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Post-saccadic changes disrupt attended pre-saccadic object memory

Anne-Sophie Laurin¹, Maxime Bleau², Jessica Gedjakouchian², Romain Fournet², Laure Pisella³,
Aarlenne Zein Khan²

Affiliations:

¹University of Montreal, Department of Psychology

²University of Montreal, School of Optometry

³ImpAct, INSERM UM1028, CNRS UMR 5292, University Claude Bernard Lyon 1

Corresponding author:

Aarlenne Khan

School of Optometry

University of Montreal

Room 260-25, 3744 rue Jean Brillant

Montreal, QC, CANADA H3T 1P1

Abstract (366 words, is that OK? No words limit?)

Trans-saccadic memory is involved in keeping track of objects' locations and features across saccadic eye movements. Pre-saccadic information is remembered across a saccade and compared with post-saccadic information. Trans-saccadic memory has been shown to have limited resources and attention plays a role in the selection of objects and features for trans-saccadic memory. In support, it has been previously shown that the recognition of distinct post-saccadic objects in the visual scene is impaired when pre-saccadic objects are relevant and thus already encoded in memory (Poth, et al., 2015). Here we investigated the inverse, i.e., how the memory of pre-saccadic objects is affected by various abrupt but irrelevant changes in the post-saccadic visual scene. It is known that attention is directed to the upcoming saccade goal location, prioritizing it for allocation to memory, a phenomenon called pre-saccadic attentional facilitation. We therefore varied the attention to the relevant pre-saccadic object by having participants either make a saccade to it or elsewhere, and observed that pre-saccadic attentional facilitation also affected the saliency of post-saccadic changes, i.e. their ability to disrupt trans-saccadic memory of pre-saccadic object.

Participants were asked to identify a briefly flashed symbol (d, b, p or q, randomly selected, among 2 and 5 distracters), at one of six placeholders (figures "8") arranged in circle around fixation while planning a saccade to one of them. They reported the identity of the flashed symbol after the saccade. We changed the post-saccadic scene in two ways. In experiment one, we removed different parts (entire scene, only the placeholder where the pre-saccadic symbol was presented, or all other placeholders except this one). We observed reduced identification performance when only the saccade-target placeholder disappeared after the saccade. In experiment two, we changed one placeholder location (inward/outward shift or rotation re. saccade vector) after the saccade and observed that identification performance decreased with increased shift/rotation of the saccade-target placeholder.

We conclude that pre-saccadic memory is disrupted by abrupt attention-grabbing post-saccadic changes of visual scene, particularly when these changes involve the object prioritized by being the goal of a saccade. These findings support the notion that limited trans-saccadic memory resources are disrupted when object correspondence at saccadic goal is broken through removal or location change.

Keywords: pre-saccadic attentional facilitation, trans-saccadic memory, eye movements

Introduction

Trans-saccadic memory is involved in keeping track of an object's location and its features across saccadic eye movements (Cavanagh et al., 2010; Mathôt & Theeuwes, 2011; Rolfs, 2015; Rolfs et al., 2011; Poth & Schneider, 2018; Jeyachandra et al., 2018; Prime et al., 2007), allowing an accurate comparison of pre- and post- saccadic information about the object (Ganmor et al., 2015; Hayhoe et al., 1991; Mathôt & Theeuwes, 2011; Vaziri et al., 2006; Wolf & Schütz, 2015).

There is consensus that trans-saccadic memory relies on visual working memory and involves attention (Frost et al., 2019; Prime et al., 2007; Irwin, 1992; Irwin, 1996; Irwin & Andrews, 1996; David & Bays, 2019; Mathot & Theeuwes; Melcher, 2009; Poth, Herwig & Schneider, 2015; Poth & Schneider, 2016, 2018; Stewart & Schutz, 2017; 2018). Researchers have shown similar limited memory capacity for trans-saccadic and visual working memory (Irwin, 1992; Irwin, 1996; Irwin & Andrews, 1996; Prime et al., 2007). Further, it has been proposed that attention may be the mechanism by which an object is allocated to trans-saccadic memory (Mathot & Theeuwes, 2011), supported by the finding that cued objects were better remembered across saccades compared to un-cued objects (Prime et al., 2007; Melcher, 2009). Similarly, removing attention impaired the integration of peripheral and foveal object information across saccades, likely due to a disruption in allocation to trans-saccadic memory (Stewart & Schutz, 2018). A recent study by Poth & Schneider (2018) also showed that attended objects are prioritized for access to memory at the expense of other objects when object correspondence is broken. Specifically, attended pre-saccadic objects impaired recognition of different post-saccadic objects, with the number of pre-saccadic attended objects directly related to the level of post-saccadic recognition impairment. In a previous study (Poth et al., 2015), they suggested that breaking object correspondence between the pre- and post-saccadic objects taxes trans-saccadic memory resources. Besides task-based object relevance, it has been suggested that the saccade goal object also receives an attentional benefit and is therefore prioritized to be stored in trans-saccadic memory (Mathot & Theeuwes, 2011; Rolfs, 2015; Rolfs & Ohl, 2014; Irwin, 1992; Irwin, 1996; Irwin & Andrews, 1996). Indeed, attention is known to be spontaneously allocated toward the object located at the saccadic goal before it is executed, a phenomenon called pre-saccadic facilitation (Deubel, 2008; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Khan et al., 2010, 2015; Kowler et al., 1995; Castet et al., 2006; Deubel &

Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler et al., 1995; Mikula et al., 2018). In summary, both relevant and saccade goal objects are prioritized for allocation into limited trans-saccadic memory resources.

While previous studies have shown that pre-saccadic memorized objects impair recognition of post-saccadic objects(), the inverse remains unknown, that is how attended post-saccadic objects influence the memory of pre-saccadic objects. Besides relevance, attention can also be grabbed by abrupt onsets/offsets, or displacements in the visual scene, typically known as exogenous attention (references). Do such post-saccadic objects' changes impair the memory of pre-saccadic objects? This finding would support the idea of a limited resource trans-saccadic memory with attention influencing both the encoding of information as well as its retention.

We investigated how the memory of relevant pre-saccadic object features was affected by abrupt post-saccadic changes in the visual scene. In experiment one, we removed parts of the visual scene post-saccadically in different ways. In experiment two, we changed one placeholder location post-saccadically in different ways. Participants had to identify and remember a symbol presented pre-saccadically at one of six placeholders arranged circularly around fixation. At the same time, they made a saccade to one of the six placeholders as indicated by a central cue. The attention directed toward the relevant pre-saccadic object was thus varied by having participants either make a saccade to it (valid trials) or make a saccade elsewhere (invalid trials). The attention was also directed post-saccadically toward the saccadic goal location, thereby increasing the saliency of post-saccadic changes breaking object correspondence at this specific location.

Experiment 1

Methods

We tested how changes in the visual scene after the saccade influenced discrimination of the target before the saccade. There were 4 different conditions, 1) baseline condition with no change after the saccade, 2) OneOff condition, in which only one placeholder disappeared, either at the saccade goal location or at a distractor location, 3) AllOff condition, in which all placeholders disappeared after the saccade, 4) OneOn condition in which all but the placeholder at the saccade goal or at a distractor location disappeared.

Participants

Ten participants took part in the experiment (3 male, $M = 22.9$ years, $SD = 6.1$ years). Authors AL, AK and JG were participants in the experiment. All participants had normal or corrected-to-normal vision (glasses, contact lenses). They gave their consent in writing and were reimbursed for their time. The study was approved by the Health Research Ethics Board (CERES) of the University of Montreal, QC, Canada. We calculated a sample size of 8 using G*Power (Faul, Erdfelder, Lang & Buchner, 2007), with an effect size of 0.4, with 1 group and 8 measurements using a repeated-measures within group ANOVA. The effect size was calculated from a previous similar study (Mikula et al., 2018).

Apparatus and Procedure

The experiment took place in a semi-dark room. Participants sat in front of an LCD screen (VIEWPixx, VPixx Technologies, 53x30cm (22.5 inch display size), 1920x1200 pixels, 60 Hz refresh rate, 34 cm eye-screen distance) with their heads stabilized by using head and chin rests. The height of the support and chair were adjusted to center their eyes on the screen. The participants' right eye movements were recorded by the Eyelink-1000-plus recording system (SR Research, Mississauga, ON, Canada) at a frequency of 1000 Hz. Participants responded on a button box (RESPONSEPixx, VPixx Technologies). The eye tracker was calibrated and validate using a 9-point calibration sequence at the beginning of each block of 96 trials as described below.

