Do eye movements enhance visual memory retrieval?

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ABSTRACT

When remembering an object at a given location, participants tend to return their gaze to that location even after the object has disappeared, known as Looking-at-Nothing (LAN). However, it is unclear whether LAN is associated with better memory performance. Previous studies reporting beneficial effects of LAN have often not systematically manipulated or assessed eye movements. We asked 20 participants to remember the location and identity of eight objects arranged in a circle, shown for 5 s. Participants were prompted to judge whether a location statement (e.g., "Star Right") was correct or incorrect, or referred to a previously unseen object. During memory retrieval, participants either fixated in the screen center or were free to move their eyes. Results reveal no difference in memory accuracy and response time between free-viewing and fixation while a LAN effect was found for saccades during free viewing, but not for microsaccades during fixation. Memory performance was better in those free-viewing trials in which participants made a saccade to the critical location, and scaled with saccade accuracy. These results indicate that saccade kinematics might be related to both memory performance and memory retrieval processes, but the strength of their link would differ between individuals and task demands.

1. Introduction

Eye movements are critically important to the acquisition of visual information and for interactions with the visual world. Humans use eye movements to scan visual scenes and objects which are then processed and stored in memory. Recent studies suggest that eye movements may also be related to the retrieval of stored visual information. For example, when retrieving memory content associated with spatial information, participants tend to fixate the blank location that previously corresponded to the relevant stimulus, a phenomenon termed "Looking-at-Nothing" (LAN; Richardson & Spivey, 2000; Ferreira, Apel, & Henderson, 2008). The LAN phenomenon has been observed in various contexts, including situations in which the participants' task did not involve remembering a stimulus location, e.g., during memory tasks related to language processing, categorization, reasoning, and decision making (for a review, see Scholz, Klichowicz, & Krems, 2018). For example, Richardson and Spivey (2000) asked participants to remember a sentence spoken by a face shown on the computer screen and to provide a judgment about the sentence. Participants reliably looked at the previous location of the face in a blank grid even though their task involved no localization.

A better understanding of the nature and function of LAN could provide insights into the mechanism of memory retrieval and memory representation (Ferreira et al., 2008; Richardson, Altmann, Spivey, & Hoover, 2009). To date, the literature on the LAN phenomenon and on its underlying mechanisms is largely inconclusive with inconsistent correlations between eye movements and memory performance. The current study addresses the need for a more systematic manipulation and detailed analysis of eye movements to investigate the relation between eye movements and memory retrieval performance.

1.1. Are eye movements spatial indexes of memory representations?

A brief review of the literature of the past 20 years reveals that some studies have observed correlations between eye movements and memory performance whereas other studies have found no systematic relationship. Studies on the link between eye movements and memory retrieval differ in their experimental approach, for example, in whether eye movements were merely described or directly manipulated, and which part of the memory process was used as the dependent variable. Most notably, studies can be distinguished based on whether they examined the effects of naturally occurring eye movements on memory

performance, or whether memory performance was systematically compared between different eye movement manipulations. A theoretical assumption behind manipulating eye movements during memory tasks is that they may function as "spatial indexes", which are part of internal memory representations for an object or an event (Richardson et al., 2009). If this was true, then allocating gaze to a position where previously to-be-remembered information was given should enhance retrieval performance, akin to perceptual boosts following the allocation of covert or overt spatial visual attention to an object location (Carrasco, 2018). Correspondingly, restricting eye movements by asking participants to fixate should impair performance (Scholz et al., 2018).

One group of studies compared memory performance between trials with and without a certain pattern of naturally-occurring eye movements, for example, with or without LAN (Altmann, 2004; Brandt & Stark, 1997; Exp. 1 in Damiano & Walther, 2019; Hannula & Ranganath, 2009; Hoover & Richardson, 2008; Laeng, Bloem, D'Ascenzo, & Tommasi, 2014; Johansson, Holsanova, & Holmqvist, 2006; Laeng et al., 2007; Martarelli, Chiquest, Laeng, & Mast, 2017; Richardson & Kirkham, 2004; Exp. 1 & 2 in Richardson & Spivey, 2000; Spivey & Geng, 2001). The other group of studies systematically manipulated eye movements and compared task performance between conditions (Bochynska & Laeng, 2015; Exp. 2 in Damiano & Walther, 2019; Hanning, Jonikaitis, Deubel, & Szinte, 2016; Johansson, Holsanova, Dewhurst, & Holmqvist, 2012; Johansson & Johansson, 2014; Laeng & Teodorescu, 2002; Martarelli & Mast, 2013; Exp. 3, 4, & 5 in Richardson & Spivey, 2000; Ohl & Rolfs, 2017, 2018; Scholz et al., 2018; Scholz, Mehlhorn, & Krems, 2016; Staudte & Altmann, 2017; Wantz, Martarelli, & Mast, 2016). Some of these studies involved manipulations of visual attention via spatial cueing. They compared memory performance between congruent and incongruent cue locations with regard to the previous target position (e.g., Ohl & Rolfs, 2017, 2018; Scholz et al., 2018) or to sequences of eye movements during encoding (e.g., Bochynska & Laeng, 2015). Other studies asked participants to move their eyes freely or to maintain fixation either in the center of the screen (e.g., Johansson et al., 2012) or at other locations (e.g., Damiano & Walther, 2019). Some select studies combined these different methodological approaches (e.g., Johansson & Johansson, 2014). Moreover, studies with gaze manipulation focused on different aspects of the memory process, e.g., encoding, retention, retrieval, or both encoding and retrieval. Overall, there is an agreement in the literature that restricting eye movements during encoding impairs memory performance (Damiano & Walther, 2019; Johansson et al. 2012; Laeng & Teodorescu, 2002; Richardson & Spivey, 2000).

However, findings are less consistent for retrieval, with reports of impaired memory accuracy (e.g., Johansson et al., 2012; Laeng et al., 2014; Laeng & Teodorescu, 2002; Scholz et al., 2016) or mixed results with some experiments yielding benefits, others yielding null effects (Damiano & Walther, 2019; Johansson and Johansson, 2014; Laeng et al. 2014; Scholz et al., 2018; Staudte & Altmann, 2017). For instance, Johansson and Johansson (2014) restricted gaze behavior and found benefits of free viewing as compared to fixation for reaction time (RT) but not accuracy. Although this result was interpreted as evidence for the impact of eye movements on visuospatial memory, the effect was not robust and it is unclear why only RT but not accuracy was positively impacted. These differences emphasize the need for systematic manipulations and analyses of eye movements during memory retrieval.

1.2. Current methodological approaches to investigating eye movements during retrieval

These inconsistent results reported in the literature could be due to different levels of manipulation and analysis of eye movements. More specifically, the following factors might have contributed to conflicting findings.

First, studies manipulating gaze mostly set lenient criteria for fixation, implying that trials with incomplete fixation might have been included in many results. For example, Johansson and Johansson (2014) excluded trials in which the eyes moved out of a three-degree radius of the fixation cross, a relatively large range that still allowed saccades of up to 6 degrees of visual angle (°) in size. Damiano and Walther (2019; Experiment 2) used an area of interest around their fixation cross that spanned 6.8° squared, resulting in a removal of only approx. 5% of trials per participant. The present study set more stringent criteria for fixation.

