The influence of a moving object's location on object identity judgments

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Abstract

People have the ability to combine both 'what' and 'where' information to recognize objects. Prior studies have revealed several ways location information can influence object identity judgments, even when location is irrelevant or uninformative. Specifically, in tasks determining whether two sequentially shown objects are the same or different, two types of location effects have been reported: facilitation (through reaction time priming and/or enhanced sensitivity) and "spatial congruency bias" (where people are more likely to judge objects as identical) when objects are in the same location. However, previous studies mainly focused on stationary instead of moving objects, with minimal exploration into how object movement affects object identity judgment and the underlying reference frames for such effects. To address these gaps, we conducted two pre-registered experiments using moving stimuli. In Experiment 1, subjects were required to fixate at one fixation location and judge whether two sequentially presented moving stimuli were the same or different object identities. The first stimulus emerged from an occluder and moved along a linear trajectory to pass behind another occluder. The second stimulus then emerged (still moving) from either the predictable location along the occluded spatiotemporal trajectory (predictable trajectory), from the same initial location (same exact trajectory), or from a different location (different trajectory). We found the most pronounced sensitivity and spatial congruency bias for stimuli on the same exact trajectory, with a smaller but significant bias effect for the predictable trajectory. In Experiment 2, subjects were required to perform a saccade during the occlusion period, further revealing that the spatial congruency bias on the same exact trajectory relies on retinotopic coordinates, while the (smaller) bias on the predictable trajectory is based on both retinotopic and spatiotopic coordinates across the eye movement. Our findings suggest that object-location binding for moving objects is still strongly retinotopic, but may also reflect more ecologically relevant predictable and spatiotopic information.

Key words: object-location binding, location facilitation, object movements, retinotopic and spatiotopic, spatial contiguity

Significance Statement

How does task-irrelevant location information influence object identity judgments when objects are moving? By conducting two pre-registered experiments, we demonstrated that two objects moving sequentially along the same exact trajectory (identical spatial locations) result in both enhanced sensitivity (spatial facilitation) and are more likely to be judged as the same identity ("spatial congruency bias"). We also found a weaker spatial congruency bias when the second object continued along the first object's spatiotemporally predictable trajectory. Further, we explored if/how these biases persist across eye movements. Our findings 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. Overall, our study provides new insights into the complex interactions between object identity and location information for moving objects.

Introduction

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 priming and enhanced sensitivity (Kravitz et al., 2008; Maljkovic & Nakayama, 1996; Tsal & Lavie, 1993). 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).

A recent robust measurement of object-location binding is the "spatial congruency bias," which shows that participants are more likely to judge two (stationary) objects presented sequentially as being the same identity if they appeared in the same location compared to in different locations, despite the irrelevance of location information to the experimental task (Cave & Chen, 2017; Golomb et al., 2014; Shafer-Skelton et al., 2017; Starks et al., 2020). There has been debate over what underlies the spatial congruency bias, with studies testing accounts of response conflict (Golomb et al., 2014), spatiotemporal contiguity (Bapat et al., 2017), learned statistical regularities (Babu et al., 2023), and developmental effects (Gao et al., 2024). However, most of these studies have been done with stationary objects, which may not be as realistic or appropriate for investigating spatiotemporal contiguity. Moreover, a recent study revealed that dynamic context – e.g., multiple eye movements instead of static fixation – can result in more stable and ecologically relevant object-location binding (Lu & Golomb, 2024). 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 et al., 2004, 2009; Flombaum & Scholl, 2006; 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).

However, a recent study using the Spatial congruency bias paradigm found that it is primarily the same original location that influences object identity judgments, 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 congruency bias effects were only found when the second object was presented in the same original location. However, are these results an apt counter-example to our earlier assumption of the spatiotemporal congruity effect, suggesting the predictable trajectory could hardly influence identity judgments? As we mentioned, in the Bapat et al. (2017) experimental design, there was a stationary presentation of the object before its movement. The stationary object binding effect might override the effect of object movement. Therefore, if the object is constantly moving, could we observe an influence of the predictable trajectory on object identity? Or will there still be only facilitation or congruency bias effect on the same exact original trajectory?

To investigate whether and how the location trajectory could influence object identity of a moving object, we modified the traditional 'Spatial congruency bias' paradigm (Golomb et al., 2014). In our pre-registered Experiment 1, we made the objects consistently move. In this moving version, 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 used the Spatial Congruency Bias paradigm to test 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 pre-registered 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

Open Practices Statement

Both Experiments 1 and 2 were preregistered (https://osf.io/y8rew, https://osf.io/n79ag) prior to data collection. Additional analyses not pre-registered are noted as exploratory. The research was approved by the Ohio State University Behavioral and Social Sciences Institutional Review Board.

Subjects.

For each experiment, sixteen subjects ranging from 18 to 29 years old (Experiment 1: 18.75 ± 0.93, 9 females; Experiment 2: 20.19 ± 3.33, 5 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. Our pre-registered power analysis, sample size, and stopping rule were as follows: A power analysis of the spatial congruency bias effect (Experiment 1 of Golomb et al., 2014, which had an effect size of dz = 1.01 for the comparison of SameLocation versus DifferentLocation bias), estimated N=13 would be needed to achieve .9 power. 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 CRT 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, http://www.tarrlab.org), except we changed the color of objects from grey to yellow to make them stand out clearer from the occluders. Stimuli were drawn from ten 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 and Shafer-Skelton et al., 2017, participants were already within the desired accuracy range (65-85%) at this easiest morph level (maximum staircase value). The stimulus was sized 2.4°×2.4°, and stimulus orientation would never be varied.