Each condition was a variant of a dual saccade execution task and a four-alternative forced choice discrimination task (Khan et al., 2010, 2015; Mikula et al., 2018). This paradigm has been modified from previous studies (e.g. Schneider & Deubel, 1995) and has been robustly shown to provide a measure of the allocation (quality and location) of pre-saccadic attention.

In the baseline condition (Figure 1A), a red fixation dot (0.5° diameter) first appeared at the center of a black screen, surrounded by six red figure 8 placeholders (dimensions of $1.2^\circ \times 0.7^\circ$, shown in white in figure 1) arranged in a circular layout (5.8° of eccentricity). After 1000 ms, the fixation dot was replaced by an arrow ($1.0^\circ \times 0.7^\circ$) pointing toward one of the placeholders at random. The participants were asked to make a saccade as quickly as possible toward the designated placeholder. 66.67 ms after the arrow's apparition, each placeholder's identity changed (for a short period of 66.67 ms). One of the figure 8's changed to one of 4 symbols (either d, b, p or q, randomly selected), named the discrimination symbol (DS). The five remaining figures changed into non-pertinent

symbols (either 2 or 5). In 50% of the trials, the DS appeared at the placeholder designated by the arrow (valid position). In the other 50%, the DS appeared randomly among the five other placeholder locations (invalid position). The DS and non-pertinent symbols remained on for 66.67ms before changing back to their previous identities, figure 8s. After making their saccade, participants were asked to identify the DS, regardless of its position, with a button box (forced choice). On the box, four buttons were identified as the possible answers. Each button was marked with a specific symbol (d, b, p or q). The mapping of symbol to button was the same for every participant and every block. Participants had to respond by choosing one of the 4 buttons for every trial (forced choice); they were asked to respond even if they weren't able to identify the DS and were asked to guess in that case. Pressing one of the buttons triggered the next trial. There was no time limit to answer and no feedback on participants' performance was provided. A block of trials consisted of 96 trials.

Figure 1.

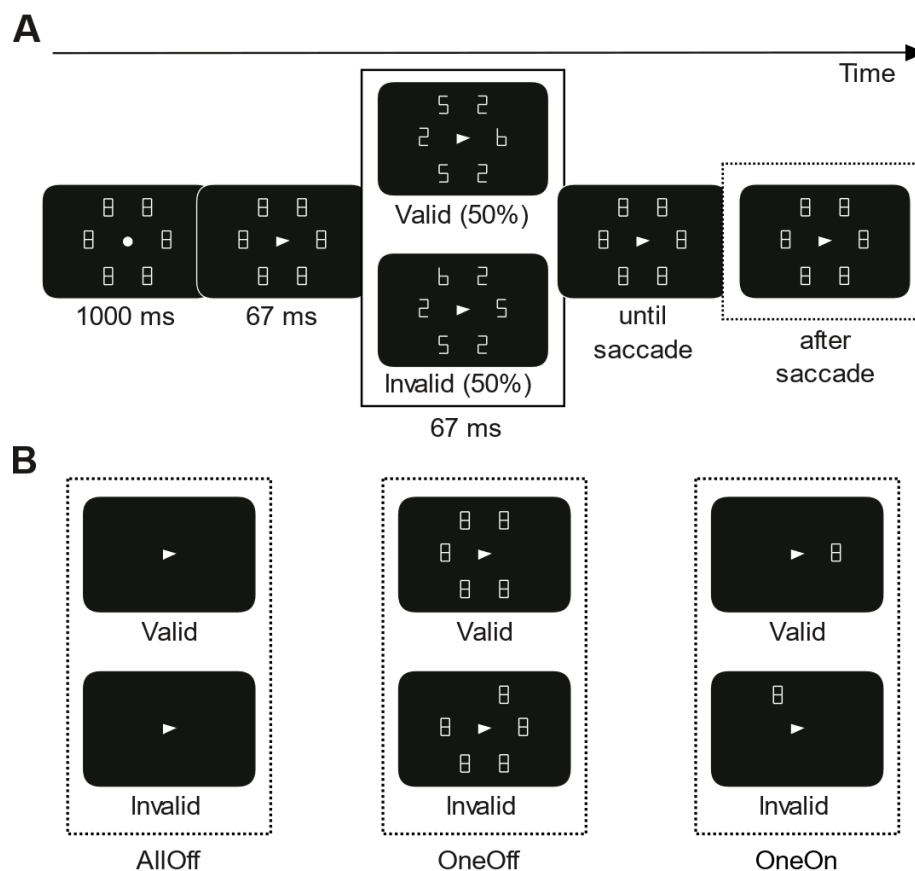


Figure 1. *Experimental tasks*. (A) Baseline dual-task paradigm. Participants fixated a central dot surrounded by six placeholders. The fixation dot was changed into an arrow for 67 milliseconds and participants made a saccade to the placeholder designated by the arrow. Then, the DS appeared either at the saccadic goal (valid) or at another placeholder (invalid). Remaining placeholders changed into other symbols. 67 milliseconds after, all placeholders changed back to their previous identities and remained until the end of the trial. (B) AllOff condition. After the saccade, all placeholders disappeared until the end of the trial. (C) OneOff condition. After the saccade, only the DS disappeared while other placeholders remained until the end of the trial. (D) OneOn condition. After the saccade, only the DS remained while other placeholders disappeared until the end of the trial.

Apart from the baseline condition, other conditions comprised post-saccadic changes triggered when the participant's eye was detected outside a zone of 3.7° of diameter around the fixation point (1.85° away from the fixation in any direction), plus an additional 50 ms to account for saccade duration. Thus, changes occurred after the eye landed.

In the OneOff condition, the placeholder where the DS was presented disappeared (for both valid and invalid positions) until the end of the trial (Figure 1C). All other symbols remained visible. Note that in the valid trials, this is the saccade goal location. In invalid trials, this is a distractor placeholder location.

In the AllOff condition, all placeholders disappeared until the end of the trial. Only the arrow remained (Figure 1B).

In the OneOn condition, only the DS placeholder remained visible (in both valid and invalid positions), whereas all other placeholders disappeared until the end of the trial (Figure 1D).

Before they could begin the experiment, participants performed at least three practice blocks (up to a maximum of nine) in the baseline condition to ensure that they could perform the task correctly. When they obtained at least 60% correct answers in the valid DS position, they could begin the experiment. They then performed one block each of the different conditions in random order.

Data Analysis

We collected 3,840 trials in total, with 960 trials for each condition. Saccade onsets and offsets were automatically detected using an algorithm with a velocity criterion to $30^\circ/\text{s}$, above which the saccade was detected. They were subsequently verified visually.

We normalized eye positions in each block by adjusting them by how much the mean saccade start position deviated from fixation point. This was to account for any errors in the calibration process;

we observed that while the pattern and distributions of eye positions were precise, there sometimes tended to be an overall shift in positions, e.g. within a block, starting eye positions (when the participant were looking at the fixation dot) were shifted up relative to the centre of the screen where the fixation dot was located. We therefore shifted all positions across the block by the mean shift at the start position.

Trials were removed from analysis according to the following criteria: 1) the camera lost the position of the eye; 2) the participant blinked between the appearance of the arrow and the disappearance of the DS or 3) the participant made more than one saccade to the target, 4) the participant responded 10s after trial start or longer, 5) the participant's saccade latencies in response to the arrow onset were shorter than 100ms and longer than 600ms, 6) trials in which the start position (when participants were fixating at centre) was more than 1.5° away from the fixation dot, 7) trials during which saccade offset occurred before DS offset, ensuring that the DS was never viewed foveally, 6) saccade amplitude was less than 3.8° or more than 7.8° (saccade target being at 5.8°) and 7) saccade direction was outside 10° of the center of the saccade target placeholder. The latter two was due to previous studies associating discrimination performance to saccade landing positions to some degree (Mikula et al., 2018; Wick et al., 2016). In total, there remained 3,031 (78.9%) trials. Details about the number of excluded trials can be found in supplemental table 1.

Discrimination performance was calculated with correct response rates (the DS was correctly identified) and the tests were separated into two categories for each condition: (i) valid position – the DS appeared at the saccade goal location designated by the arrow, and (ii) invalid position - the DS appeared elsewhere.

