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Reinstating location improves mnemonic access but not fidelity of visual mental representations

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Reinstating location improves mnemonic access but not fidelity of visual mental representations

Abstract

In a virtual reality environment combined with a continuous delayed estimation paradigm, we investigated how manipulation of location at recall (i.e., corresponding vs. non-corresponding to the location where the object was previously encoded) affected mnemonic access and mnemonic fidelity of color information in 100 participants with a within-subjects design. We predicted that the reinstatement of location during recall would improve mnemonic access and mnemonic fidelity. The results suggest that congruent location enhances color access. However, congruent location seems to play no role, or a small role not yet identified in enhancing the details of visual mental representations (weak evidence for the null hypothesis). Explorative analyses revealed that self-reported object imagery preferences modulate the effect of location manipulation on mnemonic access. Overall, the results support the conceptualization of spatial information as a basic feature to help access visual mental representations. Taken together, these findings are in line with the scaffolding hypothesis of visual mental imagery.

Keywords: location, color, visual memory, mnemonic fidelity, memory access, virtual reality

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1. Introduction

Imagine that somebody asks you how an object, like for example a pencil looks. Returning to the room that you last used the pencil in and looking back at where you previously used the pencil might allow you to remember the details of the pencil, such as the color of the pencil. These experiences suggest a special relationship between encoding context and details of the to-be-remembered object. Several studies have found that our eyes revisit the location where an event was encoded, when this information is later recalled even when there is nothing to look at (Altmann, 2004; Brandt & Stark, 1997; Chiquet et al., 2021; Fourtassi et al., 2013; Johansson et al., 2006; 2012; Johansson & Johansson, 2014; Laeng & Teodorescu, 2002; Laeng et al., 2014; Martarelli & Mast, 2011; 2013; Martarelli et al., 2017; Richardson & Spivey, 2000; Scholz et al., 2016; 2018; Spivey & Geng, 2001; Umar et al., 2021). It has been suggested that “looking back to nothing” is functional to mental representations by binding objects in the world to cognitive processes such as visual memory (e.g., Ballard, Hayhoe, Pook, & Rao, 1997). Executing eye movements to the areas where the stimuli were encoded activates parts of an integrated memory trace and thus can increase memory performance (e.g., Ferreira, Apel, Henderson, 2008; Richardson, Altmann, Spivey, & Hoover, 2009). Investigating whether reinstating location enhances the fidelity of visual memory was the primary goal of our study.

There is evidence that participants are better at performing visual memory tasks when they are free to move their eyes, or when their gaze is constrained to areas visited during encoding compared to when their gaze is constrained to other areas not visited during encoding (Bochynska & Laeng, 2015; Damiano & Walther, 2019; Johansson et al., 2012; Johansson & Johansson, 2014; Laeng & Teodorescu, 2002; Laeng et al., 2014; Olsen et al.,

2014). Expanding on this work, a recent review of Wynn et al. (2019) proposed that eye movements play a functional role by reinstating the encoding context: “We propose that eye movements support online memory retrieval; that is, active retrieval that continuously updates as viewers move their eyes, by broadly reinstating the spatiotemporal encoding context based on the demands of the task...” (p. 6). In their theory, the authors focus primarily on memory access and suggest that location is a fundamental feature with a scaffolding function for further retrieval when it comes to the organization of visual memory. Returning the eyes to the previously visited areas serves as a strong retrieval cue for other features of the object (e.g., Henderson & Hollingworth, 2003). Given previous suggestions that eye movements are functional to visual mental representations, it is legitimate to assume that location reinstatement positively affects the fidelity of visual mental representations.

Research in the field of visual memory using eye position manipulations is mainly based on quantitative binary measures of memory retrieval, such as true/false answers about distinctive features of the previously seen object (e.g., color). Existing studies have - thus far - failed to directly assess the impact of location manipulations on the mnemonic fidelity of visual mental representations. Even though there is evidence that reinstating former locations improves memory for information associated with that location (e.g., Laeng et al., 2014), it is still unclear whether reinstating previous locations can enhance mnemonic fidelity of mental representations.