Experiment 1: Object movement without eye movement.

We modified the original Golomb et al., 2014 spatial congruency bias 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°×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°× 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 participants were asked to remain fixated on the displayed fixation cross. After 800-1200ms of fixation, Stimulus 1 was presented. It emerged from behind a section of the occluder and moved through one of the cutout regions for 750ms 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 4 possible Stimulus 1 trajectories (Figure 1A). After Stimulus 1 passed behind the next part of the occluder, there was a 375ms delay, during which the object was invisible. After that, Stimulus 2 emerged from behind the occluder moving for 750ms at the same speed (9.6° per second). There were 4 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 seconds ('No response' on the screen).

The 16 different Stimulus 1 configurations (4 fixations x 4 trajectories) were counterbalanced and equally likely. The main 8 conditions of interest were the 4 Stimulus 2 trajectory conditions (Same Exact trajectory, Predictable trajectory, Different A trajectory, and Different B trajectory) x 2 object identity conditions (Same or Different identity). Subjects completed 8 blocks with 64 trials per block (512 trials in total, 64 trials for each of the 8 conditions, in randomized order and randomly divided into 8 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 participants 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 participant completed the saccade during the 375ms 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 6 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 8 possible saccade routes, each with only 1 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 spatial congruency bias 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 8 possible saccade routes, and each with 1 possible Stimulus 1 location (Figure 1C). Thus, there would be 6 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 spatial congruency bias 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 (6 Moving Object Task blocks and 6 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 x 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 spatial congruency bias 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 response times (RTs) greater than or less than 2.5 standard deviations from the subject's mean. We pre-registered 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, participants were instructed to respond with a keystroke only after the second moving object disappeared, meaning that the reaction time (RT) was measured from the moment the second moving object disappeared to the moment of the participant's keystroke response. However, participants 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 (Table S1-S6). 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(hit rate) – z(false alarm rate)

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

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 vs. Different trajectory (averaging Different trajectory A and B), and Predictable trajectory vs. 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 vs. Different trajectory (averaging Different A and B trajectories), Predictable Retinotopic trajectory vs. Different trajectory (averaging Different A and B trajectories), Same Exact Spatiotopic trajectory vs. Different trajectory (averaging Different A and B trajectories), and Predictable Spatiotopic trajectory vs. Different trajectory (averaging Different A and B trajectories). Then we conducted 2 × 2 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 pre-registrations.

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 vs. the average of Different A, B, C, and D locations, and between Same Spatiotopic location vs. 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 vs. the average of Different trajectory C and D, and between Same Spatiotopic location vs. 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, p-values, effect sizes using Cohen's d, and Bayes factors.

In addition to the pre-registered 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.
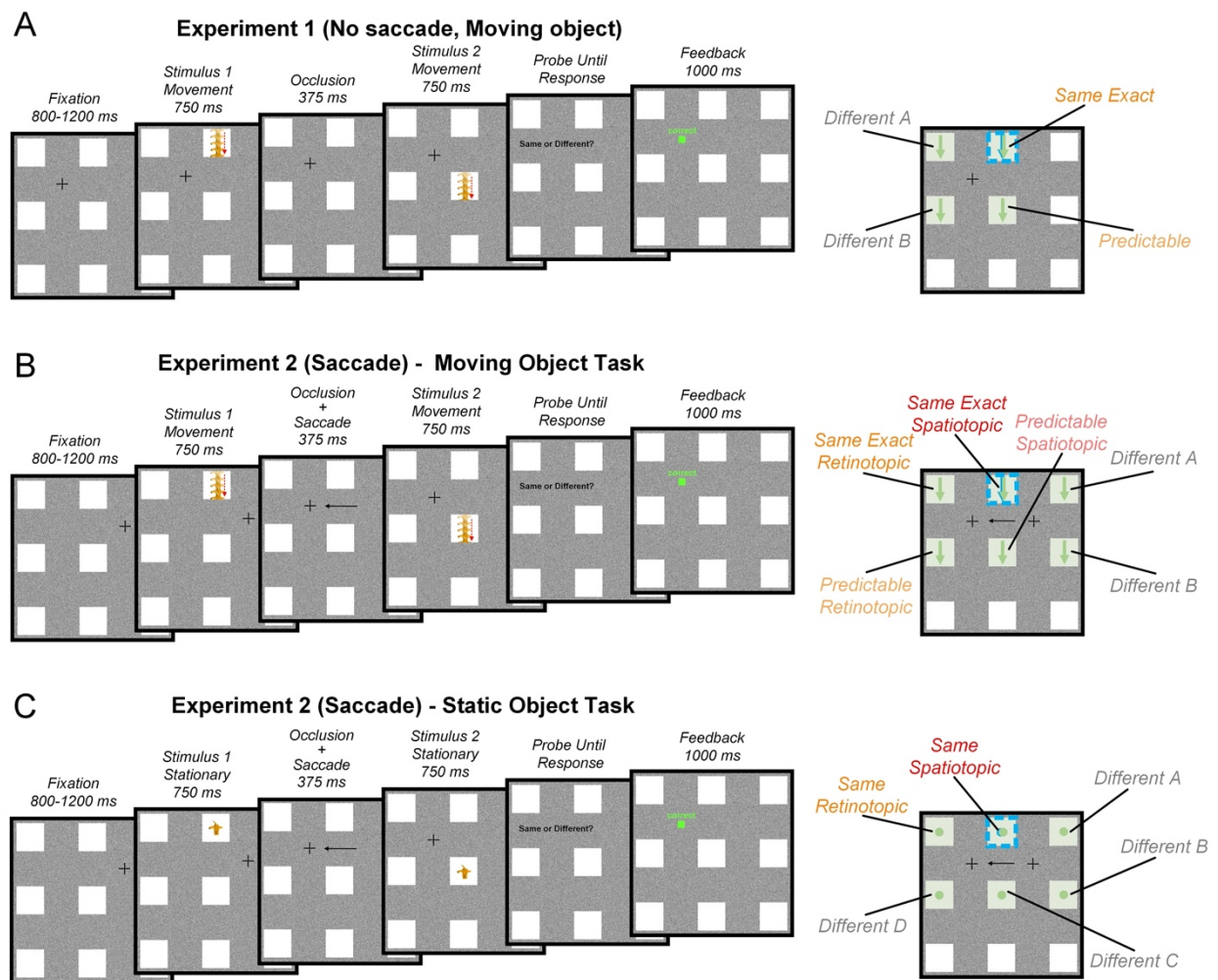
Figure 1 Example trial progressions and location conditions of (A) Experiment 1 (No saccade, Moving object), (B) Experiment 2 (Saccade) - Moving Object Task, and (C) Experiment 2 (Saccade) - Static Object Task. The blue square and arrow/circle in right figures indicate the visible area and trajectory/location of Stimulus 1, and the green arrows indicate the possible trajectory/locations of Stimulus 2. In Experiment 1, for a given Stimulus 1 trajectory