We performed repeated-measures ANOVAs and Holm-Bonferroni family-wise corrected paired t-tests to compare performance. ANOVA degrees of freedom reported were Greenhouse-Geiser corrected if Mauchly's test of sphericity was significant. We estimated the extent to which performance differences could be explained by our manipulations with effect sizes, reporting partial eta squared (η^2_p) s for ANOVAs (Lakens, 2013). We also reported Bayes factors for all ANOVAs (BF_M) and t-tests (BF_{10}) performed.

Results

Baseline performance

We confirmed that pre-saccadic attentional facilitation occurred by analyzing participants' performance in the baseline condition, where the visual scene did not change after the saccade. Figure 2 (leftmost data) depicts mean performance for the valid and invalid positions for the baseline condition. Individual mean performance is also shown (filled dots). Performance for the valid position was significantly higher than the invalid positions (one-way repeated measures ANOVA, $F(1,9) = 144$, $p < .001$, $\eta^2_p = 0.941$, $BF > 100$). In addition, while performance was significantly different from chance (25%) in the valid position (76.6% correct, $t(9) = 19.5$, $p < .001$), it was not for the invalid positions (31.3%, $t(9) = 2.1$, $p = .064$). These findings are very similar to our and others' findings demonstrating that attention is shifted to the goal of the saccade and not elsewhere when planning a saccade (Castet et al., 2006; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Khan et al., 2015; Mikula et al., 2018).

Figure 2.

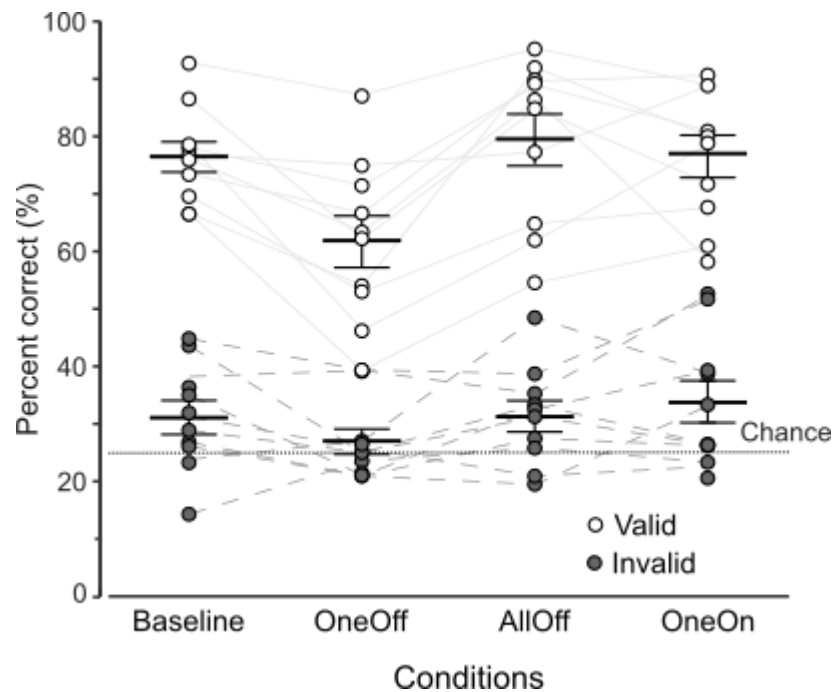


Figure 2. *Pre-saccadic discrimination performance across conditions in valid and invalid positions.* Performance for individual participants is shown as white circles connected by light gray solid lines for the valid position and as grey circles connected by gray dashed lines for the invalid position. Mean correct discrimination rate in percentage (%) is shown by the wider black horizontal bars. Lighter grey bars represent standard error of the mean (s.e.m.). Chance is depicted by the dotted line at 25% of correct discrimination.

Experimental conditions

Figure 2 depicts performance for all 4 conditions (Baseline, OneOff, AllOff, OneOn) in valid and invalid positions. A two-way repeated measures ANOVA revealed significant main effects for both Condition ($F(3,27)=7.4$, $p<.001$, $\eta^2_p = 0.451$, $BF_M>100$) and Position ($F(1,9)=165$, $p<.001$, $\eta^2_p = 0.948$, $BF_M=4.85$). There was also a significant interaction effect ($F(3,27)=4.8$, $p=.008$, $\eta^2_p = 0.347$, $BF_M=3.18$). Comparing across the valid position, post-hoc Bonferroni-Holm corrected paired t-tests confirmed significantly lower performance for the OneOff condition ($M= 61.9\%$, $SD = 14.2\%$) compared to all other conditions (baseline - $M =76.6\%$, $SD = 8.3\%$, $t(9)=4.5$, $p=.001$, $BF_{10}=27$, AllOff - $M= 79.6\%$, $SD= 14.2$, $t(9) = 5.7$, $p<.001$, $BF_{10}>100$, OneOn - $M= 76.7\%$, $SD= 11.6\%$, $t(9) = 4.1$, $p=.003$, $BF_{10}=23$). Performance for the AllOff and the OneOn condition were not different from the baseline condition ($p>0.05$, $BF_{10}=0.4$ and $BF_{10}=0.3$ respectively). Comparing across the invalid condition, post-hoc comparisons revealed no differences between any of the conditions ($p>0.05$, all $BF_{10}<1$, except for between the AllOff and the OneOn condition, where $BF_{10}=5.5$).

Timing of placeholder change

To test whether differences in timing of the placeholder change could explain the results, we calculated the time between the change in the placeholders and the time of saccade offset (completion of the saccade). As mentioned earlier, post-saccadic changes were programmed to occur when the eyes moved more than 1.85° in any direction outside of fixation plus 50 ms. Saccade durations were on average 40.3 ms (SD across participants = 4.58 ms, average within participant $SD = 5.37$ ms). The mean placeholder change was 39.7ms (SD across participants = 4.58 ms, average within participant $SD = 5.37$ ms) after the saccade was completed; a repeated-measures ANOVA with condition and position as factors revealed no main effect for Condition (OneOff, AllOff and OneOn) or Position nor a significant interaction effect (all $p>0.05$, $BF_M<1.2$). Thus, we conclude that differences across conditions in the timing of the placeholder change cannot explain the results.

Saccade latencies

The mean saccade latencies were similar across the 4 conditions (Baseline – $M= 243$ ms, SD across participants = 22ms, average within participant $SD = 27$ ms; OneOff – $M= 239$ ms, SD across participants = 19ms, average within participant $SD = 25$ ms; AllOff – $M= 242$ ms, SD across participants = 27ms, average within participant $SD = 30$ ms; OneOn – $M= 249$ ms, SD across participants = 21ms, average within participant $SD = 28$ ms). We confirmed that there were no

differences in saccade latencies across condition or position (valid vs invalid) nor any interaction effects (all $p > 0.05$, $BF_M < 0.5$).

Experiment 1 summary

First in the baseline condition, we showed that performance was better when the DS was flashed at the saccade goal location than at another placeholder location. This confirms that attention was shifted to the goal of the saccade pre-saccadically which lead to a better trans-saccadic encoding and/or retention of the DS when it also represents the saccade goal (valid position).

When the DS was presented at invalid position, where identification performance at baseline was at floor (chance level), the decrease in performance when only the DS location disappeared (invalid OneOff) did not reach significance, performance was also unaffected when all but the DS location disappeared (invalid OneOn) and when all the placeholders disappeared (AllOff). For the valid position (when the DS also represented the saccade goal location), we observed a decrease in performance when there was a post-saccadic change only at the saccade goal location (valid OneOff condition), there was no change from baseline when all the placeholders disappeared (AllOff) and when all but the saccade goal location placeholder disappeared (valid OneOn).

Considering these results, we speculate that performance decreased when there was a change in the visual scene breaking object correspondence only the saccade goal location. In contrast, removing all the placeholders in the AllOff condition did not affect performance, thus the memory of the pre-saccadic object was likely not disrupted by a global change of the post-saccadic visual scene. Also, abrupt offsets of the visual scene not concerning the saccade goal, such as in the OneOn condition, did not affect performance, suggesting that post-saccadic changes occurring outside the focus of attention did not seem to disrupt memory of the pre-saccadic object. Instead memory disruption appeared to depend on a specific removal involving the most attended object between the pre- and post-saccadic views relative to a constant scene.

