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The Influence of a Moving Object's Location on Object Identity Judgments

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People integrate "what" and "where" information to recognize objects. Even when irrelevant or uninformative, location information can influence object identity judgments. When two sequential stationary objects occupy the same location, people are faster and more accurate to respond (sensitivity effects) and are more likely to judge the objects as identical (spatial congruency bias [SCB]). Other paradigms using moving objects highlight spatiotemporal contiguity's role in object processing. To bridge these gaps, we conducted two preregistered experiments asking how moving objects' locations (trajectories) affect identity judgments, both at fixation and across eye movements. In Experiment 1, subjects fixated a constant location and judged whether two sequentially presented moving stimuli were the same or different object identities. The first stimulus moved linearly from behind one occluder to another. The second stimulus reappeared (still moving) continuing along the same spatiotemporal trajectory (Predictable trajectory), or from the same initial location (Same Exact trajectory), or a different location (Different trajectory). We found the strongest sensitivity and SCB for Same Exact trajectory, with a smaller but significant SCB for Predictable trajectory. In Experiment 2, subjects performed a saccade during occlusion, revealing a robust SCB for Same Exact trajectory in retinotopic coordinates, with a smaller SCB for Predictable trajectory in both retinotopic and spatiotopic coordinates. Our findings strengthen prior reports that object-location binding is primarily retinotopic after both object and eye movements, but the presence of concurrent weak SCB effects along predictable and spatiotopic trajectories suggests more ecologically relevant information may also be incorporated when objects are moving more continuously.

Public Significance Statement

By conducting two preregistered experiments, we examined how judgments of moving objects' identities are affected by their spatial locations and movement paths. Our study demonstrates that both Same Exact trajectory (identical spatial location) and Predictable trajectory (spatiotemporal trajectory of the object movement) can influence object identity judgments. Furthermore, our results suggest that object-location binding for moving objects is still strongly based on low-level retinotopic information, but may also reflect more ecologically relevant predictable and spatiotopic information following eye movements. Overall, we provide new insights into the complex interactions between object identity and location information for moving objects.

Keywords: object–location binding, location facilitation, object movements, retinotopic and spatiotopic, spatial contiguity

When standing on a street with a heavy traffic flow, people need to identify and predict the location of a number of objects. Some of those are relatively stationary, such as crosswalks and signs, while others are moving, such as moving cars and pedestrians. In order to cross the street safely, we need to be able to combine object identity with location information for both stationary and moving objects in each second.

Many studies have found that (stationary) object location can influence object identity judgments in several key ways. In particular, object location can even influence judgments of object identity when location is irrelevant or uninformative. First, there is a location facilitation effect that objects in the same location can lead to reaction time (RT) priming and enhanced sensitivity (Kravitz et al., 2008; Maljkovic & Nakayama, 1996; Tsal & Lavie, 1993).

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Second, a number of studies have found an object-location binding effect, suggesting that object location information can be automatically bound to object identity during visual perception (Ashby et al., 1996; Cave & Chen, 2017; Duncan & Humphreys, 1989; Golomb et al., 2014; Johnston & Pashler, 1990; Kovacs & Harris, 2019; Shafer-Skelton et al., 2017; Starks et al., 2020) and visual working memory (Hollingworth, 2007; Hollingworth & Rasmussen, 2010; Jiang et al., 2000; Olivers et al., 2006; Olson & Marshuetz, 2005; Pertzov & Husain, 2014; Soto et al., 2005; Treisman & Zhang, 2006; Wheeler & Treisman, 2002).

Here we use the term object-location binding to refer to the association of objects with their spatial positions, in the classic sense that successful object recognition requires processing both what an object is and where it is, raising the fundamental challenge of linking "what" and "where" (Treisman, 1996). In addition to the vast research exploring neural mechanisms and computational models of object-location binding (Arcaro et al., 2009; Carlson et al., 2011; Chen & Naya, 2020; Cichy et al., 2011; DiCarlo & Maunsell, 2003; Hannula & Ranganath, 2008; Hemond et al., 2007; Nummenmaa et al., 2017; Roelfsema, 2006; Salehi et al., 2024; Yang et al., 2017), a recent behavioral phenomenon has provided a robust and accessible window into various aspects of object-location binding, via the "spatial congruency bias" (SCB; Golomb et al., 2014). In these studies, two objects are presented sequentially in peripheral locations. The two objects can appear in the same spatial location or in different spatial locations, and the objects can be the same or different identity. Participants are asked to report whether the objects are the same or different identity, while location is irrelevant to the task. Whereas classic studies (including those reviewed above) had focused on priming or sensitivity effects—that people are faster or more accurate to respond when an object is in the same location it was previously seen in—Golomb et al. (2014) reported a novel, independent effect, the SCB: that subjects are more likely to judge two objects as being the same identity if they appeared in the same location compared to in different locations. It is important to note that the SCB is not simply a priming effect. A simple neural priming or sensitivity account would predict that objects appearing in the same location should be easier to compare–meaning increased likelihood to correctly see them as the same when they are the same identity/shape, and correctly distinguish them as different when they are different identities/shapes. In contrast, the SCB reveals that people are more likely to report it as the same object they saw before, even when the identity is actually different. The SCB has proven an extremely robust effect, influencing judgments of oriented Gabors, object shapes, colors, letters, facial identity, and facial expression, and it tends to be present even when sensitivity effects are not (Cave & Chen, 2017; Golomb et al., 2014; Shafer-Skelton et al., 2017; Starks et al., 2020). Moreover, although it is often assumed that response bias measures reflect decision-level processes, response bias measures can also reflect perceptual-level processes (Witt et al., 2015), and there is convincing evidence that the SCB effect reflects a perceptual phenomenon (Babu et al., 2023; Golomb et al., 2014; Shafer-Skelton et al., 2017). The SCB has subsequently been used to gain insight into various theoretical questions about the nature of object-location binding (Bapat et al., 2017; Cave & Chen, 2017; Lu & Golomb, 2024; Shafer-Skelton et al., 2017; Starks et al., 2020), and even its developmental origins (Gao et al., 2024). However, most of these studies have been done with stationary objects. Here, we set out to ask whether the influence of location on object identity is different for moving objects.

Spatiotemporal contiguity is often considered a reliable principle of object persistence (L. Burke, 1952; Cox et al., 2005; Flombaum & Scholl, 2006; Flombaum et al., 2004, 2009; Mitroff & Alvarez, 2007). For moving objects, if we see a red ball rolling behind a pillar, and another ball then emerging from the pillar, moving in the constant direction and speed as the first ball, we can effortlessly imagine an invisible trajectory behind the pillar, linking the movements of these two balls so we assume that it is a continuous movement of one ball through the pillar, even if the second ball looks different from the first ball. This capability has been found as early as 3–4 months of age in infants (L. Burke, 1952; M. B. Burke, 1980), suggesting that human visual system may actively predict the trajectory and existence of occluded moving objects to maintain a consistent perception of a moving object (Baillargeon, 1987; Baillargeon et al., 1985; Clark, 2013; Friston, 2005; Leslie, 1984; Peters & Kriegeskorte, 2021; Spelke et al., 1995; Spoerer et al., 2017; Teichmann et al., 2022; Yuille & Kersten, 2006).

Thus, one might predict that object-location binding updates with object movements. However, a recent study found a SCB primarily for the same original object location, not an updated location based on spatiotemporal contiguity (Bapat et al., 2017). The first stimulus was presented statically for 500 ms, then moved toward a new location before disappearing. The second stimulus was then presented at the final/predictable location of the spatiotemporal motion or the original location. Reliable sensitivity and SCB effects were only found when the second object was presented in the same original location. However, a key aspect of the experimental design may not have been as realistic or appropriate for investigating spatiotemporal contiguity, since there was a sustained stationary presentation of the object before its movement. The stationary object binding effect might have overridden the effect of object movement. In contrast, if the object were constantly moving, might we observe an influence of the Predictable trajectory on object identity? Or would there still be only sensitivity and SCB effects for the Same Exact original trajectory?

To investigate whether and how the location trajectory could influence object identity of a moving object, we modified the above paradigm to make the objects consistently move. In our preregistered Experiment 1, the object moved at a constant speed from initial appearance (emerging from behind an occluder) until disappearance (passing behind another occluder). It then reappeared (still moving) from either the predictable location along the occluded spatiotemporal trajectory (Predictable trajectory), from the same initial location (Same Exact trajectory), or from an entirely different location (Different trajectory). Subjects were asked to keep fixation at a single location on each trial and judge whether the two moving objects (presented before and after the occlusion) had the same or different identity (shape).

After understanding how task-irrelevant locations affect identity judgments of moving objects, we further aim to explore how these effects extend across an eye movement. In the real world, there are object movements and our own eye movements when we perceive the world. When a saccadic eye movement is made, visual information can be represented in different reference frames: retinotopic (gaze-centered) and spatiotopic (world-centered) coordinates. How does a moving object's trajectory influence judgments of its identity when eye movements intervene, and what is the reference frame of these effects?

Previous studies have also tested whether object identity judgments are bound to retinotopic or spatiotopic location across saccades, using static objects. An initial set of studies found only retinotopic object-location binding, that subjects were more likely to judge two objects as having the same identity when they were in the same retinotopic location (Shafer-Skelton et al., 2017). The interpretation was that object-location binding is a low-level visual effect that occurs in retinotopic coordinates, in which case we might expect a moving object's location effect to be based on retinotopic coordinates as well. On the other hand, a more recent study found significant spatiotopic object-location binding in a dynamic saccade context (Lu & Golomb, 2024), including where the stimuli are presented while the eyes are moving, with the interpretation being that this dynamic saccade context triggers more spatiotopic stability. If the object itself is moving, can the object movement similarly create a dynamic context that triggers a spatiotopic object-location binding effect?

In our preregistered Experiment 2, we asked subjects to perform a saccade during the delay on each trial to distinguish the retinotopic and spatiotopic coordinates. Additionally, we compared these data to a control task where subjects executed the same eye movements and the stimuli were in the same general locations, but where the objects were static instead of moving, to confirm if our findings are specific to a moving object.

