The influence of visual landmarks on spatiotopic localization and object-location binding

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Abstract

Despite receiving visual inputs based on retinotopic (gaze-centered) coordinates, we are able to perceive the spatiotopic (world-centered) locations of objects. Intriguingly, some studies have reported strong evidence that object-location binding occurs in retinotopic coordinates, but other recent studies have explored whether more naturalistic contexts and factors can trigger spatiotopic object-location binding. Here, we examined the influence of visual landmarks. While previous work has supported a benefit of landmarks on spatial localization, it remains unclear whether this benefit would also extend to object-location binding across saccades. In separate blocks, participants completed two tasks: a spatiotopic localization task and a location-irrelevant object identity judgment task known to elicit a spatial congruency bias (SCB, a measure of object-location binding); we examined performance on both tasks with and without visual landmarks. As expected, in the localization task, landmarks consistently improved spatiotopic location memory precision. However, in the object identity judgement task, landmarks alone were not sufficient to induce spatiotopic object-location binding. In Experiment 1, when participants performed a single saccade during the delay between two stimuli (static context), the SCB was purely retinotopic and not different between landmark conditions (present vs. absent). However, in a more dynamic context (Experiment 2) when participants performed additional eye movements during stimulus presentation, the presence of landmarks led to a significant spatiotopic SCB. In summary, landmarks alone aren't enough to trigger spatiotopic object-location binding, but they can help in a more dynamic context. These results provide new insight into visual stability across eye movements in complex, dynamic environments.

Introduction

Object-location binding refers to the phenomenon in which spatial location can be automatically encoded and bound to object identity during object recognition—even when location is task-irrelevant (Cave & Chen, 2017; Hollingworth, 2007; Hollingworth & Rasmussen, 2010; Kahneman et al., 1992; Treisman, 1996; Treisman & Gelade, 1980). In everyday life, we constantly make numerous eye movements as we explore the complex visual world. But what happens to object-location binding when our eyes move? This question is related to the "hard binding problem", a debate of how object features and identity are processed across eye movements (Cavanagh et al., 2010; Golomb & Mazer, 2021). Most previous studies have found evidence primarily for retinotopic (gaze-centered) object-location binding, suggesting that it is the retinotopic—not spatiotopic (gaze-independent or world-centered)—location that is bound to object identity (Shafer-Skelton et al., 2017). But under what conditions does object-location binding become spatiotopic—the form that more effectively supports visual stability? Recent research has begun to identify ecologically relevant factors that may promote spatiotopic binding, such as dynamic saccade contexts (Lu & Golomb, 2024), object movements (Ran et al., 2025), and saccade target status (Chiu & Golomb, 2025), all of which can trigger spatiotopic binding in addition to the retinotopic binding. But are there other naturalistic factors that can also contribute to eliciting spatiotopic object-location binding?

In our daily lives, even when we fixate on a single object, there are often various landmarks present in the surrounding environment. These landmarks, as integral components of real-world scenes, have been shown to facilitate or influence the processing of target localization. Previous research on visual perception has demonstrated that visual landmarks serve as critical reference points for self-localization and reorientation, route learning and planning, and path integration (Etienne et al., 1996; Gothard, Skaggs, & McNaughton, 1996; Gothard, Skaggs, Moore, et al., 1996; Ishikawa & Nakamura, 2012; Jeffery, 1998; Julian et al., 2018; Knierim et al., 1995; McNaughton et al., 1991; Michon & Denis, 2001; Philbeck & O'Leary, 2005; Tlauka & Wilson, 1994; Waller & Lippa, 2007; Yesiltepe et al., 2021). In parallel, theoretical models have emphasized the role of landmarks in reducing spatial computation errors (Burgess et al., 2007; Fuhs & Touretzky, 2006; Monaco et al., 2011; Newman & McNamara, 2022; Sreenivasan & Fiete, 2011). Importantly, the benefits of landmarks extend beyond static gaze conditions. Some studies have highlighted that landmarks can facilitate visual stability and enhance target localization not only during fixation (Obhi & Goodale, 2005), but also across saccadic eye movements (Deubel, 2004; Steinberg et al., 2022; Zhang & Golomb, 2018). However, these findings have primarily focused on spatiotopic localization, where the location is task-relevant. A critical open question remains: can landmarks also influence spatiotopic object-location binding, for tasks in which object identity is task-relevant, but location is task-irrelevant?

Here, we aimed to investigate the role of landmarks in spatiotopic object-location binding, and included a spatiotopic localization task as a control. To assess object-location binding, we adapted the spatial congruency bias paradigm (Golomb et al., 2014), in which two objects are presented sequentially, and participants judge whether their identities (shapes) are the same or different. In this Identity Judgment Task, the object's location is task-irrelevant, but prior studies using this paradigm have found that participants are more likely to judge two objects as the same

identity when they appear in the same location. This spatial congruency bias suggests that object identity can be automatically bound to object location—thus providing an effective behavioral index of object-location binding (Bapat et al., 2017; Cave & Chen, 2017; Gao et al., 2024; Golomb et al., 2014; Starks et al., 2020). Critically, if participants are cued to make a saccadic eye movement changing their fixation position in the interval between the two objects' presentations, we can test whether the spatial congruency bias is present in retinotopic (gaze-centered) and/or spatiotopic (world-centered) coordinates under different contexts. In Experiment 1, we examined whether visual landmarks alone are sufficient to support spatiotopic object-location binding, by testing a relatively static context in which participants executed a single saccade after the first stimulus on each trial (as in Shafer-Skelton et al, 2017). In Experiment 2, we tested whether landmarks can promote spatiotopic object-location binding when combined with an additional stability cue –a more dynamic saccade context, in which participants made additional eye movements during stimulus presentation (as in Lu et al, 2024). To evaluate spatiotopic localization, in a separate task we presented a single object and asked participants to memorize its spatiotopic location and to report it with a mouse click after an analogous delay containing an eye movement. This Spatiotopic Localization Task served as a control task in which the object location was explicitly task-relevant, in contrast to the Identity Judgment Task.