Second, none of the studies that manipulated gaze during retrieval considered the role of miniature eye movements—known as microsaccades—during fixation (Rucci & Poletti, 2015). Microsaccades are a smaller version of saccades; both are controlled by the same neuronal mechanisms (Martinez-Conde, Macknik, & Hubel, 2004; Rucci & Poletti, 2015). Microsaccades likely occurred during fixation in memory studies that restricted gaze, potentially producing similar benefits on performance as saccades during free viewing. Moreover, investigating microsaccades might reveal covert shifts of attention toward the targets in the absence of larger saccadic eye movements (Engbert & Kliegl, 2003; Hafed & Clark, 2002; van Ede, Chekround, & Nobre, 2019). The current study measures and compares memory performance between microsaccades during fixation and saccades during free viewing and investigates whether a similar LAN effect occurs in microsaccades and in saccades.

Third, memory tasks usually require participants to engage for a longer encoding or retrieval period and eye blinks are likely to occur during this period, possibly impacting cognitive processes. For example, Jongkees and Colzato (2016) suggest a possible function of eye blinks as updating of representations in frontal cortex. A possible relation between eye movements and memory might thus be modulated by eye blinks. There has been no consensus in the literature on how much signal loss should be considered a blink. Some researchers suggest signal loss between 200 and 500 ms (ms) as a likely blink (Jongkees & Colzato, 2016). Here, we set a strict criterion to exclude trials with blinks.

Forth, previous studies did not specify which eye movement parameters are linked to benefits on memory retrieval, i.e., it is unclear how close the eye has to land to the previous target location, and how long the eye has to fixate this location in order to boost retrieval performance. Most studies have used static eye movement measures related to eye position: mean gaze dwell time at the critical location (e.g., Laeng & Teodorescu, 2002; Laeng et al., 2007; Laeng et al., 2014; Martarelli & Mast, 2013; Martarelli et al., 2017; Exp. 1 in Richardson & Kirkham, 2004; Wantz et al., 2016) or proportion of fixation spent at the critical location (e.g., Richardson & Spivey, 2000; Exps. 2 & 3 in Richardson & Kirkham, 2004; Scholz et al., 2016; Scholz et al., 2018).

Our study addresses the need for a more systematic manipulation and detailed analysis of eye movements to investigate the relation between eye movements and retrieval performance. We compare memory performance between fixation and free-viewing conditions in an experiment that manipulated and measured eye movements at high accuracy and with strict quality control for fixation and eye blinks. We used various measures for eye movement parameters in terms of spatial accuracy and temporal dynamics to depict the nature of LAN.

2. Method

2.1. Participants

Twenty participants (mean age 22.9 ± 3.4 years, 16 females) with normal or corrected-to-normal visual acuity participated (in this paper, '±' always indicates a mean value and its standard deviation). This sample size is similar to samples tested in previous publications that obtained a LAN effect (e.g., $n = 20$ and 21 in Exps. 3 and 4 in Johansson et al., 2012; $n = 24$ in Johansson & Johansson, 2014; $n = 18$ and 16 in Exps. 1 and 2 in Richardson and Spivey). Participants were

recruited through flyers posted on communication boards on the University of British Columbia (UBC) campus and a paid-studies mailing list. All participants were unaware of the purpose of the experiment and gave written informed consent before participation. The study was approved by the UBC Behavioral Research Ethics Board. Participants received a remuneration of $12 CAD per hour.

2.2. Apparatus and stimuli

Visual stimuli were presented on a 22-inch CRT monitor (NEC MultiSync, Downers Grove, IL) with a refresh rate of 60 Hz and a resolution of 1600 (H) × 1200 (V) pixels in a display window of 39.6 (H) × 29.7 (V) cm. Stimulus display and data collection were controlled by a PC operated on Windows 10 with an Intel UHD 630 graphics card. The experiment was programmed in Matlab R2018a using the Psychophysics Toolbox 3.0.14 (Brainard, 1997; Pelli, 1997; Kleiner et al., 2007). Participants were seated in a dimly lit room at 61 cm distance from the screen with their head supported by a combined chin- and forehead rest, and viewed stimuli binocularly. Auditory verbal cues were generated by the program and presented through multimedia speakers (Labtec, Vancouver, WA). Images of everyday objects were selected from an image database (Rossion & Pourtois, 2004, downloaded from http://titan.cog.brown.edu:8080/TarrLab/stimuli/objects/svlo.zip/download). We selected 128 pictures for experimental trials and eight pictures for the practice phase based on a rule where object names had to be one word with three to eight letters. Each of the 128 pictures was repeated once, but never within the same block or condition. For non-target stimuli, 96 names of concrete objects (plus three for the practice phase) were chosen based on the same rule as above.

2.3. Experimental procedure and design

At the beginning of the experiment, all participants completed a picture familiarization phase. They viewed a printed list of the picture stimuli and were asked to name them aloud so that the experimenter could ensure participants knew the names of pictured objects. The experiment started with a brief practice block with nine trials, followed by four experimental blocks. Eye movements were manipulated in separate blocks of 72 trials each: half of the participants first completed two blocks during which they were asked to fixate, followed by two blocks during which they were free to move their eyes; the other half of participants completed blocks in reversed order. Each observer completed 288 trials total. Within each block of trials, congruent, incongruent and new trials occurred equally often and were randomly interleaved. Target pictures were repeated up to two times within the experiment, but they never appeared twice in the same block or within one condition. New names were never repeated. Block order was counterbalanced across participants.

Each block consisted of eight encoding-interruption-retrieval modules (Fig. 1), each containing eight different picture stimuli (64 pictures used per block). Each module started with drift correction of the eye position, followed by an encoding phase, during which observers viewed eight pictures on the computer screen for 5 s. They were asked to remember them and their locations. Pictures were presented in pairs of two at 12 o'clock, 3 o'clock, 6 o'clock and 9 o'clock, respectively. The pairwise arrangement was chosen to restrict saccades to cardinal directions because auditory cues for diagonal directions (e.g., "up-right") would be two-syllable words and thus longer than for cardinal directions (e.g., "up"). The interruption task consisted of a simple arithmetic equation shown on the screen (e.g., $7 \times 2 - 3 + 9 = 20$?). Observers were asked to judge whether the equation was correct or not by pressing an assigned key on the computer keyboard. The purpose of this task was to prevent verbal rehearsal of remembered stimulus names. Following encoding and interruption, each module then consisted of nine trials with retrieval prompts asking observers to judge whether an auditory, verbal location statement (e.g., "Star Right") was congruent (i.e., the star was previously shown on the right) or incongruent (i.e., the star was shown in another location) by pressing an assigned "yes" or "no" key. In one third of trials in each module, the location statement introduced a new object that was not part of the previous set of images. These had to be correctly identified by pressing an assigned "new" key. Observers were instructed to respond as accurately and quickly as possible after the end of the question statements. After each response, observers received auditory feedback (high-pitch beep for correct and low-pitch beep for incorrect answers). This procedure allowed us to distinguish eye movements during the first word (e.g., "Star")—presumably spontaneous responses to access memory about the object—from those during the second word (e.g., "Right")—likely an intentional inspection of the location to access the memory.

The design was a 2 (gaze manipulation: free viewing and fixation) × 3 (retrieval conditions: congruent, incongruent, and new) within-subject design. The experiment took about 90 min to complete and participants were encouraged to take breaks between blocks.

