RUNNING HEAD: POSITION AND HEADING ESTIMATIONS

Selective Resetting Position and Heading Estimations While Driving in a Large-Scale Immersive Virtual Environment

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Abstract

Two experiments investigated how self-motion cues and landmarks interact in determining a human's position and heading estimations while driving in a large-scale virtual environment by controlling a gaming wheel and pedals. In an immersive virtual city, participants learned the locations of five buildings in the presence of two proximal towers and four distal scenes. Then participants drove two streets without viewing these buildings, towers, or scenes. When they finished driving, either one tower with displacement to the testing position or the scenes that had been rotated reappeared. Participants pointed in the directions of the five buildings. The least squares fitting method was used to calculate participants' estimated positions and headings. The results showed that when the displaced proximal tower reappeared, participants used this tower to determine their positions, but used self-motion cues to determine their headings. When the rotated distal scenes reappeared, participants used these scenes to determine their headings. If they were instructed to continuously keep track of the origin of the path while driving, their position estimates followed self-motion cues, whereas if they were not given instructions, their position estimates were undetermined. These findings suggest that when people drive in a large-scale environment, relying on self-motion cues, path integration calculates headings continuously but calculates positions only when they are required; relying on the displaced proximal landmark or the rotated distal scenes, piloting selectively resets the position or heading representations produced by path integration.

1. Introduction

Knowing our positions (where we are located) and headings (which direction we are facing) in an environment is important for successful navigation, such as planning a route from our current position to home. We use two navigation methods to estimate (update) our positions and headings: path integration and piloting (Etienne, Maurer, Georgakopoulos, & Griffin, 1999; Gallistel, 1990; Gallistel & Matzel, 2013). Path integration relies on self-motion cues to obtain our current moving directions and distances, adds these new directions and distances to the previously estimated positions and headings, and then updates estimates of our positions and headings (Etienne & Jeffery, 2004; Loomis, Klatzky, Golledge, & Philbeck, 1999; Mittelstaedt & Mittelstaedt, 1980). Self-motion cues comprise optic flow and idiothetic cues. The latter includes vestibular cues, proprioceptive cues, and motor efference copies. Piloting, also called landmark-based navigation, uses previously encoded visual landmarks in the environment to determine our positions and headings (e.g., Cheng & Spetch, 1998; Etienne, Maurer, Boulens, Levy, & Rowe, 2004; Etienne, Maurer, & Séguinot, 1996; Foo, Warren, Duchon, & Tarr, 2005; Wehner, Michel, & Antonsen. 1996). Several studies have examined the roles of path integration and piloting in position and heading estimations when participants walk in a small space (e.g., Mou & Zhang, 2014; Zhang & Mou, 2017). The purpose of the current study, however, was to examine the roles of path integration and piloting in position and heading estimations when people drive in a large-scale immersive virtual environment by controlling a gaming wheel and pedals.

In everyday life, people usually see visual landmarks while walking around. Therefore, piloting using landmarks and path integration using self-motion cues usually work together in updating people's positions and headings. One popular theory about the roles of these two methods in people's estimations of positions and headings is that path integration dynamically

updates estimates of people's positions and headings, whereas piloting intermittently corrects the errors accumulated in path integration (Etienne & Jeffery, 2004; Gallistel, 1990; but see Tcheang, Bülthoff, & Burgess, 2011). Many studies have demonstrated that people dynamically update estimates of their positions and headings using self-motion cues (Loomis et al., 1993; Rieser, 1989; see Loomis et al., 1999 for a review). Studies also suggest that path integration is not only dynamic but also automatic (Farrell & Robertson, 1998; May & Klatzky, 2000). However, path integration involves errors (Fujita, Klatzky, Loomis, & Golledge, 1993; Maurer & Séguinot, 1995). Errors in path integration could be accumulated quickly with the increase in the number of turns if there are no external cues (Benhamou et al. 1990; Kelly, McNamara, Bodenheimer, Carr, & Rieser, 2008). But when there are external landmarks, the visual landmarks can remove errors in the path integration of humans (e.g., Kelly et al., 2008) and non-human animals (Etienne et al., 2004; see Etienne & Jeffery, 2004 and Etienne et al., 1996 for reviews). This error-correcting process is called resetting (Etienne et al., 2004).