(blue arrow), there were four possible trajectories (green 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 arrow), there were six possible trajectories (green 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 2 fixations during stimulus), Predictable Retinotopic trajectory (predictable trajectory along the same path as Stimulus relative to 2 fixations during stimulus), and Different A and B trajectories. In Experiment 2 Static Object Task, for a given Stimulus 1 location (blue circle), there were six possible locations (green circles) for Stimulus 2: Same Spatiotopic location (same screen position as Stimulus 1), Same Retinotopic location (same location as Stimulus 1 relative to 2 fixations during stimulus), and Different A, B, C and D locations.
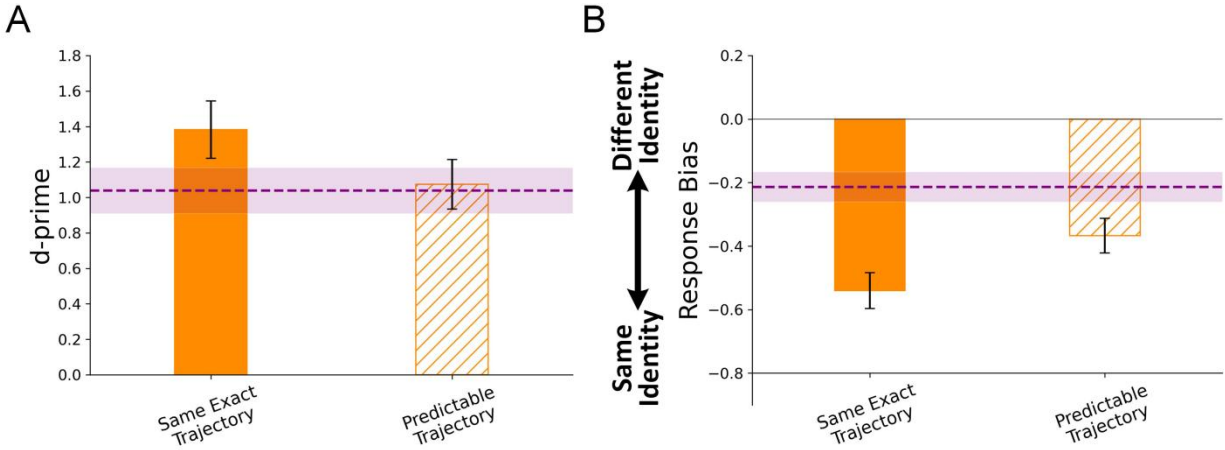
Results

Experiment 1: Object movement without eye movement.

How does location influence identity judgments when the initial object is moving?

For location facilitation effect (Figure 2A), we found significantly greater d-prime for Same Exact trajectory ($t(15) = 3.7095$, $p = .0021$, $d = .5855$, $BF_{10}= 20.284$), but not for Predictable trajectory ($t(15) = 0.3967$, $p = .6972$, $d = .0649$, $BF_{10}= .274$), compared to the Different trajectories baseline. The d-prime for Same Exact trajectory was significantly greater than that for Predictable trajectory ($t(15) = 3.5491$, $p = .0029$, $d = .5078$, $BF_{10}= 15.342$).

For spatial congruency bias (Figure 2B), we found significantly greater response bias for both Same Exact ($t(15) = -6.9179$, $p < 0.001$, $d = -1.5692$, $BF_{10} = 4190$) and Predictable trajectories ($t(15) = -3.4432$, $p = .0036$, $d = -.7440$, $BF_{10} = 12.767$) compared to the Different trajectories baseline. Also, the response bias for Same Exact trajectory was significantly greater than that for Predictable trajectory ($t(15) = -3.4982$, $p = .0032$, $d = -.7798$, $BF_{10} = 14.043$). Table S1-2 report the condition mean and statistics for all behavioral measures, including RT, accuracy, d-prime, and proportion 'Same' response in Experiment 1.

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 facilitation and spatial congruency bias. However, the significant spatial congruency bias for Predictable trajectory suggests that object-location binding may reflect spatiotemporal contiguity in addition to initial spatial location when the initial object is moving.