Method

Transparency and Openness Statement

All experiments were preregistered on the Open Science Framework (Experiment 1: https://osf.io/y8rew and Experiment 2: https://osf.io/n79ag) prior to starting data collection. Our original theoretical motivation, hypotheses, study design, sample size (rationale and stopping rule), exclusion criteria, variables, and analyses can be found there. Any analysis included here that was not listed in the preregistration is declared as exploratory. Data were analyzed using MATLAB, Version R2022a, Python, Version 3.9, and IBM SPSS Statistic, Version 29. Data and code are available on the Open Science Framework (https://osf.io/8y7cs).

Subjects

For each experiment, 16 subjects ranging from 18 to 29 years old (Experiment 1: 18.75 ± 0.93, nine females; Experiment 2: 20.19 ± 3.33, five females) were recruited via the first-year course credit website and advertising. All subjects reported normal or corrected-to-normal vision and were compensated with course credit or payment. The research was approved by the Ohio State University Behavioral and Social Sciences Institutional Review Board.

Our preregistered power analysis, sample size, and stopping rule were as follows: A power analysis was conducted using G*Power software, with a power level of .9, an α value of .05 (two-tailed test). It estimated that the SCB effect (Experiment 1 of Golomb et al., 2014, which had an effect size of $dz = 1.01$ for the comparison of SameLocation vs. DifferentLocation bias) would need $N = 13$. We set the sample size at $N = 16$ (matching prior studies). Subjects with poor task performance were excluded (overall accuracy <55%). Thus, we stopped the experiment once we got 16 subjects to meet the requirements for each experiment.

Experimental Setup

Stimuli were presented using Psychtoolbox extension (Brainard, 1997) for MATLAB (Math Works), on a 21-in. (53.34-cm) flat-screen cathode ray tube monitor. Subjects were seated at a chinrest 60 cm from the monitor.

Eye Tracking

Eye position was monitored with an EyeLink 1000 eye-tracking system recording pupil and corneal reflection position. Fixation was monitored for all experiments.

Stimuli

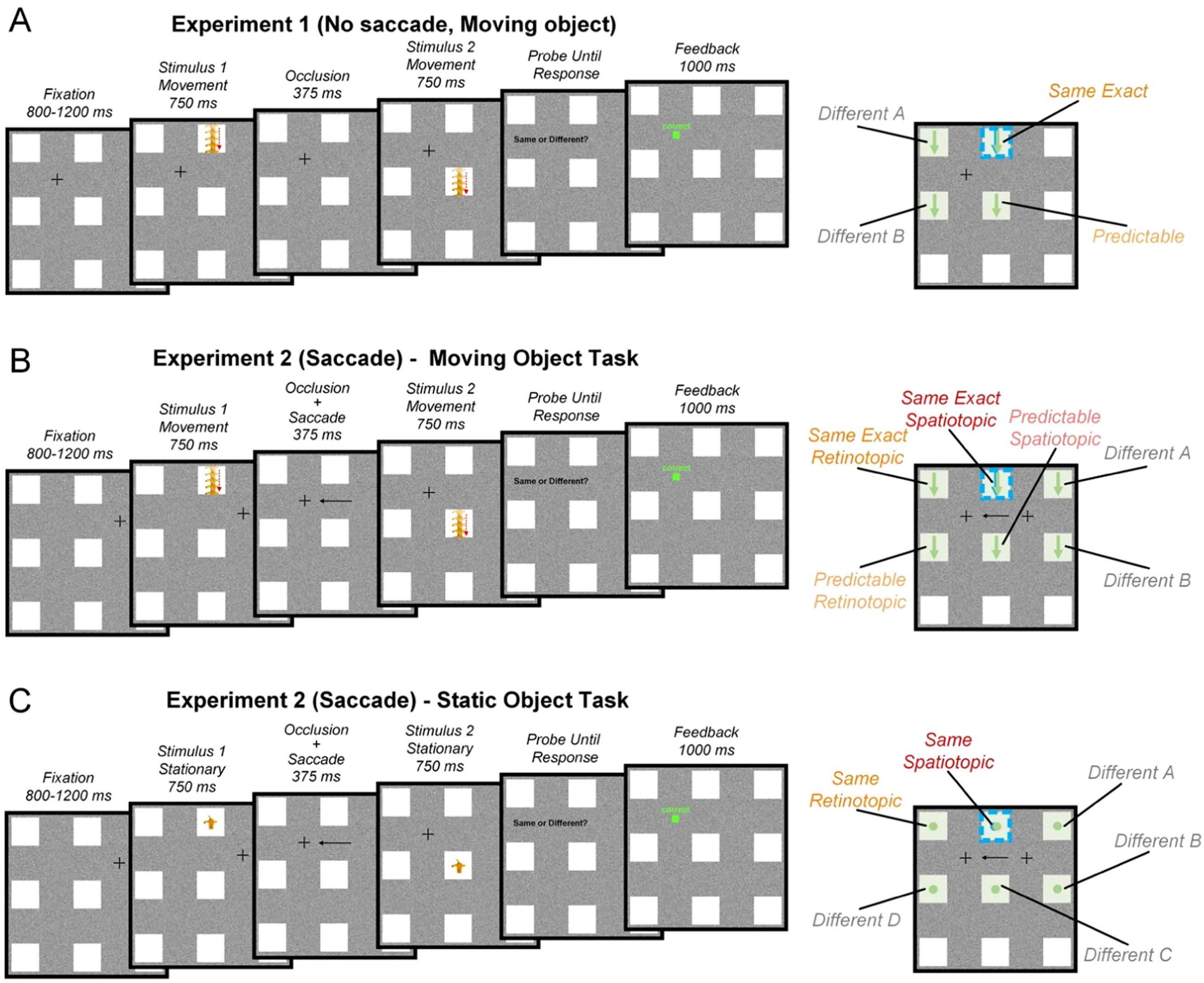
Stimuli were the same as those in Golomb et al. (2014), from the Tarr stimulus set (stimulus images courtesy of Michael J. Tarr, Center for the Neural Basis of Cognition and Department of Psychology, Carnegie Mellon University, https://www.tarrlab.org), except we changed the color of objects from gray to yellow to make them stand out clearer from the occluders. Stimuli were drawn from 10 families of shape morphs; within each family, the "body" of the shape remains constant, while the "appendages" could vary in shape, length, or relative location. The Stimulus 1 shape was randomly chosen on each trial. On same shape trials, the Stimulus 2 shape was the identical image. On different shape trials, the second shape was chosen as a different shape from the same morph family. We used the easiest morph level (the two images with the greatest morph distance within a family) for all subjects instead of individual staircase task difficulty since in Golomb et al., 2014; Shafer-Skelton et al., 2017, subjects were already within the desired accuracy range (65%–85%) at this easiest morph level (maximum staircase value). The stimulus was sized $2.4° \times 2.4°$, and stimulus orientation would never be varied.

Experiment 1: Object Movement Without Eye Movement

We modified the original Golomb et al. (2014) experiment to test moving objects that appeared and disappeared from behind occluders (Figure 1A). Present on the screen at all times was a large occlusion mask (each pixel in the mask is colored a random grayscale value [between 0 and 255]), with nine $4.8° \times 4.8°$ square cutouts where an object could be seen without occlusion. The nine square cutouts formed a 3×3 grid, with four possible fixation locations centered on the intersections (corners of an invisible $10.8° \times 10.8°$ square), such that each fixation location had four adjacent unoccluded areas (cutouts) of equal eccentricity (7.6368° from fixation to the center of cutout).

For each trial, a fixation cross was displayed at one of the four fixation locations, and subjects were asked to remain fixated on the displayed fixation cross. After 800–1,200 ms of fixation, Stimulus 1 was presented. It emerged from behind a section of the occluder and moved through one of the cutout regions for 750 ms at a constant speed (9.6° per second). Stimulus 1 always emerged from one of the outer edges of a cutout adjacent to the fixation, such that each fixation had four possible Stimulus 1 trajectories (Figure 1A). After Stimulus 1 passed behind the next part of the occluder, there was a 375 ms delay, during which the object was invisible. The occlusion duration of 375 ms was carefully determined based on the width of the occlusion and the velocity of the stimulus before entering the occlusion. Given this design, subjects should perceive the stimulus

Figure 1
Paradigms of Experiment 1 and 2



Note. Example trial progressions and location conditions of (A) Experiment 1 (no saccade, moving object), (B) Experiment 2 (saccade)—Moving Object Task, and (C) Experiment 2 (saccade)—Static Object Task. The blue (dark gray) square and arrow/circle in the right figures indicate the visible area and trajectory/location of Stimulus 1, and the green (light gray) arrows indicate the possible trajectory/locations of Stimulus 2. In Experiment 1, for a given Stimulus 1 trajectory (blue [dark gray] arrow), there were four possible trajectories (green [light gray] arrows) for Stimulus 2: Same Exact trajectory (same trajectory as Stimulus 1), Predictable trajectory (Predictable trajectory along the same path as Stimulus 1), and Different A and B trajectories. In Experiment 2 Moving Object Task, for a given Stimulus 1 trajectory (blue [dark gray] arrow), there were six possible trajectories (green [light gray] arrows) for Stimulus 2: Same Exact Spatiotopic trajectory (same screen trajectory as Stimulus 1), Predictable Spatiotopic trajectory (Predictable trajectory along the same screen path as Stimulus 1), Same Exact Retinotopic trajectory (same trajectory as Stimulus 1 relative to two fixations during stimulus), Predictable Retinotopic trajectory (Predictable trajectory along the same path as Stimulus relative to two fixations during stimulus), and Different A and B trajectories. In Experiment 2 Static Object Task, for a given Stimulus 1 location (blue [dark gray] circle), there were six possible locations (green [light gray] circles) for Stimulus 2: Same Spatiotopic location (same screen position as Stimulus 1), Same Retinotopic location (same location as Stimulus 1 relative to two fixations during stimulus), and Different A, B, C, and D locations. See the online article for the color version of this figure.

as continuing its path smoothly during the occlusion, without any noticeable pause or hesitation. After that, Stimulus 2 emerged from behind the occluder moving for 750 ms at the same speed (9.6° per second). There were four possible Stimulus 2 trajectory conditions: On 25% of trials, it would be presented along the Same Exact trajectory (emerging from the same exact initial location and moving in the same direction as Stimulus 1). In 25% of trials, it would be presented along the Predictable trajectory (emerging from the predictable location and direction assuming constant movement of Stimulus 1 behind the occluder). In the remaining trials, Stimulus 2 would emerge from a completely different location (25% Different trajectory A and 25% Different trajectory B).