In the next experiment, we shifted the target instead of causing it to disappear, thus changing location in different ways rather than removing the object. Along the same logic as experiment 1, a shifted rather than removed placeholder at the saccade goal location relative to an otherwise

constant visual scene should also impact performance, because it also induces a mismatch between the pre- and post-saccadic representations of the most-attended object only.

Experiment 2

Methods

Here, we tested how changing the location of the placeholder after the saccade influenced pre-saccadic discrimination performance. We tested 2 conditions, 1) the saccade goal or distractor placeholder shifted inwards or outwards relative to fixation and 2) the saccade goal or distractor placeholder rotated (Figure 3A).

Participants

Nineteen participants (7 male, $M = 23.3$ years, $SD = 5$ years) were recruited for the shift condition. Twelve participants took part in the rotate condition (4 male, $M = 24.5$ years, $SD = 5.8$ years), eleven of which were the same as in the shift condition. All participants, apart from authors AL, JG and AK, who participated in both experiments, were naïve to the goals of the experiments. All had normal or corrected to normal vision. They gave their written consent and were reimbursed for their participation. The experiment was approved by the Health Research Ethics Board (CERES) of the University of Montreal, QC, Canada. We calculated a sample size of 11 using G*Power (Faul, Erdfelder, Lang & Buchner, 2007), with an effect size of 0.4, with one group and 7 measurements using a repeated-measures within group ANOVA. The effect size was calculated from a previous similar study (Mikula et al., 2018).

Apparatus and Procedure

We used the same setup as experiment 1. For all conditions, 50% of the trials, the DS was located at the saccadic target (valid position) and for the remaining 50%, it was located elsewhere (invalid position). Both the shift and rotate conditions comprised post-saccadic changes, triggered when the participant's eye was detected outside a zone of 2.9° of diameter around the fixation point, with no additional delays (Figure 3A). Thus, changes occurred during the saccade before the eye landed.

Figure 3.

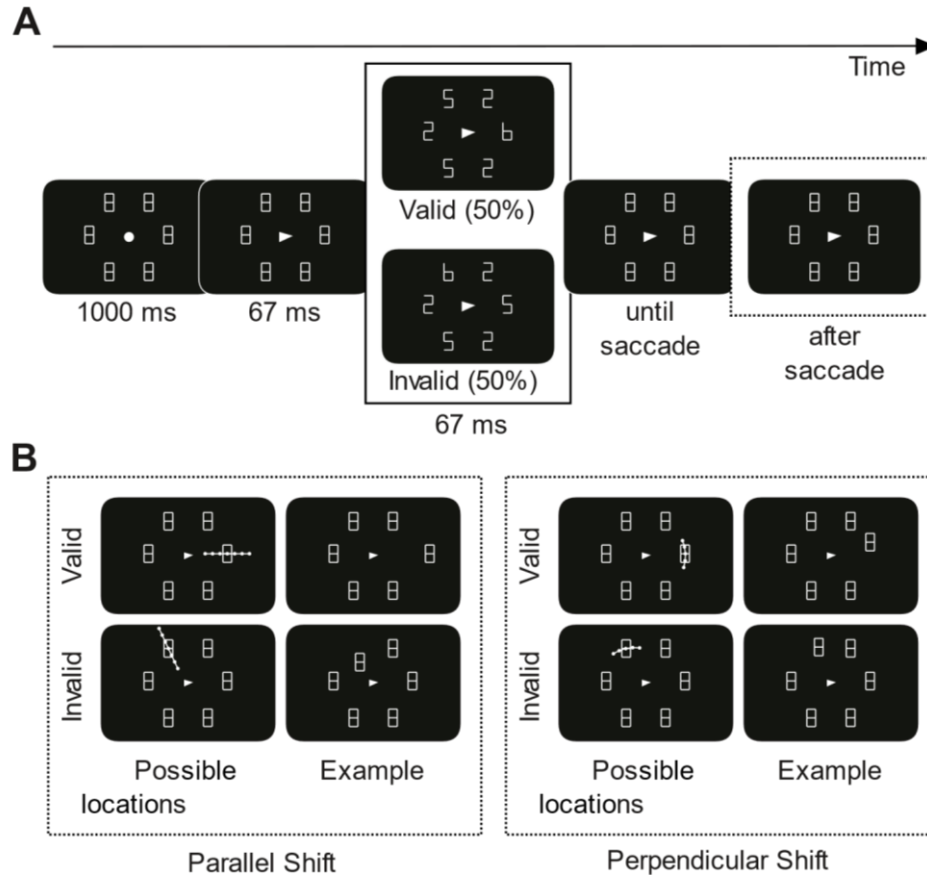


Figure 3. *Experimental dual-task paradigm.* (A) Baseline condition. Participants fixated a central dot surrounded by six placeholders. The dot was changed into an arrow for 67 milliseconds and participants made a saccade to the placeholder designated by the arrow. Then, the DS appeared either at the saccadic goal (valid) or at another placeholder (invalid). Other placeholders changed into other symbols. 67 milliseconds after, all placeholders changed back to their previous identities and remained until the end of the trial. (B) Condition of location shift along the visual vector direction (Parallel Shift) is displayed on the left panel. After the saccade, the DS was shifted at either 0° (no shift), 1° , 2° or 3° , either inwards towards fixation or outwards. Rotated shift condition (Perpendicular Shift) is displayed on the right panel. After the saccade, the DS was shifted at either 0° (no shift), 10° or 20° either clockwise or counter-clockwise.

In the parallel shift condition, upon the participants' saccade, the DS location shifted to one of 7 locations, 3° inwards, 2° inwards, 1° inwards, 0° (no shift), 1° outwards, 2° outwards and 3° outwards. All other symbols remained at their original positions and this configuration did not change until the end of the trial. The 7 possible shifts were balanced across the block and trial order was randomized. The DS would shift regardless of its position, even when it was not at the saccadic goal location (invalid position).

In the perpendicular shift/rotate condition, the DS placeholder rotated 20° counter-clockwise, 10° counter-clockwise, 0° (no shift), 10° clockwise and 20° clockwise upon the participants' saccade. All other symbols remained at their original positions. The 5 possible rotations were balanced across the block and trial order was randomized.

Participants first completed 1 to 6 practice blocks in the baseline condition until they obtained 60% to 70% of correct answers in the valid position. They then completed 5 to 9 blocks (84 trials each) for the parallel shift condition and 3 to 6 blocks (100 trials each) for the rotate condition in a randomized order. In total, each participant completed 720 to 1256 trials. The number of trials completed by each participant depended on the amount of their lost trials due to the absence of a saccade or the presence of invalid saccades found in data analysis.

Data Analysis

We collected 10,500 trials for the shift condition and 4,496 trials for the rotate condition. Along the lines of experiment 1, saccades were detected automatically with a velocity criterion of 30°/s of velocity, then verified visually. Start and end positions were normalized to the mean saccade start position for each block. We removed the trials in which 1) the camera lost eye position, 2) the participant blinked 3) made more than one saccade to the target 4) responded more than 10 seconds after trial start, 5) saccade latencies were shorter than 100ms or longer than 600 ms, 6) the participant's initial eye fixation position was more than 1.5 cm away from central fixation point, 7) saccade offset occurred before DS offset, 8) saccade amplitudes were smaller than 3° or greater than 8° and 9) saccade directions were outside of 20° of the center of the placeholder position. In contrast to experiment 1 where we selected precise saccade trials, here we included a larger range of saccade endpoints in order to test for the impact of saccade variability. There remained 8,828 trials for the shift condition and 3,673 trials for the rotate condition. Details about the number of excluded trials can be found in the supplemental tables 2 and 3.

Discrimination performance was calculated as in experiment 1. Repeated measures ANOVAs and post-hoc Holm-Bonferroni corrected t-tests were conducted for all statistical analyses. ANOVA degrees of freedom reported were Greenhouse-Geiser corrected if Mauchly's test of sphericity was significant. We estimated the extent to which performance differences could be explained by our manipulations with effect sizes, reporting partial eta squared (η_p^2) s for ANOVAs (Lakens, 2013). We also reported Bayes factors for all ANOVAs (BF_M) and t-tests (BF_{10}) performed.

Results

We conducted two separate repeated-measures ANOVAs for parallel and perpendicular shifts and for the valid and invalid positions.

