Post-saccadic changes disrupt attended pre-saccadic object memory

Anne-Sophie Laurin University of Montreal, Department of Psychology, Montreal, Quebec, Canada ✉

Maxime Bleau University of Montreal, School of Optometry, Montreal, Quebec, Canada ✉

Jessica Gedjakouchian University of Montreal, School of Optometry, Montreal, Quebec, Canada

Romain Fournet University of Montreal, School of Optometry, Montreal, Quebec, Canada ✉

Laure Pisella ImpAct, INSERM UM1028, CNRS UMR 5292, University Claude Bernard Lyon 1, Lyon, France ✉

Aarlenne Zein Khan University of Montreal, School of Optometry, Montreal, Quebec, Canada ✉

Trans-saccadic memory consists of keeping track of objects' locations and features across saccades; pre-saccadic information is remembered and compared with post-saccadic information. It has been shown to have limited resources and involve attention with respect to the selection of objects and features. In support, a previous study showed that 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, Herwig, Schneider, 2015). Here, we investigated the inverse (i.e. how the memory of pre-saccadic objects is affected by abrupt but irrelevant changes in the post-saccadic visual scene). We also modulated the amount of 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 affected how much post-saccadic changes disrupted trans-saccadic memory of pre-saccadic objects.

Participants identified a flashed symbol (d, b, p, or q, among 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 symbol after the saccade. We changed the post-saccadic scene in Experiment one by removing the 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-capturing 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.

Introduction

Trans-saccadic memory is involved in keeping track of an object's location and its features across saccadic eye movements (Cavanagh, Hunt, Afraz, & Rolfs, 2010; Jeyachandra, Nam, Kim, Blohm, & Khan, 2018; Mathôt & Theeuwes, 2011; Poth & Schneider, 2018; Prime, Tsotsos, Keith, & Crawford, 2007; Rolfs, 2015; Rolfs, Jonikaitis, Deubel, & Cavanagh, 2011), allowing an accurate comparison of pre- and post-saccadic information about the object (Ganmor, Landy, & Simoncelli, 2015; Hayhoe, Lachter, & Feldman, 1991;

Citation: Laurin, A.-S., Bleau, M., Gedjakouchian, J., Fournet, R., Pisella, L., & Khan, A. Z. (2021). Post-saccadic changes disrupt attended pre-saccadic object memory. *Journal of Vision*, *21*(8):8, 1–18, https://doi.org/10.1167/jov.21.8.8.

https://doi.org/10.1167/jov.21.8.8 Received December 31, 2020; published August 4, 2021 ISSN 1534-7362

Mathôt & Theeuwes, 2011; Vaziri, Diedrichsen, & Shadmehr, 2006; Wolf & Schütz, 2015).

There is consensus that trans-saccadic memory relies on visual working memory and involves attention (Aagten-Murphy & Bays, 2019; Frost, Tomou, Parikh, Kaur, Zivcevska, & Niemeier, 2019; Irwin, 1992; Irwin, 1996; Irwin & Andrews, 1996; Mathôt & Theeuwes, 2011; Melcher, 2009; Poth, Herwig & Schneider, 2015; Poth & Schneider, 2016; Poth & Schneider, 2018; Prime et al., 2007; Stewart & Schütz, 2018a; Stewart & Schütz, 2018b). 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 (Mathôt & Theeuwes, 2011), supported by the finding that cued objects are better remembered across saccades compared to uncued objects (Prime et al., 2007; Melcher, 2009). Similarly, removing attention impairs the integration of peripheral and foveal object information across saccades, likely due to a disruption in allocation to trans-saccadic memory (Stewart & Schütz, 2018a). 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 impairs the 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, Herwig, & Schneider, 2015), the authors 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 (Irwin, 1992; Irwin, 1996; Irwin & Andrews, 1996; Mathôt & Theeuwes, 2011; Rolfs, 2015). 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 (Castet, Jeanajean, Montagnini, Laugier, & Masson, 2006; Deubel, 2008; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Khan, Blohm, Pisella, & Munoz, 2015; Khan, Heinen, & McPeek, 2010; Kowler, Anderson, Dosher, & Blaser, 1995; Mikula, Jacob, Tran, Pisella, & Khan, 2018). In summary, both relevant and saccade goal objects are prioritized for allocation into limited trans-saccadic memory resources.

Although previous studies have shown that pre-saccadic memorized objects impair recognition of post-saccadic objects (Poth et al., 2015), the inverse remains unknown, that is how attended post-saccadic objects influence the memory of pre-saccadic objects. Besides relevance, attention can also be captured by abrupt onsets/offsets, or displacements in the visual scene, typically known as exogenous attention (Corbetta & Shulman, 2002; Turatto, Bonetti, Pascucci, & Chelazzi, 2018). 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). 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 pre-saccadic target. There were four 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, and (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 men, M = 22.9 years, SD = 6.1 years). Authors A.L., A.K., and J.G. were participants in the experiment. All participants had normal or corrected-to-normal vision (glasses or 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