By allowing for the differentiation between mnemonic access (quantity of retrieved information) and mnemonic fidelity (quality of retrieved information), the continuous delayed estimation paradigm (e.g., Brady, Konkle, Gill, Oliva, & Alvarez, 2013; Harlow & Yonelinas, 2016; Luck & Vogel, 2013; Tamber-Rosenau, Fintzi & Marois, 2015; Ma, Husain & Bays, 2014; Ovalle Fresa & Rothen, 2019; Richter, Cooper, Bays, & Simons, 2016) addresses the shortcomings of prior research in the field and is ideally suited to answer our research question: *Can reinstating location improve mnemonic fidelity of visual mental*

representations? Specifically, we asked whether manipulation of location at recall (i.e., corresponding vs. non-corresponding to the location where an object was previously encoded) affects whether we remember – and/or alter the fidelity of mental representations (i.e., the precision of perceptual details that are remembered). We address this issue by applying a standard mixture model analysis (Zhang and Luck, 2008) that assumes distinct parameters to estimate the likelihood of recall and the fidelity of representation for successfully recalled objects. Participants had to reinstate the previously seen colors of objects using a continuous dial of 360 increments. This method of continuous measures allowed for the calculation of error distributions, which can then be fitted by assuming the standard mixture model, including a uniform distribution to estimate the likelihood to recall the color, and a von Mises distribution to estimate mnemonic fidelity. Based on the evidence that looking back to areas where stimuli were previously encoded can facilitate retrieval of visual memory representations, we hypothesize that reinstating the encoding context to the corresponding location is a privileged route to access detailed visual mental representations (i.e., mnemonic fidelity), beyond the simple access of a memory trace in a probabilistic all-or-none manner.

While language-based processes are sufficient to access a memory trace (e.g., “the previously seen object was blue”), reinstating the exact color of an object is a perceptual process and cannot exclusively rely on semantic information. Thus, with the experimental approach adopted here, we can shed light on the nature of visual mental representations. Contrary to the idea that eye movements during mental imagery might be epiphenomenal (e.g., Pylyshyn, 2003), we expect looking back to the corresponding position to increase mnemonic fidelity, due to the functional role of eye-movements and thus, confirming the pictorial nature of visual mental representations (e.g., Borst, & Kosslyn, 2008; Laeng et al., 2014). Our hypothesis suggested that eye movements to previously visited areas support not only access to visual representations (i.e., better recall in standard mixture model terms), but also the reconstruction of a perceptual world in visual representations (i.e., enhanced fidelity

in standard mixture model terms). More generally, we hypothesize that visual memory and visual perception rely on common underlying representations in terms of spatial layout.

To this aim, we used continuous measures in a three-dimensional (3D) virtual reality (VR) approach to test the functionality of reinstating location for visual memory. The 3D VR approach permits a more naturalistic representation of space compared with 2D computer-based experiments. VR enables immersive and interactive experiences in rich contexts, which are not provided by classical experimental settings. It has been argued that external validity is not guaranteed in 2D computer-based experiments because in everyday life, memory processes take place in interactive 3D contexts (e.g., Kisker et al., 2019). Furthermore, in contrast to a real setting, the VR environment allows for a high degree of experimental control, e.g., manipulation, reposition of the entire environment as well as the accurate measurement of location, orientation, and color of virtual objects, while allowing participants to engage with their environment in a realistic manner. The VR setting allows for a complete standardization of the visual setting (e.g., inclusion of the entire visual field) as well as, for the exclusion of nuisance variables usually linked to the experimental room, such as the position of the experimenter, relative to the subject. In our pilot study we successfully validated the VR setting (see Appendix).

2. Method

2.1. Proposed Sample Characteristics

2.1.1. Determination of Sample Size

In order to deal with issues concerning power, the experiment was conducted using a Bayes factor stopping rule approach (Rouder, 2014) applied to the guess rate and precision. The pilot study ($N = 13$, see Appendix) essentially resembles the non-corresponding condition of the pre-registered experiment. In the pilot experiment we found a color guess rate (mean) of 0.17 ($SD = 0.11$) and a color precision (mean) of 22.04 ($SD = 2.54$). We expected a better performance in the corresponding condition than in the non-corresponding condition both in

terms of guess rate (smaller guess rate) and precision (smaller precision values). Thus, the maximal difference between the non-corresponding condition and the corresponding condition cannot be larger than 0.17 (standardized difference = 1.54) for guess rate and cannot be larger than 22.04 (standardized difference = 8.67) for precision. These effect sizes can be defined as the maximum expected effect sizes, and the expected difference between the non-corresponding and corresponding conditions can be half of this value (room-to-move heuristic; Dienes, 2019). The expected effect sizes are large, we thus decided to work with a range of 0.20 to 0.80 expected effect sizes (which is a reasonable range of effect sizes in psychological research). We tested our directional hypotheses (corresponding condition < non-corresponding condition) with one-tailed Bayesian paired *t*-tests with Cauchy-distributed priors (see e.g., Rouder et al., 2009) with a mode of 0, and with a scale parameter ranging from 0.20 to 0.80 to compare guess rate and precision between the corresponding location and non-corresponding location manipulations (within-subjects factor manipulation). We analyzed guess rate and precision individually. We specified a range of reasonable effect sizes (ranging from 0.20 to 0.80), and we assessed the stability of the Bayes factors across this range (see Dienes, 2019; Rouder & Haaf, 2020). With JASP (JASP Team, 2020) it is possible to produce a graph showing the Bayes factor for different scale factors. We report these graphs along the Bayes factors for small, medium, and large effects. To quantify how much the data should shift our belief in favor of the null or the alternative hypothesis, we computed Bayes factors (BF_{10} where 1 means that the two hypotheses are equally likely, larger values indicate more evidence for the alternative hypothesis, and smaller values indicate more evidence for the null hypothesis). We tested sequentially with a maximal *N* of 100 participants and defined an a priori threshold of 6 for the experimental hypothesis and 1/6 for the null hypothesis (see Schönbrodt & Wagenmakers, 2018). The chosen a priori thresholds are the minimum required thresholds of the journal. We preregistered to stop collecting data when robustness was achieved, i.e., when scales that range from small to large effects all result in $BFs > 6$ or $< 1/6$