A homing task is widely used to study path integration. In particular, participants walk an outbound path (usually with two legs and one turn between the legs) and then judge the origin of the path (Loomis et al., 1999). Participants point to the origin of the path or walk back to the origin. The vector (direction and distance) from participants' testing positions to the estimated position of the origin is referred to as the homing vector. In order to study the interaction between path integration and piloting in human homing behaviors, a cue conflict paradigm is usually used (e.g., Chen & McNamara, 2017; Nardini, Jones, Bedford, & Braddick, 2008; Zhao & Warren, 2015). In particular, before participants walk toward or point to the origin in the homing task, the visual landmarks in the environment are displaced or rotated, therefore indicating a home location different from that indicated by path integration. If participants

estimate the home location based primarily on the displaced or rotated landmarks, the conclusion

is that landmarks are dominant over self-motion cues and landmarks reset path integration (e.g.,

Zhao & Warren, 2015).

Mou and Zhang (2014) argued that examining interaction between piloting and path

integration in homing estimation might not exactly reflect how piloting and path integration

interact in estimating position and heading. The argument is based on the observation that we

cannot separate position and heading estimates at the end of the outbound path using a home

estimate because people's homing estimates are jointly determined by their estimates of positions

and headings at the end of the outbound path. Angular errors in both heading and position

estimates contribute to angular errors in homing estimates (homing error = position error –

heading error; see the Appendix). With the measured homing errors, we cannot separate

contributions from position errors and heading errors. Thus, the findings about cue interaction

between piloting and path integration in homing estimation cannot precisely illustrate how

piloting and path integration affect people's estimations of their positions and headings at the end

of the outbound path.

Mathematically, the difficulty in calculating position errors and heading errors using the

observed homing error is that we cannot use one measured error (i.e., homing error) to infer two

unknown errors (i.e., position errors and heading errors). Extending the homing paradigm, Mou

and Zhang developed a paradigm in which participants learned the locations of at least two

objects (one at the origin and the other at a location in addition to the origin) and then replaced

the two objects after walking an outbound path. With two measured errors in replacing two

separate objects, the positon error and heading error at the end of the outbound path can be

calculated (see the Appendix and Mou and Zhang (2014) for details of the calculation).

More relevant to the current study, participants in Mou and Zhang (2014) learned the locations of objects in the presence of distal landmarks and then walked the outbound path towards the testing position after the distal landmarks and objects disappeared. Before participants replaced the objects, the distal landmarks reappeared with a rotation of 100º. The estimated positions and headings of participants were calculated from the replaced locations of the objects. The results showed that the estimated headings of participants were determined by the rotated distal landmarks, whereas their estimated positions were still determined by path integration. Furthermore, in Zhang and Mou (2017), participants learned objects in the presence of a proximal landmark and then walked the outbound path towards the testing position after the landmark and objects disappeared. Before participants replaced the objects, the proximal landmark reappeared and had been displaced to the testing position. The results showed that the estimated position of participants were determined by the displaced landmark, whereas the estimated heading of participants were still determined by path integration.

These two studies suggest: (a) that people separately maintain their position and heading representations, (b) that both representations are dynamically updated by path integration while walking, and (c) that the heading or position representations from path integration can be reset selectively by rotated distal cues or by a proximal landmark displaced to the testing position. Rotated distal cues do not reset the position estimates from path integration, because distal cues alone cannot specify a location. The proximal landmark displaced to the testing position does not reset the heading estimates from path integration, because it alone cannot specify a direction. We refer to this elaborated resetting model as the selective resetting hypothesis to differentiate it from the original resetting theory (Etienne & Jeffery, 2004; Gallistel, 1990).

In the current study, we tested the selective resetting hypothesis when participants drove in a large-scale immersive virtual environment by controlling a gaming wheel and pedals while donning a head-mounted display (HMD). There are two important theoretical motivations. The first motivation is to investigate whether the selective resetting hypothesis can be generalized to a different environment scale and a different locomotion mode. The second motivation is to investigate whether the claims of dynamic updating of positions and headings from path integration depend on locomotion mode.

With regard to the first theoretical motivation, in previous studies (Mou & Zhang, 2014; Zhang & Mou, 2017), participants walked within a small-scale immersive virtual environment (approximately 4 x 4m). The environment scale (small versus large) and the locomotion mode (walking versus driving) may impact the interaction between piloting and path integration, as human spatial cognition in general depends on the environment scale (Montello, 1993) and the locomotion mode (Klatzky et al., 1998).