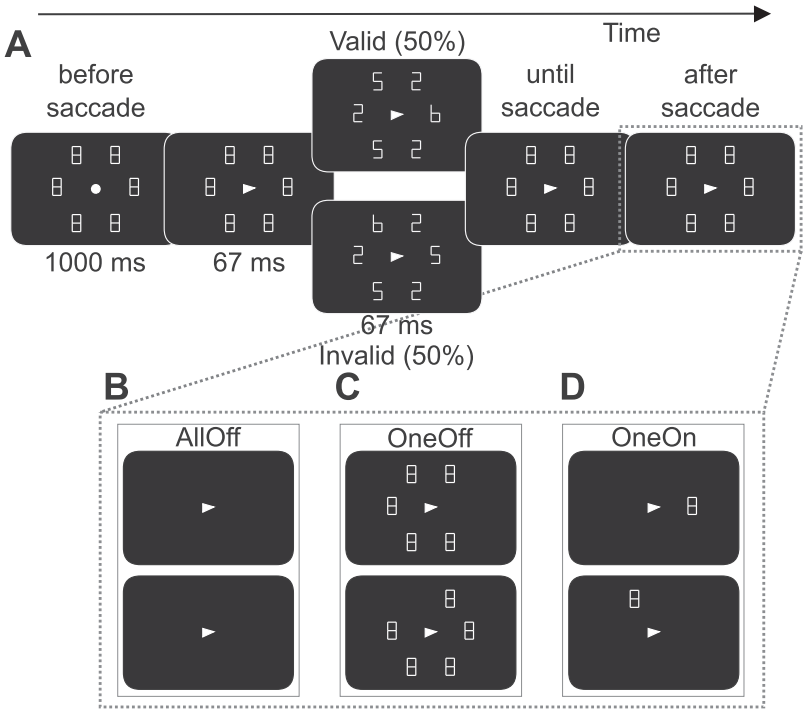

Figure 1. Experimental tasks. (**A**) Baseline dual-task paradigm. Participants fixated a central dot surrounded by six placeholders. The fixation dot was changed into an arrow for 67 milliseconds and participants made a saccade to the placeholder designated by the arrow. Then, the DS appeared either at the saccadic goal (valid) or at another placeholder (invalid). Remaining placeholders changed into other symbols. Sixty-seven 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.

size of 0.4, with one group and eight 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, 53 × 30 cm [22.5 inch display size], 1920 × 1200 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 validated using a nine-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; Khan et al., 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 degrees diameter) first appeared at the center of a black screen, surrounded by six red figure eight placeholders (dimensions of 1.2 degrees × 0.7 degrees, shown in white in Figure 1) arranged in a circular layout (5.8 degrees of eccentricity). After 1000 ms, the fixation dot was replaced by an arrow (1.0 degrees × 0.7 degrees) pointing toward one of the placeholders at random. The participants were asked to make a saccade as quickly as possible toward the designated placeholder. For 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 eights changed to one of four symbols (either d, b, p, or q, randomly selected), named the discrimination symbol (DS). The five remaining figures changed into nonpertinent 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 nonpertinent symbols remained on for 66.67 ms before changing back to their previous identities, figure eights. 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 four buttons for every trial (forced choice); they were asked to respond even if they could not 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.

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 degrees of diameter around the fixation point (1.85 degrees 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 (see 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 9) 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 3840 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 degrees/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 the fixation point. This was to account for any errors in the calibration process; we observed that although 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 center 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 10 seconds after trial start or longer; (5) the participant's saccade latencies in response to the arrow onset were shorter than 100 ms and longer than 600 ms; (6) trials in which the start position (when participants were fixating at center) was more than 1.5 degrees away from the fixation dot; (7) trials during which saccade offset occurred before DS offset, ensuring that the DS was never viewed foveally; (8) trials in which saccade amplitude was less than 3.8 degrees or more than 7.8 degrees (saccade target being at 5.8 degrees); and (9) trials in which saccade direction was outside 10 degrees of the center of the saccade target placeholder. The latter two were due to previous studies associating discrimination performance to saccade landing positions to some degree (Mikula et al., 2018; Wick, Garaas, & Pomplun, 2016). In total, there remained 3031 (78.9%) trials. Details about the number of excluded trials can be found in Supplementary Table S1.

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) seconds for ANOVAs (Lakens, 2013). We also reported Bayes factors for all ANOVAs and *t*-tests performed. We used JASP 0.14.1 for statistical analysis (JASP Team, 2020). We used default priors from JASP for all analyses and report BF_{10} values for the best model compared to the null hypothesis.

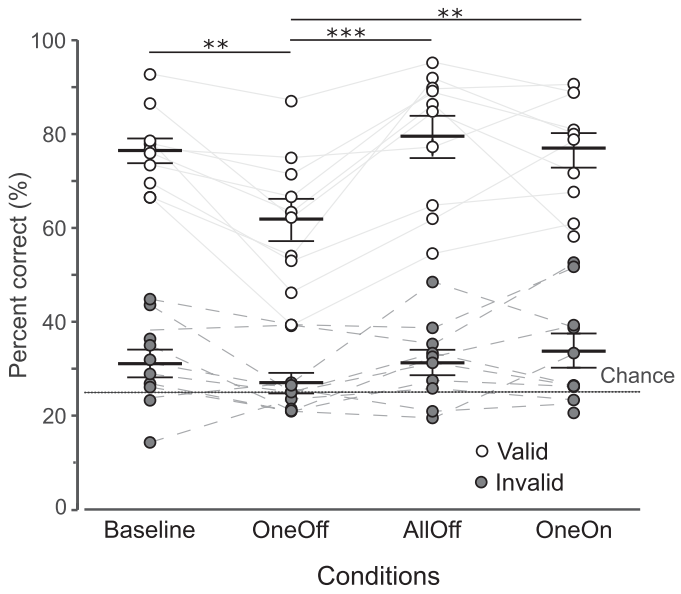

Figure 2. Pre-saccadic discrimination performance across conditions in valid and invalid positions. Performance for individual participants is shown as white circles connected by light gray solid lines for the valid position and as grey circles connected by gray dashed lines for the invalid position. Mean correct discrimination rate in percentage (%) is shown by the wider black horizontal bars. Lighter grey bars represent standard error of the mean (SEM). Chance is depicted by the dotted line at 25% of correct discrimination. ** = $p < 0.01$, *** = $p < 0.001$, for valid condition only.

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 (1-way repeated measures ANOVA, F(1,9) = 144, $p < 0.001$, $\eta^2_p = 0.941$). A Bayesian paired samples *t*-test strongly favored the alternative hypothesis of a difference between the two positions compared to the null hypothesis ($BF_{10} = 19706.9$). In addition, while performance was significantly different from chance (25%) in the valid position (76.6% correct, $t(9) = 19.5$, $p < 0.001$), it was not for the invalid positions (31.3%, $t(9) = 2.1$, $p = 0.064$). 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).

