA = 370 ms conditions ($t(14) = 3.15$,
 $p = 0.007$) and the SOA = 160 ms and SOA = 370 ms ($t(14) = 2.93$,

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$p = 0.011$) conditions, but not between the $SOA = 13\text{ ms}$ and $SOA = 160\text{ ms}$ ($t(14) = 1.87, p = 0.083$), demonstrating that the effect of SOA was mainly due to larger number of errors for the longest SOA.

3.2.3. Intersaccadic intervals

Distributions of intersaccadic intervals, defined as the time between the end of the erroneous saccade towards the cue and the start of the correcting saccade towards the target, are shown in Fig. 5d. Visual inspection of the distributions across SOAs suggests that the distribution of intersaccadic intervals shifts towards larger values for longer SOAs. The $SOA = 13\text{ ms}$ curve peaks in the 25–75 ms time-bin, but the $SOA = 160\text{ ms}$ and the $SOA = 307\text{ ms}$ distribution peak in the 75–125 ms time-bin. Interestingly, in comparison with Experiment 1, an earlier peak is found for the 13 ms SOA (compared to the 0 ms SOA of Experiment 1), while the peaks for the $SOA = 160\text{ ms}$ and $SOA = 307\text{ ms}$ are in the same time bin as before. One-sample Kolmogorov–Smirnov tests demonstrate significant differences between the $SOA = 13\text{ ms}$ and the $SOA = 160\text{ ms}$ distribution ($k = 0.58, p = 0.0012$) and between the $SOA = 13\text{ ms}$ and $SOA = 307\text{ ms}$ distribution ($k = 0.43, p = 0.032$), but not between the $SOA = 160\text{ ms}$ and $SOA = 307\text{ ms}$ distributions ($k = 0.39, p = 0.065$).

3.2.4. Saccade trajectory deviations

Saccade trajectory deviations away from the cued location (on incongruent trials with the cued direction orthogonal to the required saccade direction, relative to the neutral condition ‘XXXX’ for the corresponding target location and SOA) are shown in Fig. 5e. A repeated measures ANOVA revealed no difference between the three different SOAs ($F(2,28) = 0.77, p = 0.47$). Saccade trajectory deviations at each of the different SOAs were not significantly different from zero ($SOA = 13\text{ ms}: t(14) = 0.50, p = 0.62$; $SOA = 160\text{ ms}: t(14) = 1.25, p = 0.23$; $SOA = 307\text{ ms}: t(14) = 0.60, p = 0.56$). Fig. 5f plots trajectory deviations depending on the time to initiate the eye movement (latency) for each quartile (‘bin’) across participants against the average trajectory deviation. The time-dependent trajectory deviations do not show a clear downward or upward trend and in none of the bins for either of the SOAs, the average deviation differed significantly from zero (all p -values larger than 0.24).

3.2.5. Discussion

Experiment 2 investigated whether allowing for longer processing of the word name increased its influence on the trajectories of a saccade towards a target position. While responses became faster, but also less accurate with increasing SOAs, saccade trajectory deviations remained absent for the three SOAs tested, failing to provide support for the idea that the lack of curvature for words in Experiment 1 was due to insufficient processing time.

The comparison of response times across the different SOAs showed an additive effect of the SOA. Response times were generally faster with longer SOAs, but the difference between congruent, neutral and incongruent target–cue conditions was unaffected. These additive effects of the SOAs are likely to be the consequence of the appearance of the word acting as a general warning signal for the upcoming target. This effect could be similar to one of the effects of the offset of the fixation symbol, as in the gap effect (Saslow, 1967).

The largest number of errors were found for the long stimulus onset asynchrony. Because responses were fastest in this condition as well, these larger error rates suggest a speed–accuracy trade-off. A possible cause of the larger percentage of errors and faster response times could be the mixing of the different SOAs within a block. In an earlier study, using a peripheral target and a gaze cues, SOAs were tested across (Experiments 1 and 2 of Hermens &

Walker (2010)) and within blocks (Experiment 3 of Hermens & Walker (2010)). For the longest SOA (300 ms) error rates were smaller when tested in a separate block compared to when the SOA was intermixed with shorter SOAs (13 ms and 150 ms). Possibly participants adopt a strategy in which a similar response threshold is used across trials (with different SOAs and congruency conditions). Interestingly, faster correct response times were obtained for the longer SOA both for congruent and incongruent trials. This suggests that the findings of Experiment 2 were not due to the direction words generating more saccade related activity in the oculomotor map at longer SOAs. If this would have been the case, an interaction between congruency and SOA would have been expected (extra fast response times for the congruent long SOA condition, and extra slow response times for the incongruent long SOA condition, which were not found).

As for Experiment 1, incorrect initial saccades in the direction indicated by the word name were quickly corrected. Fastest corrections were found for the shortest SOA, but even for the longer SOAs the correction times were sufficiently short to suggest residual activity at the target location in the oculomotor map during the preparation and onset of the incorrect saccades.