Performance as a function of DS placeholders parallel shifts

In the invalid condition, the repeated-measures ANOVA showed no identification performance difference between any shift conditions, $F(6, 108) = 1.42, p > 0.05$, $BF_M = 0.2$ (range: 30.2% to 36.2%, all significantly different from chance of 25% ($p < 0.05$) except for -3° and -2° shifts ($p > 0.05$)).

Figure 4A shows discrimination performance for every DS parallel shifts (-3° to $+3^\circ$) for the valid condition. For valid positions, performance varied as a function of target shift, $F(4.2, 76.1) = 4.51, p < 0.001, \eta_p^2 = 0.2, BF_M = 64.33$. We performed Holm-Bonferroni corrected post-hoc t -tests to test for differences from the baseline (0°) condition; they revealed differences between the highest performance observed for 0° shift (baseline position; $M = 74.1\%$, $SD = 15.9$) and performance observed for almost every other shifts of location (with -3° inwards, $M = 64.4\%$, $SD = 19.3\%$: $t(18) = 2.74, p < 0.05, BF_{10} = 4.03$; with $+1^\circ$ outwards, $M = 66.3\%$, $SD = 19.4\%$: $t(18) = 2.85, p < 0.05, BF_{10} = 4.96$; with $+2^\circ$ outwards, $M = 64.4\%$, $SD = 17.9\%$: $t(18) = 2.96, p < 0.05, BF_{10} = 6.02$; with $+3^\circ$ outwards, $M = 62.4\%$, $SD = 19.5\%$: $t(18) = 3.24, p < 0.05, BF_{10} = 10.11$, Holm-Bonferroni corrected), except the -2° ($p > 0.05, BF_{10} = 1$) and -1° inward locations ($p > 0.05, BF_{10} = 0.26$). In sum, the best performance was at 0° , which corresponded to baseline. Compared to this position, performance was impaired especially in the most inwards shift (-3°) and all outwards shifts ($+1^\circ, +2^\circ$ and $+3^\circ$).

Figure 4.

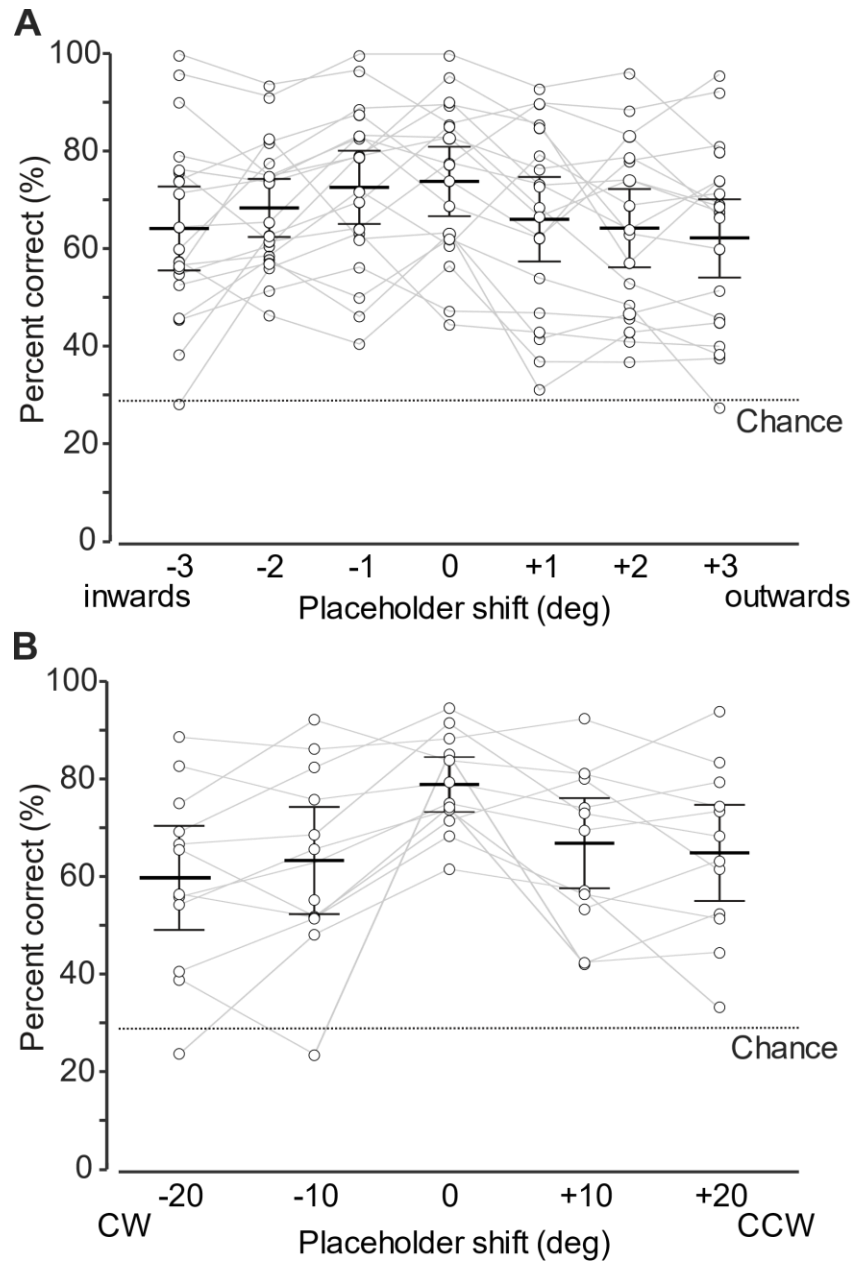


Figure 4. *Pre-saccadic discrimination performance across shift conditions in valid position.* Performance for individual participants is shown as white circles connected by solid gray lines. Mean correct discrimination rate in percentage (%) is shown by the wider black horizontal bars. Lighter grey bars represent standard error of the mean (s.e.m.). Chance is depicted by the dotted line at 25% of correct discrimination (A) Discrimination performances is shown for every parallel shift of the placeholder. (B) Discrimination performance is shown for every perpendicular shift of the placeholder.

Performance as a function of rotated DS placeholders

In this condition, the DS could rotate 10° or 20° clockwise or counter-clockwise from its initial position (-20, -10, +10, +20), during the participants' saccade and in both valid and invalid positions. As with the previous analysis, the repeated-measures ANOVA comparing DS placeholder rotations in the invalid position showed no differences in performance for any rotation, $F(4, 44) = 0.65$, $p > 0.05$, $BF_M = 0.19$ (range: 31% to 36.4%, all significantly different from chance of 25% ($p < 0.05$) except for -3° and -2° shifts ($p > 0.05$)).

Figure 4B shows discrimination performance for every DS rotated location in the valid condition. The repeated-measures ANOVA for the valid condition found differences as a function of DS placeholder rotation, $F(4, 44) = 7.54$, $p < 0.01$, $\eta_p^2 = 0.41$, $BF_M = 232$. We performed Holm-Bonferroni corrected post-hoc t -tests to test for differences from the baseline (0°) condition; these tests revealed decreased performances in rotations of -20° ($M = 61\%$, $SD = 18.8\%$; $t(11) = 4.22$, $p < 0.05$, $BF_{10} = 34$), -10° ($M = 64.9\%$, $SD = 16.1\%$; $t(11) = 3.64$, $p < 0.05$, $BF_{10} = 6.31$), $+10^\circ$ ($M = 66.6\%$, $SD = 15.8\%$; $t(11) = 2.83$, $p < 0.05$, $BF_{10} = 4$) and $+20^\circ$ ($M = 64.6\%$, $SD = 16.1$; $t(11) = 4.01$, $p < 0.05$, $BF_{10} = 24$), compared to no rotation baseline ($M = 77\%$, $SD = 9\%$). In sum, the best performance was at 0° (baseline), while it was lower for all other placeholder rotations.

Saccade landing positions

We observed that the -1° and -2° shift were not different from baseline in the valid condition, while the other shifts and all rotations were different and we wished to determine whether this was related to saccade distribution patterns. In accordance with this observation, we performed some exploratory analysis to determine whether the distribution of landing positions endpoints was linked to discrimination performance.

Figures 5A and C show saccade endpoints for all participants for the parallel shift and rotation conditions respectively, for all trials. Previous studies have shown elliptical distributions with wider distributions parallel compared to perpendicular to the saccade vector (van Opstal & van Gisbergen, 1989; Wexler & Collins, 2014). We observed a similar pattern for cardinal directions, while oblique directions tended to have more circular distributions.