Experimental conditions

Figure 2 depicts performance for all four conditions (Baseline, OneOff, AllOff, and OneOn) in valid and invalid positions. A 2-way repeated measures ANOVA revealed significant main effects for both condition (F(3,27) = 7.4, $p < 0.001$, $\eta^2_p = 0.451$) and position (F(1,9) = 165, $p < 0.001$, $\eta^2_p = 0.948$). There was also a significant interaction effect (F(3,27) = 4.8, $p = 0.008$, $\eta^2_p = 0.347$). A two-way Bayesian repeated measures ANOVA strongly favored the alternative hypothesis with the model with condition and position as factors with no interaction ($BF_{10} = 1.628e + 29$, best model) compared to the null model. This model was slightly better than the model that included the interaction effect ($BF_{10} = 1.316e + 29$).

Comparing across the valid position, post hoc Bonferroni-Holm corrected paired *t*-tests confirmed significantly lower performance for the OneOff condition (M = 62.2%, SD = 14.2%) compared to all other conditions (baseline - M = 76.6%, SD = 8.3%, $t(9) = 4.4$, $p = 0.002$, AllOff – M = 79.7%, SD = 14, $t(9) = 5.7$, $p < 0.001$, OneOn - M = 76.8%, SD = 11.4%, $t(9) = 4.3$, $p = 0.002$). Performance for the AllOff and the OneOn condition were not different from the baseline condition (AllOff – t(9) = 0.777, $p = 0.457$, OneOn - t(9) = 0.046, $p = 0.964$). For Bayesian paired samples *t*-tests, there was strong evidence in favor of the alternative hypothesis of a difference between the OneOff compared to all other conditions (baseline – $BF_{10} = 26.9$, AllOff – $BF_{10} = 111.06$, OneOn – $BF_{10} = 22.9$). In contrast, there was moderate evidence in favor of the null hypothesis when comparing between the other conditions (Alloff versus baseline – $BF_{10} = 0.397$, OneOn versus baseline – $BF_{10} = 0.309$).

Comparing across the invalid position, post hoc comparisons revealed no differences between any of the conditions (OneOff versus baseline - t(9) = 1.783, $p = 0.108$; AllOff versus baseline - t(9) = 0.098, $p = 0.924$; OneOn versus baseline - t(9) = 0.844, $p = 0.421$; OneOff versus AllOff - t(9) = 1.571, $p = 0.151$; OneOff versus OneOn - t(9) = 3.161, $p = 0.012$; AllOff versus OneOn - t(9) = 0.975, $p = 0.355$; Holm-Bonferroni corrected). For Bayesian paired samples *t*-tests, there was moderate support in favor of the alternative hypothesis of a difference between the OneOff and OneOn conditions ($BF_{10} = 5.528$), while all other comparisons showed evidence that supported the null hypothesis or showed equal evidence for either hypothesis (Alloff versus baseline – $BF_{10} = 0.31$, OneOff versus baseline – $BF_{10} = 0.997$, OneOn versus baseline – $BF_{10} = 0.415$, AllOff versus OneOn - $BF_{10} = 0.456$).

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 degrees 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 39.7 ms (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, $F(2,18) = 0.904$, $p = 0.422$) or position ($F(1,9) = 4.123$, $p = 0.073$ nor a significant interaction effect ($F(2,18) = 1.771$, $p = 0.198$). A Bayesian repeated-measures ANOVA revealed weak to moderate support for the null hypothesis (best model = condition factor only, $BF_{10} = 0.524$ compared to null hypothesis). 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 four conditions (baseline – M = 243 ms, SD across participants = 22 ms, average within participant SD = 27 ms; OneOff – M = 239 ms, SD across participants = 19 ms, average within participant SD = 25 ms; AllOff – M = 242 ms, SD across participants = 27 ms, average within participant SD = 30 ms; and OneOn – M = 249 ms, SD across participants = 21 ms, average within participant SD = 28 ms). We confirmed that there were no differences in saccade latencies across condition or position (valid versus invalid) nor any interaction effects (condition - $F(3,27) = 1.293$, $p = 0.297$) or position - $F(1,9) = 5.075$, $p = 0.051$ nor a significant interaction effect - $F(3,27) = 0.119$, $p = 0.948$). A Bayesian repeated-measures ANOVA revealed equal support for any model and the null hypothesis (best model = condition factor only, $BF_{10} = 1.4$ compared to null hypothesis).

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 led 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 the invalid position, 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 at 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. In addition, 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 one, 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 two conditions: (1) the saccade goal or distractor placeholder shifted inward or outward relative to fixation, and (2) the saccade goal or distractor placeholder rotated (Figure 3A).

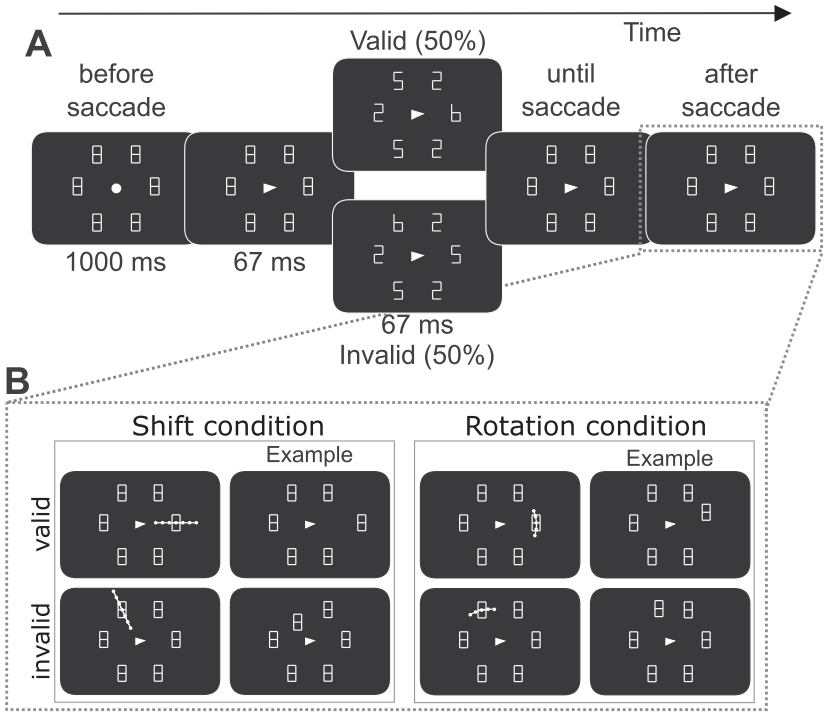

Figure 3. Experimental dual-task paradigm. (**A**) Baseline condition. Participants fixated a central dot surrounded by six placeholders. The dot was changed into an arrow for 67 milliseconds and participants made a saccade to the placeholder designated by the arrow. Then, the DS appeared either at the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

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), 11 of which were the same as in the shift condition. All participants, apart from authors A.L., J.G., and A.K., 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 seven 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 one. 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 degrees of diameter around the fixation point, with no additional delays (see Figure 3A). Thus, changes occurred during the saccade before the eye landed.