for both of our dependent variables (guess rate and precision). We started with an initial pool of 25 participants and tested our hypotheses for the first time. We selected this number of participants based on previous studies using the continuous delayed estimation paradigm to investigate visual memory, that tested a number of participants in a range of 5-25 participants per condition (see e.g., Brady et al., 2013). If the BFs did not exceed the defined thresholds, the sample size was increased with one additional participant. Then we tested the hypothesis again, etc. We continued testing until all Bayes factors were at least 6 times in favor of the experimental hypothesis over the null hypothesis (or vice versa) or until we achieved a sample size of 100 participants. We specified a maximum feasible sample size at which data collection ceases regardless of the Bayes factors. We consider 100 participants a number sufficiently large that inconclusive results would nevertheless be an important message for the field.

Moreover, if a participant could not complete the experiment (for technical problems with the VR system or cybersickness) the dataset was excluded. However, if participants reported feeling dizzy or unwell after completion, the dataset was not excluded. We planned to collect data from participants (age range of 18 to 40 years) recruited from the general population who were willing to complete the study in our laboratories close to the main station of Brig (Switzerland). We screened participants for motion sickness and only invited participants that did not report motion sickness. Moreover, participants were screened for color vision defects with the online version of the Farnsworth Dichotomous Test (D-15; <https://www.color-blindness.com/color-arrangement-test/>; e.g., Vingrys and King-Smith 1988). Participants showing a total error score (TES) larger than 17, or a deviation in one of the other values suggested by Vingrys and King-Smith (1988), were not invited to participate to our study.

Participants were free to stop the experiment at any point. All participants gave written-informed consent and received a payoff of CHF 25. The local Ethics Committee

approved the study, which was conducted according to the principles expressed in the Declaration of Helsinki.

2.1.2. Final Sample Size and Demographics

We tested 111 participants, screened for motion sickness (i.e., we only invited participants who did not report motion sickness) and for color vision defects with the online version of the Farnsworth Dichotomous Test (D-15; <https://www.color-blindness.com/color-arrangement-test/>). Two participants showed a total error score above 17 on this test and were thus excluded. All other participants showed a total error score below 17 and no defects in the specific indices (i.e., confusion angle, major and minor radius, selectivity index, confusion index), suggesting no color vision defects. We further excluded six participants because of technical problems with the VR system, two participants because they did not complete the task and one participant because she did not follow the instructions of the task. The final sample of 100 participants was constituted of 69 female participants. The mean age of the sample was of 27.5 years (ranging from 18 to 40).

2.2. Materials and Design

2.2.1. Virtual Environment and Virtual Objects

The study was conducted in a VR environment (HTC Vive system, see under equipment for more information). We validated the paradigm (continuous delayed estimation paradigm in VR) with a pilot experiment (see Appendix).

As stimulus material, we used a set of 120 validated virtual objects (see Popic et al., 2020). The objects were common in daily usage and belonged to categories such as furniture, electronic devices, and food. Also, they were not rotationally symmetric (i.e., they looked differently in each distinct orientation, e.g., a cup with one handle instead of a cup with two handles). The objects were uniformly scaled (i.e., approximately same size). We used these objects twice. The objects were built in Maya versions 18 and 19 (Autodesk Maya software,

<https://www.autodesk.com/products/maya/>). Lighting for objects was dynamic and shadow of objects was eliminated. See Figure 3 for example objects.

The environment was also built using Maya. It consisted of an empty room with a round table at its center. Footprints marked the position at which participants were asked to stand for each block (see Figure 1). The lighting for the environment was baked into the textures. The model was exported from Maya to FBX format and online rendered using Unreal Engine 4 version 4.21.2 (Epic games). The task was run on a Windows machine with an Intel Core i7-7700K-CPU with 4.2GHz 16 GB of RAM. The machine had an Asus GeForce GTX 1080 Ti (11GB GDDR5X) graphics card. The task was programmed in the game engine Unreal Engine 4.