After Stimulus 2 disappeared behind the next occluder, subjects saw the question “Same or Different?” and were instructed to make a two-alternative forced choice of same/different judgment comparing the two objects' identities (shapes). They were instructed that location was irrelevant to the task. Subjects responded by button press ("j" for "Same" and "k" for "Different") and were presented with visual feedback ("correct" in green or "incorrect" in red on the screen).

Eye positions were monitored with an EyeLink 1000 eye-tracking system, recording pupil and corneal reflection position. If the subject's fixation deviated greater than 2° at any point, the trial was aborted and repeated later in the block. Subjects were provided feedback if they broke fixation at any time point during the trial ("Please look at the fixation!" on the screen) or did not give a response in 3 s ("No response" on the screen).

The 16 different Stimulus 1 configurations (4 Fixations × 4 Trajectories) were counterbalanced and equally likely. The main eight conditions of interest were the 4 Stimulus 2 Trajectory Conditions (Same Exact trajectory, Predictable trajectory, Different A trajectory, and Different B trajectory) × 2 Object Identity Conditions (same or different identity). Subjects completed eight blocks with 64 trials per block (512 trials in total, 64 trials for each of the eight conditions, in randomized order and randomly divided into eight blocks), in addition to any trials that were aborted due to eye-tracking errors (which were repeated later in randomized order in the same block).

Experiment 2: Object Movement With Saccadic Eye Movement

Experiment 2 used the same stimuli as Experiment 1 but added a saccade to the paradigm to distinguish different reference frame conditions. In this within-subject design study, we conducted two versions of the task: In the main task (Moving Object Task), the stimuli were moving objects; in the control task (Static Object Task), the stimuli were static objects.

In Moving Object Task (Figure 1B), after Object 1 moved behind the occluder, during the occlusion period, the fixation cross jumped to either the adjacent horizontal or adjacent vertical fixation location, and subjects were asked to make a saccade to the new fixation location. The saccade direction was orthogonal to the object movement direction. Eye-tracking was used to make sure that the subject completed the saccade during the 375 ms occlusion period. If the subject did not complete the saccade in that time, the trial would be aborted and repeated later in the block. There were six possible Stimulus 2 location/trajectory conditions for Moving Object Task: On one sixth of trials, it would be presented along the Same Exact Retinotopic trajectory (emerging from the same exact initial location as Stimulus 1 based on the retinotopic coordinate and moving in the same direction as Stimulus 1). On one sixth of trials, it would be presented along the Predictable Retinotopic trajectory (emerging from the predictable location and direction assuming constant movement behind the occluder based on the retinotopic coordinates). On one sixth of trials, it would be presented along the Same Exact Spatiotopic trajectory (emerging from the same exact initial location based on the spatiotopic coordinates and moving in the same direction as Stimulus 1). On one sixth of trials, it would be presented along the Predictable Spatiotopic trajectory (emerging from the predictable location and direction assuming constant movement behind the occlude based on the spatiotopic coordinates). In the remaining trials, Stimulus 2 would emerge from a completely different location (one-sixth Different trajectory A and one-sixth Different trajectory B). Stimulus 1 always emerged from the outer edges of a cutout adjacent to both fixations before and after the saccade. Thus, there were eight possible saccade routes, each with only one possible Stimulus 1 trajectory (Figure 1B).

In Static Object Task (Figure 1C), procedures were essentially the same as in Moving Object Task, except those stimuli were static. This control task was intended to overcome a potential limitation of the current study design. In Moving Object Task, the Stimulus 1 movement direction was always perpendicular to saccade direction. For example, if the object was moving down, subjects always made a saccade to the horizontal adjacent fixation. They might be able to predict the saccade target after practicing. If we found a spatiotopic SCB in Moving Object Task, we wanted to make sure if this was indeed due to the intended manipulation (object's movements), rather than the prediction of the saccade trajectory. Thus, we designed a static version of our task as a control, where everything was identical, but the objects were stationary, located in the middle of the given cutout area for the full stimulus duration. There were also eight possible saccade routes, each with one possible Stimulus 1 location (Figure 1C). Thus, there would be six possible Stimulus 2 location conditions in Static Object Task: On one sixth of trials, it would be presented in the Same Exact Retinotopic location. On one sixth of trials, it would be presented in the Same Exact Spatiotopic location. Moreover, in the remaining trials, Stimulus 2 would be presented at a different location (Different A, B, C, and D locations, one sixth of trials for each). Importantly, in this control task, the saccade trajectory was still predictable from the Object 1 location, unlike the prior SCB studies with static objects and saccades (Lu & Golomb, 2024; Shafer-Skelton et al., 2017). If saccade predictability was not a critical factor, we expected the control task to replicate the prior findings of retinotopic-only bias (Shafer-Skelton et al., 2017).

Subjects completed 12 blocks (six Moving Object Task blocks and six Static Object Task blocks, in randomized block order), with 64 trials per block. Each block contained 64 trials for each of the 6 Location/Trajectory Conditions × 2 Object Identity Conditions (Same or Different identity). This resulted in 768 trials in total, 384 trials for each task, and 32 trials for each of the 24 conditions. This was half the number of trials per condition as Experiment 1, but sufficient to reliably detect a SCB according to previous studies (Bapat et al., 2017; Golomb et al., 2014; Lu & Golomb, 2024; Shafer-Skelton et al., 2017; Starks et al., 2020).

The task and other design details are identical to Experiment 1. Trials that were aborted due to eye-tracking errors were repeated later in a randomized order in the same block.

Analysis

We excluded trials on which subjects responded with RTs greater than or less than 2.5 *SD*s from the subject's mean. We preregistered analyses focused on response bias, sensitivity (d'), and RT to measure possible location effects. However, due to a procedural issue, RT may not have been reliable. During our data collection of both experiments, subjects were instructed to respond with a keystroke only after the second moving object disappeared, meaning that the RT was measured from the moment the second moving object disappeared to the moment of the subject's keystroke response. However, subjects were capable of initiating their response as soon as the second stimulus appeared from behind the occluder, but these early button presses were not recorded accurately. This procedural constraint likely limited the range of recorded RTs, potentially contributing to the absence of observable differences in RT across conditions (Tables A1–A6). Given this limitation, our analyses reported below focus on sensitivity (d') and response bias measures.

For each subject, we calculated hit and false alarm rates for each location/trajectory condition. We defined a "hit" as a "Same" response when the two stimuli were actually the same (same identity condition), and a "false alarm" as a "Same" response when the two stimuli were different (different identity condition). Using signal detection theory, we applied the standard formula (Stanislaw & Todorov, 1999) to calculate d' and response bias (criterion) for each subject, for each location condition:

$$d' = z(\text{hit rate}) - z(\text{false alarm rate}),$$
$$\text{Response bias} = -\frac{[z(\text{hit rate}) + z(\text{false alarm rate})]}{2}. \quad (1)$$

We define the "sensitivity effect" as the difference in d' for same exact (or predictable) versus different location conditions, and the "spatial congruency bias (SCB) effect" as the difference in response bias for same exact (or predictable) versus different location conditions.

For Experiment 1, we conducted two-tailed paired t tests to determine whether there were significant differences of d' and response bias between Same Exact trajectory versus Different trajectory (averaging Different trajectory A and B), and Predictable trajectory versus Different trajectory (averaging Different trajectory A and B). In addition, we conducted a two-tailed paired t test between Same Exact trajectory and Predictable trajectory.

For Moving Object Task of Experiment 2, we conducted two-tailed paired t tests to determine whether there were significant differences of d' and response bias between Same Exact Retinotopic trajectory versus Different trajectory (averaging Different A and B trajectories), Predictable Retinotopic trajectory versus Different trajectory (averaging Different A and B trajectories), Same Exact Spatiotopic trajectory versus Different trajectory (averaging Different A and B trajectories), and Predictable Spatiotopic trajectory versus Different trajectory (averaging Different A and B trajectories). Then we conducted 2 × 2 analyses of variance (ANOVAs) comparing trajectory types (same exact and predictable) and reference frames (retinotopic and spatiotopic). Due to the larger eccentricity in the two Different trajectory conditions compared to the other conditions, we also conducted pairwise two-tailed paired t tests on the four experimental conditions with same eccentricity (Same Exact Spatiotopic trajectory, Same Exact Retinotopic trajectory, Predictable Spatiotopic trajectory, and Predictable Retinotopic trajectory) based on our preregistrations.

For Static Object Task of Experiment 2, we first conducted two-tailed paired t tests to determine whether there were significant differences in d' and response bias between Same Retinotopic location versus the average of Different A, B, C, and D locations, and between Same Spatiotopic location versus the average of Different A, B, C, and D locations. We also conducted matched-eccentricity analyses with two-tailed paired t test to determine whether there were differences of d' and response bias between Same Retinotopic location versus the average of Different trajectory C and D, and between Same Spatiotopic location versus the average of Different trajectory C and D. In addition, we conducted a two-tailed paired t test between Same Retinotopic location and Same Spatiotopic location.

For all analyses, we report frequentist statistics and p values, effect sizes using Cohen's d, and Bayesian statistics. For the Bayes factors (BF_{10}), we used the default Cauchy distribution prior (scale parameter = 0.707).

In addition to the preregistered analyses, we conducted an exploratory analysis to further evaluate whether several significant results were due to a difference in eccentricity. As noted above, in Experiment 2 Moving Object Task, the Different trajectories had larger eccentricity than the other conditions. Although there wasn't an eccentricity-matched Different condition in the Moving Object Task, there was in the Static Object Task. Since all subjects performed both tasks, we conducted cross-task comparisons using each subject's mean of Static Object Task Different C and D (matched eccentricity) as an alternative baseline for their main location/trajectory conditions in both tasks.

Results

Experiment 1: Object Movement Without Eye Movement

How Does Location Influence Identity Judgments When the Initial Object Is Moving?