In the present study, all participants completed both the Spatiotopic Localization Task and Identity Judgment Task in each experiment, allowing us to assess how landmarks influence both spatiotopic localization and object-location binding. Given the prior literature, we expected landmarks to facilitate spatiotopic localization and enhance performance in the localization task. The main question is whether landmarks can also induce spatiotopic object-location binding, either on their own or in conjunction with other stability cues.

Methods

Subjects. The research was approved by the Ohio State University Behavioral and Social Sciences Institutional Review Board. Sixteen subjects at least 18 years old were recruited for each experiment from The Ohio State University (with a different set of subjects in each experiment; Experiment 1: age: 19.33±1.05, gender: 6 males and 10 females; Experiment 2: age: 19.69±2.65; gender: 8 males and 8 females). All subjects reported normal or corrected-to-normal vision and gave informed consent. Subjects were compensated with course credit or payment. A power analysis of the retinotopic spatial congruency bias effect with one saccade (Shafer-Skelton et al., 2017), which had an effect size of dz = 0.92 for the comparison of SameRetinotopicLocation versus ControlLocation bias, estimated N=15 would be needed to achieve .9 power. Also, a power analysis of the spatiotopic congruency bias effect with multiple saccades (Lu & Golomb, 2024), which had an effect size of dz = 0.94 for the comparison of SameSpatiotopicLocation versus ControlLocation bias, estimated N = 12 would be needed to achieve .9 power. We set sample size at N = 16 (matching prior studies), which should have sufficient power to detect both types of effects.

Experimental setup. Stimuli were presented using Psychtoolbox extension (Brainard, 1997) for MATLAB, on a 21-in (53.34-cm) flat screen CRT monitor. Subjects were seated at a chinrest 60 cm from the monitor.

Eye tracking. Eye position was monitored monocularly with an EyeLink 1000 eye-tracking system recording pupil and corneal reflection position with 1000 Hz sample rate. Fixation was monitored for all experiments. Before the start of each experiment, the nine-point calibration procedure was performed to clibrate the eye-tracker.

Stimuli. Stimuli were the same as those in Golomb et al., 2014, from the Tarr stimulus set (stimulus images courtesy of Michael J. Tarr, Center for the Neural Basis of Cognition and Department of Psychology, Carnegie Mellon University, http://www.tarrlab.org). Stimuli were drawn from ten families of shape morphs; within each family, the "body" of the shape remained constant, while the "appendages" could vary in shape, length, or relative location. Stimuli were sized 4°×4°, and stimulus orientation was never varied.

Both experiments and tasks used the same stimuli, and subjects needed to follow the fixation point throughout the task. There were four possible fixation locations, centered on the screen and forming the corners of an invisible 10°×10° square. Object stimuli could appear within nine possible stimulus regions, arranged as a 3×3 grid. In the Identity Judgment Task, stimuli appeared at the centers of these regions, such that each fixation location had four adjacent stimulus positions of equal eccentricity (7.06°). In the Spatiotopic Localization Task, stimulus locations were sampled continuously within these same regions.

Experiment 1: Static context (single critical saccade). Subjects were asked to conduct two tasks, Identity Judgement Task and Spatiotopic Localization Task (Figure 1A).

The Identity Judgement Task was modified from Shafer-Skelton et al., 2017. For each trial, the fixation cross appeared at one randomly chosen (counterbalanced) fixation location (Fixation 1) for 500ms, and Stimulus 1 was then presented in a peripheral location for 500ms while the fixation cross remained visible. The stimulus was then masked (50ms blank followed by 100ms scrambled mask image). Then, the fixation cross jumped to either the adjacent vertical or horizontal fixation location and stayed at the new fixation location (Fixation 2) for 500ms. Stimulus 2 was then presented for 500ms during Fixation 2 and then masked. At the end of the trial, subjects saw the question 'Same or Different' and were instructed to make a two-alternative forced choice same/different judgement by button press ('j' for 'Same' and 'k' for 'Different') comparing the two objects' identities (shapes); object location was irrelevant to the task. Subjects were provided feedback at the end of each trial ('correct' or 'incorrect' in green or red on the screen). During the task, they were also provided feedback if they broke fixation at any time during the trial ('Please look at the fixation' on the screen) or didn't give a response within 3 seconds ('No response' on the screen).

The Stimulus 1 shape was randomly chosen for each trial from the stimulus set described above. On Same Shape trials, the Stimulus 2 shape was an identical image. On Different Shape trials, the second shape was chosen as a different shape from the same morph family. As in Lu & Golomb, 2024, we used the easiest morph level (the two images with the greatest morph distance within a family) for all subjects instead of individually staircasing task difficulty because in Golomb et al., 2014 and Shafer-Skelton et al., 2017, participants were already within the desired

accuracy range at this easiest morph level (maximum staircase value) in both no-saccade and saccade tasks.

The location of Stimulus 1 was chosen from one of two possible locations for the given saccade (on either side of the eye movement route). There were three possible location conditions for Stimulus 2: On one-third of trials it appeared in the same absolute screen location as Stimulus 1 (Same Spatiotopic Condition). On one-third of trials it appeared in the same location as Stimulus 1 relative to current fixation (Same Retinotopic Condition). On the remaining one-third of trials it appeared in one of two eccentricity-matched control locations which were neither the same spatiotopic nor same retinotopic locations (Control Condition).

The Spatiotopic Localization Task procedures were largely the same as the Identity Judgement Task, except that subjects were asked to memorize the spatiotopic location of Stimulus 1 and use the mouse to move Stimulus 2 to the memorized spatiotopic location of Stimulus 1 for the response. Stimulus 2 was always the same shape as Stimulus 1, and the mask was removed, but the overall temporal structure of the trial was matched to the Identity Judgement Task. Participants could start to do the response by moving the mouse when they saw Stimulus 2.