Figure 2 Experiment 1 results. (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 facilitation and Spatial Congruency Bias, these were compared to the baseline Different-Trajectory conditions: Purple dotted line indicates the mean of Different A and Different B trajectories. Error bars and shaded lines are standard error of the mean.

Experiment 2: Object movement with eye movement.

How does location influence identity judgments across a saccade when the initial object is moving?

In Moving Object Task, for location facilitation effect (Figure 3A), we found significantly greater d-prime for all spatiotopic and retinotopic conditions compared with the pre-registered Different trajectory baseline (green dotted lines in Figure 3): Same Exact Spatiotopic: $t(15) = 4.2271$, $p < .001$, $d = .9844$, $BF_{10} = 50.089$; Predictable Spatiotopic: $t(15) = 4.5510$, $p < .001$, $d = 1.0072$, $BF_{10} = 87.974$; Same Exact Retinotopic: $t(15) = 6.1606$, $p < .001$, $d = 1.4439$, $BF_{10} = 1293$; 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: $F(1,15) = .255$, $p = .621$, $\eta^2p = .017$; reference framework: $F(1,15) = .0004$, $p = .985$, $\eta^2p < .01$; interaction: $F(1,15) = .791$, $p = .388$, $\eta^2p = .050$).

For spatial congruency bias (Figure 3B), we also found significantly greater response bias for all conditions compared with the pre-registered 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: $t(15) = -10.1065$, $p < .001$, $d = -3.1290$, $BF_{10} = 307530$; Predictable Retinotopic: $t(15) = -7.8393$, $p < .001$, $d = -$

1.7268, BF_{10}= 16122), 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 ($F(1,15) = 6.37$, $p = .023$, $\eta^2p= .298$) and a significant interaction effect ($F(1,15) = 7.59$, $p = .015$, $\eta^2p= .336$). The main effect of trajectory type was not significant ($F(1,15) = 1.46$, $p = .246$, $\eta^2p= .089$). The response bias for Same Exact Retinotopic trajectory was significantly greater compared to all other conditions (Same Exact Retinotopic vs. Same Exact Spatiotopic: $t(15) = -3.7265$, $p = .0020$, $d = -.9956$, BF_{10}= 20.893; Same Exact Retinotopic vs. Predictable Spatiotopic: $t(15) = -2.9641$, $p = .0097$, $d = -.6984$, BF_{10}= 5.631; Same Exact Retinotopic vs. Predictable Retinotopic: $t(15) = -3.5085$, $p = .0032$, $d = -.8423$, BF_{10}= 14.297), and there was no significant difference between Same Exact Spatiotopic, Predictable Spatiotopic, and Predictable Retinotopic trajectories (all -2 < t's < 2, p's > .05, BFs < 1).

In the Static Object Task, for location facilitation effect (Figure 3C), we found significantly greater d-prime for both Same Spatiotopic and Retinotopic locations compared to the pre-registered baseline mean of all Different locations (green dotted line): Same Spatiotopic: $t(15) = 2.7223$, $p = .0157$, $d = .5692$, BF_{10}= 3.7715; Same Retinotopic: $t(15) = 3.2301$, $p = .0056$, $d = .7930$, BF_{10}= 8.8429. The difference between Same Spatiotopic and Retinotopic locations ($t(15) = -1.1576$, $p = .2651$, $d = -.3194$, BF_{10}= .453) was not significant.