Figure 2 illustrates the average d-prime and response bias values for each location condition for Experiment 1, while Figure 4 depicts these data in terms of individual subjects' sensitivity effects (difference scores: d' for Same Exact or Predictable trajectories minus Different trajectory) and SCB effects (difference scores: response bias for Different trajectory minus Same Exact or Predictable trajectory). Additionally, Tables A1 and A2 report the condition means and statistics for all behavioral measures, including RT, accuracy, d-prime, and proportion "Same" response (hits, false alarms) in Experiment 1.

For the sensitivity effect (Figure 2A), we found significantly greater d-prime for Same Exact trajectory, $t(15) = 3.7095$, $p = .0021$, $d = 0.5855$, $BF_{10} = 20.284$, but not for Predictable trajectory, $t(15) = 0.3967$, $p = .6972$, $d = 0.0649$, $BF_{10} = 0.274$, compared to the Different trajectories baseline. The d-prime for Same Exact trajectory was significantly greater than that for Predictable trajectory, $t(15) = 3.5491$, $p = .0029$, $d = 0.5078$, $BF_{10} = 15.342$.

For SCB effect (Figure 2B), we found a significantly greater response bias for both Same Exact, $t(15) = -6.9179$, $p < .001$, $d = -1.5692$, $BF_{10} = 4{,}190$, and Predictable trajectories, $t(15) = -3.4432$, $p = .0036$, $d = -0.7440$, $BF_{10} = 12.767$, compared to the Different trajectories baseline. Also, the response bias for Same Exact trajectory was significantly greater than that for Predictable trajectory, $t(15) = -3.4982$, $p = .0032$, $d = -0.7798$, $BF_{10} = 14.043$.

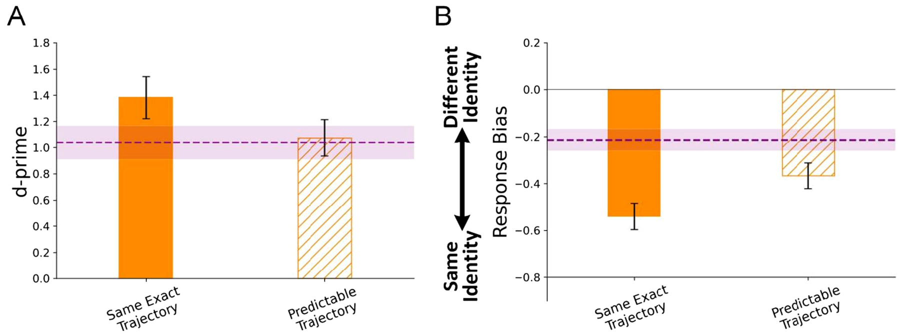
These results first demonstrate that even if the object is initially moving, the Same Exact trajectory has the largest influence on object identity judgments in terms of both sensitivity and SCB effects. However, the significant SCB for Predictable trajectory suggests that object-location binding may reflect spatiotemporal contiguity in addition to initial spatial location when the initial object is moving.

Experiment 2: Object Movement With Eye Movement

How Does Location Influence Identity Judgments Across a Saccade When the Initial Object Is Moving?

Figure 3 illustrates the average d-prime and response bias values for each location condition for Experiment 2, while Figure 4 depicts

Figure 2
Experiment 1 Results



Note. (A) *d*-prime and (B) response bias (criterion, where positive values refer to higher likelihood for participants to judge the objects as different identities, and negative values indicate higher likelihood for "same identity" responses). Bars show the main trajectory conditions. To evaluate sensitivity and SCB effects, these were compared to the baseline Different trajectory conditions: purple [dark gray] dotted line indicates the mean of Different A and Different B trajectories. Error bars and shaded lines are standard error of the mean. See the online article for the color version of this figure.

these data in terms of individual subjects' sensitivity effects and SCB effects (difference scores using the mean of Different C and D location conditions as the baseline for both tasks). Additionally, Tables A3–A6 report the condition means and statistics for all behavioral measures, including RT, accuracy, *d*-prime, and proportion "Same" response (hits, false alarms) in Experiment 2 Moving and Static Object Tasks.

In Moving Object Task, for sensitivity effect (Figure 3A), we found significantly greater *d*-prime for all spatiotopic and retinotopic conditions compared with the preregistered Different trajectory baseline (green [light gray] dotted lines in Figure 3): Same Exact Spatiotopic, $t(15) = 4.2271$, $p < .001$, $d = 0.9844$, $BF_{10} = 50.089$; Predictable Spatiotopic, $t(15) = 4.5510$, $p < .001$, $d = 1.0072$, $BF_{10} = 87.974$; Same Exact Retinotopic, $t(15) = 6.1606$, $p < .001$, $d = 1.4439$, $BF_{10} = 1{,}293$; and Predictable Retinotopic, $t(15) = 3.4087$, $p = .0039$, $d = 1.0002$, $BF_{10} = 12.027$. However, as noted below, the Different trajectory conditions were presented at a larger visual eccentricity so may not be an appropriate baseline; see exploratory analyses below with an alternative baseline. Directly comparing the main conditions, the 2 × 2 ANOVA on *d*-prime with within-subjects factors of trajectory type (Same Exact or Predictable) and reference framework (Spatiotopic or Retinotopic) found no significant main effects or interaction, trajectory type, $F(1, 15) = 0.255$, $p = .621$, $\eta_p^2 = .017$; reference framework, $F(1, 15) = 0.0004$, $p = .985$, $\eta_p^2 < .01$; and interaction, $F(1, 15) = 0.791$, $p = .388$, $\eta_p^2 = .050$.

For the SCB effect (Figure 3B), we also found significantly greater response bias for all conditions compared with the preregistered Different trajectory baseline, Same Exact Spatiotopic, $t(15) = -4.1464$, $p < .001$, $d = -1.2683$, $BF_{10} = 43.515$; Predictable Spatiotopic, $t(15) = -5.7560$, $p < .001$, $d = -2.0488$, $BF_{10} = 672.5$; Same Exact Retinotopic, $t(15) = -10.1065$, $p < .001$, $d = -3.1290$, $BF_{10} = 307{,}530$; and Predictable Retinotopic, $t(15) = -7.8393$, $p < .001$, $d = -1.7268$, $BF_{10} = 16{,}122$, although again this may not have been an appropriate baseline condition. Directly comparing the main conditions, the 2 × 2 ANOVA on response bias found a significant main effect of reference framework, $F(1, 15) = 6.37$, $p = .023$, $\eta_p^2 = .298$, and a significant interaction effect, $F(1, 15) = 7.59$, $p = .015$, $\eta_p^2 = .336$. The main effect of trajectory type was not significant, $F(1, 15) = 1.46$, $p = .246$, $\eta_p^2 = .089$. The response bias for Same Exact Retinotopic trajectory was significantly greater compared to all other conditions, Same Exact Retinotopic versus Same Exact Spatiotopic, $t(15) = -3.7265$, $p = .0020$, $d = -0.9956$, $BF_{10} = 20.893$; Same Exact Retinotopic versus Predictable Spatiotopic, $t(15) = -2.9641$, $p = .0097$, $d = -0.6984$, $BF_{10} = 5.631$; and Same Exact Retinotopic versus Predictable Retinotopic, $t(15) = -3.5085$, $p = .0032$, $d = -0.8423$, $BF_{10} = 14.297$, and there was no significant difference between Same Exact Spatiotopic, Predictable Spatiotopic, and Predictable Retinotopic trajectories (all $ts < |2|$, $ps > .05$, though most Bayes factors were inconclusive; see Table A4).

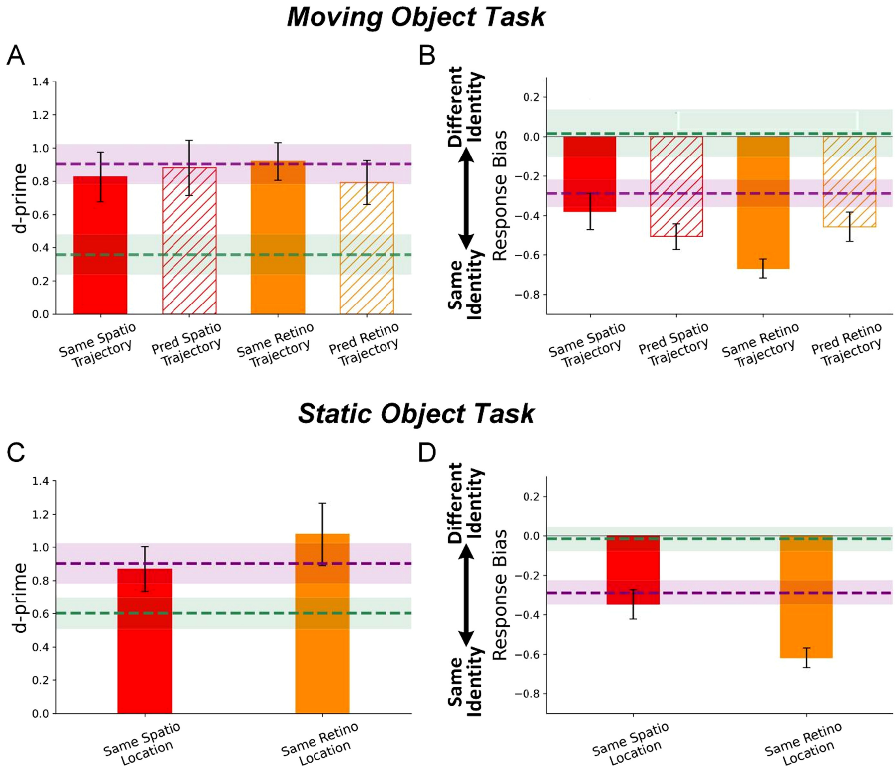
In the Static Object Task, for sensitivity effect (Figure 3C), we found significantly greater *d*-prime for both Same Spatiotopic and Retinotopic locations compared to the preregistered baseline mean of all Different locations (green [light gray] dotted line): Same Spatiotopic, $t(15) = 2.7223$, $p = .0157$, $d = 0.5692$, $BF_{10} = 3.7715$; Same Retinotopic, $t(15) = 3.2301$, $p = .0056$, $d = 0.7930$, $BF_{10} = 8.8429$. The difference between Same Spatiotopic and Retinotopic locations, $t(15) = -1.1576$, $p = .2651$, $d = -0.3194$, $BF_{10} = .453$, was not significant, though the Bayes factor suggests only anecdotal evidence for the absence of a difference.