For the Localization Task, the Stimulus 1 shape was selected randomly for each trial and was irrelevant. The location of Stimulus 1 was selected in the same way as in the Identity Judgment task (stimulus position on either side of the eye-movement route), but instead of the stimulus appearing at the center of that grid location, it appeared at a random location anywhere within the 10° × 10° square grid area. Stimulus 2 appeared at a random location within one of four 10° × 10° square areas adjacent to Fixation 2. To match the spatial layout of the Identity Judgement Task, the initial position of Stimulus 2 was equally often sampled from the region corresponding to the same spatiotopic location as Stimulus 1, the same retinotopic location relative to Fixation 2, or an eccentricity-matched control region. Regardless of where Stimulus 2 initially appeared, participants were instructed to move Stimulus 2 to match the exact Stimulus 1 location. These initial-probe-location conditions were induced only to balance the starting position of the response probe, and the dependent measure was always the absolute distance between the reported location and the true spatiotopic location of Stimulus 1. At the end of each trial, participants received feedback indicating the distance between the reported location and the true location of Stimulus 1 (e.g., “Difference: 2.103 degrees,” displayed in green).

Critically, for both tasks, we manipulated the presence or absence of visual landmarks (Figure 1B). In the landmarks-present condition, we added a line grid on the background of the screen, consisting of two blue and two magenta think lines with a width of 0.26°. The two blue lines intersected with the left-top fixation, and the two magenta lines intersected with the right-bottom fixation (see Figure 1), which made the visual information framing each of the nine spatiotopic stimulus zones different and emphasized differences among the four fixation locations, thus reinforcing spatiotopic location cues. All landmark lines were cut off a little bit as they passed through the fixation location to keep the fixation dots clear. In the landmark-absent condition, there was just a plain color background without any landmark lines. The background colors were designed to be different in landmarks-present and landmark-absent conditions (pale pink or pale yellow, balanced between subjects) to better differentiate these two conditions.

Each subject performed 3 landmarks-present and 3 landmark-absent Identity Judgement blocks with 64 trials per block, and 1 landmarks-present and 1 landmark-absent Spatiotopic Localization blocks with 72 trials per block. In both tasks, if the subject's fixation deviated greater than 2° at any point, the trial was aborted and repeated later in randomized order in the same block. The order of the 8 blocks was random for each subject.