On one hand, the interaction between piloting and path integration in a large-scale environment may differ from that in a small space. In a small space, people usually see all items while standing in a single position. Therefore, the role of piloting might be critical, whereas the role of path integration is trivial to updating of positions and headings in a small space. In contrast, in a large-scale environment, people cannot view all items while standing in a single position and need to locomote to view them. As a result, estimating positions and headings is more challenging in piloting and thus requires more contributions from path integration in the large-scale environment than in a small space (e.g., Ishikawa & Montello, 2006).

On the other hand, the interaction between piloting and path integration while driving may also differ from that while walking (Waller, Loomis, & Haun, 2004; Waller, Loomis, &

Steck, 2003). Waller, Loomis, and Steck showed that spatial knowledge of participants who were sitting in a car while donning an HMD and acquired spatial knowledge through a car trip in a large-scale environment was compared with participants who were sitting in a laboratory and learned the same environment by watching the video taken from the car trip. In contrast, Waller, Loomis, and Haun reported that the spatial knowledge of a large-scale environment was better when participants walked in the environment while donning an HMD than when participants were sitting in the laboratory and watched the video that had been taken while walking. These studies indicated that self-motion cues available while walking but not while driving might be critical to spatial learning. As optic flow and inertial (vestibular) cues are available while both driving and walking but proprioceptive cues are only available while walking, proprioceptive cues might be critical to spatial learning. Furthermore, Chrastil and Warren (2013) reported that proprioceptive cues are critical to spatial learning via path integration. Hence, path integration may be much less efficient while driving than while walking due to the lack of proprioceptive cues while driving. In addition, compared with driving in the physical world, participants driving in an immersive environment even do not have inertial cues, which might make the spatial learning from path integration even harder in driving in an immersive environment (e.g. Klatzky et al., 1998).

Therefore, it is not clear whether the selective resetting heading/position estimates from distal/proximal landmarks, observed when participants walked in a small space, can be generalized to a situation in which participants drive in a large-scale immersive virtual environment by controlling a gaming wheel and pedals. As the selective resetting of heading or position estimates is the core claim of it, the selective resetting hypothesis will be much

strengthened if selective resetting occurs regardless of the scale of the environment (small or

large) and the locomotion mode (driving by controlling a gaming wheel and pedals, or walking).

With regard to the second theoretical motivation of our research design (investigating

whether the claims of dynamic updating of positions and headings from path integration depend

on locomotion mode), we speculate that the claim of dynamic updating of positions and headings

might not be true when people drive in an immersive environment by controlling a game wheel

and pedals. The resetting hypotheses, both the original resetting hypothesis and the selective

resetting hypothesis, claim that path integration continuously calculates one's positions and

headings. However, spatial updating by path integration might be less efficient while driving in

immersive virtual environment than while walking (Waller et al., 2004; Waller et al., 2003) due

to the lack of idiothetic information (Chrastil & Warren, 2013; Klatzky et al., 1998). As a

consequence, path integration might not be able to continuously update positions and headings of

individuals as proposed in the resetting hypotheses.

Furthermore, Loomis and his colleagues (1999) proposed that spatial updating of the

homing estimates might not always be continuous. In addition to continuous spatial updating,

people may represent the travel distances and turning angles during locomotion instead of

calculating the homing vector continuously. They calculate the homing vector only when they

reach the end of the outbound path (referred to as configural updating). Configural updating

more likely occurs when the path complexity increases, suggested by the findings that latency in

homing increased with the number of turns in the outbound path. In addition, Wiener, Berthoz,

and Wolbers (2011; see also He & McNamara, 2017) showed that homing estimates were

continuously updated when participants were asked to keep track of the origin of the outbound

path during locomotion, whereas homing estimates were only updated at the end of the outbound

path when participants were asked to pay attention to the shape of the outbound path while walking.

Inspired by these theoretical ideas and empirical findings, we hypothesize that path integration updates people's position estimates continuously while walking but not continuously (i.e., only when required) while driving; by contrast, path integration updates people's heading estimates continuously regardless of the locomotion methods (walking or driving). We assume that whether people continuously update spatial representations (estimates of their positions and headings) or not depends on the difficulty of updating spatial representations. People more likely continuously update spatial representations when difficulty of doing so is lower (e.g., Loomis et al., 1999). Moreover, the difficulty of updating spatial representations is jointly determined by both computational complexity of spatial updating and self-motion cues available during locomotion. We conjecture that computational complexity of updating position estimates is much higher than that of updating heading estimates. However, this difference in terms of computational complexity could be attenuated by rich idiothetic cues that are available while walking but not available while driving.