For Static Object Task spatial congruency bias (Figure 3D), we also found 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}= 595420). 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, 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 facilitation and spatial congruency bias 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 facilitation and spatial congruency bias results reported above were due to the difference in eccentricity.
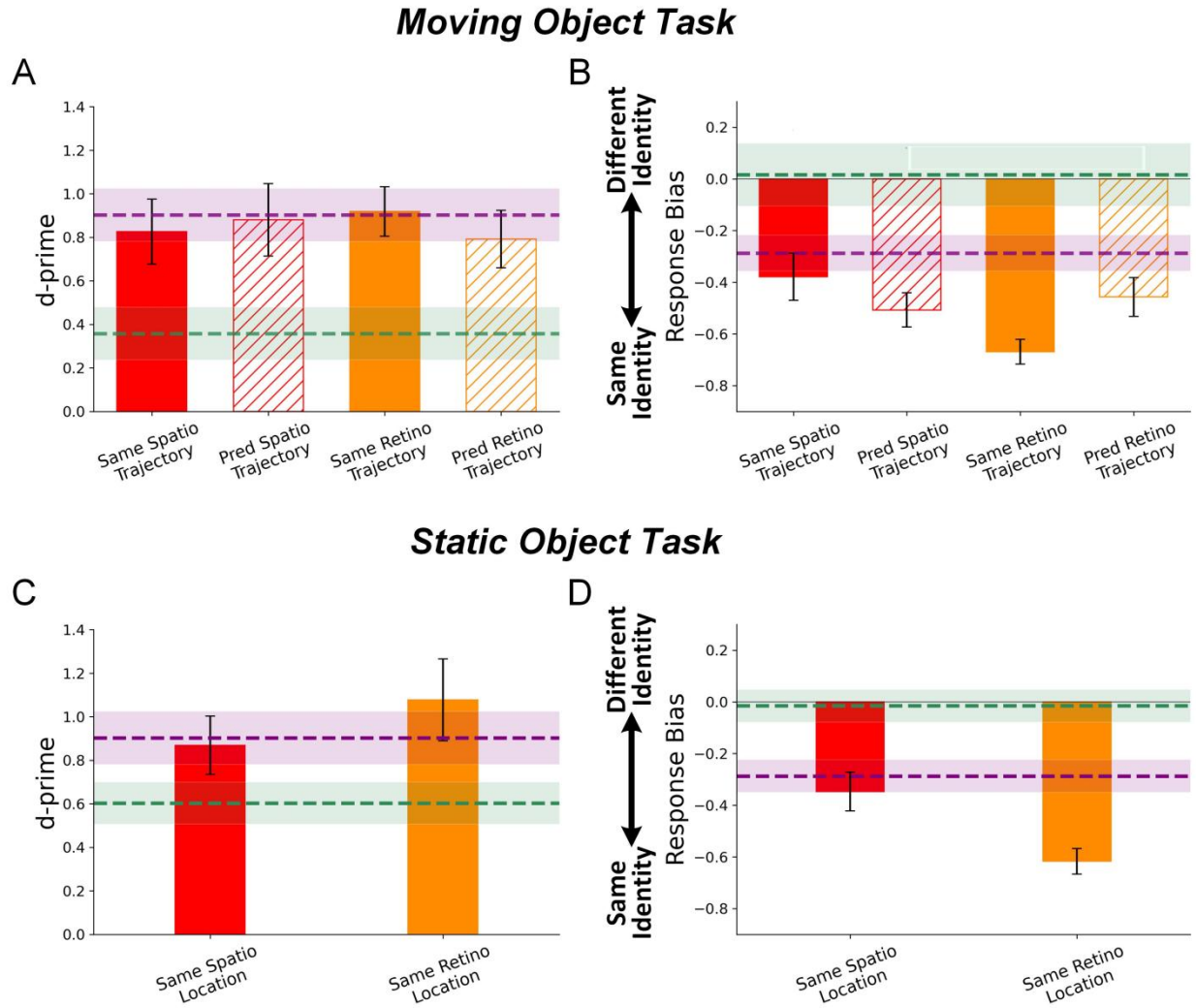
Figure 3 Experiment 2 results. (A) d-prime and (B) response bias (criterion) of Moving Object Task for each of the main trajectory conditions. To evaluate facilitation and Spatial Congruency Bias, these were compared to the Different-Trajectory conditions: Green dotted line indicates the mean of Different A and B Trajectories (pre-registered comparison). Purple 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 dotted line indicates the mean of Different A, B, C and D locations. Purple dotted line indicates the mean of Different C and D locations (eccentricity matched). Error bars and shaded lines are standard error of the mean.

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 the 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 participants 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 dotted lines in Figure 3).

In the Moving Object Task, for the location facilitation effect, none of the retinotopic or spatiotopic d-prime effects were significantly greater than the eccentricity-matched baseline (all -1<t's<1, p's> 0.05, BFs<1). For Spatial congruency bias, we found significantly greater response bias for Predictable Spatiotopic trajectory ($t(15)$ = -3.0574, p = .0080, d = -.8103, BF_{10} = 6.590), Same Exact Retinotopic trajectory ($t(15)$ = -6.6031, p < .001, d = -1.6062, BF_{10} = 2589), and Predictable Retinotopic trajectory ($t(15)$ = -3.4327, p = .0037, d = -.5873, BF_{10} = 12.54), but there was no significantly greater response bias for Same Exact Spatiotopic trajectory ($t(15)$ = -1.5516, p = .1416, d = -.5873, BF_{10} = .6918). This suggests that the facilitation results were likely driven by eccentricity, but the response bias result were mostly driven by the location trajectory effect.

In Static Object Task, there was no significantly greater d-prime for Same Retinotopic ($t(15)$ = 1.1247, p = .2784, d = .2765, BF_{10} = .4391) or Same Spatiotopic location ($t(15)$ = -.3391, p = .7392, d = -.0657, BF_{10} = .269) compared to the eccentricity-matched baseline. We only found significantly greater response bias for Same Retinotopic location ($t(15)$ = -10.6705, p < .001, d = -1.3686, BF_{10} = 2331), and no significantly greater response bias for Same Spatiotopic location ($t(15)$ = -.9608, p = .3519, d = -.2076, BF_{10} = .381), compared to the eccentricity-matched baseline. After accounting for eccentricity, these findings were consistent with previous studies using spatial congruency bias paradigm with static objects that only found retinotopic spatial congruency bias effects (Experiment 2 in Lu & Golomb, 2023a; Shafer-Skelton et al., 2017). Thus, it suggests that even if subjects could have predicted the saccade route during the task, it did not affect the pattern of spatial congruency bias on object identity judgments.

Tables S3-6 report the condition mean and statistics for all behavioral measures, including RT, accuracy, d-prime, and proportion 'Same' response in Experiment 2 Moving and Static Object Tasks.

Discussion

In the present two experiments, we demonstrated that 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 judgment through two key ways: location facilitation effect and spatial congruency bias. For the location facilitation effect, participants can benefit from shared spatial attention resources when objects appear in the same position. This effect leads to faster response time, known as RT priming (Maljkovic & Nakayama, 1996; Tsal & Lavie, 1993), and sensitivity enhancement (Kravitz et al., 2008). For spatial congruency bias,

participants 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 modified the "Spatial congruency bias" paradigm and found that the location of a moving object can significantly influence object identity judgments through the two key ways mentioned previously as well. In Experiment 1, for the location facilitation effects, our findings revealed a significant facilitation (d-prime) effect when the second object followed the same location trajectory (Same Exact trajectory) compared to a Different trajectory, but there was no significant facilitation when the second object followed a spatiotemporally consistent trajectory (Predictable trajectory) as the initially presented moving object. For the spatial congruency bias, we found significant effects for both Same Exact and Predictable trajectories, but the spatial congruency bias 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 participants to do a static object version of the task. We found significant spatial congruency biases 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 spatial congruency bias 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 spatial congruency bias on the same exact trajectory relies on retinotopic coordinates, while the bias on the predictable trajectory is based on both retinotopic and spatiotopic coordinates across an eye movement. This suggests that object-location binding for moving objects is still strongly retinotopic, but may also reflect more ecologically relevant predictable and spatiotopic information.