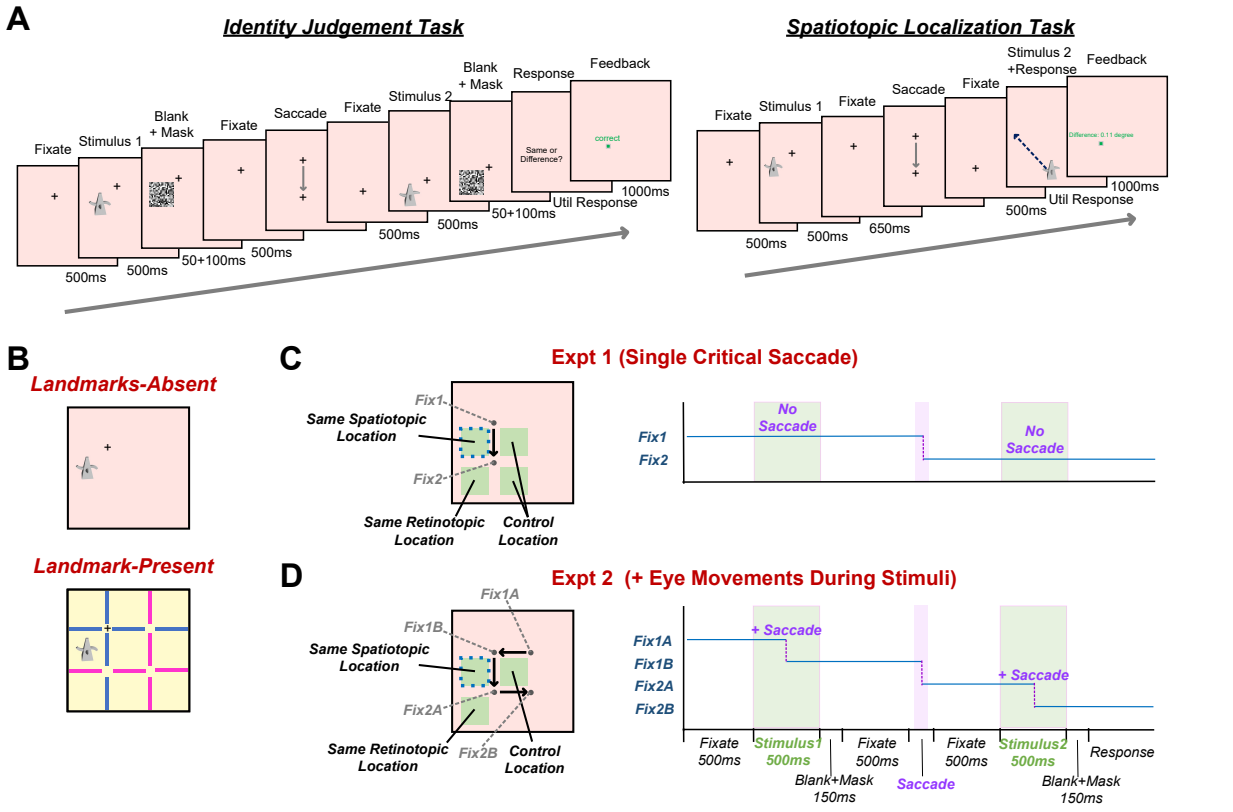

Figure 1 Experimental designs of Experiment 1 and 2. (A) Trial timing for the two tasks in Experiment 1. The example trials depict a same-retinotopic, different-identity, landmarks-absent condition for the Identity Judgment Task (left), and a landmarks-absent trial for the Spatiotopic Localization Task (right). Solid and dashed arrows depict eye and mouse movements, respectively (arrows not visible on screen during the task). (B) Illustration of the screen background for landmarks-present and landmark-absent conditions. The landmarks-present and landmarks-absent conditions were presented in separate blocks; the respective background was present for the duration of the block. (C-D) Illustration of the three location conditions and the trial timing of the Identity Judgement Task for Experiment 1 (C) and Experiment 2 (D). Left panels illustrate the possible Stimulus 2 locations (colored in green and labeled by condition names), for an example trial with the same Stimulus 1 location (blue dotted square) and critical saccade (vertical arrow) illustrated in panel A. Right panel illustrates the fixation position over time for this trial, with the corresponding trial events marked along the *X*-axis. The light green blocks indicate the periods of time that the two stimuli were presented on each trial. The light purple block indicates the period of time that the critical saccade happens on each trial. Note: For the Spatiotopic Localization Task, timing was the same, but participants could respond as soon as Stimulus 2 was presented, so there was no third saccade in Expt 2.

Experiment 2: More dynamic saccade context (critical saccade + additional eye movements during stimuli). In Experiment 2, the tasks and timing of each trial were the same as in

Experiment 1, except that subjects were asked to perform additional saccades on each trial. In addition to the critical saccade happening during the delay between presentation of the two shape stimuli, subjects were also cued to make an orthogonal saccade *during* the presentation of each stimulus (Figure 1D), for a total of 3 saccades per trial (similar to Experiment 4 of Lu & Golomb 2024).

In the Identity Judgement Task, for each trial, the fixation cross began at one randomly chosen (counterbalanced) fixation location (Fixation 1A) for 500ms, and then jumped to a second fixation location (Fixation 1B; either horizontal or vertical adjacent fixation position). Stimulus 1 was presented simultaneously with the Fixation 1B saccade cue, and remained on the screen for 500ms before being removed and masked. Participants were instructed to execute the saccade as soon as they saw the fixation cross move. Because the stimulus was presented for 500ms, and average saccadic reaction time (aSRT) in this task was anticipated to be approximately 250ms (actual aSRT = 244.51±11.71ms), the intention was that Stimulus 1 would be visible before, during, and after the saccade (see Figure 1D). Eye tracking was used to ensure that this was the case; in order for a trial to be included in analysis, the saccade must begin after stimulus onset and be completed before stimulus offset; trials that did not meet this criterion were aborted and repeated later in the block. After an additional 500ms fixation period, the fixation cross jumped to a third fixation location (Fixation 2A) - the "critical saccade" in the orthogonal direction - and remained there for 500ms. The fixation cross then jumped to a fourth fixation location (Fixation 2B), simultaneous with the appearance of Stimulus 2, which remained visible for 500ms before being masked. As with Stimulus 1, included trials required the saccade from Fixation 2A to Fixation 2B to begin after stimulus onset and end before stimulus offset, ensuring that Stimulus 2 was also visible before, during, and after the saccade. Participants were then probed to report whether the two stimuli were the same or different identity (shape).

The three saccades were always arranged such that the critical second saccade was either horizontal or vertical, and the saccades occurring during stimulus presentation (first and third saccades) were in the orthogonal direction, and opposite to each other. For example, the three saccades could be left-down-right, or up-right-down, etc. Critically, the three location conditions for Stimulus 2 were defined with respect to the critical saccade in the same way as in Experiment 1. Specifically, on one-third of trials Stimulus 2 appeared in the same absolute screen location as Stimulus 1 (Same Spatiotopic Condition); on one-third of trials it appeared in the same location as Stimulus 1 relative to the post-critical-saccade fixation position as Stimulus 1 had appeared relative to the pre-critical-saccade fixation position (Same Retinotopic Condition); and on the remaining one-third of trials it appeared at a control location that was matched in eccentricity but was neither spatiotopically nor retinotopically aligned with Stimulus 1 (Control Condition) (Figure 1D). In Experiment 2, only one control location was used for each possible trial sequence. This was an intentional constraint: although another eccentricity-matched location was geometrically possible, it could partially overlap with Stimulus 1 in retinotopic coordinates given the additional saccades during stimulus presentation. We therefore selected the control location that avoided both spatiotopic alignment and full or partial retinotopic alignment with Stimulus 1. Otherwise the task was the same as in Experiment 1.

Similarly, in the Spatiotopic Localization Task for Experiment 2, subjects performed the same sequence of saccades with the same timing, except there was no third saccade cued during

Stimulus 2, because participants start their mouse response in this task as soon as they see Stimulus 2.

Other procedures were exactly the same as in Experiment 1. Each subject performed eight blocks in total, consisting of three landmarks-present and three landmark-absent Identity Judgement blocks, as well as one landmarks-present and one landmark-absent Spatiotopic Localization block, with the localization blocks intermixed with the Identity Judgement blocks in a fully randomized block order.

Analysis. For the Identity Judgement Task, our primary measure was the spatial congruency bias (SCB), which is calculated as the difference in response bias for the same location versus a different location condition (Golomb et al., 2014).

We calculated hit and false alarm rates for each location condition. We defined a 'hit' as a 'Same shape' response when the two stimuli were the same (Same Identity condition), and a 'false alarm' as a 'Same shape' response when the two stimuli were different (Different Identity condition). Based on signal detection theory, we applied the standard formula (Stanislaw & Todorov, 1999) to obtain response bias for each location condition, separately for each subject and landmark condition:

response bias = -(z(hit rate) + z(false alarm rate))/2

Then we calculated the spatial congruency bias (SCB) measures, based on the difference in response bias across location conditions (i.e., whether there was a greater bias to report two stimuli as the same identity when they appeared in the same retinotopic and/or spatiotopic locations). We calculated spatiotopic SCB and retinotopic SCB by substracting Same Spatiotopic from Control and subtracting Same Retinotopic from Control, respectively:

$SCB_{spatiotopic}$ = $response\ bias_{control}$ – $response\ bias_{spatiotopic}$

$SCB_{retinotopic}$ = $response\ bias_{control}$ – $response\ bias_{retinotopic}$

A positive SCB means an increased bias to respond 'Same shape' for the identity comparison when the objects appeared in the Same Location condition vs Different Location control.