Figures 5B and D show the frequency counts of binned participants' saccade amplitudes compared with average performance for the different placeholder parallel shifts, and of binned participants' saccade directions compared with average performance for the different placeholder perpendicular shifts, respectively, for the valid position. We did not look at the invalid position as there were no

differences in performance. As it can be seen, the distribution of saccade amplitudes and directions seems to be linked to participants' performance; performance is high at the landing positions of most saccades and lower where fewer saccades landed.

Figure 5.

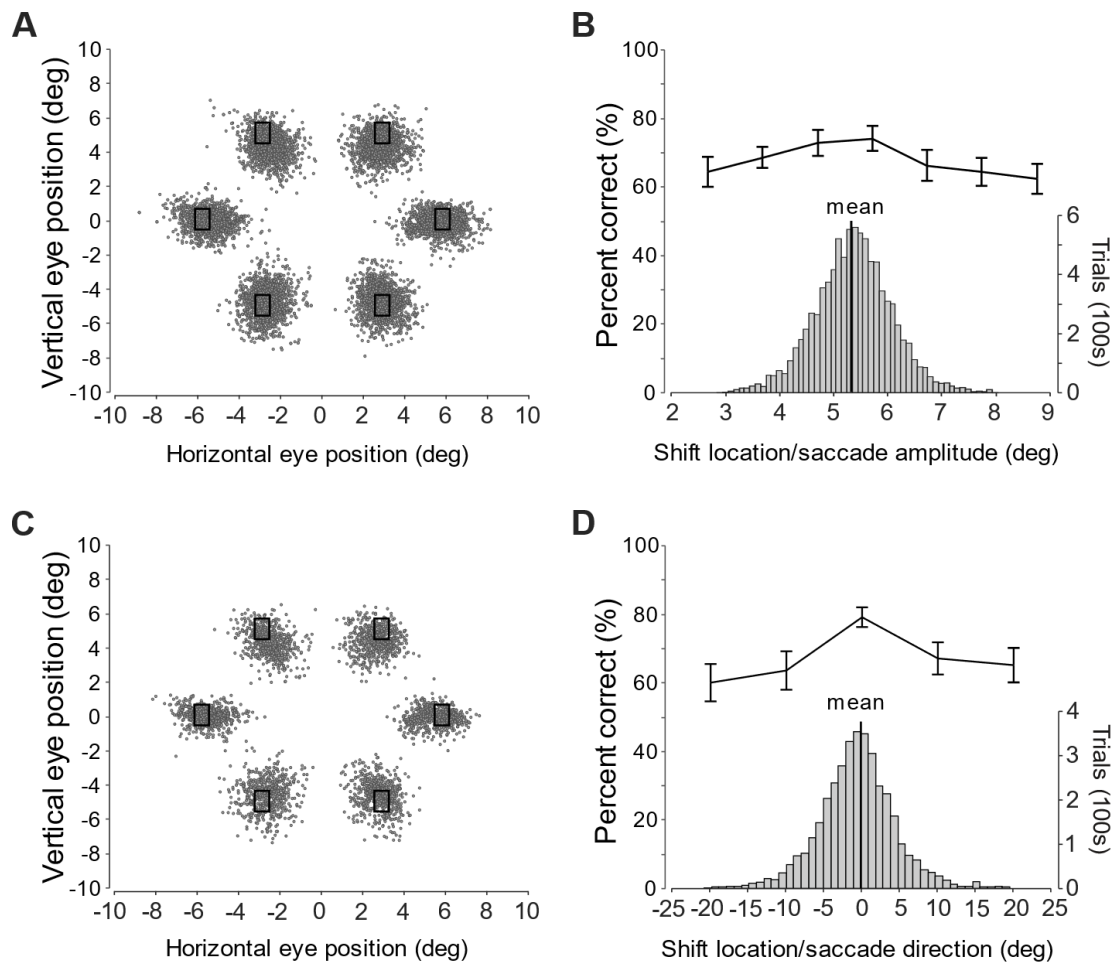


Figure 5. *Saccade endpoint distribution and its relation to performance across parallel shift and rotate conditions in valid position.* (A) Saccade endpoint positions in the array are shown as grey dots for every trial in the parallel shift condition. Placeholder locations are shown in black. (C) Saccade endpoint positions in the array are shown for every trial in the perpendicular shift/rotate condition. (B) Mean correct discrimination rate in percentage (%) is represented by the curve for each change in location inwards or outwards. Smaller grey bars represent standard error of the mean (s.e.m.). Saccade amplitude

distribution is represented by the histogram. (D) Mean correct discrimination rate in percentage (%) is represented by the curve for each rotation clockwise or counter-clockwise. Saccade direction distribution is represented by the histogram.

Most saccades had amplitudes varying between 4° and 7° for placeholders arranged in a circular layout with 5.8° of eccentricity; the mean saccade amplitude was at 5.38° ($SD = 0.3^\circ$), which was significantly smaller than the placeholder distance ($t(18)=5.7$, $p<0.001$, $BF_{10}>100$). This is consistent with many studies which show that participants tend to undershoot targets particularly for centrifugal saccades (Gillen et al., 2013; Irving et al., 2006; Nuthmann et al., 2016). First, we investigated participants' mean amplitudes to determine whether they undershot the pre-saccadic placeholder location, consistent with good performance at the no shift, -1° and -2° placeholder parallel shifts. We tested whether there was a correlation between the parallel shift at which a participant had their best performance and their mean saccade amplitude. We did not find a significant correlation ($p<0.05$). It should be noted that most participants (9 of them) had their best performance at the no shift baseline position and that the range of mean saccade amplitudes across participants was small. We also tested within each participant whether performance was different when their saccade amplitudes were smaller compared to bigger. We performed a median split on each participant's saccade amplitudes and then calculated performance at each DS parallel shift separately for the trials with smaller amplitudes (M across participants = 4.88° vs. bigger amplitudes (M across participants = 5.88°). We then compared performance using a repeated measures ANOVA with median group (smaller vs. bigger saccades amplitudes) and shift (all 7 positions) as factors. We found no significant main effect of group ($F(1,18)=2.5$, $p<0.05$, $BF_M=0.019$) nor a significant interaction effect ($F(6,108)=1.4$, $p>0.05$, $Bf_M = 0.46$) as would be expected if there was a different in performance depending on saccade amplitude.

Next, we tested whether participants with wider distributions of saccade endpoints would show smaller decreases in performance for the biggest parallel shifts. We performed a median split of distributions/variability, separating participants into those with narrower distributions vs. wider distributions, i.e. smaller vs. bigger standard deviations for landing position. We then compared the two groups in terms of change in performance from baseline to the inward 3° shift and as well from baseline to the outward 3° shift. We found no differences between the two groups ($p>0.05$, $BF_{10}<0.67$, narrow distribution group $SD = 0.57^\circ$, 13.72% inwards decrease in performance and 5.3% outwards; wide distribution group $SD = 0.7^\circ$, 14.4% inwards and 8.6% outwards).

We performed the same analyses for the rotation condition. Mean relative saccade direction was at -0.01° (SD = 0.75°), which was not significantly different from the placeholder direction (0° , $t(11)=0.05$, $p=0.9$, $BF_{10}=0.28$). We did not find a significant correlation ($p<0.05$) between the rotation position of best performance and mean individual saccade direction; the best identification performance was at the no rotation baseline position for 8 of our 12 participants and the range of mean saccade directions across participants was small. We also tested within each participant whether the pattern of performance across the different rotations was different when their saccade directions were more clockwise compared to more counter-clockwise, using a median split analysis (M across participants more clockwise = -0.57° , M across participants = 0.56° more counter-clockwise) but found no significant effects ($p>0.05$, $BF_M<0.6$). Finally, we found that participants with wider distributions in direction did not show differences in decreases in performance from baseline to the outward-most rotations ($p>0.05$, $BF_{10}<0.5$).

In summary, we did not find a relationship between saccade distribution patterns and discrimination performance in either the parallel shift or the rotation condition.