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. Spatial congruency bias has been considered as 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 Introduction, a previous study (Bapat et al., 2017) investigated whether the spatial congruency bias updates with object movement, but tested a context where the objects were presented statically (500ms static presentation time), and then moved. In that context, spatial congruency

bias 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 spatial congruency bias effects of object movements with this novel design.

Despite this more compelling object motion context, we still observed the strongest spatial congruency bias 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 spatial congruency bias (Babu et al., 2023; Bapat et al., 2017; Finlayson & Golomb, 2016; Shafer-Skelton et al., 2017). However, here we additionally observed a spatial congruency bias on the Predictable trajectory, although this effect was notably weaker than that on the Same Exact trajectory. This finding reveals that spatial congruency bias can be sensitive to spatiotemporal continuity cues, but it may require the 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 spatial congruency bias was found at the moving object's Same Exact Retinotopic trajectory. This finding aligns with previous findings of retinotopic spatial congruency bias 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 area MT 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 spatial congruency bias (Shafer-Skelton et al., 2017), in our Moving Object Task we additionally found weaker but still significant spatial congruency bias 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 spatial congruency bias for the spatiotopic predictable condition is particularly notable in terms of the long "hard binding problem' debate (Cavanagh et al., 2010): When we combine the object features and identity across eye movement (i.e. tracking football and recognizing each player while watching a football game), we intuitively feel that we can integrate spatiotopic location into the object identity, but evidence for this has been elusive.

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 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.

Location Facilitation Effects for Moving Objects

In addition to spatial congruency bias, we also investigated location facilitation effects for moving objects. We only observed facilitated sensitivity (d-prime) for Same Exact trajectory (compared to Different trajectory) in Experiment 1, and did not observe any facilitation effects that survived the eccentricity-matched comparison in Experiment 2 after saccades. However, it is crucial to acknowledge that the absence of location facilitation effects does not undermine the conclusions about object-location binding gleaned from the spatial congruency bias measure. Previous studies have repeatedly found that the sensitivity measure is less consistent compared to the spatial congruency bias measure in this paradigm (Cave & Chen, 2017; Golomb et al., 2014; Lu & Golomb, 2024; Shafer-Skelton et al., 2017; Starks et al., 2020).

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, 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, etc) or other kinds of object movement (e.g., circular motion, projectile motion). Secondly, 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 sensitivity facilitation and spatial congruency bias effects. Specifically, the Same Exact trajectory showed the strongest facilitation effect and spatial congruency bias, followed by the Predictable trajectory. Additionally, our results showed strong object-location binding in retinotopic coordinates across a saccade, even when stimuli are constantly moving, as evidenced by the robust spatial congruency bias on the Same Exact Retinotopic trajectory. The Predictable trajectory effect also remained (again to a lesser extent) across a saccade, and was based in 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.

Acknowledgements

Open Practices Statement

All experiments were pre-registered on the Open Science Framework (OSF, 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 analyses included here

that were not listed in the pre-registration are declared as exploratory. Data will also be made available post-publication on OSF (https://osf/io/8y7cs).

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Supplementary Materials

Possible movement trajectories of Stimulus 1 for different fixation conditions
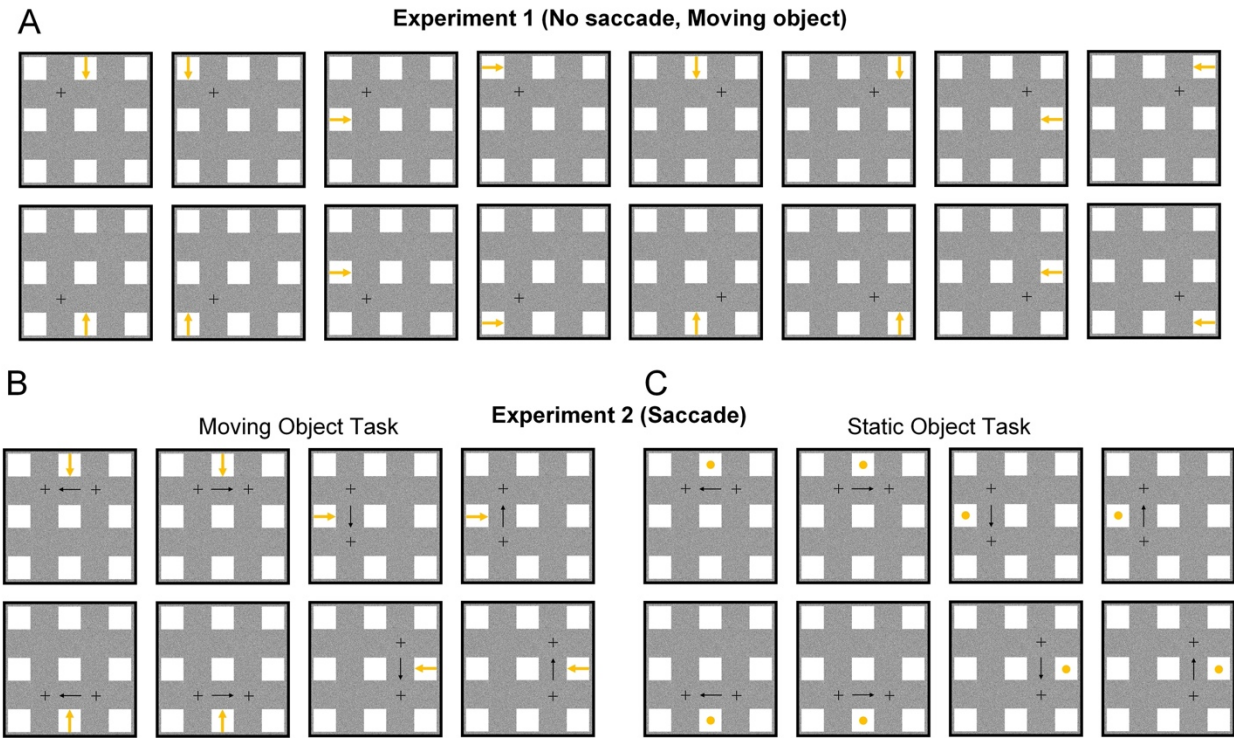
SFigure 1 Possible conditions movement trajectories of Stimulus 1 for different fixation conditions in (A) Experiment 1, Experiment 2 (B) Moving Object Task and (C) Static Object Task.