Figure 1. Sample image of a potential view of the room. Participants were asked to stand on the footprints to standardize their starting position.

2.2.2. Equipment

We employed an HTC Vive system. The set-up contained an HTC Vive Head Mounted Display (HMD), two HTC Vive motion controllers (see Figure 2) and two infrared laser

emitter units (lighthouses). This system allowed users to move within a 4 x 4 m space and offered tracking of location and orientation. These measurements were in a coordinate system which was bound to the physical ground plane. Objects were displayed with the HMD at a constant frame rate of 90 Hz through 2 displays at a resolution of 1080 x 1200 pixels per display. End-to-end system latency was estimated at 22ms (Niehorster, Li & Lappe, 2017). This is sufficiently low for the environment to appear stable. The experiment was conducted in a 10 x 10 x 3 m simulated room. The table had a diameter of 156 cm and a height of 91 cm. Lighthouses were mounted on tripod at a height of 2 m from the ground.

2.3. Procedure

The procedure was divided into a practice phase and a test phase (two times 40 encoding-recall blocks including a total of 240 trials, 120 per manipulation, i.e., corresponding vs. non-corresponding location). Computing the standard mixture model with a small number of trials is not reliable and can result in bad convergence. A number of 120 trials can be considered as a minimum number of trials when computing mixture models. In the practice phase, participants were exposed to one block (including a total of 3 objects) to allow them to familiarize themselves with the environment, the set-up, motion controllers and the task itself. Participants were allowed to repeat the practice block as many times as needed in order to reduce starting differences due to familiarity with the VR environment and ensure they felt comfortable with the setting.

In the first part of the experiment, 120 objects were distributed across 40 blocks, with every block containing 3 trials each. Participants were allowed to take a short break in the middle of the experiment. After the break, the same objects were used again, but were presented in other locations, with other orientations and with other colors (randomly chosen). See Figure 3 for some example objects.

During encoding the objects were positioned on a table in the virtual environment (see Figure 3). In each encoding phase, participants were presented with three distinctly colored objects, each of which were consecutively presented for 2 seconds, preceded by a fixation cross presented for 100ms in the center of the table. Location was selected at random from a circular parameter with 360 increments (from 0 to 359 degrees) and the same increment was only used once. Color was selected at random from a circular parameter (from 0 to 359 degrees), representing colors on the H plane in HSV color space with equal radius (i.e., equal saturation). Color was converted to 8-bit RGB values from HSV in the Unreal Engine. The same color was only used once. Orientation of the objects was randomly selected from a circular parameter with 360 increments (from 0 to 359 degrees) and the same increment was only used once. Rotation was along the y axis. Each encoding block was followed by a recall block. Before the object was displayed, participants needed to return to the footprint mark in front of the table.

Location was manipulated during recall. In each block of three trials, two objects were presented in a corresponding or non-corresponding location compared to the location during encoding (2:1 ratio). In total, 120 trials were presented in the corresponding location and 120 in a non-corresponding location. Corresponding and non-corresponding locations were always located on the circle shown on the table. The non-corresponding location was at least 50° away from the original location. Corresponding objects were presented in the original location. Orientation was not manipulated (original orientation). Participants were presented with the three previously encoded objects in random order in a grey color and they were tasked to reinstate color using the motion controllers (see Figure 2). Color could be changed using a continuous dial of 360 increments and could be logged in by double click of the confirmation button. The color dial was rotated randomly in each trial to avoid confounds between colors and their spatial locations in the dial. The 360 colors that participants could

select were approximately equidistant values in a circular similarity space. See Figure 3 for a visual representation of the procedure.

Figure 2. Motion Controller. Color could be changed using a continuous dial of 360 increments and could be logged in using two confirmation buttons. Technique was entrained during a practice phase.

Figure 3. Sample experimental procedure of the VR phase. A) With the VR headset participants viewed an empty room with a round table at its center. They were instructed to stand on the footprints to standardize starting position. B) In encoding, 3 objects were presented for 2s, separated by a

fixation cross for 100ms. C) After each encoding phase, the recall phase of 3 objects followed. Objects appeared at corresponding or non-corresponding locations (at least 45° from the original location). Participants were asked to reinstate color of the original object.

Even though we were not using a perceptually uniform color space on a calibrated monitor, it was still reasonable to assume to observe the predicted effects as a function of our within-subject design, manipulating the location of object presentation (corresponding vs. non-corresponding). That is, while we were not able to estimate absolute differences between conditions, we were still able to measure relative differences between conditions. In other words, we could not quantify the gain in precision between the conditions, but we were still able to determine whether recalling the color of an object was indeed more precise in the corresponding in comparison to the non-corresponding condition. This was especially the case since we were sampling a large number of object color associations per condition, averaging out the noise in the perceptually non-uniform color space across our conditions.