For Static Object Task SCB effect (Figure 3D), we also found a significantly greater response bias for both Same Spatiotopic and Retinotopic locations compared to the mean of all Different locations, Same Spatiotopic, $t(15) = -4.8454$, $p < .001$, $d = -1.1969$, $BF_{10} = 146.1$; Same Retinotopic, $t(15) = -10.6705$, $p < .001$, $d = -2.6524$, $BF_{10} = 595{,}420$. The Same Retinotopic bias was significantly greater than the Same Spatiotopic bias, $t(15) = -3.1861$, $p = .0061$, $d = -1.0597$, $BF_{10} = 8.203$.

However, as noted above, in Moving Object Task, the eccentricity of the second object in the Different trajectories conditions was larger than for the other trajectories in this design (see Figure 1). Similarly, in Static Object Task, the eccentricity for Different A and B locations was also larger than that for the other locations,

Figure 3

Experiment 2 Results



Note. (A) *d*-prime and (B) response bias (criterion) of Moving Object Task for each of the main trajectory conditions. To evaluate facilitation and SCB, these were compared to the Different trajectory conditions: Green (light gray) dotted line indicates the mean of Different A and B Trajectories (preregistered comparison). Purple (dark gray) dotted line indicates the mean of Different C and D locations from Static Task (eccentricity-matched comparison). (C) *d*-prime and (D) response bias (criterion) of Static Object Task for each of the main location conditions. Green (light gray) dotted line indicates the mean of Different A, B, C, and D locations. Purple (dark gray) dotted line indicates the mean of Different C and D locations (eccentricity matched). Error bars and shaded lines are standard error of the mean. SCB = spatial congruency bias. See the online article for the color version of this figure.

which may lead to a slower and less accurate performance (Carrasco et al., 1995, 2003; Hilz & Cavonius, 1974; J. M. Wolfe et al., 1998) and result in smaller values of d' and response bias for the Different trajectories/locations baseline. This eccentricity misalignment might cause inflated sensitivity and SCB effects for all non-Different conditions compared to the Different trajectories/locations baseline, confounding the location trajectory effect. Therefore, we conducted the exploratory analyses below to investigate whether the sensitivity and SCB results reported above were due to the difference in eccentricity.

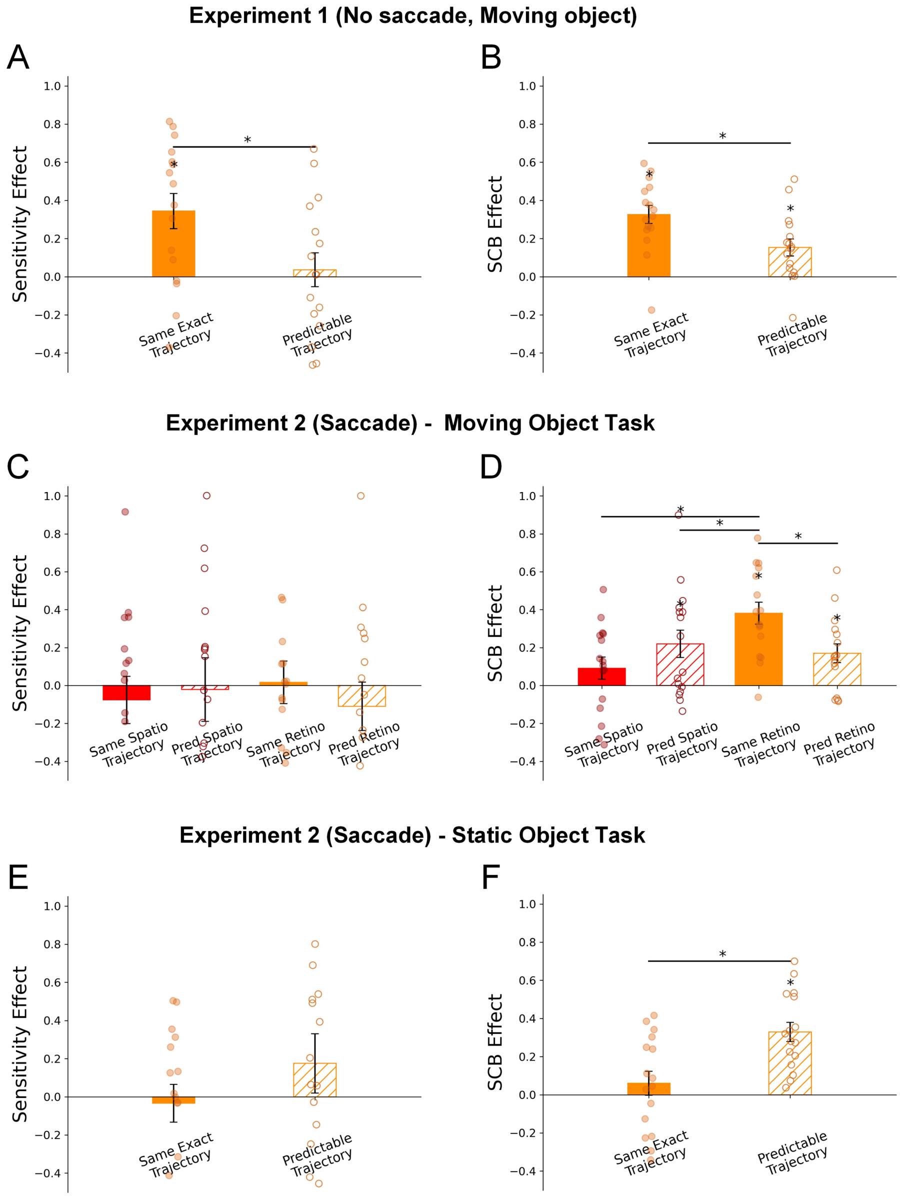
Exploratory Analyses Using a Same-Eccentricity Baseline

Although the Moving Object Task did not have any eccentricity-matched Different trajectory conditions, the Static Object Task had two Different Location conditions with larger eccentricity (Different A and B), and two Different Location conditions with eccentricity matched to the spatiotopic and retinotopic conditions (Different C and D locations). Because this was a within-subject design where all subjects performed both tasks, we reconducted the comparisons for both tasks using the mean of the two eccentricity-matched conditions (Different C and D) from Static Object Task as an alternative baseline (purple [dark gray] dotted lines in Figure 3).

In the Moving Object Task, for sensitivity effect, none of the retinotopic or spatiotopic *d*-prime effects were significantly greater than the eccentricity-matched baseline (all ts<|1|, ps > 0.05, all BF_{10}s < 0.35; see Table A4). For the SCB effect, we found significantly greater response bias for Predictable Spatiotopic trajectory, $t(15) = -3.0574$, $p = .0080$, $d = -0.8103$, $BF_{10} = 6.590$, Same Exact Retinotopic trajectory, $t(15) = -6.6031$, $p < .001$, $d = -1.6062$, $BF_{10} = 2{,}589$, and Predictable Retinotopic trajectory, $t(15) = -3.4327$, $p = .0037$, $d = -0.5873$, $BF_{10} = 12.54$, compared to the eccentricity-matched baseline. Response bias for Same Exact Spatiotopic trajectory was not significantly different from the baseline, $t(15) = -1.5516$, $p = .1416$, $d = -0.5873$, $BF_{10} = 0.6918$, although the Bayes factor suggests that the evidence is insufficient to definitively support or refute the alternative hypothesis. This analysis suggests that the facilitation results were likely driven by eccentricity, but the response bias results were mostly driven by the location trajectory effect.

Figure 4

Summary of Sensitivity and SCB Effects Across Experiments



Note. Experiment 1 (A and B). (A) Sensitivity effect (difference score) for Same Exact and Predictable trajectories relative to Different trajectory baseline (Same Exact or Predictable minus Different). (B) SCB effect (difference score) for Same Exact and Predictable trajectories relative to Different trajectory baseline (Different minus Same Exact or Predictable). Each dot indicates an individual subject. Error bars are standard error of the mean. Experiment 2 (C–F), with difference score effects for all conditions calculated relative to the eccentricity-matched baseline ("mean of Different C and D locations" from Static Task, purple [dark gray] dashed line in Figure 3). SCB = spatial congruency bias. See the online article for the color version of this figure.
* $p < .05$.

In Static Object Task, there was no significantly greater *d*-prime for Same Retinotopic, $t(15) = 1.1247$, $p = .2784$, $d = 0.2765$, $BF_{10} = 0.4391$, or Same Spatiotopic location, $t(15) = -0.3391$, $p = .7392$, $d = -0.0657$, $BF_{10} = 0.269$, compared to the eccentricity-matched baseline, though the Bayes factors only suggest reliable evidence for the absence of a spatiotopic effect. In terms of SCB, we only found significantly greater response bias for Same Retinotopic location compared to the eccentricity-matched baseline, $t(15) = -10.6705$, $p < .001$, $d = -1.3686$, $BF_{10} = 2{,}331$. We did not find significantly greater response bias for Same Spatiotopic location compared to the eccentricity-matched baseline, $t(15) = -0.9608$, $p = .3519$, $d = -0.2076$, $BF_{10} = 0.381$, though the Bayes factor suggests only anecdotal evidence for the absence of a difference. After accounting for eccentricity, these findings were consistent with previous studies using the SCB paradigm with static objects that only found retinotopic SCB effects (Experiment 2 in Lu & Golomb, 2024; Shafer-Skelton et al., 2017). Thus, it suggests that even if subjects could have predicted the saccade route during the task, it did not reliably affect the pattern of SCB on object identity judgments.