In the shift condition, upon the participants' saccade, the DS location shifted to one of seven locations, 3 degrees inward, 2 degrees inward, 1 degree inward, 0 degrees (no shift), 1 degree outward, 2 degrees outward, and 3 degrees outward. All other symbols remained at their original locations and this configuration did not change until the end of the trial. The seven possible shifts were balanced across the block and trial order was randomized. The DS would shift regardless of its

location, even when it was not at the saccadic goal location (invalid position).

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

Participants first completed one to six practice blocks in the baseline condition until they obtained 60% to 70% of correct answers in the valid position. They then completed five to nine blocks (84 trials each) for the shift condition and three to six 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 4496 trials for the rotate condition. Along the lines of Experiment one, saccades were detected automatically with a velocity criterion of 30 degrees/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) the participant made more than one saccade to the target, (4) the participant responded more than 10 seconds after trial start, (5) saccade latencies were shorter than 100 ms 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 degrees or greater than 8 degrees, and (9) saccade directions were outside of 20 degrees of the center of the placeholder position. In contrast to Experiment one 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 8828 trials for the shift condition and 3673 trials for the rotate condition. Details about the number of excluded trials can be found in the Supplementary Tables S2 and S3.

Discrimination performance was calculated as in Experiment one. 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^2_p) seconds for ANOVAs (Lakens, 2013). We also reported Bayes factors for all ANOVAs and *t*-tests performed in the same manner as Experiment one.

Results

We conducted separate repeated-measures ANOVAs for the shift and rotation experiments and for the valid and invalid positions.

Performance as a function of DS placeholder shifts

In the invalid position, the repeated-measures ANOVA showed no identification performance difference across shift location, $F(6, 108) = 1.42$, $p = 0.213$ (range: 30.2% to 36.2%, 3 significantly different from chance of 25% ($-1°$ - $t(18) = 3.152$, $p = 0.006$; 0 degrees - $t(18) = 3.202$, $p = 0.005$; +3 degrees - $t(18) = 3.083$, $p = 0.006$) and four not significantly different from chance (-3 degrees - $t(18) = 1.518$, $p = 0.146$; -2 degrees - $t(18) = 2.01$, $p = 0.06$; +1 degrees - $t(18) = 2.484$, $p = 0.023$; +1 degrees - $t(18) = 2.671$, $p = 0.016$, Holm-Bonferroni corrected). The Bayesian repeated measures ANOVA strongly favored the null hypothesis (position – $BF_{10} = 0.2$).

Figure 4A shows discrimination performance for every DS parallel shifts (-3 degrees to +3 degrees) for the valid position. Performance varied as a function of target shift, $F(4.2, 76.1) = 4.51$, $p < 0.001$, $\eta_p^2 = 0.2$. For Bayesian analyses, the alternative hypothesis with a model with position as a factor was also strongly favored against the null hypothesis ($BF_{10} = 1.945e + 21$).

We performed Holm-Bonferroni corrected post hoc *t*-tests to test for differences from the baseline (0 degrees) condition; they revealed differences between the highest performance observed for 0 degrees shift (baseline; M = 74.1%, SD = 15.9) and performance observed for almost every other shift (-3 degrees inward, M = 64.4%, SD = 19.3%, $t(18) = 2.735$, $p = 0.014$; +1 degree outward, M = 66.3%, SD = 19.4%, $t(18) = 2.852$, $p = 0.011$; +2 degrees outward, M = 64.4%, SD = 17.9%, $t(18) = 2.959$, $p = 0.008$; +3 degrees outward, M = 62.4%, SD = 19.5%: $t(18) = 3.241$, $p = 0.005$), except for the -2 degrees ($t(18) = 1.865$, $p = 0.079$) and -1 degree inward locations ($t(18) = 0.446$, $p = 0.661$). Bayesian paired samples *t*-tests revealed moderate support for the alternative hypothesis of a difference from the baseline location for the -3 degrees inward ($BF_{10} = 4.03$), the +1 degrees outward ($BF_{10} = 4.96$), the +2 degrees outward ($BF_{10} = 6.02$), and the +3 degrees outward locations ($BF_{10} = 10.11$). There was equal support for the alternative hypothesis