During locomotion (whether walking or driving in immersive virtual environments), computational complexity of updating individuals' position estimates is much higher than that of updating individuals' heading estimates. In path integration, position estimations during locomotion rely on heading estimations. Path integration calculates the new heading estimate only by updating the new travelling direction but calculates the new position estimate by adding the new travelling vector (travelling distance in the travelling direction) to the previous position estimate. By contrast, in path integration, heading estimations do not rely on position

estimations. Because of this asymmetrical dependency between position and heading estimations, estimating one's position is much more complex than estimating one's heading.

However, the difficulty of estimating positions compared with estimating heading might not be significant or noticeable when participants walk, but becomes significant and noticeable when participants drive (controlling a gaming wheel and pedals). Individuals have rich idiothetic cues while walking. By contrast, while driving in immersive virtual environment, idiothetic cues are rare and optic flows might be the primary self-motion cues. Rich idiothetic cues might lead to effortless or automatic spatial updating whereas optic flows may not (e.g., Chrastil & Warren, 2013; Klatzky et al., 1998; Rieser, 1989; Ruddle & Lessels, 2009). Consequently, rich idiothetic cues available while walking might attenuate the differences in computational complexity between estimating positions and headings, and therefore support the continuous updating of both positions and headings while walking. By contrast, because there are rare idiothetic cues while driving (by controlling a game wheel and pedals), updating position and heading estimates might not be automatic and requires cognitive effort. Consequently, the computational complexity significantly influences the difficulty of spatial updating. Thus, spatial updating of heading estimates might be continuous due to the low computational complexity of heading estimations, whereas spatial updating of position estimates might not be continuous and occur only when required while driving due to high computational complexity of position estimations.

Given that the mechanism of position updating (i.e., continuous versus only when required) in path integration might depend on the locomotion mode, we modify the selective resetting hypothesis. In the modified version, when people drive by controlling a game wheel and pedals, path integration produces heading estimations continuously but produces position estimations only when required, whereas when people walk, path integration produces both

heading and position estimations continuously. By contrast, according to the original selective

resetting hypothesis, path integration produces both heading and position estimations

continuously regardless of walking or driving. Despite this modification, the heading or position

representations from path integration can still be reset selectively by rotated distal cues or by a

displaced proximal landmark when people drive. We refer to this modified hypothesis as the

locomotion-dependent selective resetting hypothesis. Table 1 summarizes the similarities and

differences between these two hypotheses (with differences highlighted in red). Two experiments

were conducted to test the selective resetting hypothesis and the locomotion-dependent selective

resetting hypothesis.

2. Experiment 1

In an immersive virtual city, participants, donning a HMD, learned the locations of five

buildings in the presence of four distal scenes and two proximal towers (illustrated in Figure 1A

and Figure 2A). Without viewing these buildings, scenes, and towers, they then drove on a street,

turned at one intersection, and drove on a second street by controlling a gaming wheel and

pedals. Some irrelevant buildings were presented on the street to provide rich optic flow and to

block the complete view of the shape of the driving path (Figure 1B). After driving, participants

who were standing at the end of the second street (i.e. P) and facing in the travelling direction of

the second street (i.e. h) pointed to the five buildings in different cue conditions. In the *no-

piloting cue condition* (Figure 1C and Figure 2B), no landmarks reappeared. In the *displaced

proximal landmark* condition (Figure 1D and Figure 2C), one of the towers was displaced and

reappeared at the testing position. In the *rotated distal scene* condition (Figure 1E and Figure

2D), the distal scenes were rotated and reappeared.

We calculated participants' estimated positions (P') and headings (h') using the least squares method to fit their responses of the directions of the buildings.[1] The direction of the estimated heading (h') and the bearing from the origin (O) to the estimated position (P') (in short, b_OP') were then used to diagnose whether position and heading estimations followed self-motion cues or piloting cues. Note that we used headings and bearings (both specified as an angle from an allocentric direction in the environment; e.g., the travelling direction on the first street, the direction from O to T in Figure 2) but not distance as measures to test hypotheses. The use of directions rather than distances is because perceived distance in immersive virtual environments might be underestimated (Thompson et al., 2004). However, there is no report yet about distortion in direction perception. We summarize the cues available to estimation of the headings and positions in the three conditions in Table 2 (see b_OP' and h').