2.4. Eye movement recordings and analysis

We recorded the position of each participant's right eye with a high-accuracy and high-resolution video-based eye tracker (Eyelink 1000; SR Research Ltd, Ottawa, ON, Canada) at a sampling rate of 1000 Hz. All data were analyzed off-line using custom-made routines in Matlab for the detection and analysis of saccades and microsaccades. Eye velocity profiles were filtered using a low-pass, second-order Butterworth filter with cutoff frequencies of 15 Hz (position) and 30 Hz (velocity). Saccades and microsaccades were detected based on a combined velocity and acceleration criterion: Five consecutive frames had to exceed a fixed velocity criterion of 50°/s for saccades and 6°/s for microsaccades. Saccade on- and offsets were then determined as acceleration minima and maxima, respectively (Edinger, Pai, & Spering, 2017). Fixations were defined as eye movements within a diameter of 2° around the central fixation cross (0.7° black '+' sign). We analyzed saccades during free viewing and microsaccades during fixation. If there were no saccade or microsaccades in a given trial, the number of saccades/microsaccades was counted as zero in that condition. For saccades and microsaccades, we calculated the following parameters: average number of saccades and microsaccades and their temporal dynamics during the instruction period. For saccades only, we also analyzed the proportion of gaze dwell time at the critical AOI during this period, and the amplitude of saccades towards the critical AOI.

In order to analyze saccades and microsaccades without any potential effect of eye blinks, all eye position traces with a missing sample (as defined by Eyelink) at any time point during the trial were removed from analysis. All traces were manually inspected to confirm blinks were removed. To avoid high blink rates, participants were asked to blink between trials; this resulted in 14% of blink trials in the free-viewing condition and 10% of blink trials in the fixation condition across participants. Participants held stable fixation in 75% out of all trials in the fixation condition. We included 2490 valid trials in the free-viewing condition and 2113 trials in the fixation condition in the analysis.

To analyze the LAN phenomenon, we set a 1200 × 1200 pixel critical region around where the target pictures were shown during encoding; this analysis region was divided into four areas of interest (AOI) by two crossing diagonal lines to evenly cover all possible stimulus locations (see Fig. 3). For analysis and illustration purposes, we defined the critical AOI to always be in the upper quadrant (labeled AOI1), and rotated eye position data accordingly. We labeled non-critical regions as AOI2, AOI3, and AOI4 in clockwise direction. The new condition was not assigned a critical region, as there was no physical target presented. To focus on eye movements related to memory retrieval, and not on decision making (Saito, Kinjo, & Ohtani, 2015; Saito, Nouchi, Kinjo, & Kawashima, 2017), we analyzed responses during the
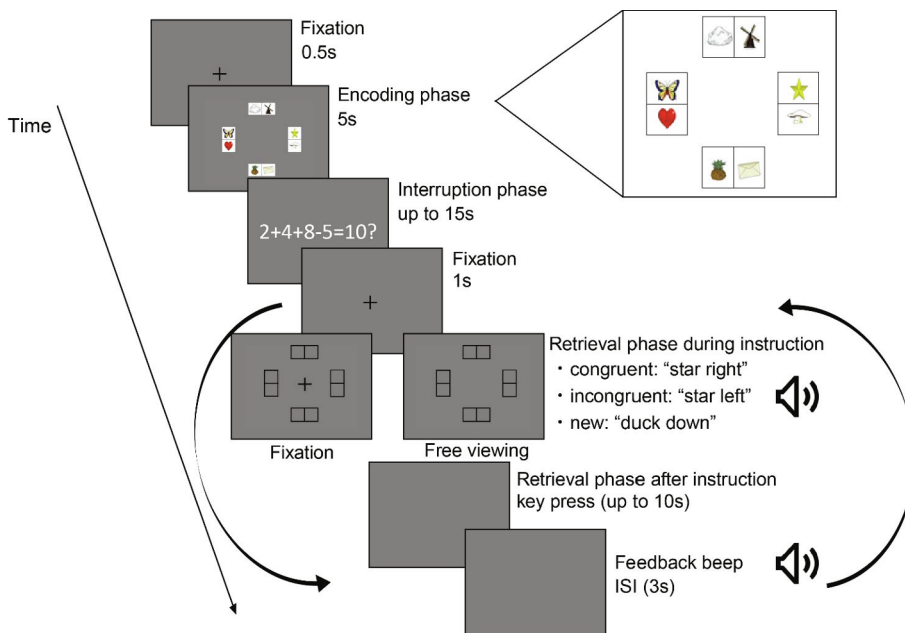
Fig. 1. Module time sequence of events. Each module began with a 500-ms fixation period. Eight pictures were presented for 5 s during the encoding phase, followed by an interruption task. After observers fixated again for 1 s, eight blank squares were shown at the same position as the pictures previously presented. Each module included nine trials with retrieval prompts that were either congruent, incongruent, or new. As soon as the observer pressed one of the three pre-assigned keys to give a response, a new retrieval prompt was given. Auditory feedback indicated whether the response was correct (high beep: correct; low beep: incorrect).

auditory prompt (instruction) period only; this period lasted on average 2668 ± 350 ms. One of the advantages of relating eye movements to memory performance is that eye movements are a continuous response. We analyzed eye movement measures (such as saccade rate, dwell time) over time by splitting the instruction period into 200-ms bins across 200–1400 ms for the 1st-word period and 1600–2800 ms for the 2nd-word period. We chose the 1st-word period based on the average duration for the 1st word, 1230 ± 343 ms. We did not include a third analysis interval after the offset of the direction word, because observers' blink rate during this time interval was high. Including this additional analysis interval would have yielded too few usable trials for analysis.

2.5. Hypotheses and statistical analyses

First, regarding memory performance, if LAN enhances memory retrieval, we would expect differential effects of gaze manipulations on memory performance: memory accuracy would be higher and response time faster during free-viewing (allowing saccades that could follow the LAN phenomenon) vs. during fixation. As a secondary assumption, if microsaccades triggered similar beneficial effects as saccades, we would expect to see LAN effects during fixation, i.e., in microsaccades. Second, regarding eye movements, we expected a LAN effect during free viewing, i.e., the majority of saccades made during the auditory prompt period would go to AOI1. We expected the magnitude of this effect to be similar in congruent and incongruent conditions during the 1st-word instruction period. Here, the experimental design allows us to measure spontaneous eye movements during retrieval without interference by the effect of instruction including direction words, i.e., "Right". We expected a smaller LAN effect for the incongruent condition vs. the congruent condition during the entire (1st and 2nd) word instruction period, where direction words will likely bias gaze.

These hypotheses were tested as follows. For behavioral measures, we calculated memory accuracy (percent correct) and mean RT of correct trials for each participant in each experimental condition, and conducted a 2 (gaze condition) $\times$ 3 (retrieval condition) repeated-measures ANOVA on each behavioral measure. For eye movement measures, we evaluated the LAN effect in correct and incorrect trials in four eye movement parameters—average number of saccades and microsaccades and their temporal dynamics during the instruction period, the proportion of gaze dwell time at the critical AOI during this period,

and the amplitude of saccades towards the critical AOI. On the average number of saccades and microsaccades we conducted a 3 (retrieval condition) $\times$ 4 (AOI) repeated-measures ANOVA. On their temporal dynamics, we conducted a 4 (the critical AOI vs. the other AOIs in congruent and incongruent condiitons) $\times$ 6 (time bins) repeated-measures ANOVA for the 1st-word instruction period, and a 4 (the critical AOI vs. the other AOIs in congruent and incongruent con-diitons) $\times$ 8 (time bins) ANOVA for the 2nd-word period.

Since the LAN phenomenon was not found in any measure of microsaccades in the above analyses, the following analyses were only conducted for saccades. On the proportion of gaze dwell time, we conducted a 4 (the critical AOI vs. the other AOIs in congruent and incongruent condiitons) $\times$ 6 (time bin) repeated-measures ANOVA during the 1st-word instruction period, and a 4 (the critical AOI vs. the other AOIs in congruent and incongruent condiitons) $\times$ 8 (time bin) ANOVA for the 2nd-word instruction period. To investigate saccade accuracy, we compared the amplitude of the first saccades towards the critical AOI for correct trials among the three retrieval conditions via a one-way repeated-measures ANOVA.