For exploratory reasons, the experiment concluded with a computerized Object-Spatial Imagery Questionnaire (OSIQ; Blajenkova, Kozzhevnikov & Motes, 2006). The OSIQ measures individual differences in visuospatial imagery preferences and experiences. It consists of 30 items. Participants rated their agreement/disagreement on a 5-point scale.

2.4. Dependent Variable and Analysis

We measured color recall error. This refers to the difference between the original color of the objects at encoding and the adjusted color of the objects at recall. Recall error was measured in degrees and could lie between 0° (no deviation) and $\pm 180^\circ$ (full deviation). Descriptive statistics of raw recall error and aggregated recall error (see analyses of pilot study, 5.1.1. and 5.1.2.) are reported in Figures 4 and 5 (left).

Figure 4. Distribution of errors (difference between a given response and the original color) of the corresponding (C) and non-corresponding (NC) manipulations, also visualized in circular space.

2.4.1. Estimated Parameters (Standard Mixture Model)

The standard mixture model (Zhang & Luck, 2008) was fitted to the data to estimate access of visual mental representations and mnemonic fidelity. The model uses a mixture of two distributions to explain the distribution of recall errors: A uniform distribution, taken to reflect memory access, and a von Mises distribution taken to reflect mnemonic fidelity. Specifically, we used the estimated height of the uniform distribution as a measure of

mnemonic access (guess rate) and the estimated standard deviation of the von Mises distribution as a measure of mnemonic fidelity (precision). Parameters were estimated using a Bayesian MCMC approach with the functionalities of the CatContModel package (Hardman, 2017, see also Hardman, Vergauwe, and Ricker, 2017). Details about the model specification can be found in the Appendix. We compared the estimated mnemonic access (guess rate) and fidelity (precision) between conditions with one-tailed Bayesian paired t -tests. We share the full non-aggregated dataset and the code to reproduce the analyses on OSF (<https://osf.io/e8fxr/>).

Figure 5. $N = 100$. Recall error (model free, left), probability of guessing (middle), and precision (right) as a function of location manipulation (C = corresponding and NC = non-corresponding). Large points show the condition means with error bars representing 95% confidence intervals for recall error and 95% credible intervals for guess rate and precision. Boxplots are shown with lower and upper hinges corresponding to the first and third quartiles (the 25th and 75th percentiles) and whiskers extending from the hinge to the largest / smallest value no further than $1.5 \times$ inter-quartile range from the hinge. Smaller points represent the average value per participant. Lower values indicate better performance.

3. Results

The resulting parameters *guess rate* (modeled as a uniform distribution, reflecting mnemonic access) and *precision* (modeled as a Von Mises distribution, reflecting mnemonic fidelity) are depicted in Figure 5 (middle and right). Smaller values on both measures are indicative of better performance.

3.1. Guess rate

Color was recalled with less guessing when the object was presented in the corresponding location ($M = 0.116$, $SD = .058$) when compared to the non-corresponding condition ($M = 0.134$, $SD = .067$). Following our preregistration plan, we tested three directional hypotheses (corresponding condition < non-corresponding condition) with one-tailed Bayesian paired t -tests with Cauchy-distributed priors with a mode of 0, and with a scale parameter ranging from 0.20 to 0.80. Bayes factors are reported in Table 1 and the sequential analyses are reported in Figure 6. The BFs were all ≥ 202.745 , thus revealing strong evidence for the alternative hypothesis. The corresponding condition, leading participants to look back where the objects were presented during encoding, enhanced color access during recall when compared to the non-corresponding location manipulation.

3.2. Precision

Despite testing the maximal preregistered number of participants (100 participants) we did not achieve clear evidence in favor or against the alternative hypothesis with precision as dependent variable ($M = 22.591$, $SD = 4.087$ when the object was presented in the corresponding location and $M = 22.836$, $SD = 3.992$ when the object was presented in the non-corresponding location). Bayes factors are reported in Table 1 and the sequential analyses are reported in Figure 7. The BFs were ≤ 0.629 , thus revealing anecdotal evidence for the null hypothesis.

Table 1. Bayesian Paired Samples T-Tests

Scale parameter	Comparison C - NC	BF ₀
0.2	Guess rate	236.734
0.5	Guess rate	253.085
0.8	Guess rate	202.745
0.2	Precision	0.629
0.5	Precision	0.314
0.8	Precision	0.204

Note. For all tests, the alternative hypothesis specifies that guess rate or precision in the corresponding (C) condition is smaller than guess rate or precision in the non-corresponding (NC) condition (directional hypotheses).