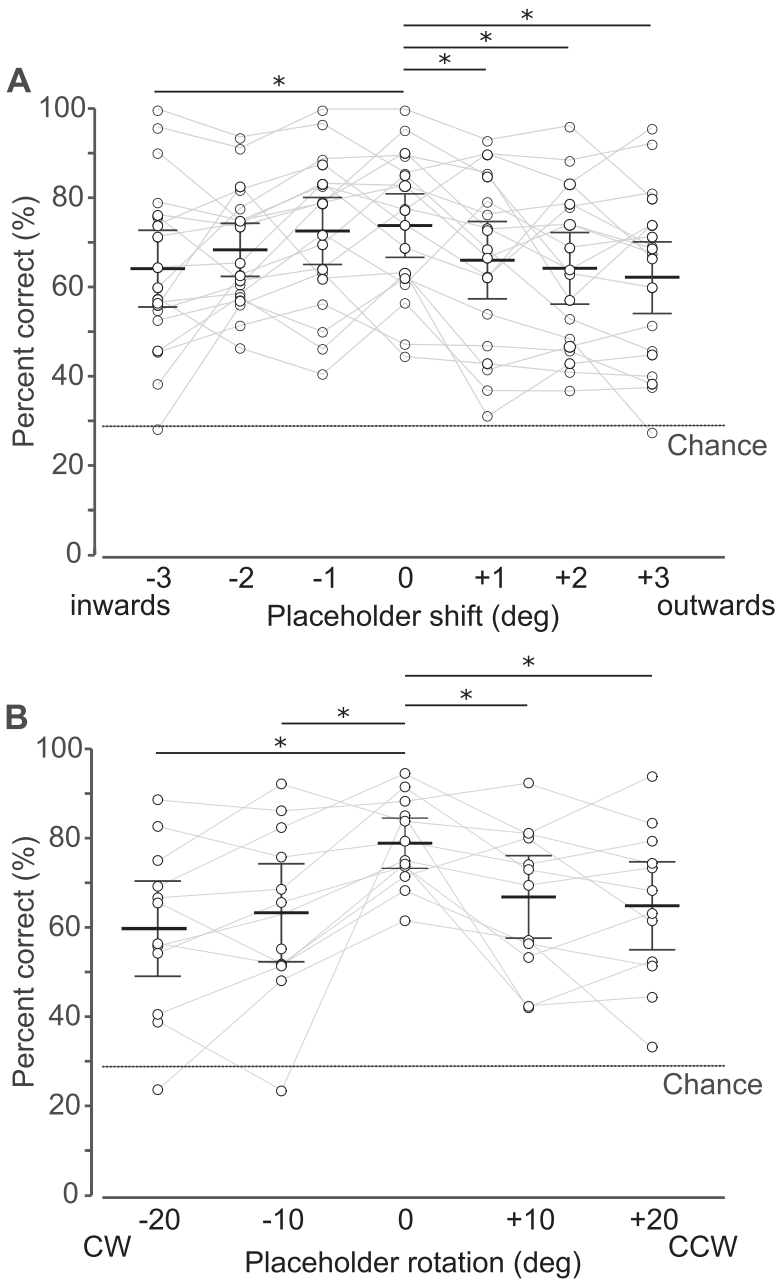

Figure 4. Pre-saccadic discrimination performance across shift conditions in valid position. Performance for individual participants is shown as white circles connected by solid gray lines. Mean correct discrimination rate in percentage (%) is shown by the wider black horizontal bars. Lighter grey bars represent standard error of the mean (SEM). Chance is depicted by the dotted line at 25% of correct discrimination. (**A**) Discrimination performances is shown for every shift of the placeholder. (**B**) Discrimination performance is shown for every rotation of the placeholder. * = $p < 0.05$.

of a difference between the −2 degrees inward location and the null hypothesis ($BF_{10} = 1$) and support in favor of the null hypothesis for the −1 degree inward location ($BF_{10} = 0.26$).

In sum, the best performance was at 0 degrees, which corresponded to baseline. Compared to this location, performance was impaired especially in the most inward shift (−3 degrees) and all outward shifts (+1 degrees, +2 degrees, and +3 degrees).

Performance as a function of rotated DS placeholders

In the rotation condition, the DS could rotate 10 degrees or 20 degrees clockwise or counter-clockwise from its initial location (−20, −10, +10, and +20).

As with the previous analysis, the repeated-measures ANOVA comparing DS placeholder rotations in the invalid position showed no differences in performance for the Rotation factor ($F(4, 44) = 0.845$, $p = 0.504$,

range = 31% to 36.4%, 2 significantly different from chance of 25% (0 degrees, $t(11) = 5.407$, $p < 0.001$; +10 degrees, $t(11) = 3.407$, $p = 0.006$), three not significantly different from chance (−20 degrees, $t(11) = 1.956$, $p = 0.076$; −10 degrees, $t(11) = 1.823$, $p = 0.096$; +20 degrees, $t(11) = 2.777$, $p = 0.018$, Holm-Bonferroni corrected). Consistent with this, the Bayesian repeated-measures ANOVA strongly supported the null hypothesis ($BF_{10} = 0.19$).

Figure 4B shows discrimination performance for every DS rotated location in the valid position. The repeated-measures ANOVA for the valid position found differences as a function of DS placeholder rotation, $F(4, 44) = 7.54$, $p < 0.001$, $\eta_p^2 = 0.41$). For Bayesian analyses, the alternative model was also strongly favored against the null hypothesis ($BF_{10} = 232$).

We performed Holm-Bonferroni corrected post hoc *t*-tests to test for differences from the baseline (0 degrees) condition; these tests revealed significantly decreased performances in all rotations, −20 degrees (M = 61%, SD = 18.8%; $t(11) = 4.324$, $p = 0.001$), −10 degrees (M = 64.9%, SD = 16.1%; $t(11) = 3.15$, $p = 0.009$), +10 degrees (M = 66.6%, SD = 15.8%; $t(11) = 2.833$, $p = 0.016$) and +20 degrees (M = 64.6%, SD = 16.1; $t(11) = 4.083$, $p = 0.002$), compared to no rotation baseline (M = 77%, SD = 9%).

Bayesian paired samples *t*-tests revealed moderate to strong support for the alternative hypothesis of a difference from the baseline condition for all rotations, the −20 degrees rotation ($BF_{10} = 34$), the −10 degrees rotation ($BF_{10} = 6.31$), the +10 degrees rotation ($BF_{10} = 4$), and the +20 degrees rotation ($BF_{10} = 24$).

In sum, the best performance was at 0 degrees (baseline), whereas it was lower for all other placeholder rotations.

Saccade landing positions

We observed that the −1 degree and −2 degrees shift were not different from baseline in the valid position, whereas the other shifts and all rotations were different and we wished to determine whether this was related to the distribution of landing positions, comprising saccade accuracy (e.g. how much undershoot and saccade variability, e.g. how broad an area). 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 end points for all participants for the parallel shift and rotation conditions, respectively, for all trials. Previous studies have shown elliptical distributions with more variability parallel to the saccade vector compared to perpendicular to the saccade vector (van Opstal & van Gisbergen, 1989; Wexler & Collins, 2014). We observed a similar pattern for cardinal directions, whereas 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 shifts, and of binned participants' saccade directions compared with average performance for the different placeholder rotations, 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.