The first purpose of this experiment was to investigate whether resetting also occurred when participants drove in a large-scale immersive virtual environment by controlling a gaming wheel and pedals. The *displaced proximal landmark* condition was used to investigate whether the displaced proximal landmark reset participants' position estimates. In this condition, as the proximal landmark (tower) was displaced to the testing position (from the location of L to P in Figure 2C), the positions determined by self-motion cues available in driving were in conflict with those available by the proximal landmark (P versus P' in Figure 2C). If participants' positions followed the displaced proximal landmark, then we would conclude that the proximal landmark had reset the participants' position estimates from path integration. The *rotated distal*

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[1] Note that we did not use the method developed in Mou and Zhang (2014), because this method requires people to indicate targets' locations. In a large-scale environment, however, it is more realistic to point to the targets' directions.

scene condition was used to investigate whether the rotated distal scenes reset participants'

heading estimations. In this condition, as the distal scenes were rotated 100° in the testing phase

(Figure 2D), the headings determined by self-motion cues available while driving and by the

rotated distal scenes reappearing at testing were in conflict (h versus h' in Figure 2D). If

participants' heading followed the rotated distal scenes, then we would conclude that distal

landmarks had reset participants' heading estimations from path integration.

As the locomotion-dependent selective resetting hypothesis follows the original selective

resetting hypothesis regarding the selective resetting mechanism (see Table 1), both hypotheses

predicted that the displaced proximal landmarks (towers) would determine the position

estimation in the condition of *displaced proximal landmark* (predicted cues for b_OP' in Table 2)

and that the rotated distal landmarks (scenes) would determine the heading estimation in the

condition of *rotated distal scene* (predicted cues for h' in Table 2).

The second purpose of this experiment was to investigate whether updating estimates of

positions and headings occurs continuously or only when required. We examined the estimated

heading, h', in the *displaced proximal landmark* condition and the estimated position, b_OP', in

the *rotated distal scene* condition. Because both the selective resetting hypothesis and the

locomotion-dependent selective resetting hypothesis predict that path integration updates

heading continuously, the estimated headings (h') in the condition of *displaced proximal*

landmark should follow self-motion cues (see predicted cues for h' in Table 2).

However, the selective resetting hypothesis and the locomotion-dependent selective

resetting hypothesis have different predictions for position estimation (i.e., b_OP') in the *rotated*

distal scene condition. The selective resetting hypothesis claims that path integration

continuously produces people's position estimates in driving as in walking. According to this

hypothesis, participants' position estimates have been produced continuously in driving by path integration before the rotated distal scenes reappear. Consequently, participants' position estimations would follow self-motion cues available in driving. In contrast, the locomotion-dependent selective resetting hypothesis claims that path integration produces people's position estimates only when required. According to this hypothesis, when participants stop driving, path integration has not yet updated the position representation using self-motion cues and has only encoded the moving distances and turning angle of the path. Furthermore, the rotated distal scenes, reappearing when participants stop driving, disrupt the position calculation in path integration. The rotated distal scenes indicate a turning angle that conflicts with that indicated by self-motion cues. Path integration might not be able to decide which turning angle should be used as the previous travelling direction for the position calculation. As there was no position representation updated yet in path integration when participants stopped driving and no further position estimates could be calculated accurately due to the disruptions from the rotated distal scenes, the position estimates would not follow self-motion cues and might be random (or undetermined). This key difference in predicted position estimations (predicted cues for b_OP') in the *rotated distal scene* condition between these two hypotheses is highlighted in red in Table 2.

We also used the *no-piloting cue* condition as a baseline to measure how accurately participants could primarily use self-motion cues to update their positions and headings in our experimental setup. Participants in our experimental setup primarily used optic flow as self-motion cues. Waller et al. (2003) showed that participants were able to use optic flow to estimate the locations of objects (see also Kearns, Warren, Duchon, & Tarr, 2002; Riecke, Cunningham, & Bulthoff, 2007). Other studies, however, showed that optic flow was insufficient for spatial

updating (Klatzky et al., 1998; Ruddle & Lessels, 2009). Hence, although we know the

theoretical values of the position and heading estimations that follow self-motion cues, it is also

important to empirically measure these values and show if the empirical values are consistent

with the theoretical values. In addition, the consistency between the empirical measurements and

the theoretical values can also ensure that our method (the least square fitting) to calculate

participants' position and heading estimations is valid.