Timing of the placeholder change

We confirmed that there were no differences across location changes (collapsed across valid and invalid positions) in the timing of the placeholder rotation relative to saccade offset for either the shift condition ($p>0.05$, $BF_M=0.3$) or the rotation condition ($p>0.05$, $BF_M = 0$). Post-saccadic changes in experiment 2 were programmed to occur when the eyes moved more than 1.85° in any direction outside of fixation. Saccade durations for the shift condition were on average 40.8 ms (SD across participants = 3.55 ms, average participant SD = 7.35ms). For the rotation condition, average saccade duration was 41.8 ms (SD across participants = 5.14 ms, average participant SD = 7.23ms). On average the placeholder changed positions 10.78ms (SD across participants = 3.68 ms, average participant SD = 9.4ms) *before* saccade offset for the parallel shift condition and 11.75ms (SD across participants = 4.32 ms, average participant SD = 8.84ms) *before* saccade offset for the rotation condition.

Saccade latencies

The mean saccade latency for the parallel shift condition was 282ms (SD across participants = 53ms, average within participant SD = 41ms) while for the rotate condition, it was 310ms (SD across participants = 72ms, average within participant SD = 44ms). We confirmed that there were no differences across (parallel or perpendicular) shifts or position (valid vs invalid) nor any interaction effects for either the parallel shift condition (all $p > 0.05$, $BF_M < 0.5$) or the rotation condition (all $p > 0.05$, $BF_M < 0.5$).

Experiment 2 summary

We observed that pre-saccadic discrimination performance decreased when the placeholder at the saccade goal changed location during the saccade. Moreover, while there was a decrease in performance for all rotations and most parallel shifts, notably performance did not decrease for the two smallest inward shifts. In terms of saccade behaviour, the distribution of saccade landing positions has been shown to play a role in the capacity to determine trans-saccadic object correspondence, within the context of saccadic suppression of displacement (Van der Stigchel et al., 2020; Wexler & Collins, 2014; but see Schut et al., 2018; Joosten & Collins, 2018). Even though saccades are generally precise, a certain variability exists in their landing positions, from one person to another. These abovementioned studies showed that when a saccade's target was shifted within an elliptic region corresponding to the habitual distribution of saccade landing positions, its shift was not perceived, and the object's stability was assumed. On the other hand, when the shift fell outside this region, it was noticed by the observer. Thus, for the system to determine object correspondence, it may take into consideration the distribution of landing positions, comprising saccade accuracy, e.g. how much undershoot and saccade variability, e.g. how broad an area.

We therefore tested whether our participants' pattern of performance was related to saccade endpoint distributions but did not find a significant relationship.

General Discussion

We tested how performance in a pre-saccadic discrimination task was influenced by post-saccadic changes in the visual scene. We varied attention directed to the relevant pre-saccadic object (discrimination symbol DS) by requiring a saccade either to that object or to another placeholder. We manipulated the post-saccadic visual scene after the saccade in various ways (removals or

location changes) and found that pre-saccadic attentional facilitation not only affected the encoding pre-saccadic symbol in memory but also the ability of the abrupt but nevertheless irrelevant post-saccadic visual scene changes to disrupt the report of the pre-saccadic symbol. In other words, pre-saccadic exclusive allocation of attention to the saccade goal rendered post-saccadic change involving *exclusively* the saccade goal object more salient and disruptive of trans-saccadic memory, probably because they break the correspondence of the most attended object between the pre- and post-saccadic views relative to a constant scene.

In both experiments, in the baseline conditions with no change to the post-saccadic scene, participants showed above chance discrimination when the symbol appeared pre-saccadically at the saccade target goal location. The report of the symbol was after the saccade, showing that participants were able to encode, remember and retrieve it well across the saccade. In contrast, discrimination performance was at chance level when the symbol did not appear at the saccade goal location, even though it was relevant to the task since participants were asked to discriminate the symbol regardless of its position. This shows that preparing and executing a saccade toward another location led to an exclusive allocation of attention to the saccade goal and prevented the selection of the relevant symbol for trans-saccadic memory. This may have been because the task was too difficult with remaining attentional resources needed to be distributed among 5 possible invalid positions and chance level at 25% because of the four alternative choice discrimination (p,b,q,p). However, even previous studies using simpler versions of this task (only 2 possible invalid positions and two-alternative forced choice discrimination task) have shown chance level discrimination at the invalid location. (Khan et al 2009). Of note, although this was not significant we did observe here a performance decrease across most individuals in the OneOff invalid condition compared to the invalid baseline condition, similar to the performance decrease in the OneOff valid condition compared to the valid baseline condition (Figure 2). We speculate that if there had been above chance discrimination in the invalid location (no floor effect), we may have similarly seen a significant dip in discrimination performance. In theory post-saccadic changes at the object location relevant to the task (discrimination symbol to report after the saccade), albeit a saccade is to be executed elsewhere, should also disrupt trans-saccadic memory, although to a smaller degree as there were fewer attentional resources allocated to this object. However, pre-saccadic attentional

571 facilitation is strongly directed at the saccade goal location at the expense of other, even relevant
572 locations. Facilitation by covert attention is not so exclusive (Khan et al 2015 EJN)

573 We thus observed above chance level discrimination performance and could study its modulation by
574 various irrelevant post-saccadic changes, only when the symbol appeared at the saccade goal location
575 (valid position). When we removed the entire scene after the saccade, there was no change to the
576 pattern of discrimination. Similarly, when we removed all placeholders but the saccade target
577 placeholder, there was no decrease in performance in the report of the symbol after the saccade.
578 However, when the saccade goal placeholder disappeared but all other placeholders remained, we
579 observed a decrease in discrimination performance. In a second experiment, we changed the
580 placeholder location (inward/outward shift or rotation re. saccade vector) and observed that
581 performance decreased with increased location change, but again only when the change occurred at
582 the saccade goal location relative to a constant visual scene. Taken together, these results imply that
583 the pre-saccadic memory of the symbol is disrupted due to a relative change in the visual scene
584 involving only the saccade goal placeholder, i.e. a disruption in object/scene correspondence. Since
585 performance was still well above chance (unlike when the DS appeared at a non saccade goal
586 location), we conclude attentional prioritizing into trans-saccadic memory still took place, but that
587 retention was disrupted because of this post-saccadic change.

588 We propose that abrupt post-saccadic changes occurring only at the saccade goal breaks pre- and
589 post-saccadic correspondence of the most attended object relative to a constant visual scene. This
590 specific post-saccadic change captured attention, leading to the encoding of this post-saccadic object
591 into memory, which consequently affected retention of pre-saccadic object information, due to
592 trans-saccadic memory resource limitation. It has been previously suggested that trans-saccadic
593 memory plays an important role in comparing information before and after a saccade (Aagten-
594 Murphy & Bays, 2019; Mathôt & Theeuwes, 2011; Van Eccelpoel et al., 2008). Trans-saccadic
595 memory has been considered to be based on visual working memory (Luck & Vogel, 1997), due to
596 the similarities in limited memory capacity as well as the timing duration of a few seconds (Irwin,
597 1992; Irwin, 1996; Irwin & Andrews, 1996; Luck & Vogel, 1997). Previous studies have shown
598 evidence for automatic attention leading to automatic encoding into visual working/trans-saccadic
599 memory (references), at the expense of the item already in memory, namely here memory of the pre-
600 saccadic symbol is disrupted, resulting in decreased discrimination performance. The observed

601 disruption of trans-saccadic memory due to post-saccadic changes therefore adds arguments for
602 limited resources in trans-saccadic memory (references to Poth studies here). If memory resources
603 were unlimited, we would expect no memory disruption, and thus no decreased discrimination
604 performance.

605 Our results also support the idea that pre-saccadic attentional facilitation is involved in selecting
606 information to be stored in trans-saccadic memory and compared after the saccade (Deubel et al.,
607 1998; Rolfs et al., 2011; Wolf & Schütz, 2015; Irwin & Robinson, 2015). It has been previously
608 suggested that pre-saccadic attention acts as a ‘gatekeeper’ for transsaccadic memory, or alternatively
609 as a predictive ‘pointer’ to remember and update objects’ identity and location across saccades
610 (Cavanagh et al., 2010; Rolfs et al., 2011; Van Eccelpoel et al., 2008; Prime et al., 2007; Melcher,
611 2009). We show evidence here that the saccade target grabs a large part of the attentional resources
612 before and also after the saccade execution, at the expense of other, even relevant objects.