For the shift condition, most saccades had amplitudes varying between 4 degrees and 7 degrees for placeholders arranged in a circular layout with 5.8 degrees of eccentricity; the mean saccade amplitude was at 5.38 degrees (SD = 0.3 degrees), which was significantly smaller than the placeholder distance ($t(18) = 5.7$, $p < 0.001$). A Bayesian one sample *t*-test strongly favored the alternative hypothesis that mean amplitude was different from the placeholder location ($BF_{10} = 1119$). This is consistent with many studies which show that participants tend to undershoot targets particularly for centrifugal saccades (Gillen, Weiler, & Heath, 2013; Irving, Steinbach, Lillakas, Babu & Hutchings, 2006; Nuthmann, Vitu, Engbert, & Kliegl, 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 degree and −2 degrees placeholder shifts. We tested whether there was a correlation between the shifts at which a participant had their best performance and their mean saccade amplitude. We did not find a significant correlation ($r(19) = 0.016$, $p = 0.947$). It should be noted that most participants (9 of them) had their best performance at the no shift baseline location 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 shift separately for the trials with smaller amplitudes (M across participants = 4.88 degrees versus bigger amplitudes (M across participants = 5.88 degrees). We then compared performance using a repeated measures ANOVA with median group (smaller versus bigger saccades amplitudes) and shift (all 7 locations) as factors. We found no significant main effect of the group ($F(1,18) = 2.493$, $p = 0.132$) nor a significant interaction effect ($F(6,108) = 1.4$, $p = 0.21$) as would be expected if there was a difference in performance depending on saccade amplitude. A Bayesian repeated-measures ANOVA revealed strong support for the null hypothesis

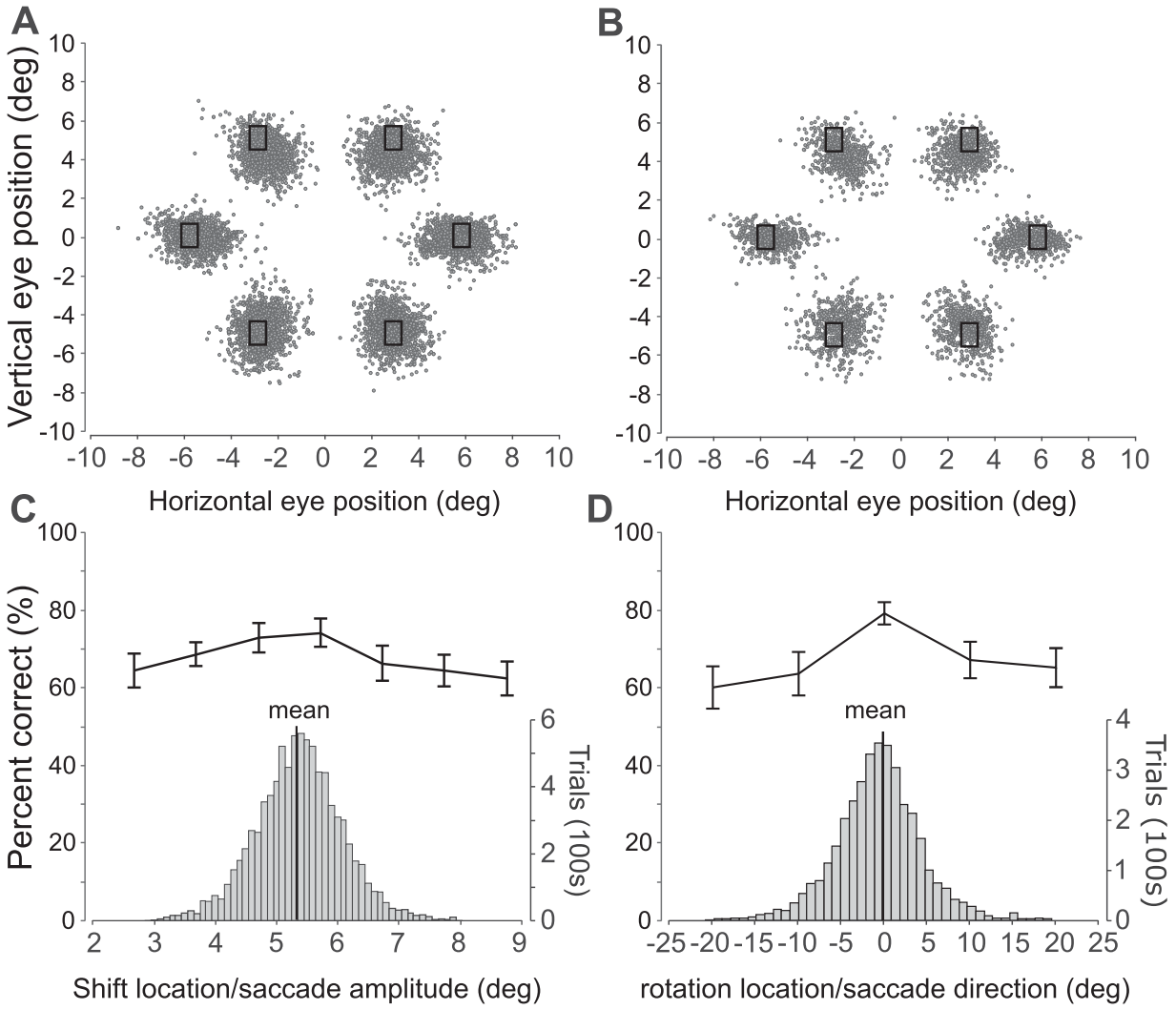

Figure 5. Saccade endpoint distribution and its relation to performance across the shift and rotate conditions in valid position. (**A**) Saccade landing positions in the array are shown as grey dots for every trial in the shift condition. Placeholder locations are shown in black. (**B**) Mean correct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

as opposed to the alternative hypothesis with the model of the Group factor ($BF_{10} = 0.00007$).