2.1 Method

2.1.1 Participants

Thirty-six university students (18 men and 18 women) participated in the experiment to

fulfill a partial requirement for an introductory psychology course. Before the experiment, all

participants signed the consent form approved by the University of Alberta Research Ethics

Board. We used 36 participants in total so 12 for each cue condition following the same number

of participants that had been used in the previous studies (Mou & Zhang, 2014; Zhang & Mou,

2017).

2.1.2 Materials and Design

The virtual city was displayed in stereo with an nVisor SX60 head-mounted display

(HMD) (NVIS, Inc., Virginia), with 1280×1024 24-bit color pixels per eye, a 60° diagonal field

of view, and a 60 Hz refresh rate. Participants used a gaming wheel and pedals from Logitech

Driving Force GT (Logitech International S.A., California) for driving. Their head motions were

tracked with an InterSense IS-900 motion tracking system (InterSense, Inc., Massachusetts).

Therefore, participants could turn their heads to change their viewing directions while driving the

virtual car in the environment, although the travelling direction of the virtual car was only

determined by the gaming wheel (for turning) and pedals (for moving forwards or backwards).

Participants also used an InterSense IS-900 Wand to control a virtual stick for pointing to the

directions of the buildings. The virtual stick is a colorful stick, extending from the location of the

InterSense IS-900 Wand in the virtual environment. Participants could move the wand to change

the orientation of the virtual stick and indicate their response of a direction or a location in the

virtual environment, analogous to using a mouse to move a cursor to indicate a position on a

computer screen.

In the virtual city (Figure 1), five buildings (7-11, DQ, Subway, HSBC, and NQ) were

used as the targets that participants pointed to in the testing phase. Four different scenes (ocean,

forest, mountain, and city) were used as distal landmarks, and two different towers (a grey tower

and a golden tower) were used as proximal landmarks. We raised the towers up on narrow stalks

so that participants in the *displaced proximal landmark* condition could see themselves standing

at the base of the tower in the testing phase. To encourage participants to perceive the locations

of the buildings and towers more accurately, we had participants perceive them at two viewing

locations: the starting position (S) and the origin of the driving path (O). The distance between

these two positions was 200 m.

The four different scenes were set at infinity as distal orientation cues. The two towers

were located 51.76 m from O in the direction of 75° clockwise (i.e. the golden one on the right in

Figure 1A) and counter-clockwise (i.e. the grey one on the left in Figure 1A) with respect to the

first street (i.e., the direction from O to T in Figure 2). The five buildings were located 44.72 m,

364.01 m, 443.27 m, 379.47 m, and 360.56 m away from the origin O. The driving path started

from O and consisted of two streets (100 m each) and one turn with 50° either left or right. The

first street extended the road from S to O. Only the first street was presented to participants in

the study phase. Each participant completed two trials in the experiment (driving two paths with either a left or right turn). The order of the trials was randomized.

The primary independent variable was the cues available to participants after driving the path. In the *no-piloting cue* condition, neither the distal scenes nor the towers were presented (Figure 2B). In the *displaced proximal landmark* condition, only the tower that was in the same direction of the turning path (e.g. the golden one on the right in Figure 1A for the driving path with the right turn) with respect to the first street was presented (Figure 2C). The tower was displaced to the testing position (i.e., P). Thus, participants saw that they were standing at the base of the tower after driving. If participants used the displaced tower to estimate their position, they would feel that they stood at the original location of the tower (i.e., L in Figure 2C). In the *rotated distal scene* condition, the distal scenes reappeared with a rotation of 100° (Figure 2D). The direction of the rotation was opposite to the turning direction on the path. Thus, if participants used the rotated distal scenes to estimate the turning angle, they would feel that they had turned 150°. Twelve participants (six men and six women) were randomly assigned to each of the three cue conditions. We used the same number of participants in each cue condition as in the previous studies (Mou & Zhang, 2014; Zhang & Mou, 2017) (12 participants and each participant had two paths). The dependent variables were the bearing between the origin and the estimated testing positions (i.e., b_OP') and headings (h'), which were calculated from participants' pointing directions of the five buildings.