Figure 6. Sequential analysis. The alternative hypothesis specifies that guess rate in the corresponding condition is smaller than guess rate in the non-corresponding condition. One-tailed Bayesian t -tests with Cauchy-distributed priors with a mode of 0 and with a scale parameter of 0.2 (left), 0.5 (middle), and 0.8 (right).

Figure 7. Sequential analysis. The alternative hypothesis specifies that precision in the corresponding condition is smaller than precision in the non-corresponding condition. One-tailed Bayesian t -tests with Cauchy-distributed priors with a mode of 0 and with a scale parameter of 0.2 (left), 0.5 (middle), and 0.8 (right).

3.3.Exploratory Analyses

We planned to conduct exploratory analyses to investigate whether individual differences in visuospatial imagery (OSIQ) moderate the effects reported above. For each participant we computed the average scores for the self-reported ratings for object imagery ($M = 3.331$, $SD = 0.570$) and spatial imagery ($M = 2.901$, $SD = 0.617$). The two subscales did not correlate with each other ($r = -0.011$, $p = 0.916$). We computed two mixed model analyses with location (corresponding vs. non corresponding), visual imagery scores, spatial imagery scores, the interaction between location and visual imagery scores, and the interaction between location and spatial imagery scores as fixed effects, participants as random effects, and guess rate and precision respectively as dependent variables. The scores of the two subscales were mean-centered and we used a restricted maximum likelihood method. Degrees of freedom were approximated with the Satterthwaite method. The analyses were computed with *jamovi* (The jamovi project 2022).

3.3.1. *Does visuospatial imagery moderate the effect of location manipulation on mnemonic access?*

We found a significant main effect of location on guess rate (corresponding vs. non-corresponding; $F(1, 97) = 16.118$, $p < 0.001$), thus confirming the analyses reported above. Interestingly, we also observed a significant interaction of location x object imagery scores, $F(1, 97) = 5.754$, $p = 0.018$. We did not observe a significant main effect of object imagery scores, $F(1, 97) = 1.910$, $p = 0.170$, spatial imagery scores, $F(1, 97) = 1.937$, $p = 0.167$, nor a significant interaction between location and spatial imagery scores, $F(1, 97) = 2.300$, $p = 0.133$.

To tease apart the interaction between location and object imagery, we conducted a simple slope analysis. This revealed that the conditional effect of location manipulation on guess rate was significantly different from zero at the mean ($b=0.017$, $SE=0.004$, 95% CIs [0.009, 0.026], $p < 0.001$) and one standard deviation below the mean of object imagery scores ($b=0.028$, $SE=0.006$, 95% CIs [0.016, 0.040], $p < 0.001$) but not one standard deviation above the mean ($b=0.007$, $SE=0.006$, 95% CIs [-0.005, 0.019], $p = 0.258$). These results indicate that the facilitatory role of corresponding spatial information on color access during recall is not relevant for individuals who score high on the object imagery scale. Figure 8 depicts the significant interaction by visualizing the corresponding – non-corresponding differences at high, medium, and low scores of the object imagery scale.

Figure 8. $N = 100$. A visual depiction of the interaction between location manipulation (C = corresponding and NC = non-corresponding) and the object imagery scale. Smaller values of guess rate are indicative of better performance.

3.3.2. Does visuospatial imagery moderate the effect of location manipulation on mnemonic fidelity?

Computing the same model as above but with precision instead of guess rate as dependent variable revealed no significant results. We did not observe a significant main effect of location, $F(1, 97) = 0.586$, $p = 0.446$, object imagery scores, $F(1, 97) = 0.047$, $p = 0.828$, spatial imagery scores, $F(1, 97) = 0.436$, $p = 0.511$, nor a significant interaction between

location and object imagery scores, $F(1, 97) = 0.007, p = 0.932$, and between location and spatial imagery scores, $F(1, 97) = 0.254, p = 0.616$.

4. Discussion

In this registered report we aimed to test two hypotheses, pertaining to the influence of location reinstatement on mnemonic access and mnemonic fidelity respectively. We found enhanced access when recalling color information of an object presented in the corresponding (vs. non-corresponding) location where the object was previously encoded. This result is in line with previous research in the field of mental imagery using eye position manipulations. Researchers showed that eye movements to the area in which the stimuli were previously displayed, facilitate recognition accuracy (e.g., Foulsham & Kingstone, 2012). Similarly, it has been demonstrated that, when answering questions about previously encoded stimuli, participants make fewer errors when they are free to move their eyes during mental image generation compared with central fixation (Laeng et al., 2014). Consistent with these results we found that looking back to the location where the information was encoded enhanced access of color recall. This suggests that spatial information is a fundamental feature that plays a scaffolding role in visual representations by facilitating mnemonic access to related features (Henderson & Hollingworth, 2003; Treisman & Gelade, 1980; Treisman & Zhang, 2006; Wynn et al., 2019; Schneegans & Bays, 2017).