613 We speculated that the determination of object correspondence for the saccade goal played a role in
614 the disruption of trans-saccadic memory, rather than an abrupt attention-grabbing change in saccade
615 placeholder. This was based on our observations of 1) no discrimination disruption in the AllOff
616 condition in the first experiment and 2) clear discrimination disruption when the saccade goal object
617 shifted of only 1° outwards in the second experiment. It has been suggested that breaking object
618 correspondence results in separate memory items of the pre- and post-saccadic objects, which
619 compete for limited trans-saccadic memory (Poth & Schneider, 2015). Numerous studies have
620 supported the relative importance of the post-saccadic object compared to the pre-saccadic one, for
621 visual stability (Deubel, Bridgeman & Schneider, 1998), i.e. the pre-saccadic information becomes
622 less relevant at the expense of the post-saccadic new object/scene, and so has fewer memory
623 resources. Further, the observation that discrimination performance decreased only when there was
624 a relative change at the saccade placeholder location, supports the idea that object correspondence
625 determination might be more related to the visual scene than just the saccade goal object itself. This
626 is consistent with a recent finding that other stimuli similar to the target may be perceptually
627 grouped and attended pre-saccadically (Shurygina, Pooresmaeili & Rolfs, 2019) and that factors such
628 as the relative positions of other objects in the scene (Deubel et al., 1998) also play a role in object
629 correspondence. We suggest that the removal of the entire visual scene (AllOff condition) in our
630 first experiment does not disrupt predictive mechanisms, likely because there is no comparison to
631 make between pre- and post-saccadic scenes. Specifically, since the entire scene changed and all

landmarks were gone, there was no comparison to make about the relative target position in the scene. Note that such removal of the whole visual scene may be more predictable than a specific change only at the saccade goal since it occurs as frequently as we blink.

Concerning the clear discrimination disruption when the saccade goal object shifted of only 1° outwards in our second experiment, we speculated that the determination of object correspondence might be related to saccadic variability. Indeed, previous studies on saccadic suppression of displacement have shown that there is an assumption of object correspondence for pre- and post-saccadic objects and that relatively large shifts are necessary to break this assumption (Bridgeman et al., 1975; Mathôt & Theeuwes, 2011; Deubel et al., 1996). Within the context of saccadic suppression of displacement, further studies have shown that the distribution of saccade landing positions plays a role in the capacity to determine trans-saccadic object correspondence (Van der Stigchel et al., 2020; Wexler & Collins, 2014; but see Schut et al., 2018; Joosten & Collins, 2018). Along these lines, and given the distinct pattern of discrimination performance we observed for the inward shifts of the saccade placeholder compared to the outwards shifts, we studied the correlation between saccade landing positions and identification performance in our data. However, we did not find any strong relationship between performance and saccade landing positions neither between individuals nor between individual trials. This suggests that a general estimate of the noise in the eye movement system may play a role in determining object correspondence, rather than the actual saccade landing positions per se. Similarly, in a recent study investigating visual and proprioceptive integration for reaching, we showed that the weighting of visual information did not depend on the actual visual and proprioceptive variabilities of the dominant and non-dominant hands, but rather on a learned constant estimate (Mikula et al., 2021). Thus it could be that there is some more general variability estimate which is used by the system to determine object correspondence instead of one based on saccade execution. This would explain some discord in previous related studies within the context of saccadic suppression of displacement (Van der Stigchel et al., 2020; Wexler & Collins, 2014; Schut et al., 2018; Joosten & Collins, 2018) on whether trans-saccadic perception (object correspondance) is related to saccade variability or not. .

Timing of change

The timing of the post-saccadic changes was different for the first and second experiments. Specifically, the post saccadic changes occurred after the saccade landed at the placeholder for the first experiment and occurred during the saccade for the second experiment. Previous studies on trans-saccadic memory and object correspondence had post saccadic changes that occurred right at the end of the saccade as well as long after the saccade landed, after 100ms (Poth & Schneider, 2015). They observed that object letter discrimination was worse when the postsaccadic changes occurred long after the saccade landed. However, this cannot explain the results of our study.

Not backward masking

An alternative explanation for our results could have been backward masking. Specifically, the appearance of a distractor after the target can result in decreased visibility of the target resulting in decreased performance (Macknik & Livingstone, 1998). Typically, in backward masking, changes in target identity leads to a decrease in performance. However, in all our conditions, the DS switches back to a figure 8 , already masking it, only 140 ms after the cue indicating the saccade goal and thus before occurrence of the saccade. In addition, object disappearance or change in location to our knowledge is not known to cause backward masking. Furthermore, the timing of the changes is also not consistent with backward masking. In an elegant study, Macknik and Livingstone (1998) showed the peak backward masking occurs at about 100 ms between the termination of the target and termination of the mask. In our paradigm, the DS was presented for 66.67ms then replaced by a figure 8 placeholder, which remained visible for an average of 190ms (SD = 35ms) before its disappearance.

Conclusions

In this pre-saccadic attentional facilitation study, we changed the visual scene in different ways after the saccade. This manipulation was irrelevant to the pre-saccadic discrimination task. We found that discrimination performance was nevertheless negatively affected by post-saccadic changes involving specifically the saccade goal location. This confirms the notion of pre-saccadic attentional facilitation being involved in visual stability across saccades, rather than being an independent phenomenon

whose role was limited to the pre-saccadic period. We explored the effects of various post-saccadic object disappearance(s) on visual stability in experiment one and the spatial limits of pre- and post-saccadic object location continuity in experiment two. Visual stability (or trans-saccadic memory) is disrupted when object correspondence is broken between the pre- and post-saccadic objects (Poth & Schneider, 2015; Poth et al. 2015). The present results provide insights into the criteria used by the visual system to determine object correspondence across saccades.

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844 **Supplemental table 1**

845 **Excluded trials for experiment 1**

Exclusion	Number of trials	% of total trials/mean across participants*	Number of participants who had such trials	Range across participants (trials)	SD across participants
Camera lost eye position/participant blinked/participant made more than one saccade	257	6.69%	10/10	7-74/384	5.86%
Response >10s	4	0.1%	2/10	1-3	0.25%
Saccade latencies less than 100ms	4	0.1%	3/10	1-2	0.18%
Saccade latencies more than 600 ms	5	0.13%	5/10	1-1	0.14%
Eye fixation more than 1.5cm away from centre	57	1.48%	9/10	2-15	1.24%
Saccade offset before DS offset	5	0.13%	2/10	2-3	0.28%
Saccade direction outside of 10°/saccade amplitude <3.8° or >7.8°	477	12.42%	10/10	19-105	7.59%

846 * because of the even number of trials for each participant the total % and mean % across
847 participants is identical

848

849 **Supplemental table 2**

850 **Excluded trials for experiment 2 parallel condition**

Exclusion	Number of trials	% of total trials/ mean across participants	Number of participants who had such trials	Range across participants (trials)	SD across participants

Camera lost eye position/participant blinked/participant made more than one saccade	736	7% (6.2%)	19/19	3-168/304-756	6.7%
Response >10s	22	0.21%(0.25%)	4/19	1-17	0.92%
Saccade latencies less than 100ms	47	0.45%(0.33%)	4/19	1-42	1.27%
Saccade latencies more than 600 ms	323	3.08%(2.4%)	10/19	1-262	7.88%
Eye fixation more than 1.5cm away from centre	202	1.92%(1.75%)	16/19	1-84	3.18%
Saccade offset before DS offset	12	0.11%(0.13%)	2/19	1-11	0.5%
Saccade direction outside of 20°/saccade amplitude <3° or >7°	327	3.11%(3.18%)	19/19	4-60	3.18%

851

852 **Excluded trials for experiment 2 perpendicular condition**

Exclusion	Number of trials	% of total trials/mean across participants	Number of participants who had such trials	Range across participants (trials)	SD across participants
Camera lost eye position/participant blinked/participant made more than one saccade	339	7.54%(7.36%)	12/12	4-75/300-500	5.35%
Response >10s	7	0.16%(0.16%)	3	1-4	0.33%
Saccade latencies less than 100ms	0	-	-	-	-
Saccade latencies more than 600 ms	236	5.25%	6	1-197	14.0%
Eye fixation more than 1.5cm away from centre	116	2.58%(2.46%)	11	1-33	2.87%
Saccade offset before DS offset	30	0.67%(0.63%)	1	30	-
Saccade direction	67	1.49%(1.43%)	11	2-16	0.97%

outside of 20°/saccade amplitude <3° or >7°					
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