Because our primary question was whether object-location binding was present in retinotopic and/or spatiotopic coordinates under each landmark condition, we first conducted planned one-sample t-tests comparing each SCB measure against zero. These tests indicate whether there was a reliable spatial congruency bias in a given reference frame and landmark condition. We then conducted a 2 × 2 repeated-measures ANOVA with within-subject factors of landmark condition (landmarks-present vs. landmark-absent) and reference frame (spatiotopic vs. retinotopic) to test whether SCB magnitude was modulated by landmarks and/or reference frame.

Although our main analyses for the Identity Judgement Task focused on the spatial congruency bias, we also calculated the response time (RT) and sensitivity (d'), z(hit rate)-z(false alarm), to measure potential facilitation effects as a function of location condition. (We didn't observe any significant location facilitation effects in Identity Judgement Task, so do not report these further, though for completeness Tables A1 and A2 report the condition mean and statistics for all behavioral measures, including RT, accuracy, d-prime, and proportion 'Same' response.)

For the Spatiotopic Localization Task, our measure of interest was spatial memory error. We calculated the memory error by calculating the absolute distance between the reported location and real Stimulus 1 location on each trial and then averaging across trials for each subject and each landmark condition. Then we conducted paired t-tests to determine whether the magnitude of memory error under landmarks-present and landmark-absent conditions were significantly different.

For all tasks and experiments, trials on which subjects responded with RTs greater than or less than 2.5 standard deviations from the subject's mean RT, were excluded. For all analyses, we report frequentist statistics using *t*- and *p*-values, effect sizes using Cohen's *d*, and Bayesian statistics using the Bayes factors (BF_{10}) based on the default Cauchy distribution prior (scale parameter = 0.707).

Results

The influence of landmarks in a static context (Expt 1).

Experiment 1 aims to test whether landmarks can trigger spatiotopic object-location binding and/or enhance spatiotopic localization in a relatively static context. In this context, participants viewed each stimulus during a period of stable fixation, but were asked to execute one single saccade during the delay between the two stimuli, so that we could manipulate the different location conditions to dissociate retinotopic and spatiotopic coordinates.

In the Identity Judgement Task, our primary question was whether SCB was reliably present in retinotopic and/or spatiotopic coordinates under each landmark condition (Figure 2A). We therefore first conducted planned one-sample t-tests comparing each SCB measure against zero. These planned comparisons revealed significant retinotopic SCB in both landmark conditions (landmarks-present: $t(15) = 4.5181$, $p = .0004$, $d = 1.1506$, $BF_{10} = 83.092$; landmark-absent: $t(15) = 3.7500$, $p = .0019$, $d = 1.4347$, $BF_{10} = 21.766$). In contrast, spatiotopic SCB was not significant in either landmark condition (landmarks-present: $t(15) = -1.3901$, $p = .1848$, $d = -.3551$, $BF_{10} = 0.575$; landmark-absent: $t(15) = .7717$, $p = .4523$, $d = .2462$, $BF_{10} = .331$), though the Bayes factor suggests only anecdotal evidence for the absence of spatiotopic SCB under landmarks-present condition.

The 2 × 2 ANOVA with within-subjects factors of landmark condition (landmarks-present or landmark-absent) and reference framework (Spatiotopic or Retinotopic) revealed a significant main effect for reference framework ($F(1,15) = 16.1188$, $p = .0002$, $\eta^2p = .2118$) but no significant main effect for landmark condition ($F(1,15) = 3.1542$, $p = .0808$, $\eta^2p = .0499$) nor interaction ($F(1,15) = .0255$, $p = .8737$, $\eta^2p = .0004$). Thus, in the static context, object-location binding was primarily retinotopic, and landmarks did not significantly alter the pattern of SCB.

In the Spatiotopic Localization Task (Figure 2B), spatiotopic memory precision was significantly improved in landmarks-present condition compared to landmark-absent condition ($t(15) = 7.5321$, $p < .0001$, $d = 2.2371$, $BF_{10} > 1000$).

Together, these results suggest that landmarks can significantly improve spatiotopic localization but do not help spatiotopic object-location binding in a static context. In a static context, we still only observed retinotopic instead of spatiotopic object-location binding across a saccade, regardless of having the landmark or not.