Tables with full results for all behavioral measures and conditions

Table S1. Means (and standard deviations) for all behavioral measures and conditions in Experiment 1.

Expt 1	Same/Different Identity	Same Exact	Predictable	Different A	Different B
RT(s)	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	0.87(0.07)	0.80(0.08)	0.77(0.10)	0.74(0.09)
	Different Identity	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)

Table S2. Statistical comparisons, p-values (and BF_{10}), for measures between different location conditions in Experiment 1. $Different_{AB}$ = the mean of Different A and B.

Expt 1	Same/Different Identity	Same Exact vs. Predictable	Same Exact vs. $Different_{AB}$	Predictable vs. $Different_{AB}$
RT(s)	Same Identity	p=0.414 BF= 0.347	p=0.930 BF=0.256	p=0.380 BF=0.36
	Different Identity	p=.903 BF=0.257	p=.565 BF=0.298	p=.399 BF=0.355
Accuracy	Same Identity	**p<0.001 BF=119.9**	**p<0.001 BF=1597**	**p=0.024 BF=2.719**
	Different Identity	p=0.665 BF=0.279	**p=0.002 BF=20.31**	**p=0.007 BF=7.410**
P('Same')	Same Identity	**p<0.001 BF=119.9**	**p<0.001 BF=1597**	**p=0.024 BF=2.719**
	Different Identity	p=0.665 BF=0.279	**p=0.002 BF=20.31**	**p=0.007 BF=7.410**
d-prime		**p=0.0029 BF=15.34**	**p=0.002 BF=20.28**	p=0.697 BF=0.274

	p=0.0032	p<0.001	p=0.0040
Response Bias	BF=14.04	BF=4190	BF=12.77

Table S3. Means (and standard deviations) for all behavioral measures and conditions in Experiment 2 Moving Object Task. SS = Same Exact Spatiotopic; PS = Predictable Spatiotopic; SR = Same Exact Retinotopic; PR = Predictable Retinotopic; DA = Different A; DB = Different B.

Expt 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	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)	0.53(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)

Table S4. Statistical comparisons, p-values (and BF_{10}), for measures between different location conditions in Experiment 2 Moving Object Task. 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.

Expt 2 Moving Object	Same/Different Identity	SS vs. PS	SS vs. SR	SS vs. PR	PS vs. SR	PS vs. PR	SR vs. PR
RT(s)	Same Identity	p=0.5549 BF=0.300	p=0.9872 BF=0.255	p=0.6557 BF=0.279	p=0.5317 BF=0.306	p=0.3218 BF=0.402	p=0.6739 BF=0.277
	Different Identity	p=0.4081 BF=0.350	p=0.5294 BF=0.307	p=0.9194 BF=0.257	p=0.1270 BF=0.748	p=0.4331 BF=0.339	p=0.2931 BF=0.425
Accuracy	Same Identity	p=0.3093 BF=0.411	**p=0.0020** **BF=20.96**	p=0.5191 BF=0.309	**p=0.0170** **BF=3.546**	p=0.5866 BF=0.293	**p=0.0149** **BF=3.938**

		SS vs. D_{AB}	PS vs. D_{AB}	SR vs. D_{AB}	PR vs. D_{AB}	SS vs. D_{Static_CD}	PS vs. D_{Static_CD}
	Different Identity	p=0.1720	**p=0.0373**	p=0.4323	p=0.0757	p=0.8135	**p=0.0083**
		BF=0.604	**BF=1.889**	BF=0.339	BF=1.095	BF=0.262	**BF=6.356**
P('Same')	Same Identity	p=0.3093	**p=0.0020**	p=0.5191	**p=0.0170**	p=0.5866	**p=0.0149**
		BF=0.411	**BF=20.96**	BF=0.309	**BF=3.546**	BF=0.293	**BF=3.938**
	Different Identity	p=0.1720	**p=0.0373**	p=0.4323	p=0.0757	p=0.8135	**p=0.0083**
		BF=0.604	**BF=1.889**	BF=0.339	BF=1.095	BF=0.262	**BF=6.356**
d-prime		p=0.7038	p=0.4963	p=0.7958	p=0.7455	p=0.5671	p=0.2499
		BF=0.273	BF=0.316	BF=0.263	BF=0.268	BF=0.297	BF=0.470
Response Bias		p=0.1276	**p=0.0020**	p=0.2297	**p=0.0097**	p=0.5288	**p=0.0032**
		BF=0.745	**BF=20.89**	BF=0.497	**BF=5.631**	BF=0.307	**BF=14.30**