Discussion

In the present two experiments, we demonstrated how moving objects' location trajectories could influence object identity judgments in multiple ways. People recognize numerous stationary and moving objects by combining their location and identity information every day. Previous work has indicated that location information not only serves as one of the object properties but also influences object identity judgments through two key effects: increased sensitivity and SCB. For the sensitivity effect, subjects can benefit from shared spatial attention resources when objects appear in the same position. This effect leads to faster RT, known as RT priming (Maljkovic & Nakayama, 1996; Tsal & Lavie, 1993), and sensitivity enhancement (Kravitz et al., 2008). For SCB, subjects are more likely to judge two objects represented sequentially as the same identity if they appear in the same location (Golomb et al., 2014). This effect demonstrates that even task-irrelevant location information can influence object identity perception, which reflects an object-location binding effect. For moving objects, this has seldom been reported in previous studies.

Here, we proposed a consistently moving version of the traditional paradigm (Golomb et al., 2014) to test both sensitivity and SCB effects and found that the location of a moving object can significantly influence object identity judgments through the two key ways. In Experiment 1, our findings revealed a significant sensitivity effect when the second object followed the same location trajectory (Same Exact trajectory) compared to a Different trajectory, but there was no significant sensitivity effect when the second object followed a spatiotemporally consistent trajectory (Predictable trajectory) as the initially presented moving object. For the SCB, we found significant effects for both Same Exact and Predictable trajectories, but the SCB was significantly greater for the Same Exact trajectory.

Furthermore, in Experiment 2, we retained the experimental design of Experiment 1 but added a saccade during the delay between two appearances to distinguish the retinotopic and spatiotopic coordinates. We categorized our main conditions as follows: Same Exact Spatiotopic trajectory, Same Exact Retinotopic trajectory, Predictable Spatiotopic trajectory, Predictable Retinotopic trajectory, and Different trajectories. Participants were asked to judge whether the two moving objects presented before and after the occlusion and a saccade have the same or different identities (shapes). As a control, we also asked subjects to do a static object version of the task. We found significant SCB of the moving object for Same Exact Retinotopic, Predictable Retinotopic, and Predictable Spatiotopic trajectories, with the strongest bias for Same Exact Retinotopic trajectory. We also replicated a significant SCB of a static object for Same Retinotopic location, which was consistent with previous studies using static objects (Lu & Golomb, 2024; Shafer-Skelton et al., 2017). These findings suggest that for moving objects, the SCB on the Same Exact trajectory relies on retinotopic coordinates, while the (weaker) bias on the Predictable trajectory is based on both retinotopic and spatiotopic coordinates across an eye movement. Our findings strengthen prior reports that object-location binding is preserved in primarily retinotopic coordinates after both object movements and eye movements, but the presence of concurrent weak SCB effects along the predictable and spatiotopic trajectories suggests that more ecologically relevant information may also be incorporated when the objects are moving more continuously.

Spatial Congruency Bias of a Moving Object Without Saccade

Our results have implications for understanding the relationship between object location and identity representations, especially when the location is task-irrelevant. SCB has been considered a fundamental behavioral measure to investigate object-location binding for different types of objects and different types of location (Bapat et al., 2017; Golomb et al., 2014; Lu & Golomb, 2024; Shafer-Skelton et al., 2017; Starks et al., 2020). As mentioned in the introductory part, a previous study (Bapat et al., 2017) investigated whether the SCB updates with object movement, but tested a context where the objects were presented statically (500 ms static presentation time), and then moved. In that context, SCB was predominantly found for the original (starting) object location instead of the end landing location (Bapat et al., 2017), but the initially static state in that design may lead to a possibility that the stationary object binding effect overrode the effect of object movement. In the current study, we used a more naturalistic design (from a spatiotemporal contiguity perspective), kept objects in continuous motion from appearance to disappearance, and attempted to isolate the pure SCB effects of object movements with this novel design.

Despite this more compelling object motion context, we still observed the strongest SCB for the Same Exact trajectory condition, analogous to the "Start" location condition of Bapat et al. (2017). This further underscores the role of low-level visual information underlying the SCB (Babu et al., 2023; Bapat et al., 2017; Finlayson & Golomb, 2016; Shafer-Skelton et al., 2017). However, here we additionally observed an SCB on the Predictable trajectory, although this effect was notably weaker than that on the Same Exact trajectory. This finding reveals that SCB can be sensitive to spatiotemporal continuity cues, but it may require a more compelling and naturalistic object motion context to emerge. Spatiotemporal contiguity effects have been frequently found for other aspects of object recognition in previous studies, indicating that the human brain can integrate elements of the same moving object in different time stages to maintain a stable experience (Baillargeon, 1987; Baillargeon et al., 1985; Flombaum & Scholl, 2006; Leslie, 1984; Mitroff & Alvarez, 2007; Spelke et al., 1995).

Our results indicate that two moving objects on a single, continuous trajectory are more likely to be perceived as having the same identity, compared to a Different trajectory. This observation reveals an inherent bias in the human perceptual process, bringing insight into questions related to object persistence and the relatively automatic visual processing in the human brain.

Spatial Congruency Bias of a Moving Object Across a Saccade

Testing the coordinate systems of these effects across saccades in Experiment 2, we discovered an analogous pattern. The strongest

SCB was found at the moving object's Same Exact Retinotopic trajectory. This finding aligns with previous findings of retinotopic SCB for stationary objects across a saccade (Shafer-Skelton et al., 2017), and with broader studies showing that object spatial representations are coded in retinotopic coordinates throughout the human visual brain (Gardner et al., 2008; Golomb & Kanwisher, 2012; Lu et al., 2022). The fact that we still found predominantly retinotopic effects even for moving objects is particularly interesting in light of debates over whether visual motion middle temporal area is spatiotopic (D'Avossa et al., 2007; Gardner et al., 2008; Golomb & Kanwisher, 2012; Latimer & Curran, 2016; Melcher & Morrone, 2003; Ong et al., 2009).

Critically, while our Static Object Task replicated the previously reported pattern of exclusively retinotopic SCB (Shafer-Skelton et al., 2017), in our Moving Object Task we additionally found weaker but still significant SCB for both Predictable Retinotopic and Predictable Spatiotopic trajectories. This suggests that the binding effect observed for Predictable trajectory in Experiment 1 was likely based on both retinotopic and spatiotopic coordinates, which could be consistent with mixed results in the literature showing both retinotopic- and spatiotopic-based representations of object movements, such as motion aftereffect (Knapen et al., 2009; Marino & Mazer, 2016; Melcher, 2005, 2009; Wittenberg et al., 2008; B. A. Wolfe & Whitney, 2015;) and perception of causality (Kominsky & Scholl, 2020; Rolfs et al., 2013). The presence of a SCB for the spatiotopic predictable condition is particularly notable in terms of the long "hard binding problem" debate (Cavanagh et al., 2010), which addresses the challenge of linking the representation of locations to object identities across eye movements to achieve stable perception. The main reason it is considered "hard" lies in the dynamic process of binding spatial location, attention, and object identity, while maintaining (or updating) these bindings consistently across rapid eye movements and constantly changing visual environments. When we combine the object features and identity across eye movements (i.e., tracking football and recognizing each player while watching a football game), it seems intuitive that we can integrate spatiotopic location into the object identity, but evidence for this has been elusive, and the neural mechanisms underlying this complex process remain largely unexplained.

The current results suggest a key role for spatiotemporal contiguity as a dynamic cue in triggering spatiotopic object-location binding. A recent study also found that a more dynamic saccade context could trigger spatiotopic object-location binding (Lu & Golomb, 2024). In their experiments, the dynamic saccade context required both multiple eye movements and eye movements during stimulus presentation. Here, our study tested a different type of dynamic content, suggesting that either dynamic saccade context or dynamic object motion and spatiotemporal contiguity cues can trigger more ecologically relevant spatiotopic binding. Tellingly, in both cases, the spatiotopic effects coexisted with retinotopic effects, rather than overriding them.

Sensitivity Effect for Moving Objects

In addition to SCB, we also investigated the sensitivity effect for moving objects. We only observed the sensitivity effect for Same Exact trajectory (compared to Different trajectory) in Experiment 1, and did not observe any sensitivity effect that survived the eccentricity-matched comparison in Experiment 2 after saccades. However, it is crucial to acknowledge that the absence of sensitivity effect does not undermine the conclusions about object-location binding gleaned from the SCB measure. Previous studies have repeatedly found that the sensitivity measure is less consistent compared to the SCB measure in this paradigm (Cave & Chen, 2017; Golomb et al., 2014; Lu & Golomb, 2024; Shafer-Skelton et al., 2017; Starks et al., 2020). However, an alternative possibility might be that object movement reduces or overwrites some location effects, leading to a failure to observe sensitivity facilitation even when biases in reporting object identity remain. This possibility suggests that there could be multiple reasons sensitivity and SCB might not always co-occur, and further research is needed to explore under what conditions they diverge and what it implies for object-location binding.

Limitations and Future Directions

Although our study provides strong evidence of how location influences object identity judgments of moving objects, our study has a few limitations. Firstly, our behavioral results offer important insights into location influences on object identity judgments of moving objects, but cannot reveal how these influences/bindings occur from a mechanistic perspective, which remains an important question for future research. This behavioral study might inspire future questions to uncover the neural mechanisms underlying these processes. Secondly, we only tested one type of motion design (occlusive linear motion), so it is unclear whether those effects we found in the current study generalize to other kinds of moving stimuli (e.g., real-world objects, faces) or other kinds of object movement (e.g., circular motion, projectile motion). Thirdly, in Experiment 2, we could not set an eccentricity-matched control trajectory condition in the Moving Object Task saccade paradigm, thus we used the mean of Different location C and D in Static Object Task as an eccentricity-matched control, which is not as ideal as a within-task baseline, though it is still a meaningful within-subject baseline.

Our findings on object-location binding for moving objects also raise interesting further questions. How sensitive is the human visual system to moving object location? Would even stronger, even more naturalistic visual contexts result in stronger object-location binding for the predicable spatiotopic trajectory (most ecological condition) relative to the same exact retinotopic trajectory (most low-level visual condition)? It would also be meaningful to further examine which specific aspects of moving object trajectory (e.g., direction, location coverage, speed) drive these effects. Furthermore, future work investigating neural mechanisms could provide more insight into which brain regions are sensitive to spatiotemporal contiguity and the representation of object movement updates across a saccade.