Next, we tested whether participants with wider distributions of saccade landing positions would show smaller decreases in performance for the biggest shifts. We performed a median split of distributions/variability, separating participants into those with narrower distributions versus wider distributions (i.e. smaller versus bigger standard deviations for saccade landing positions). We then compared the two groups in terms of change in performance from baseline to the inward 3 degrees shift and as well from baseline to the outward 3 degrees shift. We found no differences between the two groups (inwards shift - $t(17) = 1.2$, $p = 0.248$; outward shift - $t(17) = 0.79$, $p = 0.442$; narrow distribution group SD = 0.57 degrees, 13.72% inward decrease in performance and 5.3% outward; wide distribution group SD = 0.7 degrees, 14.4% inward and 8.6% outward). A Bayesian independent samples *t*-test weakly favored the null hypothesis ($BF_{10} = 0.406$).

We performed the same analyses for the rotation condition. Mean relative saccade direction was at −0.01 degrees (SD = 0.75 degrees), which was not significantly different from the placeholder direction of 0 degrees ($t(11) = 0.05$, $p = 0.9$). A Bayesian one sample *t*-test strongly favored the null hypothesis of no difference ($BF_{10} = 0.28$). We did not find a significant

correlation (r(12) = -0.062, $p = 0.848$) between the rotation location of best performance and mean individual saccade direction; the best identification performance was at the no rotation baseline location for eight 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 degrees, M across participants = 0.56 degrees more counter-clockwise) but found no significant effects (Group main effect – F(1,11) = 0.193, $p = 0.669$; interaction effect – F(4,44) = 2.032, $p = 0.067$). Consistent with this, the Bayesian repeated measures ANOVA strongly favored the null hypothesis above the alternative one with the Group factor ($BF_{10} = 0.198$). Finally, we found that participants with wider distributions in direction (SD = 5.73 degrees) did not show differences in decreases in performance from baseline to the outward-most rotations compared to those with narrower distributions (SD = 4.32 degrees, inward - t(10) = 0.619, $p = 0.55$, outward - t(10) = 0.443, $p = 0.67$). Consistent with this result, Bayesian independent samples *t*-tests strongly favored the null hypothesis (inward – $BF_{10} = 0.528$, outward – $BF_{10} = 0.498$).

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 (shift factor – F(6,108) = 1.685, $p = 0.132$) or the rotation condition (rotation factor – F(4,44) = 0.496, $p = 0.738$). Bayesian repeated measures ANOVAs strongly supported the null hypotheses in both cases (shift factor – $BF_{10} = 0.324$, rotation factor – $BF_{10} = 0.123$).

Post-saccadic changes in Experiment two were programmed to occur when the eyes moved more than 1.85 degrees 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 =7.35 ms). For the rotation condition, average saccade duration was 41.8 ms (SD across participants = 5.14 ms, average participant SD =7.23 ms). On average, the placeholder changed location 10.78 ms (SD across participants = 3.68 ms, average participant SD = 9.4 ms) *before* saccade offset for the parallel shift condition and 11.75 ms (SD across participants = 4.32 ms, average participant SD =8.84 ms) *before* saccade offset for the rotation condition.

Saccade latencies

The mean saccade latency for the parallel shift condition was 282 ms (SD across participants = 53 ms, average within participant SD = 41 ms) whereas for the rotate condition, it was 310 ms (SD across participants = 72 ms, average within participant SD = 44 ms). We confirmed that there were no differences across shifts or rotations or position (valid versus invalid) nor any interaction effects for either the parallel shift condition (position – F(1,18) = 3.39, $p = 0.082$, shift location – F(6,108) = 1.535, $p = 0.174$, interaction – F(6,108) = 1, $p = 0.425$) or the rotation condition (position – F(1,11) = 0.109, $p = 0.747$, rotation – F(4,44) = 1.481, $p = 0.224$, interaction – F(4,44) = 1.418, $p = 0.244$). Bayesian repeated measures ANOVAs weakly favored the alternative hypothesis for the shift condition (best model, position factor only, $BF_{10} = 2.026$) and strongly favored the null hypothesis for the rotation condition (best model, position factor only, $BF_{10} = 0.351$).

Experiment 2 summary

We observed that pre-saccadic discrimination performance decreased when the placeholder at the saccade goal changed location during the saccade. Moreover, whereas there was a decrease in performance for all rotations and most parallel shifts, notably performance did not decrease for the two smallest inward shifts. We therefore tested whether our participants' pattern of performance was related to saccade end point 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 the amount of attention directed to the relevant pre-saccadic object (discrimination symbol DS) by requiring a saccade either to that object or to another placeholder. We found that pre-saccadic attentional facilitation had two major effects. First, it affected the encoding of the pre-saccadic symbol in memory. Pre-saccadic attentional facilitation also changed 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, likely because the correspondence of the most attended object between the pre- and post-saccadic views relative to a constant scene was broken.

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 because participants were asked to discriminate the symbol regardless of its location. 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 five possible invalid positions and chance level at 25% because of the four alternative choices (p, b, q, and 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 (Deubel & Schneider, 1996; Khan et al., 2010). Of note, although this was not significant, we did observe 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 (see Figure 2). We speculate that if there had been above chance level discrimination in the invalid position (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 facilitation is strongly directed at the saccade goal location at the expense of other, even relevant locations. In contrast, facilitation by covert attention does not appear to be as exclusive (Khan et al., 2015).