Post-hoc pairwise comparisons with Bonferroni correction were computed for any significant interaction effects. Wherever sphericity assumptions were violated as indicated by Mendoza's multi-sample sphericity test, Huynh-Feldt-Lecoutre's corrections were applied to adjust the number of degrees of freedom for within-group effects. An alpha level of 0.05 was used for all statistical tests. All statistical analyses were carried out in R version 3.4.2. To evaluate the strength of reported null effects we calculated the Bayes factor BF_{01} with default prior scales using the 'BayesFactor' package in R (Morey et al., 2015; Rouder et al., 2009). A Bayes factor < 1 is considered evidence against the null hypothesis, a Bayes factor between 1 and 10 is considered anecdotal evidence, and a Bayes factor > 10 (or, in some cases, > 20) is regarded as strong evidence for the null hypothesis (Jarosz & Wiley, 2014).

3. Results

We will first report behavioral results in the memory task, then describe eye movement characteristics during the memory task, investigate LAN with various eye movement measures, and finally relate eye movements to memory performance.

3.1. Memory performance

We first confirmed that our task successfully prevented rehearsal and analyzed performance in the mental arithmetic interruption task. Observers correctly responded to arithmetic questions in 85.7 ± 15.9% of trials on average. Across all trials, arithmetic and memory performance were uncorrelated ($r = 0.01$ for accuracy, and $r = -0.06$ for RT), indicating that rehearsal was not a factor contributing to memory performance in our study.

To investigate whether memory performance depends on eye movements, we compared memory accuracy and RT between fixation and free viewing trials. We found similar patterns of results across eye movement manipulations for both memory accuracy (compare left and right panels in Fig. 2A) and RT (left vs. right panels in Fig. 2B). This observation was confirmed by a non-significant main effect of eye movements on memory accuracy ($F(1,19) = 1.43$, $p = .25$, $\eta_p^2 = 0.07$) and RT ($F(1,19) = 4.15$, $p = .06$, $\eta_p^2 = 0.18$). These findings indicate that allowing observers to move their eyes freely did not necessarily result in benefits in either memory accuracy (proportion correct in fixation: 0.85 ± 0.07, free viewing: 0.84 ± 0.07; $BF_{01} = 2.29$) or reaction time (fixation: 3452 ± 399 ms, free viewing: 3576 ± 546 ms; $BF_{01} = 0.78$).

Memory accuracy was overall higher in new trials (0.92 ± 0.07) than in congruent (0.80 ± 0.10) or incongruent trials (0.81 ± 0.09; Fig. 2A), reflected in a significant main effect of retrieval on accuracy ($F(2,38) = 27.25$, $p < .001$, $\eta_p^2 = 0.59$). RT was faster in new (3469 ± 396 ms) and congruent trials (3493 ± 517 ms) than in incongruent trials (3580 ± 578 ms; Fig. 2B), reflected in a significant main effect of retrieval on RT ($F(1.22,19) = 5.32$, $p = .02$, $\eta_p^2 = 0.22$). These findings show that observers discriminated new stimuli from previously-viewed stimuli accurately. We investigated the possibility of a decision bias to respond with "new", which resulted in faster reaction. The bias for judging "new" in the congruent and incongruent conditions was 0.07 ± 0.05 and 0.07 ± 0.04 respectively, smaller than the bias for judging "incongruent" in the congruent condition, 0.11 ± 0.07 or "congruent" in the incongruent condition 0.11 ± 0.06. Thus, it seems that there is no bias in favor of judging "new".

One of our aims was to investigate the effect of eye blinks on memory performance. Accuracy was lower in blink (0.71 ± 0.21) as compared to no-blink trials (0.80 ± 0.08), and reaction time was slower in blink (3796 ± 724 ms) versus no-blink trials (3610 ± 535 ms). However, these differences were not significant for either accuracy ($F(1,19) = 3.01$, $p = .09$, $\eta_p^2 = 0.14$) nor reaction time ($F(1,19) = 2.82$, $p = .10$, $\eta_p^2 = 0.13$). Despite these small blink-related performance differences we also found no overall significant difference in results when conducting any of our analyses with or without blink trials.
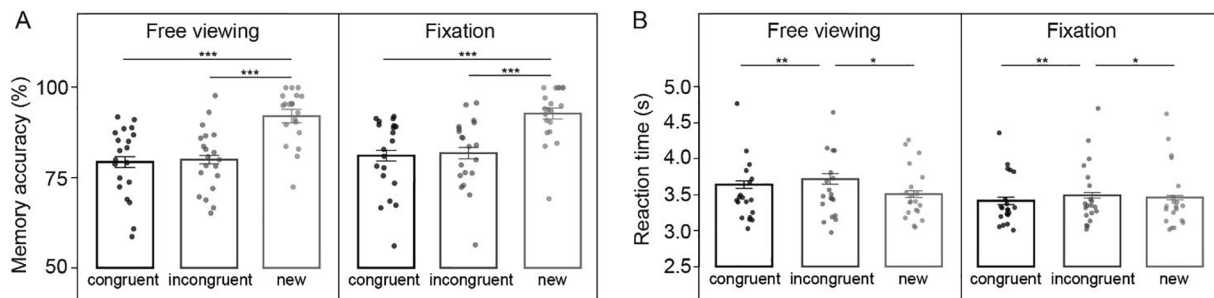

Fig. 3. Average saccade landing positions (2D position at the time of saccade offset) in congruent and incongruent conditions for one representative participant during free viewing during the 1st-word (e.g., "Star") instruction period.

3.2. Eye movement patterns

We analyzed whether eye movements—saccades during free viewing and microsaccades during fixation—went into the critical area of interest (defined as the upper quadrant for analysis and illustration purposes, see Methods and Fig. 3) and evaluated the number and amplitude of saccades and microsaccades as well as dwell time. Fig. 3 shows representative saccade landing positions from one participant during the 1st-word (e.g., "Star") instruction period in the free-viewing condition. Despite some variability in landing positions, the majority of saccades went towards the critical AOI (i.e., up) for this participant.

We next examined the number of saccades and microsaccades at each AOI across all participants during the 1st-word instruction period for congruent vs. incongruent trials. Fig. 4 shows that patterns of eye movements differed between gaze conditions: during free viewing, the eyes went to the critical AOI more frequently than to the other AOIs (Fig. 4A), confirming results shown for one participant in Fig. 3. A paired t-test comparing the horizontal landing position of the first saccade between the two target locations (i.e., left and right) within the critical AOI confirmed that the eyes targeted the critical AOI in general, rather than one individual object, with no significant difference observed between the two target locations within the critical AOI (t