The primary goal of our registered report was to test whether spatial information enhances fidelity of color recall. Thus far, there is some existing evidence that reinstating previous locations is beneficial for recall of information associated with that location (e.g., Laeng et al., 2014). However, it is still unclear whether corresponding spatial information can indeed enhance mnemonic fidelity of visual mental representations. To test this, we relied on three Bayesian t -tests. We found anecdotal evidence for the null hypothesis; the Bayes factors are not smaller than 1/6. As a result, we cannot draw strong conclusions pertaining to this

research question. Nevertheless, we believe that this inconclusive result despite an $N = 100$ carries an important message for the research field. Specifically, this finding is interesting, because mental imagery theories usually imply that looking back to areas previously visited supports not only mnemonic access but also aids in the generation and maintenance of *precise* mental images. By contrast, our results seem to suggest that spatial information is a privileged route to access a memory trace in a probabilistic all-or-none manner but rather not in terms of the mental representation's quality. It is important to note that anecdotal evidence for the null is not equal to a null finding. We thus cannot draw strong conclusions regarding the impact of spatial information on mnemonic fidelity.

If we had found the hypothesized beneficial effect of location reinstatement on mnemonic fidelity, this would have been strong evidence for the pictorial nature of visual mental representations. We cannot rule out that our findings are due to participants using semantic strategies (e.g., “the previously seen object was blue”) along with visual strategies (i.e., the pictorial depiction of blue color). This result fits well with recent theorizing and empirical work highlighting differences between visual perception and visual memory in terms of neural reinstatement, despite extended overlap (Bainbridge et al., 2021; Dijkstra et al., 2019). In the same vein, empirical investigations of aphantasia (i.e., the inability to create mental images with the mind's eye) showing dissociations between spatial and visual representations, suggest that visual memory may not necessarily be pictorial in nature (Bainbridge, Pounder et al., 2021). In fact, it has been suggested that individuals with aphantasia may combine spatial information with verbal information to compensate the lack of visual representations (Bainbridge, Pounder et al., 2021).

Finally, to explore the impact of individual differences in self-reported preferences for visuospatial imagery on mnemonic access and mnemonic fidelity we related the OSIQ (Blajenkova et al. 2006) to guess rate and precision. The OSIQ is a two-dimensional measure including the components Object Imagery (i.e., people's tendency to process and represent

information in terms of visual details such as colors, shape, and texture) and Spatial Imagery (i.e., people's tendency to process and represent information in terms of schematic spatial information). The analyses revealed that the magnitude of the location effect (corresponding vs. non-corresponding) on guess rate was associated with the ability to form clear and vivid mental images (object imagery scale). We found a stronger role for spatial information in color access during recall for individuals scoring low to medium on the object imagery scale. This is likely because individuals with strong object imagery abilities might not need to use spatial information as a scaffolding for the retrieval of visual information (Kozhevnikov et al., 2005). As such, presenting the objects in non-corresponding areas, that were not visited during encoding, does not disrupt the retrieval of color information in these individuals. This is an interesting finding hinting at distinct individual preferences and strategies when executing the same visual memory task. Future research is needed to replicate these exploratory findings.

4.1. Conclusion

Our results suggest that spatial information embedded in natural behavior acts like a scaffolding structure that facilitates the generation of visual mental representations. Color access during recall benefits from reinstating the object's location. However, spatial information does not seem to play a role or plays a small role not yet identified in the precision of visual mental representations. We thus speculate that the role of spatial information is to give a coarse spatial scaffold that helps visual mnemonic access, rather than enhancing the precision and details of the existing visual mental representations. Going forward, it will be important to replicate these findings in different laboratory settings, including VR and 2D computer-based settings. We believe that VR can complement computer-based experiments by embedding visual memory in natural behavior.

5. References

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6. Appendix

6.1. Pilot Experiment

The pilot experiment¹ was carried out in order to validate the VR setting, as - to the best of our knowledge – the delayed estimation paradigm in relation with the standard mixture model (Zhang & Luck, 2008) has only been used in a 2D computer-based settings (e.g., Brady et al., 2013, Ovalle Fresa & Rothen, 2019). Fifteen participants took part in this experiment. Due to technical problems with the VR system, two participants could not complete the experiment and were thus excluded from the analyses. The participants' average age was 25 years ($SD = 2.61$), three were women, ten men. We chose the number of participants based on previous studies using continuous measures to investigate visual memory, that tested a number of participants in a range of 5-25 participants per condition. We preregistered the pilot study on OSF (<https://osf.io/bjaup>).