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

We propose that abrupt post-saccadic changes occurring only at the saccade goal breaks pre- and post-saccadic correspondence of the most attended object relative to a constant visual scene. This specific post-saccadic change captured attention, leading to the encoding of this post-saccadic object into memory, which consequently affected retention of pre-saccadic object information, due to trans-saccadic memory resource limitation. It has been previously suggested that trans-saccadic memory plays an important role in comparing information before and after a saccade (Aagten-Murphy & Bays, 2019; Mathôt & Theeuwes, 2011; Van Eccelpoel, Germeys, De Graef, & Verfaillie, 2008). Trans-saccadic memory has been considered to be based on visual working memory (Luck & Vogel, 1997), due to the similarities in limited memory capacity as well as the timing duration of a few seconds (Bays & Husain, 2008; Cowan, 2011; Irwin, 1992; Irwin, 1996; Jeyachandra et al., 2018; Luck & Vogel, 1997). Previous studies have shown evidence for automatic attention leading to automatic encoding into visual working/trans-saccadic memory (Hollingworth & Matsukura, 2019; Jonikaitis & Moore, 2019; Kong, Kroell, Schneegans, Aagten-Murphy, & Bays, 2021), at the expense of the item already in memory, namely here memory of the pre-saccadic symbol is disrupted, resulting in decreased discrimination performance. The observed disruption of trans-saccadic memory due to post-saccadic changes therefore adds arguments for limited resources in trans-saccadic memory (Poth et al., 2015). If memory resources were unlimited, we would expect no memory disruption, and thus no decreased discrimination performance.

Our results also support the idea that pre-saccadic attentional facilitation is involved in selecting information to be stored in trans-saccadic memory and compared after the saccade (Deubel, Bridgeman,

& Schneider, 1998; Irwin & Robinson, 2015; Rolfs et al., 2011; Wolf & Schütz, 2015). It has been previously suggested that pre-saccadic attention acts as a 'gatekeeper' for trans-saccadic memory, or alternatively as a predictive 'pointer' to remember and update objects' identity and location across saccades (Cavanagh et al., 2010; Melcher, 2011; Prime et al., 2007; Rolfs et al., 2011; Szinte, Jonikaitis, Rolfs, Cavanagh, & Deubel, 2016; Van Eccelpoel et al., 2008). We show evidence here that the saccade target captures a large part of the attentional resources before and also after the saccade execution, at the expense of other, even relevant objects.

We speculated that the determination of object correspondence for the saccade goal played a role in the disruption of trans-saccadic memory, rather than an abrupt attention-grabbing change in saccade placeholder. This was based on our observations of (1) no discrimination disruption in the AllOff condition in the first experiment and (2) clear discrimination disruption when the saccade goal object shifted of only 1 degree outwards in the second experiment. It has been suggested that breaking object correspondence results in separate memory items of the pre- and post-saccadic objects, which compete for limited trans-saccadic memory (Poth et al., 2015). Numerous studies have supported the relative importance of the post-saccadic object compared to the pre-saccadic one, for visual stability (Deubel et al., 1998; Poth et al., 2015; Tas, Moore, & Hollingworth, 2012; Tas, Mordkoff, & Hollingworth, 2021; Weiß, Schneider, & Herwig, 2015), (i.e. the pre-saccadic information becomes less relevant at the expense of the post-saccadic new object/scene, and so has fewer memory resources). Further, the observation that discrimination performance decreased only when there was a relative change at the saccade placeholder location, supports the idea that object correspondence determination might be more related to the visual scene than just the saccade goal object itself. This is consistent with a recent finding that other stimuli similar to the target may be perceptually grouped and attended pre-saccadically (Shurygina, Pooresmaeili, & Rolfs, 2021) and that factors such as the relative positions of other objects in the scene (Deubel et al., 1998) also play a role in object correspondence. We suggest that the removal of the entire visual scene (AllOff condition) in our first experiment does not disrupt object correspondence, likely because there is no comparison to make between pre- and post-saccadic scenes. Specifically, because 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 because it occurs as frequently as we blink.

Concerning the clear discrimination disruption when the saccade goal object shifted of only 1 degree 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, Hendry, & Stark, 1975; Mathôt & Theeuwes, 2011; Deubel, Schneider, & Bridgeman, 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, Schut, Fabius, & Van der Stoep, 2020; Wexler & Collins, 2014; but see Joosten & Collins, 2018; Schut, Van der Stoep, Fabius, & Van der Stigchel, 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. Along these lines and given the distinct pattern of discrimination performance we observed for the inward shifts of the saccade placeholder compared to the outward 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, Blohm, Koun, Khan, & Pisella, 2021). Thus, a general variability estimate, which is used by our system to determine object correspondence, rather than one based on saccade execution, could explain our results. This would also explain some discord in previous related studies within the context of saccadic suppression of displacement (Joosten & Collins, 2018; Schut et al., 2018; Van der Stigchel et al., 2020; Wexler & Collins, 2014) on whether trans-saccadic perception (object correspondence) is related to saccade variability or not.

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. In both experiments, the post-saccadic changes disrupted trans-saccadic memory of the object presented pre-saccadically. Similarly, a previous study 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 100 ms (Poth & Schneider, 2015) and both timings showed worsening object letter discrimination, albeit to different degrees. Further studies with different timings of post-saccadic changes would be necessary to determine whether the decreased performance observed in our study varies in magnitude with timing.

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 eight, 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 66.67 ms then replaced by a figure eight placeholder, which remained visible for an average of 190 ms (SD = 35 ms) before its disappearance.

Conclusions

In this study, we asked participants to remember a symbol presented pre-saccadically while changing the visual scene after the saccade. We modulated the relevance of the symbol by directing a saccade to it (pre-saccadic attentional facilitation) or not. We explored the effects of various post-saccadic object disappearance(s) in Experiment one and the spatial limits of pre- and post-saccadic object location continuity in Experiment two. We found that discrimination performance was negatively affected by post-saccadic changes specifically involving the saccade goal location. We conclude that both pre-saccadic attentional facilitation as well as abrupt post-saccadic changes play a role in trans-saccadic memory. The present results provide insights into the limitations of trans-saccadic memory with respect to pre-saccadic attentional facilitation and object correspondence across saccades.

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

Acknowledgments

AZK is funded by the National Sciences and Engineering Council of Canada and by the Canada Research Chair program.

Data is available online at OSF (contact: aarlenne.khan@umontreal.ca).

Commercial relationships: none.
Corresponding author: Aarlenne Zein Khan.
Email: aarlenne.khan@umontreal.ca.
Address: School of Optometry, University of Montreal, Room 260-25, 3744 rue Jean Brillant, Montreal, QC, Canada H3T 1P1.

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