Fig. 2. A) Memory accuracy (percent correct) as a function of experimental conditions. B) Reaction time (RT) for correct trials as a function of experimental conditions. Each dot represents averaged accuracy and RT across trials for one participant. Error bars represent standard errors of the mean. ***$p < .001$, **$p < .01$, *$p < .05$.
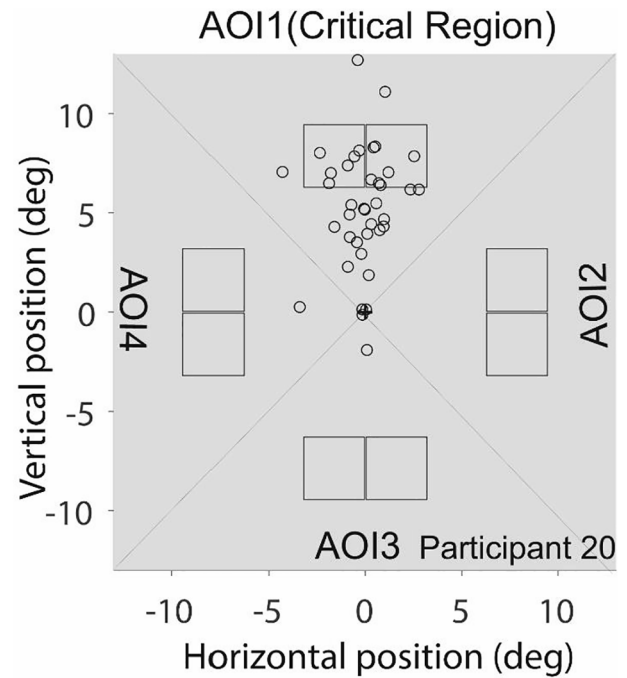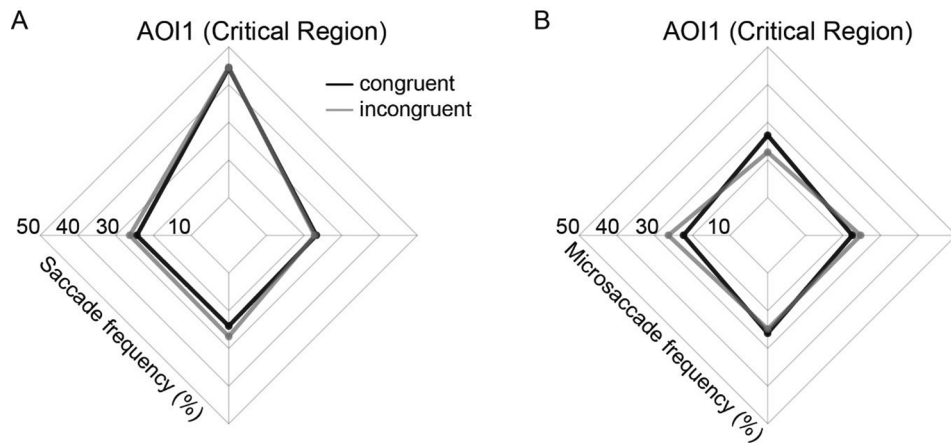
Fig. 4. Average percent frequency of A) saccades and B) microsaccades at AOIs during the 1st-word (e.g., "Star") in congruent and incongruent trials during free viewing for all participants.
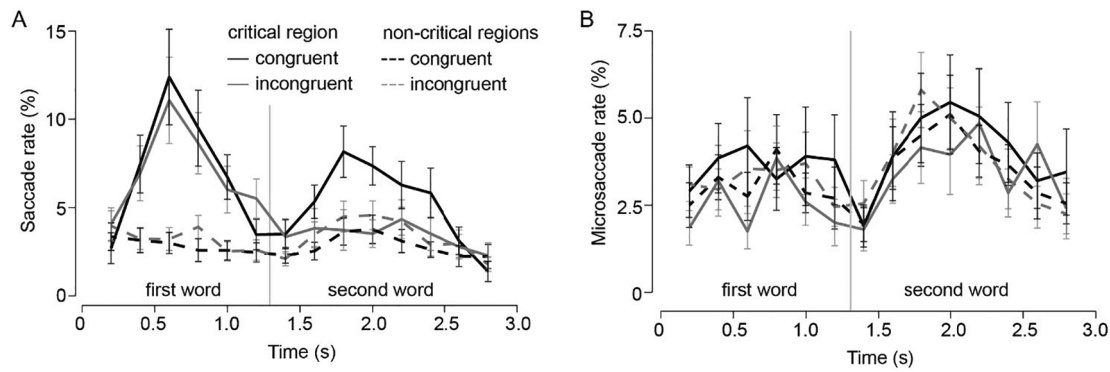

Fig. 5. Temporal dynamics of average rate of A) saccades and B) microsaccades across participants at the critical AOI and the other AOIs during instruction statements (e.g., "Star Right"') in congruent and incongruent trials. Mean rates were calculated at each 200-ms time bin in the interval 200 ms after onset to offset of instruction statements. The vertical line indicates the average end time of the 1st-word (1230 ms). Error bars represent standard error of the means.

(16) = 1.67, $p = .12$). The difference between AOIs was confirmed in a significant main effect of AOI location on saccade number ($F(1.85, 35.22) = 12.75$, $p < .001$, $\eta_p^2 = 0.40$) and a significant location × retrieval condition interaction ($F(2.63, 49.94) = 10.83$, $p < .001$ $\eta_p^2 = 0.36$), but we observed no main effect of retrieval ($F(1.87, 35.5) = 0.76$, $p = .47$, $\eta_p^2 = 0.04$). Accordingly, post-hoc analyses of saccades during free viewing revealed a LAN effect in both congruent and incongruent trials (AOI1 > AOI2 = AOI3 = AOI4; 0.42 ± 0.35, 0.17 ± 0.15, 0.17 ± 0.18, and 0.18 ± 0.15 for congruent trials; 0.43 ± 0.34, 0.16 ± 0.13, 0.22 ± 0.17, and 0.21 ± 0.17 for incongruent trials). Similar patterns of results were observed when analyzing saccade numbers during the entire (1st- and 2nd-word) instruction period (AOI1 > AOI2 > AOI3 = AOI4; 0.82 ± 0.54, 0.51 ± 0.40, 0.30 ± 0.23, and 0.32 ± 0.21 for congruent trials; 0.67 ± 0.49, 0.53 ± 0.40, 0.40 ± 0.27, and 0.38 ± 0.31 for incongruent trials).

By contrast, microsaccades did not reveal any difference across locations (AOI1 = AOI2 = AOI3 = AOI4; 0.22 ± 0.21, 0.17 ± 0.15, 0.21 ± 0.19, and 0.17 ± 0.17 for congruent trials; 0.16 ± 0.12, 0.19 ± 0.18, 0.19 ± 0.15, and 0.21 ± 0.21 for incongruent trials), and no indication that the critical AOI was targeted more often (Fig. 4B), reflected in no significant effect of AOI during the 1st word period for congruent trials ($F(2.30, 43.64) = 2.70$, $p = .07$, $\eta_p^2 = 0.12$) and incongruent trials ($F(2.57, 48.92) = 2.68$, $p = .08$, $\eta_p^2 = 0.12$).

For free viewing, we investigated the effect of the direction cue on eye movements in the "new" condition. This analysis served to investigate whether participants more correctly classified an item as new when they looked in the direction the cue was pointing to. We

conducted a one-way repeated-measures ANOVA on the number of saccades according to each direction (up, down, right, left). We find no main effect of direction instruction for any of the directions, i.e., the number of saccades was not significantly different between the direction the cue was pointing to vs. any other directions for "up", $F(1,19) = 0.57$, $p = .46$, $\eta_p^2 = 0.03$; "right", $F(1,19) = 0.004$, $p = .95$, $\eta_p^2 = 0.0002$; "down", $F(1,19) = 0.89$, $p = .36$, $\eta_p^2 = 0.04$; and "left", $F(1, 19) = 1.50$, $p = .24$, $\eta_p^2 = 0.07$.

Next, to evaluate the temporal dynamics of saccades and microsaccades, we compared the time course of the average rate of saccades and microsaccades during the 1st-word and the 2nd-word period in congruent and incongruent trials for free viewing (Fig. 5A) and fixation (Fig. 5B). Confirming observations reported above on saccade number, during the 1st-word period, participants saccaded more frequently towards the critical AOI vs. the other AOIs in congruent and incongruent conditions during free viewing; this saccade rate peaked at around 600 ms after the start of the instruction period (Fig. 5A). These result patterns, which indicate a clear LAN phenomenon, were reflected in a main effect of AOI ($F(2.46, 46.74) = 9.68$, $p = .0001$, $\eta_p^2 = 0.34$) and time bin ($F(1.24, 23.57) = 15.55$, $p = .0001$, $\eta_p^2 = 0.45$) and a significant AOI × time bin interaction ($F(7.35, 139.6) = 5.46$, $p = .0001$, $\eta_p^2 = 0.22$).