Conclusion

In summary, our study investigated how the location of moving objects influences object identity judgments. We found that the location trajectory significantly influenced moving object identity judgments, as indicated by both sensitivity and SCB effects. Specifically, the Same Exact trajectory showed the strongest sensitivity and SCB effects, followed by the Predictable trajectory. Additionally, our results suggest strong object-location binding in retinotopic coordinates across a saccade, even when stimuli are constantly moving, as evidenced by the robust SCB on the Same Exact Retinotopic trajectory. The Predictable trajectory SCB effect also remained (again to a lesser extent) across a saccade, and was based on both retinotopic and spatiotopic coordinates. These findings suggest that both low-level retinotopic coordinates and more ecologically-relevant spatiotemporal contiguity cues contribute to object-location binding for moving objects, even when task-irrelevant, providing new clues to further our understanding of how the brain achieves visual stability in the dynamic world.

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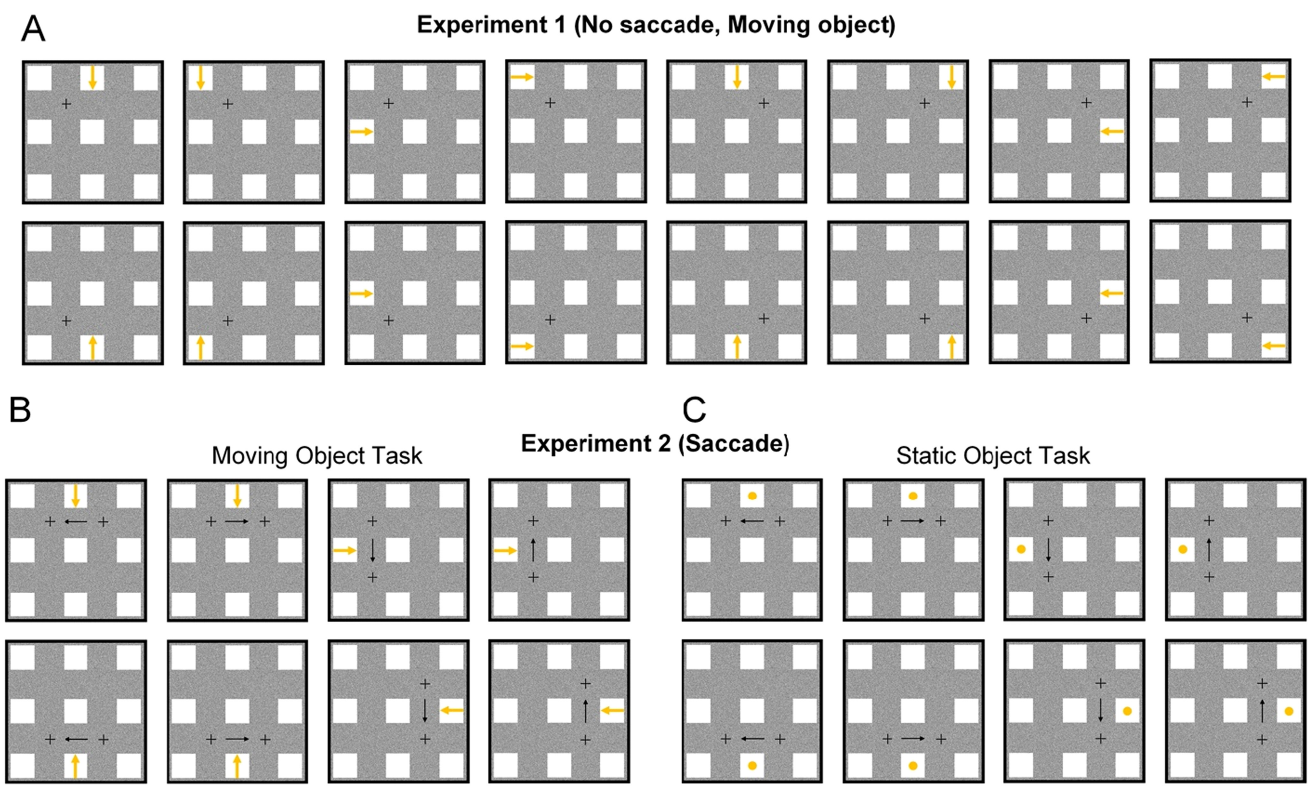
Appendix

Detailed Experimental Information and Statistical Results

Possible Movement Trajectories of Stimulus 1 for Different Fixation Conditions

Figure A1

Detailed Experiment Conditions



Note. Possible conditions movement trajectories of Stimulus 1 for different fixation conditions in (A) Experiment 1, (B) Experiment 2, moving object task, and (C) Experiment 2, static object task. See the online article for the color version of this figure.

(*Appendix continues*)

Tables With Full Results for All Behavioral Measures and Conditions

Table A1
Means (and Standard Deviations) for All Raw Behavioral Measures and Conditions in Experiment 1

Experiment 1	Same/different identity	Same exact	Predictable	Different A	Different B
RT	Same identity	0.4860 (0.20)	0.4967 (0.20)	0.4981 (0.18)	0.4711 (0.16)
	Different identity	0.4793 (0.18)	0.4811 (0.16)	0.5044 (0.18)	0.4783 (0.16)
Accuracy	Same identity	0.87 (0.07)	0.80 (0.08)	0.77 (0.10)	0.74 (0.09)
	Different identity	0.55 (0.13)	0.56 (0.13)	0.63 (0.14)	0.59 (0.09)
P ("same")	Same identity (hit rate)	0.87 (0.07)	0.80 (0.08)	0.77 (0.10)	0.74 (0.09)
	Different identity (false alarm rate)	0.45 (0.13)	0.44 (0.13)	0.37 (0.14)	0.41 (0.09)
d-prime		1.38 (0.63)	1.07 (0.54)	1.14 (0.56)	0.93 (0.47)
Response bias		−0.54 (0.21)	−0.37 (0.21)	−0.21 (0.24)	−0.21 (0.16)

Note. *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) versus different location conditions, and the "spatial congruency bias (SCB) effect" in the text is the difference in response bias for same (or predictable) versus different location conditions. RT = reaction time in seconds.

Table A2
Statistical Comparisons, p Values (and BF_{10}), for Measures Between Different Location Conditions in Experiment 1

Experiment 1	Same/different identity	Same exact versus predictable	Same exact versus Different_{AB}	Predictable versus Different_{AB}
RT	Same identity	$p = .414$, BF = 0.347	$p = .930$, BF = 0.256	$p = .380$, BF = 0.36
	Different identity	$p = .903$, BF = 0.257	$p = .565$, BF = 0.298	$p = .399$, BF = 0.355
Accuracy	Same identity	**$p < .001$, BF = 119.9**	**$p < .001$, BF = 1,597**	**$p = .024$, BF = 2.719**
	Different identity	$p = .665$, BF = 0.279	**$p = .002$, BF = 20.31**	**$p = .007$, BF = 7.410**
P("same")	Same identity (hit rate)	**$p < .001$, BF = 119.9**	**$p < .001$, BF = 1,597**	**$p = .024$, BF = 2.719**
	Different identity (false alarm rate)	$p = .665$, BF = 0.279	**$p = .002$, BF = 20.31**	**$p = .007$, BF = 7.410**
d-prime		**$p = .0029$, BF = 15.34**	**$p = .002$, BF = 20.28**	$p = .697$, BF = 0.274
Response bias		**$p = .0032$, BF = 14.04**	**$p < .001$, BF = 4,190**	**$p = .0040$, BF = 12.77**

Note. *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) versus different location conditions, and the "spatial congruency bias (SCB) effect" in the text is the difference in response bias for same (or predictable) versus different location conditions. Bold values indicate statistical significance at $p < .05$. BF = Bayes factor; Different_{AB} = the mean of Different A and B; RT = reaction time in seconds.

Table A3
Means (and Standard Deviations) for All Raw Behavioral Measures and Conditions in Experiment 2 Moving Object Task

Experiment 2 moving object	Same/different identity	SS	PS	SR	PR	DA	DB
RT(s)	Same identity	0.2976 (0.11)	0.3050 (0.14)	0.2978 (0.12)	0.2942 (0.11)	0.3092 (0.11)	0.2776 (0.11)
	Different identity	0.2987 (0.11)	0.2868 (0.11)	0.3104 (0.12)	0.2971 (0.12)	0.3221 (0.12)	0.3077 (0.12)
Accuracy	Same identity	0.77 (0.09)	0.81 (0.10)	0.86 (0.06)	0.79 (0.09)	0.53 (0.14)	0.60 (0.11)
	Different identity	0.50 (0.19)	0.47 (0.15)	0.42 (0.11)	0.48 (0.16)	0.57 (0.14)	0.57 (0.12)
P("same")	Same identity (hit rate)	0.77 (0.09)	0.81 (0.10)	0.86 (0.06)	0.79 (0.09)	0.53 (0.14)	0.60 (0.11)
	Different identity (false alarm rate)	0.50 (0.19)	0.53 (0.15)	0.58 (0.11)	0.52 (0.16)	0.43 (0.14)	0.43 (0.12)
d-prime		0.83 (0.58)	0.88 (0.64)	0.92 (0.44)	0.79 (0.51)	0.27 (0.46)	0.44 (0.37)
Response bias		−0.38 (0.35)	−0.51 (0.26)	−0.67 (0.18)	−0.46 (0.29)	0.06 (0.30)	−0.03 (0.24)

Note. *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) versus different location conditions, and the "spatial congruency bias (SCB) effect" in the text is the difference in response bias for same (or predictable) versus different location conditions. SS = Same Exact Spatiotopic; PS = Predictable Spatiotopic; SR = Same Exact Retinotopic; PR = Predictable Retinotopic; DA = Different A; DB = Different B; RT = reaction time in seconds.