The SOA manipulation did not influence saccade trajectory deviations, which remained near zero for all three SOAs, even when taking into account saccade latencies. This finding is inconsistent with an interpretation in which more time is required to process the meaning of the word, as was found for gaze and arrow cues in an earlier study (Hermens & Walker, 2010). It also argues against the automatic generation of an oculomotor response in the direction indicated by the name of the word.

4. General discussion

In two experiments, the oculomotor effects of directional words were investigated within a ‘saccadic Stroop’ paradigm. It was hypothesized that if directional words automatically induce the preparation of an oculomotor response in the direction indicated by the word, faster response times for congruent word and saccade target directions should be found, more directional errors should be made when these directions are incongruent, directional errors should be followed by fast corrective eye movements, and eye movements trajectories should deviate away from the direction indicated by the word. All these effects were found, except for the modulation of saccade trajectories (which were unaffected by the direction indicated by the word). The effects of direction words were compared to the influence of two more types of cues: peripheral onsets and centrally presented arrow cues. In contrast to the direction words, peripheral onsets produced reliable trajectory deviations away from the cued location, in addition to the effects on response times and error rates also observed with direction words. The pattern of results for arrow cues resembled that found for direction words, demonstrating non-significant saccade curvature effects. Increasing the stimulus onset asynchrony between direction words and the indicator of the saccade target, which allowed for more time to process the direction words, did not influence the trajectory deviation. The results for sudden onsets are consistent with an interpretation in which cues or distractors induce an automatic activation and successive inhibition of neurons in an oculomotor map. For direction words and arrow cues the interpretation of the results is less clear. Whereas the effects of conflicting information on response times, direction errors and intersaccadic intervals suggest that the cues lead to the automatic preparation of an oculomotor in the indicated direction, the absence of an effect on saccade curvature suggests that the interference effects observed for these measures are not originating from interactions in the oculomotor motor map.

Whereas peripheral onsets, in agreement with earlier findings (Doyle & Walker, 2001; McSorley, Haggard, & Walker, 2004, 2005, 2006, 2009; Van Zoest, Van der Stigchel, & Barton 2008; Walker, McSorley, & Haggard, 2006), resulted in a deviation of saccade trajectories away from the distractor, direction words and arrows did not influence saccade trajectories. Our findings for arrow cues are in contrast to earlier studies, which often found saccade trajectory deviations away from the direction indicated by the arrow cue (Hermens, Sumner, & Walker, 2010; Hermens & Walker, 2010; Sheliga, Riggio, & Rizzolatti, 1994; Sheliga et al., 1995; Van der Stigchel, Meeter, & Theeuwes, 2007). For example, Sheliga and colleagues (Sheliga, Riggio, & Rizzolatti, 1994; Sheliga et al., 1995) found that saccade trajectories deviated away from a peripherally presented arrow indicating the required saccade direction. Van der Stigchel, Meeter, and Theeuwes (2007) found that deviations away from the direction indicated by a centrally presented arrow can also be obtained if the arrow merely indicated the likely direction of the target, rather than providing a completely reliable cue. Hermens, Sumner, and Walker (2010) showed that deviations away from the direction of a centrally presented arrow cue can also be obtained when the arrow is presented only for a brief time and is then masked, and as a consequence, is not always consciously perceived. A direct comparison between the effects of centrally presented arrow and gaze stimuli on the one hand, and peripheral distractors on the other hand, however, demonstrated that, although centrally presented and to be ignored arrows could result in saccade trajectory deviations, the effects of centrally presented (gaze and arrow) cues were much weaker than those of peripheral distractors (Hermens & Walker, 2010). The influence of direction words on saccade trajectory deviations has not been reported before. The influence of the semantic contents of words on saccade trajectories, however, has been studied (Weaver, Lauwereyns, & Theeuwes, 2011). In their study Weaver, Lauwereyns, and Theeuwes (2011) compared the influence of peripherally presented taboo and neutral cue words on the trajectories of target directed eye movements. Eye movement trajectories were found to deviate away more strongly from taboo words than control words, suggesting an effect of word meaning on eye movements. It is not directly clear why previous studies have found an effect of words and arrows on saccade trajectory deviations, while in the present study, we did not find such an effect. One possible mechanism involved in an eye movement task involving distractor stimuli, could be the enhancement of activity in the oculomotor map at the different possible target locations before the onset of the stimulus sequence, and the suppression of possible distractor locations (Walker, McSorley, & Haggard, 2006). Such an early activation and inhibition mechanism could have a stronger influence when only two possible target locations are used (as in previous studies), than when there are four possible target locations (as in the present study), because attention needs to be distributed across a larger number of locations. More importantly, previous studies have often used distractor locations that were never target locations, and therefore in these earlier studies target locations could be enhanced before the start of the trial while suppressing distractor locations. Such an enhancement of activity would not benefit goal directed saccades in the present task, because every possible target location was also a possible distractor location.