Regarding temporal dynamics of saccades during the 2nd-word period, Fig. 5A shows that the eyes moved to the critical region only in the congruent condition, reflected in a main effect of AOI ($F(5.87, 111.51) = 9.67$, $p < .0001$, $\eta_p^2 = 0.34$). This result suggests that the eyes seem to spontaneously move to the critical region in response to the 1st word. The second peak in the congruent condition at around
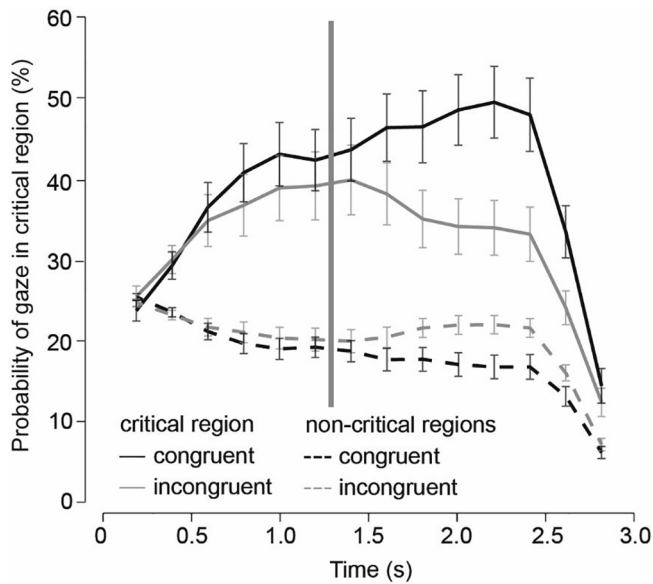
Fig. 6. Dwell time at the critical AOI and other AOI during the instruction period. Probabilities were calculated at each 200 ms time bin in the interval 200 ms from the start to the end of the question statement. The vertical line indicates the averaged offset of the 1st-word (1230 ms). Error bars represent standard error of the means.

1800 ms seems to reflect a reaction to the direction word in the instruction.

For fixation, no systematic preferences for the critical AOI were found either during the 1st-word or the 2nd-word period (Fig. 5B). Similar to saccades, microsaccade rate was also higher during the middle of the 2nd word period, likely due to spontaneous responses to the direction instruction.

Eye movement results so far focused on the frequency of saccades and microsaccades to a particular location. In the following, we will summarize results obtained for dwell time (time spent at the critical AOI) and saccade amplitude. Fig. 6 shows the temporal development of dwell time for critical vs. non-critical AOIs. Result patterns match those described above for saccade frequency: the eye tended to stay in the critical AOI in both congruent and incongruent conditions during the 1st-word period, confirmed by a main effect of AOI ($F(1.39, 26.5) = 13.47, p = .0004, \eta_p^2 = 0.41$). Dwell time decreased in the incongruent condition during the 2nd-word interval, whereas the eye continued to stay at the critical AOI until up to 2600 ms in the congruent condition, revealing the time course of the LAN phenomenon in

our task. These observations are reflected in significant main effects of AOI ($F(1.88, 35.71) = 177.67, p < .0001, \eta_p^2 = 0.90$) and time bin ($F(1.20, 22.82) = 20.77, p = .0001, \eta_p^2 = 0.52$), and their interaction ($F(3.95, 75.14) = 9.84, p < .0001, \eta_p^2 = 0.34$).

Finally, we compared the amplitude of the 1st saccade to the critical AOI for correct trials among the retrieval conditions for free viewing and found a significant main effect of gaze condition ($F(1.26, 23.94) = 7.90, p = .006, \eta_p^2 = 0.29$). Posthoc comparisons between congruent, incongruent and new conditions showed that the 1st saccade was more accurate (i.e., had a larger amplitude) in congruent ($2.30 \pm 2.29°$) and incongruent conditions ($2.11 \pm 2.07°$) than in the new condition ($0.98 \pm 1.03°$).

To summarize: higher saccade frequencies, longer dwell times at the critical AOI, and larger saccade amplitudes towards the critical AOI confirm the LAN phenomenon during free viewing. The LAN effect did not extend to microsaccades during fixation. Notwithstanding the clear indication of saccade-driven LAN during memory retrieval in our experiment, we found no difference in memory performance between fixation and free viewing (see Fig. 2).

3.3. Variability, individual differences in eye movement behavior

When preprocessing eye movement data, we observed that participants differed with regard to how frequently they made saccades or remained fixated in the free-viewing condition. To further investigate the relation between LAN and memory retrieval, we conducted additional exploratory analyses after separating trials with free-viewing instruction into those in which participants actually moved their eyes vs. trials in which they fixated during free viewing. Whereas some participants consistently moved their eyes (so-called "saccaders", such as the participant in Fig. 3), others made almost no saccades ("non-saccaders"; Fig. 7A). To systematically classify participants as saccaders or non-saccaders we performed a hierarchical cluster analysis (Ward's method) with two clusters (saccaders and non-saccaders) on the number of saccades in all retrieval conditions during free viewing. This resulted in 14 saccaders (saccade rate 0.69 ± 0.17) and six non-saccaders (saccade rate 0.07 ± 0.04). However, these two groups did not differ significantly in their memory performance ($t(6.92) = 1.13, p = .29$; Fig. 8A) or RT ($t(15.56) = 1.67, p = .11$; Fig. 8B). These findings demonstrate that individual differences in saccade rates had no measurable implication for memory performance.

Our results so far show similarities in performance in the free-viewing and fixation condition, indicating that eye movements and memory performance might not necessarily be related. These analyses were conducted across participants. We next investigated whether eye movements that followed LAN related favorably to memory performance during free viewing on a trial-by-trial basis (see Altmann, 2004
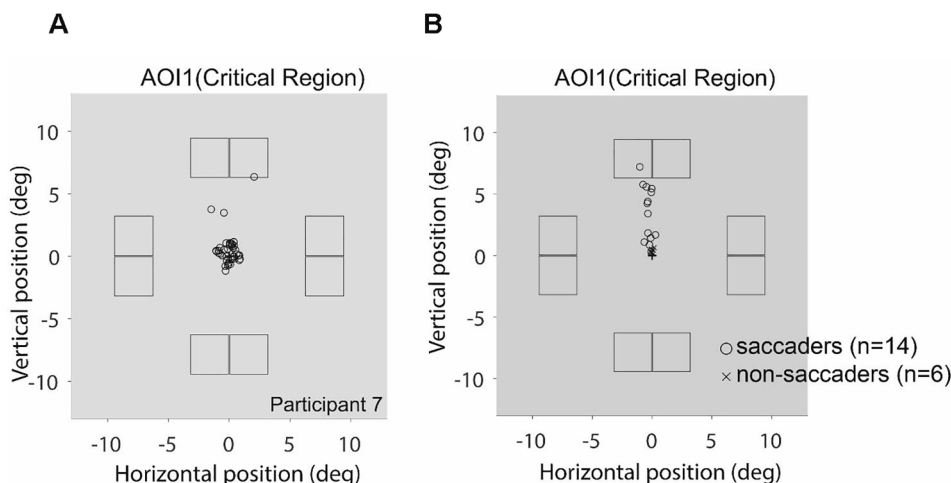