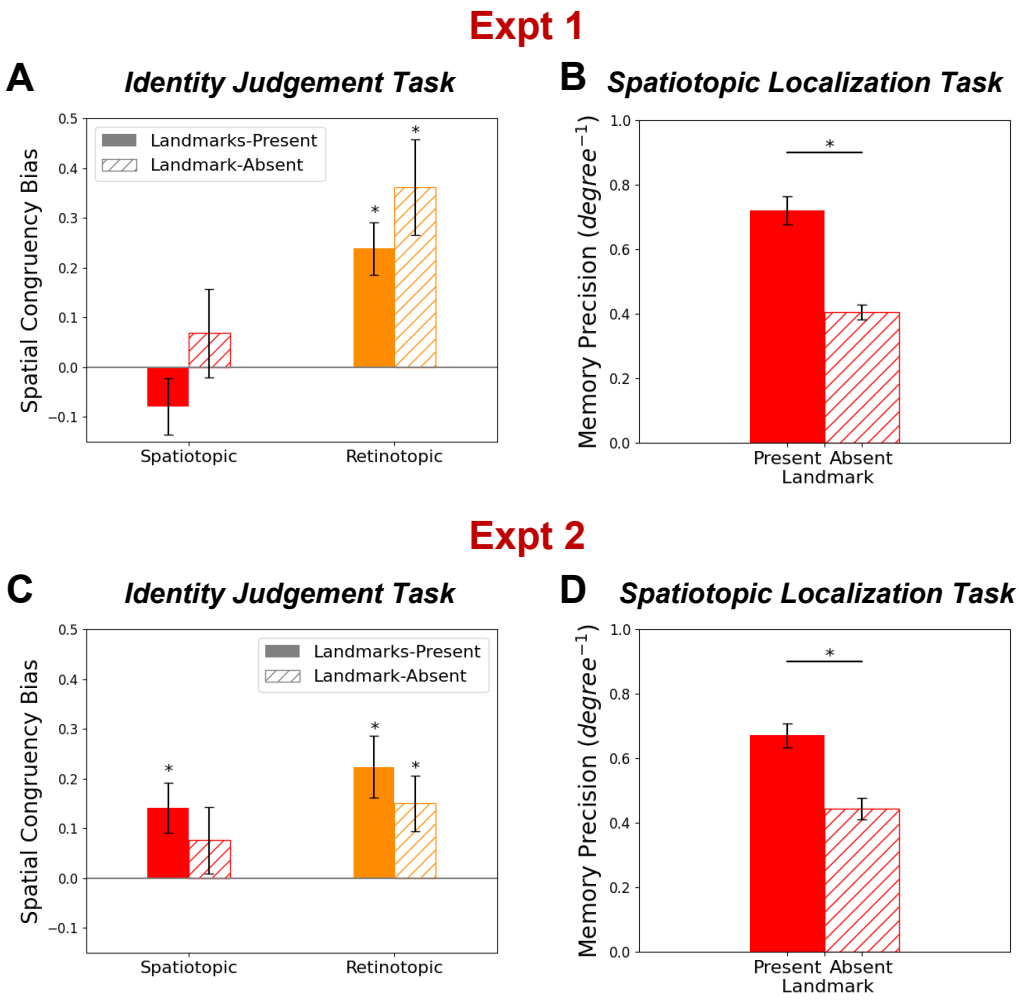

Figure 2. Results of Experiment 1 and 2. (A-B) Behavioral results of (A) identity judgement task and (B) spatiotopic localization task in Experiment 1. (C-D) Behavioral results of (C) identity judgement task and (D) spatiotopic localization task in Experiment 2. Error bars are standard errors of the mean. Asterisks above individual bars in the Identity Judgment Task indicate significant spatial congruency bias for that condition ($p < .05$; one-sample t test versus zero); asterisks between bars in the Spatiotopic Localization Task indicate significant differences between landmark conditions ($p < .05$; paired-sample t test).

The influence of landmarks in a more dynamic context (Expt 2).

Although Experiment 1 shows that landmarks alone are insufficient to support spatiotopic object-location binding, this does not preclude the possibility that landmarks may contribute to spatiotopic binding when combined with additional cues. Prior work has shown that individual dynamic saccade-related cues, such as repeated saccades or eye movements during stimulus presentation, are insufficient on their own to trigger spatiotopic object–location binding, whereas

the combination of multiple stability cues can induce spatiotopic binding (Lu & Golomb, 2024). This raises the question of whether landmarks can function in conjunction with other stability cues to promote spatiotopic object-location binding?

To test this possibility, in Experiment 2 we introduced additional saccades during stimulus presentation, thereby creating a more dynamic context (Figure 1D), while maintaining the same landmark manipulation as in Experiment 1. This design allowed us to assess whether landmarks facilitate not only spatiotopic localization, but also spatiotopic object–location binding when embedded within a context that provides additional stability cues.

In the Identity Judgement Task, as in Experiment 1, our primary question was whether SCB was reliably present in retinotopic and/or spatiotopic coordinates under each landmark condition (Figure 2C). Therefore, we first conducted planned one-sample t-tests comparing each SCB measure against zero. These planned comparisons revealed significant retinotopic SCB in both landmark conditions (landmarks-present: $t(15) = 3.5779$, $p = .0027$, $d = .6875$, $BF_{10} = 16.127$; landmark-absent: $t(15) = 2.6719$, $p = .0174$, $d = .5509$, $BF_{10} = 3.474$). Critically, spatiotopic SCB was also significant in landmark-present condition ($t(15) = 2.8486$, $p = .0122$, $d = .4264$, $BF_{10} = 4.644$) but not in landmark-absent condition ($t(15) = 1.1487$, $p = .2687$, $d = .2568$, $BF_{10} = .449$), though the Bayes factor suggests only anecdotal evidence for the absence of spatiotopic SCB.

We then conducted the 2 × 2 ANOVA on SCB with within-subject factors of landmark condition and reference frame. The ANOVA revealed no significant main effects of landmark condition ($F(1,15) = 1.3750$, $p = .2456$, $\eta^2p = .0224$) or reference framework ($F(1,15) = 1.7551$, $p = .1903$, $\eta^2p = .0284$), nor a significant interaction ($F(1,15) = .0051$, $p = .9434$, $\eta^2p = .0001$). Thus, although the planned comparisons showed reliable spatiotopic SCB only when landmarks were present, the landmark manipulation did not significantly modulate SCB in the ANOVA.

In the Spatiotopic Localization Task, we again found significant improvement of memory precision of spatiotopic location in landmarks-present condition compared to landmark-absent condition ($t(15) = 7.2668$, $p < .0001$, $d = 1.6038$, $BF_{10} > 1000$) (Figure 2D).

The Spatiotopic Localization Task results are highly similar to what we find in Experiment 1, that landmarks improve spatiotopic localization. However, in the Identity Judgement Task, unlike in Experiment 1, we observed a significant spatiotopic object-location binding effect under landmarks-present condition in Experiment 2. To directly compare this effect across experiments, we conducted a targeted independent-samples t-tests on spatiotopic SCB for the landmark-present and landmark-absent conditions. In the landmark-present condition, spatiotopic SCB was significantly greater in Experiment 2 than in Experiment 1, $t(30) = 2.9216$, $p = .0066$, $d = 1.0330$, $BF_{10} = 6.983$. In contrast, in the landmark-absent condition, spatiotopic SCB did not differ between Experiment 2 and Experiment 1, $t(30) = .0726$, $p = .9426$, $d = .0257$, $BF_{10} = .337$. Thus, although the ANOVA within Experiment 2 did not show a significant landmark-by-reference-frame interaction, this between-experiment comparison supports the interpretation that landmarks were associated with stronger spatiotopic object-location binding in the more dynamic context.