In the present study a larger effect of arrows than of peripheral onsets on response times was found, whereas often peripheral cues lead to stronger cueing effects than arrows (e.g., Müller & Rabbitt, 1989). Possibly the onsets in the present study had a relatively modest effect because the new object (a black ring) was surrounding an object already in the scene (a colored patch). It could therefore be that for the oculomotor system the black ring acted as a change to an existing object (the colored patch) rather than a new object, which could explain why its effects were relatively weak (Ludwig, Ranson, & Gilchrist, 2008; Ross & Ross, 1980).

Our results for arrows and direction words are unexpected in the context of neurophysiological findings on oculomotor activity related to distractor stimuli (Aizawa & Wurtz, 1998; McPeck, 2006; McPeck & Keller, 2001, 2002, 2004; McPeck, Han, & Keller, 2003; Murthy et al., 2007; Port & Wurtz, 2003). Following these studies, it was expected that distractors that would result in fast corrective saccades on error trials would also result in curvature away from the direction indicated by the cue. Whereas arrow cues and direction words led to fast corrective saccades, saccade trajectories were not found to be influenced by these cues. These results could have three possible interpretations. First, it could be the case that the direction indicated by centrally presented cues like direction words and arrows results in only very weak or no activity in neurons in the oculomotor map encoding *where* to make an eye movement to. Instead, they may only influence a system deciding *when* to initiate an eye movement (Findlay & Walker, 1999), or their influence is on a decision process located elsewhere in the system. In this latter case, only after a decision has been made for a certain saccade target, neurons in the oculomotor map are activated. Alternatively, strong activation, but only weak suppression of neural activity at the cued location might have occurred, which led to fast corrective saccades (activation of neurons), but not to influences on saccade trajectory deviations (insufficient suppression of neural activity), possibly as a consequence of target locations also being possible distractor locations. In a second interpretation, centrally presented symbolic cues may automatically activate neurons in the oculomotor map, but this activation does not automatically influence saccade trajectories. This interpretation, however, would deviate from a substantial body of neurophysiological findings (Aizawa & Wurtz, 1998; McPeck, 2006; McPeck & Keller, 2002; McPeck, Han, & Keller, 2003; Port & Wurtz, 2003) showing that saccade curvature is often associated with increases or reductions of activity in the oculomotor map at the location of the distractor. In a third interpretation centrally presented cues result in the automatic activation of neurons in the oculomotor map at the distractor site, but the timing of the effects for corrective saccades and saccade trajectory deviations differs. Such an interpretation would be in agreement with neurophysiological findings showing that sequential, rather than simultaneous target and distractor activation, leads to curved saccade trajectories (Port & Wurtz, 2003). This would suggest that at some stimulus onset asynchrony, curved saccade trajectories should be found for central cues, although it is not clear at which SOA this should be. In an earlier study, deviations away from arrows and gaze cues were found at a 300 ms SOA (Hermens & Walker, 2010), but this interval did not result in significant trajectory deviations in the present study (Experiment 2).

One possible way to disentangle the above possibilities could be to generate predictions about eye movements using a computational model of saccade target selection (e.g., Bompas & Sumner, 2011; Trappenberg et al., 2001; Ludwig, Mildinhall, & Gilchrist, 2007; Meeter, Stigchel, & Van der Theeuwes, 2010). The use of such a model would allow for an explicit test of the consequences of for example, the choice of using a 50% cue validity, and the use of different stimulus onset asynchronies between target and cue. Furthermore, it would simultaneously generate predictions for each of the measures used, including response times, error rates and trajectory deviations, as well as their distributions. The problem at this stage, however, is that there is no existing model that explains a large range of reaction time findings, as well as saccade trajectory results (for some datasets that appear to pose problems to existing models in this respect, see, Godijn & Theeuwes, 2004; Hermens, Sumner, & Walker, 2010). Moreover, there does not appear to be a consensus about the principles that the oculomotor system uses to select the direction and amplitude of the upcoming saccade (e.g., whether the saccade is directed towards the peak of activity in the

oculomotor map or the mean vector of activation, [Bompas & Sumner, 2011](#); [Findlay & Walker, 1999](#); [Ludwig, Mildinhal, & Gilchrist, 2007](#); [Meeter, Stigchel, & Van der Theeuwes, 2010](#)). Until these issues are resolved, there is no certain way of saying whether our present data can or cannot be explained by a single mechanism. However, as for earlier datasets ([Godijn & Theeuwes, 2004](#); [Hermens, Sumner, & Walker, 2010](#)), the present data is suggestive of a more complex mechanism of selecting the target for the upcoming saccade than extracting a location from a single interactive neural map.

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