Fig. 7. A) 2D eye positions in congruent and incongruent conditions during free viewing for a representative non-saccader during the 1st-word period. Each circle represents saccade landing position in one trial. B) Average 2D eye positions for each participant. Each circle represents the average maximum gaze position at the critical AOI per participant.
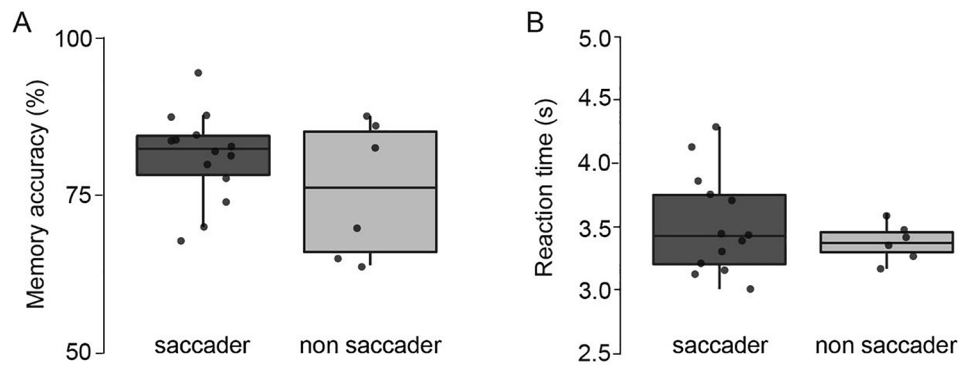
Fig. 8. Boxplots for A) memory accuracy (percent correct) and B) RT for saccaders who tended to move their eyes often vs. non-saccaders who did not move their eyes during free viewing. Error bars represent standard error of the means.

for a similar approach). We defined a "LAN trial" as a trial in which the proportion of saccades toward the AOI exceeded chance (0.25). If participants' saccades did not go into the critical AOI more frequently than chance the trial was labeled a "no-LAN trial"; if participants made no saccades in a given trial, it was considered a "no-saccade trial". Fig. 9 shows mean accuracy and RT for LAN vs. no-LAN trials and reveals significantly better memory performance in LAN as compared to no-LAN trials ($F(2,1652) = 41.86$, $p < .001$, $\eta_p^2 = 0.05$), but no main effect of retrieval condition ($F < 1$), and no interaction ($F < 1$). Congruently, RT was faster in LAN and no-saccade trials than no-LAN trials, supported by a main effect of trial type ($F(2,1312) = 27.99$, $p = .001$, $\eta_p^2 = 0.04$), but no main effect of retrieval ($F(1,1312) = 2.88$, $p = .09$, $\eta_p^2 = 0.002$), and no interaction ($F(2,1312) = 2.39$, $p = .09$, $\eta_p^2 = 0.003$).

These results reveal a link between LAN and memory performance when systematically comparing trials based on actual eye movement performance (i.e., was a saccade made or not, and where did it go) rather than instruction to fixate vs. move the eye.

4. Discussion

This study investigated the role of eye movements in visual short-term memory retrieval by manipulating gaze—fixation vs. free viewing—with strict criteria for the analysis of fixation, saccades, and blinks. We found three major results. First, as hypothesized, we replicated the LAN phenomenon in both congruent and incongruent conditions during free viewing: saccades moved towards the critical region during the 1st-word period more frequently and more accurately, and once the eyes moved to the critical region they were more likely to stay in that area during the instruction period. By contrast, microsaccades did not reveal LAN, indicating that this phenomenon may operate on a larger spatial scale. Result patterns were stable across the four eye movement metrics analyzed here – average number of saccades, their temporal dynamics during the instruction period, dwell

time at the critical AOI, and saccade amplitude toward the critical AOI. These findings implicate that the use of different eye movement metrics is not a limiting factor in interpreting LAN effects in previous studies. Second, and in spite of the evident LAN phenomenon, the behavioral data showed no impact of the eye movement manipulation on memory accuracy or RT. Notwithstanding these negative results, we did observe improved accuracy and RT in trials in which participants' eye movements actually followed the effect predicted by the LAN phenomenon, i.e., went into the critical AOI. These results could be interpreted to imply that moving the eyes towards the critical AOI improves memory performance. However, alternatively, the regressive saccade towards a previously examined location could also be reflective of ongoing retrieval processes or indicate the preparation of a response (Czoschke, Henschke, & Lange, 2019). This interpretation is in line with the finding that saccade kinematics are altered in correct vs. incorrect trials, indicating that eye movements are sensitive indicators of memory retrieval and rehearsal processes.

In the course of the analyses we noticed that some participants, termed non-saccaders, moved their eyes less frequently than saccaders to successfully retrieve visual information during free viewing. Further analysis of individual participant data revealed that memory accuracy was higher in LAN trials than in trials in which no saccade was made, and that memory performance was worse when the eyes moved to an irrelevant location than when no saccade was made. Similarly, RT in LAN trials and no-saccade trials was faster than in no-LAN trials. Taken together, these individual differences in saccade frequency and direction, and the tradeoff between the benefit and cost of making saccades, could be a factor contributing to the inconsistent results of the relation between memory performance and eye movements in the literature. The analysis of individual differences in eye movements and memory performance therefore seems crucial to unravel the origin of the discordant findings reported for the LAN effect in the literature. By contrast, the strict exclusion of trials with signal loss (e.g., due to blinks) did not significantly impact results, suggesting that leniency in the
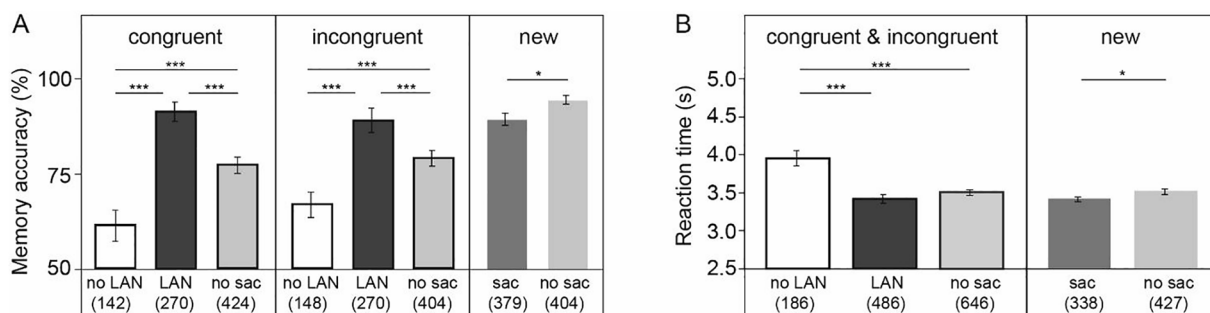

Fig. 9. A) Mean accuracy and B) RT as a function of trial type determined by eye movement patterns and retrieval condition during free viewing. Numbers in parenthesis indicate number of trials for a given trial type. Error bars represent standard error of the means. ***$p < .001$, *$p < .05$.

inclusion of blink trials is not necessarily a limiting factor in interpreting previous LAN studies. However, we did observe small performance differences between blink and no-blink trials and would generally recommend exclusion of blink trials as is standard in most eye-tracking studies.

4.1. Individual differences in making saccades

Given these results, we scrutinized previous studies and found that many studies did not discuss the potential existence of participants who were less likely to move their eyes during memory retrieval. Spivey and Geng (2001) found a LAN phenomenon in their experiment 2 for 24% of all trials, but in the remaining 76% of trials participants were reported to have maintained fixation in the screen center throughout the question period. These results are congruent with those obtained in a study assessing visual-phonological associations in typical and dyslexic adults using a LAN paradigm (Jones, Kuipers, Nugent, Miley, & Oppenheim, 2018). These authors report that approx. one third of all trials did not include fixation on the former location of a target or distractor, yet, resulted in quick and accurate performance. Other studies excluded trials without eye movements or with eye movements of small amplitudes from their main LAN analysis (Johansson et al., 2006; Laeng & Teodorescu, 2002). The literature also suggests individual differences in the magnitude of eye movements: some participants made smaller eye movements and moved their eyes less often during retrieval than during encoding (Brandt & Stark, 1997; Johansson et al., 2006).