		SS vs. D_{AB}	PS vs. D_{AB}	SR vs. D_{AB}	PR vs. D_{AB}	SS vs. D_{Static_CD}	PS vs. D_{Static_CD}
	Same Identity	p=0.7108	p=0.3239	p=0.6075	p=0.9113	p=0.3961	p=0.6227
		BF=0.277	BF=0.400	BF=0.288	BF=0.257	BF=0.356	BF=0.286
RT(s)	Different Identity	p=0.1459	**p=0.0060**	p=0.7881	p=0.1941	p=0.0836	p=0.0423
		BF=0.425	**BF=8.327**	BF=0.264	BF=0.556	BF=1.016	BF=1.711
	Same Identity	**p<0.001**	**p<0.001**	**p<0.001**	**p<0.001**	p=0.2909	p=0.0794
		BF=2028	**BF=6852**	**BF=376790**	**BF=10164**	BF=0.427	BF=1.057
Accuracy	Different Identity	p=0.0862	**p=0.0069**	**p<0.001**	**p=0.0058**	p=0.0521	**p=0.0094**
		BF=0.994	**BF=7.425**	**BF=138.6**	**BF=8.573**	BF=1.457	**BF=5.758**
	Same Identity	**p<0.001**	**p<0.001**	**p<0.001**	**p<0.001**	p=0.2909	p=0.0794
		BF=2028	**BF=6852**	**BF=376790**	**BF=10164**	BF=0.427	BF=1.057
P('Same')	Different Identity	p=0.0862	**p=0.0069**	**p<0.001**	**p=0.0058**	p=0.0521	**p=0.0094**
		BF=0.994	**BF=7.425**	**BF=138.6**	**BF=8.573**	BF=1.457	**BF=5.758**
d-prime		**p<0.001**	**p<0.001**	**p<0.001**	**p=0.0039**	p=0.5497	p=0.8997
		BF=50.09	**BF=87.97**	**BF=1293**	**BF=12.03**	BF=0.301	BF=0.257
Response Bias		**p<0.001**	**p<0.001**	**p<0.001**	**p<0.001**	p=0.1416	**p=0.0080**
		BF=43.51	**BF=672.5**	**BF=307530**	**BF=16122**	BF=0.692	**BF=6.590**

		SR vs. D_{Static_CD}	PR vs. D_{Static_CD}
RT(s)	Same Identity	p=0.4333	p=0.3393
		BF=0.339	BF=0.389

	Different Identity	p=0.3018 BF=0.418	p=0.1096 BF=0.832
Accuracy	Same Identity	**p<0.001** **BF=257.2**	p=0.1054 BF=0.856
	Different Identity	**p<0.001** **BF=542.9**	**p=0.0061** **BF=8.268**
P('Same')	Same Identity	**p<0.001** **BF=257.2**	p=0.1054 BF=0.856
	Different Identity	**p<0.001** **BF=542.9**	**p=0.0061** **BF=8.268**
d-prime		p=0.8840 BF=0.258	p=0.4013 BF=0.353
Response Bias		**p<0.001** **BF=2589**	**p=0.0037** **BF=12.54**

Table S5. Statistical Means (and standard deviations) for all behavioral measures and conditions in Experiment 2 Static Object Task. SS = Same Spatiotopic; SR = Same Exact Retinotopic; DA = Different A; DB = Different B; DC = Different C; DD = Different D.

Expt 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	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	0.47(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)

Table S6. Statistical comparisons, p-values (and BF_{10}), for measures between different location conditions in Experiment 2 Static Object Task. 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.

Expt 2 Static Object	Same/Different Identity	SS vs. SR	SS vs. D_{ABCD}	SR vs. D_{ABCD}	SS vs. D_{CD}	SR vs. D_{CD}
RT(s)	Same Identity	p=0.7563 BF=0.267	p=0.7375 BF=0.269	p=0.9707 BF=0.256	p=0.5597 BF=0.299	p=0.3455 BF=0.385
	Different Identity	p=0.8469 BF=0.260	p=0.5698 BF=0.296	p=0.7336 BF=0.269	p=0.4888 BF=0.319	p=0.6686 BF=0.278
Accuracy	Same Identity	p=0.3474 BF=0.384	**p<0.001 BF=1019**	**p<0.001 BF=49332**	p=0.3799 BF=0.364	**p<0.001 BF=55.82**
	Different Identity	**p=0.0074 BF=7.053**	**p=0.0187 BF=3.280**	**p<0.001 BF=131.2**	p=0.2230 BF=0.507	**p=0.0089 BF=5.998**
P('Same')	Same Identity	p=0.3474 BF=0.384	**p<0.001 BF=1019**	**p<0.001 BF=49332**	p=0.3799 BF=0.364	**p<0.001 BF=55.82**
	Different Identity	**p=0.0074 BF=7.053**	**p=0.0187 BF=3.280**	**p<0.001 BF=131.2**	p=0.2230 BF=0.507	**p=0.0089 BF=5.998**
d-prime		p=0.2651 BF=0.453	**p=0.0157 BF=3.772**	**p=0.0056 BF=8.8429**	p=0.7392 BF=0.269	p=0.2784 BF=0.439
Response Bias		**p=0.0061 BF=8.203**	**p<0.001 BF=146.109**	**p<0.001 BF=595420**	p=0.3519 BF=0.381	**p<0.001 BF=2331**