(*Appendix continues*)

Table A4

Statistical Comparisons, p Values (and BF_{10}), for Measures Between Different Location Conditions in Experiment 2 Moving Object Task

Experiment 2 moving object	Same/different identity	SS versus PS	SS versus SR	SS versus PR	PS versus SR	PS versus PR	SR versus PR
RT(s)	Same identity	$p = .5549$, BF = 0.300	$p = .9872$, BF = 0.255	$p = .6557$, BF = 0.279	$p = .5317$, BF = 0.306	$p = .3218$, BF = 0.402	$p = .6739$, BF = 0.277
	Different identity	$p = .4081$, BF = 0.350	$p = .5294$, BF = 0.307	$p = .9194$, BF = 0.257	$p = .1270$, BF = 0.748	$p = .4331$, BF = 0.339	$p = .2931$, BF = 0.425
Accuracy	Same identity	$p = .3093$, BF = 0.411	**$p = .0020$, BF = 20.96**	$p = .5191$, BF = 0.309	**$p = .0170$, BF = 3.546**	$p = .5866$, BF = 0.293	**$p = .0149$, BF = 3.938**
	Different identity	$p = .1720$, BF = 0.604	**$p = .0373$, BF = 1.889**	$p = .4323$, BF = 0.339	$p = .0757$, BF = 1.095	$p = .8135$, BF = 0.262	**$p = .0083$, BF = 6.356**
P("same")	Same identity (hit rate)	$p = .3093$, BF = 0.411	**$p = .0020$, BF = 20.96**	$p = .5191$, BF = 0.309	**$p = .0170$, BF = 3.546**	$p = .5866$, BF = 0.293	**$p = .0149$, BF = 3.938**
	Different identity (false alarm rate)	$p = .1720$, BF = 0.604	**$p = .0373$, BF = 1.889**	$p = .4323$, BF = 0.339	$p = .0757$, BF = 1.095	$p = .8135$, BF = 0.262	**$p = .0083$, BF = 6.356**
d-prime		$p = .7038$, BF = 0.273	$p = .4963$, BF = 0.316	$p = .7958$, BF = 0.263	$p = .7455$, BF = 0.268	$p = .5671$, BF = 0.297	$p = .2499$, BF = 0.470
Response bias		$p = .1276$, BF = 0.745	**$p = .0020$, BF = 20.89**	$p = .2297$, BF = 0.497	**$p = .0097$, BF = 5.631**	$p = .5288$, BF = 0.307	**$p = .0032$, BF = 14.30**
		SS versus D_{AB}	PS versus D_{AB}	SR versus D_{AB}	PR versus D_{AB}	SS versus D_{Static_CD}	PS versus D_{Static_CD}
RT(s)	Same identity	$p = .7108$, BF = 0.277	$p = .3239$, BF = 0.400	$p = .6075$, BF = 0.288	$p = .9113$, BF = 0.257	$p = .3961$, BF = 0.356	$p = .6227$, BF = 0.286
	Different identity	$p = .1459$ BF = 0.425	**$p = .0060$ BF = 8.327**	$p = .7881$, BF = 0.264	$p = .1941$, BF = 0.556	$p = .0836$, BF = 1.016	$p = .0423$, BF = 1.711
Accuracy	Same identity	**$p < .001$, BF = 2,028**	**$p < .001$, BF = 6,852**	**$p < .001$, BF = 376,790**	**$p < .001$, BF = 10,164**	$p = .2909$, BF = 0.427	$p = .0794$, BF = 1.057
	Different identity	$p = .0862$, BF = 0.994	**$p = .0069$, BF = 7.425**	**$p < .001$, BF = 138.6**	**$p = .0058$, BF = 8.573**	$p = .0521$, BF = 1.457	**$p = .0094$, BF = 5.758**
P("same")	Same identity (hit rate)	**$p < .001$, BF = 2,028**	**$p < .001$, BF = 6,852**	**$p < .001$, BF = 376,790**	**$p < .001$, BF = 10,164**	$p = .2909$, BF = 0.427	$p = .0794$, BF = 1.057
	Different identity (false alarm rate)	$p = .0862$, BF = 0.994	**$p = .0069$, BF = 7.425**	**$p < .001$, BF = 138.6**	**$p = .0058$, BF = 8.573**	$p = .0521$, BF = 1.457	**$p = .0094$, BF = 5.758**
d-prime		**$p < .001$, BF = 50.09**	**$p < .001$, BF = 87.97**	**$p < .001$, BF = 1,293**	**$p = .0039$, BF = 12.03**	$p = .5497$, BF = 0.301	$p = .8997$, BF = 0.257
Response bias		**$p < .001$, BF = 43.51**	**$p < .001$, BF = 672.5**	**$p < .001$, BF = 307,530**	**$p < .001$, BF = 16,122**	$p = .1416$, BF = 0.692	**$p = .0080$, BF = 6.590**
		SR versus D_{Static_CD}	PR versus D_{Static_CD}				
RT(s)	Same identity	$p = .4333$, BF = 0.339	$p = .3393$, BF = 0.389				
	Different identity	$p = .3018$, BF = 0.418	$p = .1096$, BF = 0.832				
Accuracy	Same identity	**$p < .001$, BF = 257.2**	$p = .1054$, BF = 0.856				
	Different identity	**$p < .001$, BF = 542.9**	**$p = .0061$, BF = 8.268**				
P("same")	Same identity (hit rate)	**$p < .001$, BF = 257.2**	$p = .1054$, BF = 0.856				
	Different identity (false alarm rate)	**$p < .001$, BF = 542.9**	**$p = .0061$, BF = 8.268**				
d-prime		$p = .8840$, BF = 0.258	$p = .4013$, BF = 0.353				
Response bias		**$p < .001$, BF = 2,589**	**$p = .0037$, BF = 12.54**				

Note. 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) versus different location conditions, and the "spatial congruency bias (SCB) effect" in the text is the difference in response bias for same (or predictable) versus different location conditions. Bold values indicate statistical significance at $p < .05$. SS = Same Exact Spatiotopic; PS = Predictable Spatiotopic; SR = Same Exact Retinotopic; PR = Predictable Retinotopic; D_{AB} = the mean of Different A and B; D_{Static_CD} = the mean of Different C and D in Static Object Task; RT = reaction time in seconds.

(*Appendix continues*)

Table A5

Means (and Standard Deviations) for All Raw Behavioral Measures and Conditions in Experiment 2 Static Object Task

Experiment 2 static object	Same/different identity	SS	SR	DA	DB	DC	DD
RT(s)	Same identity	0.3282 (0.09)	0.3328 (0.08)	0.3450 (0.10)	0.3401 (0.09)	0.3160 (0.09)	0.3285 (0.08)
	Different identity	0.3422 (0.09)	0.3448 (0.07)	0.3418 (0.09)	0.3516 (0.09)	0.3619 (0.10)	0.3382 (0.08)
Accuracy	Same identity	0.77 (0.09)	0.85 (0.10)	0.47 (0.17)	0.45 (0.12)	0.74 (0.12)	0.75 (0.11)
	Different identity	0.53 (0.15)	0.47 (0.14)	0.66 (0.14)	0.64 (0.13)	0.63 (0.14)	0.50 (0.16)
P("same")	Same identity (hit rate)	0.77 (0.09)	0.85 (0.10)	0.47 (0.17)	0.45 (0.12)	0.74 (0.12)	0.75 (0.11)
	Different identity (false alarm rate)	0.47 (0.15)	0.53 (0.14)	0.34 (0.14)	0.36 (0.13)	0.37 (0.14)	0.50 (0.16)
d-prime		0.87 (0.52)	1.08 (0.73)	0.37 (0.51)	0.24 (0.38)	1.07 (0.47)	0.74 (0.69)
Response bias		−0.35 (0.29)	−0.62 (0.19)	0.26 (0.39)	0.25 (0.28)	−0.20 (0.36)	−0.38 (0.25)

Note. *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) versus different location conditions, and the "spatial congruency bias (SCB) effect" in the text is the difference in response bias for same (or predictable) versus different location conditions. SS = Same Spatiotopic; SR = Same Exact Retinotopic; DA = Different A; DB = Different B; DC = Different C; DD = Different D; RT = reaction time in seconds.

Table A6

Statistical Comparisons, p Values (and BF_{10}), for Measures Between Different Location Conditions in Experiment 2 Moving Object Task

Experiment 2 static object	Same/different identity	SS versus SR	SS versus D_{ABCD}	SR versus D_{ABCD}	SS versus D_{CD}	SR versus D_{CD}
RT(s)	Same identity	$p = .7563$, BF = 0.267	$p = .7375$, BF = 0.269	$p = .9707$, BF = 0.256	$p = .5597$, BF = 0.299	$p = .3455$, BF = 0.385
	Different identity	$p = .8469$, BF = 0.260	$p = .5698$, BF = 0.296	$p = .7336$, BF = 0.269	$p = .4888$, BF = 0.319	$p = .6686$, BF = 0.278
Accuracy	Same identity	$p = .3474$, BF = 0.384	**$p < .001$, BF = 1,019**	**$p < .001$, BF = 49,332**	$p = .3799$, BF = 0.364	**$p < .001$, BF = 55.82**
	Different identity	**$p = .0074$, BF = 7.053**	**$p = .0187$, BF = 3.280**	**$p < .001$, BF = 131.2**	$p = .2230$, BF = 0.507	**$p = .0089$, BF = 5.998**
P("same")	Same identity (hit rate)	$p = .3474$, BF = 0.384	**$p < .001$, BF = 1,019**	**$p < .001$, BF = 49,332**	$p = .3799$, BF = 0.364	**$p < .001$, BF = 55.82**
	Different identity (false alarm rate)	**$p = .0074$, BF = 7.053**	**$p = .0187$, BF = 3.280**	**$p < .001$, BF = 131.2**	$p = .2230$, BF = 0.507	**$p = .0089$, BF = 5.998**
d-prime		$p = .2651$, BF = 0.453	**$p = .0157$, BF = 3.772**	**$p = .0056$, BF = 8.8429**	$p = .7392$, BF = 0.269	$p = .2784$, BF = 0.439
Response bias		**$p = .0061$, BF = 8.203**	**$p < .001$, BF = 146.109**	**$p < .001$, BF = 595,420**	$p = .3519$, BF = 0.381	**$p < .001$, BF = 2,331**

Note. *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) versus different location conditions, and the "spatial congruency bias (SCB) effect" in the text is the difference in response bias for same (or predictable) versus different location conditions. Bold values indicate statistical significance at $p < .05$. SS = Same Spatiotopic; SR = Same Exact Retinotopic; D_{ABCD} = the mean of Different A, B, C, and D; D_{CD} = the mean of Different C and D; RT = reaction time in seconds.

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