Notwithstanding the observed relationship between saccade amplitude and condition in our data, our results also reflect variability in saccade landing positions across participants and trials (see Figs. 3, 7A, & B). Taken together with reports in the literature, it is not clear to what extent saccade accuracy matters for the LAN effect to be beneficial. Whereas some studies suggest that accurate eye movements going back to the location congruent to remembered objects are important to successful retrieval (Bochynska & Laeng, 2015; Johansson & Johansson, 2014; Laeng et al. 2014), others reported that eye movements to the mental representation of a scene or object, rather than to an exact location, might be sufficient (Johansson et al., 2006). Congruently, Brandt and Stark (1997) propose that accurate eye movements are less important for tasks related to imagery than for tasks related to correctly identifying features of a scene or object. In our study, participants may have been able to carry out the memory task during fixation by mentally zooming out of the remembered visual stimulus to grasp the identity and location of the prompted object, explaining why we do not see differences depending on eye movement conditions. Thus, the magnitude of individual eye movements may depend on the size of participants' mental representation. If spatial coordinates of participants' internal representations of target positions are smaller than the actual ones, large saccades may not be necessary to retrieve memory content.

4.2. Theoretical implications for memory retrieval and eye movements

The results that eye movements might be unrelated to memory performance is in line with some of the previous literature. For example, participants can achieve high memory performance during fixation (Richardson & Spivey, 2000). In their experiment 3, Richardson and Spivey (2000) report a 15% performance difference in favor of fixation. It could be argued that the nature of the current memory task would not require participants to move their eyes during retrieval. Namely, participants may have relied on verbal rehearsal "Star is up" without actual visual or spatial representation. Yet, this possibility is unlikely because participants engaged in a distractive arithmetic task after encoding to prevent verbal rehearsal.

A large body of literature provides evidence for a tight link between eye movements, attention, and working memory. Related to the LAN phenomenon, Scholz and colleagues (2018) argue that not eye

movements per se, but covert shifts of attention to the previous target location are sufficient to successfully retrieve memory content. These authors manipulated participants' eye movements by asking them to solve an unrelated perceptual task in either a congruent or an incongruent spatial location associated with previously remembered verbal information. Half of the participants were asked to direct their eyes at the task location, the other half of participants had to covertly shift attention to it. Scholz et al. (2018) found comparably good memory accuracy in both gaze conditions. Covert shifts of attention led to better memory accuracy in congruent than in incongruent trials. In general, covert shifts of attention to critical spatial locations precede eye movements (White, Rolfs, & Carrasco, 2013) and might thus activate the same mechanisms as when the eye movement is actually executed. Other studies directly investigated how planning and executing an eye movement—and thereby how overtly directing attention to a target location—affected memory performance (Ohl & Rolfs, 2017, 2018, 2020). In each trial, these studies employed a briefly-presented array of visual targets that was then masked for a variable amount of time. A movement cue prompted a saccade to a predefined location on the array, and a response cue indicated a memory test location that could be either congruent or incongruent with the saccade target location. Results show that memory performance was increased at the saccade target location, irrespective of whether the saccade was relevant to the memory task. Critically, these findings were obtained when the saccade was executed after the memory array was masked, effectively generating a LAN-like situation. The effect was greatest when memory test and saccade target location were congruent (Ohl & Rolfs, 2018, 2020). Preferential processing for memory information presented at saccade target locations was also observed when the saccade was merely planned but not executed (Hanning et al., 2016). These findings generalize to other endpoint-oriented movements such as pointing or grasping (Heuer & Schubö, 2017; Heuer, Crawford, & Schubö, 2017). Together, these studies highlight the importance of motor target selection for visual working memory performance and emphasize the close link between eye movements and visuospatial working memory (van der Stigchel & Hollingworth, 2018).

Our experiments were not designed to systematically manipulate and test effects of attention shifts, and we did not prompt saccades to specific movement goals congruent or incongruent with the memory test target. Cued saccades are likely more accurate in general (e.g., yielding position errors of approx. 0.3° in Ohl & Rolfs, 2018) than what we observed in our "free viewing" condition, where observers received no specific eye movement instruction and merely moved their eyes in the direction of the previously shown target. Moreover, we used an "interruption" task that resulted in a much longer delay between memory array presentation and retrieval period (i.e., up to 15 s) than in previous studies, where the longest mask duration was approximately three seconds (e.g., Ohl & Rolfs, 2017, 2018). These differences in instruction and trial timeline could explain differences in findings between our study and results reported in the literature. The current finding of similar memory performance regardless of eye movement instruction might be due to similar mechanisms as those described in Scholz et al. (2018): in free-viewing trials in which participants made no saccades, and in fixation trials, participants may have accessed a mental representation using covert shifts of attention (see also Richardson et al., 2009).

4.3. On the role of microsaccades for memory retrieval

Microsaccades reflect the allocation of covert visual attention (Engbert & Kliegl, 2003; Hafed & Clark, 2002; van Ede et al., 2019; Horowitz, Fine, Fenesik, Yugenson, & Wolfe, 2007), even within the foveola (Poletti, Rucci, & Carrasco, 2017). We expected that microsaccades might also be related to memory performance, yet, we did not find evidence for a LAN effect during fixation. Van Ede and colleagues (2019) reported minimal gaze shifts toward targets (termed "looking-

towards-nothing") in a working memory task that required reproducing the orientation or color of an object (but not its location). Importantly, however, these small gaze biases were only observed if the task required participants to shift their internal focus of attention to the to-be-remembered object, but not if the object was already attended. Our experiment did not include any attentional cueing or instruction and results can therefore not be compared directly. Regardless, the lack of LAN effect in microsaccades is surprising and the possibility of a link between microsaccades and visual working memory performance remains an important issue to be investigated further.

5. Conclusion

The present results are inconclusive regarding the question whether eye movements benefit memory performance. However, the finding that performance is similar regardless of eye movement instruction and behavior suggests that both states of utilizing eye movements—either by making saccades or by maintaining fixation—can be beneficial for memory retrieval. A "non-saccadic mode" would aid performance when a covert shift of attention is sufficient to perform the task. A "saccadic mode" would imply that a mental representation needs to be accessed to obtain information beyond what can be gathered by covert shifts of attention. Individual differences within and between participants, possibly related to the ability to zoom in and out of a mental representation, appear to determine to which degree the eyes are moved. Further analysis of such individual differences might enable a better understanding of the functional role of the LAN phenomenon and help unravel the origin of contradictory findings in the previous literature.

To conclude, eye movements might be linked to both memory performance and memory retrieval processes, but the strength of their link would differ between individuals and task demands. The general notion that eye movements are sensitive indicators and building blocks of perceptual and cognitive performance (Fooken & Spering, 2019; Ohl & Rolfs, 2017; Schneider, Einhäuser, & Horstmann, 2013; van Ede et al., 2019) is in line with our observation that the eye returns to the critical object location during retrieval.

Declarations of interest

None.

CRediT authorship contribution statement

Hikari Kinjo: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Funding acquisition. **Jolande Fooken:** Software, Visualization, Formal analysis. **Miriam Spering:** Conceptualization, Resources, Writing - review & editing, Funding acquisition.

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