Discussion

In two experiments under different eye movement conditions, we investigated the influence of visual landmarks on spatiotopic localization and spatiotopic object-location binding across eye movements. We identified dissociated behavioral effects of landmarks on spatiotopic localization and spatiotopic object-location binding. In Experiment 1 (in a relatively static context) and Experiment 2 (in a more dynamic context), we consistently observed that landmarks improved spatiotopic localization. However, spatiotopic object-location binding was only observed in the presence of landmarks in Experiment 2.

Our findings from the Spatiotopic Localization Task are consistent with previous studies (Deubel, 2004; Mou et al., 2008; Steinberg et al., 2022; Zhang & Golomb, 2018), demonstrating that landmarks enhance spatiotopic localization regardless of whether the context is static or more dynamic. This suggests that during spatiotopic localization, the brain utilizes visual information that is unrelated to the target but remains stable within the spatiotopic coordinate system to facilitate better processing of the target's spatiotopic location.

However, the more novel aspect of the present study addresses a remaining critical question: When the task does not *require* processing the target's location, but only its identity, does the brain nevertheless utilize this landmark information? Unlike spatiotopic localization tasks, previous studies have not explored the role of landmarks in spatiotopic object-location binding. Therefore, our study is the first to investigate how landmarks influence object-location binding across eye movements on different (retinotopic and spatiotopic) reference frameworks. In the static context, landmarks had no significant effect – retinotopic binding was consistently observed regardless of the presence or absence of landmarks. This retinotopic-only binding effect aligns with previous findings, where object-location binding was shown to rely on retinotopic coordinates across various conditions, including shape, face, and orientation stimuli, as well as under different delay durations (Lu & Golomb, 2024; Shafer-Skelton et al., 2017).

However, Experiment 2 revealed that landmarks are not entirely ineffective at promoting spatiotopic object-location binding. In a more dynamic context, we observed that spatiotopic object-location binding emerged when additional landmarks were present, but not in the landmark-absent condition. However, the landmark effect should be interpreted cautiously because the direct difference between landmark conditions was not significant, and Bayesian evidence for the absence of spatiotopic SCB in the landmark-absent condition was weak. This weak, non-significant spatiotopic SCB trend without landmarks resembles Lu & Golomb, 2024's Experiment 4 , where eye movements during stimulus presentation (in the absence of other stability factors) also produced a weak but unreliable spatiotopic SCB. Our findings are consistent with Lu & Golomb, 2024's speculation that eye movements during stimulus presentation may serve as a switch that puts the brain into a more dynamic state; however, this factor alone appears insufficient to trigger spatiotopic binding for achieving visual stability, and the addition of another stability cue is necessary to reliably trigger spatiotopic object-location binding. This additional cue took the form of multiple repeated eye movements in Lu & Golomb, 2024's Experiment 1, and spatiotopic landmarks in our Experiment 2. Importantly, neither of these cues alone triggered spatiotopic binding, only when presented in conjunction.

More broadly, our findings add to emerging evidence that spatiotopic object-location binding may depend on the combination of multiple ecological stability cues, rather than on any single cue alone. This pattern is consistent with recent findings that other ecological cues such as object motion or saccade target status (Chiu & Golomb, 2025; Ran et al., 2025), can also promote more spatiotopic binding. Together, these findings suggest that the visual system may flexibly weight spatiotopic information when the viewing context provides stronger cues that stable object representations should be maintained across changes in gaze. Other naturalistic factors not tested here – such as richer scene structure, behavioral relevance of background objects, active navigation, or interactions with multiple objects in a scene – may also modulate whether object identity becomes bound to retinotopic or spatiotopic location.

One important question raised by this pattern is why landmarks improved spatiotopic localization in both experiments, but were associated with spatiotopic object-location binding only in the more dynamic context. It is possible that landmarks enhance spatiotopic object-location binding by increasing attention to spatial information or by sharpening spatial representations. Visual landmarks are known to anchor spatial reference frames and improve the precision of spatial localization across eye movements (Deubel, 2004; Zhang & Golomb, 2018). And at a representational level, prior fMRI work suggests that stable backgrounds can reshape spatial representations in retinotopic visual cortex (Roth, 2016), potentially enhancing the spatial codes that support spatiotopic object-location integration. However, such accounts alone are insufficient to explain our findings. Although landmarks reliably improved spatiotopic localization in both experiments, the magnitude of this localization benefit did not differ significantly between the two experiments. Critically, spatiotopic object–location binding nevertheless emerged only in Experiment 2. This dissociation indicates that improved spatiotopic localization per se is not sufficient to account for the emergence of spatiotopic binding.

Instead, our results suggest that spatiotopic object–location binding depends on an interaction between landmarks and dynamic saccade-related cues. As speculated above, eye movements during stimulus presentation may alter how stable spatial references are weighted during object processing, allowing landmarks to facilitate spatiotopic binding. Importantly, this account does not imply a general increase in all forms of spatial binding: if dynamic processing simply increased the relevance of spatial information overall, one might also expect stronger retinotopic binding, which we did not observe.

Although our study systematically examined the role of landmarks in achieving visual stability, several future directions remain worth exploring. First, because landmarks were purely task-irrevelant here, future work could test whether making landmarks or other scene elements behaviorally relevant further strengthens spatiotopic object-location binding. Second, the underlying neural mechanisms behind our experimental findings remain unknown. Previous fMRI studies have primarily focused on observing retinotopic vs. spatiotopic representations under generally static contexts within the human visual system (Crespi et al., 2011; D'Avossa et al., 2007; Gardner et al., 2008; Golomb & Kanwisher, 2012; Lu et al., 2022; McKyton & Zohary, 2007; Szinte et al., 2024). Future research may benefit from investigating spatiotopic representations under more dynamic contexts and further comparing the neural mechanisms underlying the influence of landmarks on both spatiotopic localization and object-location binding. Finally, the two experiments in our study differed not only in dynamic saccade context,

but also in oculomotor load, task difficulty, and dual-task demands. Future work will be needed to distinguish these factors.