We used a within-subject design. Participants carried out the task outlined in Section 2.2., but without any manipulation. Thus, we used 120 objects, which is considered a minimum number of trials when computing mixture models. For each block participants were first asked to encode three objects (encoding phase). Each object was presented for two seconds, preceded by a fixation cross for 100ms. Next, participants were presented with the three previously encoded objects in random order (recall phase). Participants were asked to recreate the features location, color and orientation of the object using the two controllers. A practice block of 3 objects was included in order for participants to familiarize themselves with the VR environment and the controllers. Participants were allowed to repeat the practice block, if they did not feel confident with the VR setting. For exploratory reasons, the experiment concluded with a computerized Object-Spatial Imagery Questionnaire (OSIQ; Blajenkova, Kozzhevnikov & Motes, 2006) and the Paper-Folding Test (e.g., Hegarty, Shah

¹ Unless specified, procedure and design are consistent with the main experiment.

& Miyake, 2000). The entire experimental procedure lasted approximately one hour. See Figure S1 for a visual representation of the procedure.

Figure S1. Sample experimental procedure of the VR phase. A) Using the VR headset participants viewed an empty room with a round table at its center. They were instructed to stand on the footprints to standardize starting position. B) In encoding, 3 objects were presented for 2ms, separated by a fixation cross for 100ms. C) After each encoding phase, the recall phase of 3 objects followed. D)

Presented here is a sample sequence of movements that participants could conduct to re-adjust the location, orientation and color of the original object. The motion controllers were displayed as hands in the VR environment.

5.1.1. Raw Data. The analyses were done using *R* (R core Team, 2019) with the functionalities of the *CatContModel* package (Hardman, 2017). The R code to reproduce analyses as well as the dataset is available on OSF (<https://osf.io/e8fxr/>).

Recall error was calculated as the deviation between a given response and the original feature and could lie between -180 and $+180$ degrees. The distribution of errors for the features location, color and orientation can be seen in Figure S2, also visualized in circular space (polar histograms). As can be seen in Figure S2, errors clustered around the original feature, thus suggesting precise recall in the three features, especially in the feature location.

Figure S2. Distribution of errors (difference between a given response and the original feature) of each feature, also visualized in circular space.

5.1.2. Aggregated Recall Errors. We then calculated the median recall error per participant and feature. Further, we averaged median recall errors as a function of feature and calculated the 95% confidence intervals (see Figure S3). Lowest recall error was observed for the feature location ($M = 7.45$, 95% CI [6.45, 8.44]), followed by the feature color ($M = 16.90$, 95% CI [12.80, 20.90]), whereas the feature orientation ($M = 27.70$, 95% CI [16.10, 39.20]) showed the highest recall error.

Figure S3. Recall error (model free) as a function of feature (location, color, orientation). Error bars represent 95% confidence intervals.

5.1.3. Model Parameters. The standard mixture model of Zhang and Luck (2008) was fitted to the raw recall errors to estimate memory access and mnemonic fidelity. A model was fitted for each feature. Parameters were estimated using a Bayesian MCMC approach with the functionalities of the *CatContModel* package (Hardman, 2017, see also Hardman, Vergauwe,

and Ricker, 2017). We run one chain of 10,000 iterations per feature (the first 500 iterations were removed as burn-in) and used uninformative priors. The resulting parameters *guess rate* (g , modeled as a uniform distribution, reflecting memory access) and *precision* (SD , modeled as a Von Mises distribution, reflecting mnemonic fidelity) are depicted in Figure S4. Smaller values on both measures are indicative of better performance. Location was recalled almost without guessing ($M = 0.02$, 95% CrI² [0.01, 0.04]), followed by color ($M = 0.15$, 95% CrI [0.09, 0.23]), whereas orientation revealed the highest guess rate ($M = 0.47$, 95% CrI [0.33, 0.61]). However, in terms of precision the pattern of results was different: color ($M = 22.01$, 95% CrI [20.04, 24.66]) was recalled less precisely than the other two features location ($M = 11.85$, 95% CrI [10.59, 13.21]) and orientation ($M = 16.40$, 95% CrI = [14.14, 19.98]). Location was recalled most precisely (see Figure S4).

Figure S4. Probability of guessing (g), reflecting access to memory (left) and precision (SD), reflecting mnemonic fidelity (right) as a function of feature (location, color, orientation). Error bars represent 95% Bayesian credible intervals.

² Note that here, we report 95% Bayesian credible intervals for the posteriors.

5.1.4. Conclusion. We were able to successfully validate the VR setting. We showed that it is possible to use the continuous delayed estimation paradigm in a VR setting, that the task was not too easy and not too difficult; and we were able to successfully model recall errors with the standard mixture model. This will enable us to conduct the main experiment presented in this registered report.