In summary, our study investigated how task-irrevelant landmarks influences spatiotopic localization and spatiotopic object-location binding in both static and more dynamic contexts. We identified important yet dissociated roles of landmarks in achieving visual stability. Task-irrelevant visual landmarks consistently improved spatiotopic localization across single or multiple eye movements, but supported spatiotopic object-location binding only in a more dynamic context where participants perform saccades while seeing objects. These findings enhance our understanding of how one key ecological factor – visual landmarks – contributes to and modulates visual stability, and highlights the importance of studying visual stability under more dynamic and ecologically valid conditions.

Declarations

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Ethics approval: Approval for this study was granted by The Ohio State University Behavioral and Social Sciences Institutional Review Board.

Consent to participate: All participants read and signed a consent form prior to participation.

Consent for publication: Informed consent was obtained from all participants.

Availability of data and materials: Data and materials are available on the Open Science Framework (https://osf.io/5vcp6/).

Code availability: Code is available on the Open Science Framework (https://osf.io/5vcp6/).

Author's contributions: Zitong Lu served as lead for conceptualization, data curation, formal analysis, methodology, visualization, and writing-original draft. Julie D. Golomb served as lead for funding acquisition, project administration, supervision, and writing-review and editing and served in a supporting role for resources. Zitong Lu and Julie D. Golomb contributed equally to investigation.

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Appendices

Table A1. Means (and standard deviations) for all raw behavioral measures and conditions in Experiment 1 Identity Judgement Task. RT is reaction time in seconds. P("same") is the probability of reporting the items as the same identity. D-prime and response bias are calculated from signal detection theory formulas in methods. Note that the "sensitivity effect" in the text is the difference in d-prime for same (or predictable) vs different location conditions, and the "spatial congruency bias (SCB) effect" in the text is the difference in response bias for same (or predictable) vs different location conditions.

Expt 1	Same/Different Identity	Same Spatiotopic		Same Retinotopic		Control	
		w/ landmark	w/o landmark	w/ landmark	w/o landmark	w/ landmark	w/o landmark
RT	Same Identity	0.3202(0.16)	0.3138(0.18)	0.2970(0.14)	0.3339(0.16)	0.3310(0.14)	0.3253(0.16)
	Different Identity	0.2958(0.15)	0.3240(0.16)	0.3053(0.15)	0.3305(0.21)	0.2948(0.15)	0.3624(0.21)
Accuracy	Same Identity	0.6992(0.13)	0.7213(0.13)	0.8123(0.11)	0.8394(0.12)	0.7042(0.12)	0.7234(0.16)
	Different Identity	0.7425(0.13)	0.7140(0.14)	0.6794(0.16)	0.6691(0.15)	0.7099(0.15)	0.7601(0.14)
P('Same')	Same Identity (Hit Rate)	0.6992(0.13)	0.7213(0.13)	0.8123(0.11)	0.8394(0.12)	0.7042(0.12)	0.7234(0.16)
	Different Identity (False Alarm Rate)	0.2575(0.13)	0.2860(0.14)	0.3206(0.16)	0.3309(0.15)	0.2901(0.15)	0.2399(0.14)
d-prime		1.2994(0.77)	1.3043(0.80)	1.5042(0.88)	1.5946(0.81)	1.2061(0.83)	1.4703(0.91)
Response Bias		0.0842(0.24)	-0.0197(0.29)	-0.2332(0.21)	-0.3129(0.25)	0.0053(0.19)	0.0486(0.24)

Table A2. Means (and standard deviations) for all raw behavioral measures and conditions in Experiment 2 Identity Judgement Task. RT is reaction time in seconds. P("same") is the probability of reporting the items as the same identity. D-prime and response bias are calculated from signal detection theory formulas in methods. Note that the "sensitivity effect" in the text is the difference in d-prime for

same (or predictable) vs different location conditions, and the “spatial congruency bias (SCB) effect” in the text is the difference in response bias for same (or predictable) vs different location conditions.

Expt 2	Same/Different Identity	Same Spatiotopic		Same Retinotopic		Control	
		w/ landmark	w/o landmark	w/ landmark	w/o landmark	w/ landmark	w/o landmark
RT	Same Identity	0.5269(0.18)	0.5087(0.17)	0.5407(0.16)	0.4978(0.20)	0.5566(0.10)	0.5200(0.16)
	Different Identity	0.5184(0.15)	0.4912(0.13)	0.5365(0.16)	0.5155(0.15)	0.5325(0.16)	0.5030(0.15)
Accuracy	Same Identity	0.6746(0.11)	0.6819(0.11)	0.6995(0.10)	0.6985(0.12)	0.6295(0.09)	0.6310(0.12)
	Different Identity	0.5567(0.13)	0.5683(0.15)	0.5222(0.15)	0.5388(0.09)	0.6122(0.15)	0.5785(0.12)
P(‘Same’)	Same Identity (Hit Rate)	0.6746(0.11)	0.6819(0.11)	0.6995(0.10)	0.6985(0.12)	0.6295(0.09)	0.6310(0.12)
	Different Identity (False Alarm Rate)	0.4433(0.13)	0.4317(0.15)	0.4778(0.15)	0.4612(0.09)	0.3878(0.15)	0.4215(0.12)
d-prime		0.6275(0.23)	0.6975(0.46)	0.6043(0.35)	0.6530(0.34)	0.6604(0.31)	0.5761(0.41)
Response Bias		-0.1614(0.31)	-0.1509(0.30)	-0.2439(0.30)	-0.2249(0.25)	-0.0200(0.33)	-0.0745(0.28)