2.1.3 Procedure

Before the experiment, participants were given three minutes to read and memorize a map that contained the five target buildings and two study locations (S and O). Then, while wearing a blindfold to remove any possible influence from viewing the physical room,

participants entered the testing room under the guidance of the experimenter. They then removed the blindfold and donned the HMD.

In the immersive virtual reality environment, participants were teleported to the first study location (S). They studied the distal scenes, two towers, and five buildings for three minutes (Figures 1A & 2A). Then the buildings disappeared. Participants used the wand to point the virtual stick in the directions of buildings for two blocks. Within each block, all five buildings were visually probed (by presenting their small models at the bottom right of the HMD) in a random order. Feedback on the correct location was provided after each pointing. After studying at S, participants drove from S to O and studied the five target buildings for another 30 seconds followed by the two rounds of pointing and feedback. After studying at O, participants drove a path (O-T-P; see Figure 2B, 2C, & 2D) without seeing the proximal landmarks (towers), distal scenes, or target buildings. However, some irrelevant buildings were presented on the street to provide rich optic flow and to block the complete view of the shape of the driving path. At the end of the second street (the testing position P), participants pointed to the five target buildings that were visually probed in a random order in one of the three conditions. After that, participants were teleported to S and started the second experimental trial, which was the same as the first one except for the turning direction (left or right) on the path. Before these two experimental trials, participants had one practice trial to familiarize themselves with the procedure. In the practice trial, they learned the locations of two target buildings that were different from those in the experimental trials. In addition, the turning angle of the path was 90°.

2.1.4 Data analysis

We used the least squares fitting method to calculate the estimates of the testing position and heading for each participant on each experimental path. The least squares fitting method is widely used (e.g., in a regression analysis) and has also been used in estimating people's headings (e.g., Yerramsetti, Marchette, & Shelton, 2013). For each participant and each path, we searched for a position (P') and a heading (h') that led to the least sum of squares of the errors in pointing buildings. The error in pointing to each building is measured with the angular difference between the original direction of this building, relative to this hypothetical position and heading, and the participant's responded direction to this building, relative to the participant's testing position and heading after driving.[2] For example, given a hypothetical position and heading, the direction from the hypothetical position to building A relative to the hypothetical heading is 90º; a participant points in the direction of 80º when he or she points to building A; as a result, the error will be 10º. As in our previous studies, we used the bearing from the origin to the estimated position, b_OP', as the position measurement (Mou & Zhang, 2014; Zhang & Mou, 2017). We did not use distance information of P' relative to P or O because the distance perception in virtual environments might be distorted (Thompson et al., 2004). As we were not interested in the turning direction, we flipped the signs of b_OP' and h' for the left-turning path and combined them with those of the right-turning one. Therefore, we obtained 24 estimates for b_OP' and h' respectively for each cue condition as each of the 12 participants finished two paths.

In the interest of exposition, in the experiment below we used the driving direction on the first street (i.e., the direction from O to T in Figure 2) as the reference direction (i.e. direction 0º)

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[2] We used the fminsearch function in Matlab as the searching algorithm. Please find the example of the Matlab codes online (https://doi.org/10.7939/R3057D77Q).

to specify the testing headings (h and h') and the bearing of the testing positions relative to the origin (b_OP and b_OP'). In all conditions, if participants used self-motion cues to determine their positions and headings, b_OP' should be 25°, half of the turning angle, given the equal length of the two legs; h' should be 50°, the turning angle (see Figure 2B). In the *displaced proximal landmark* condition, if participants used the displaced tower to determine their positions, b_OP' should be 75°, which is the same as the direction from O to the original location of the tower (i.e. L in Figure 2C). As the displaced tower reappeared at the testing position, it could not provide any orientation information. Consequently, the heading predicted by the displaced tower was undetermined. In the *rotated distal scene* condition, if participants used the rotated distal scenes to determine their headings, h' should be 150°, as the scenes were rotated 100° in the direction opposite to the turning angle (50°) of the path (see Figure 2D). As the distal scenes (presented in infinite distances) alone could not specify locations, the position predicted by the distal scenes was undetermined. We summarize all of these predicted values from different cues in Table 3.

We used the 95% circular confidence interval (CI) of the mean direction (of the 24 b_OP' and 24 h') in each cue condition calculated by the circular statistic software Oriana 4 (Kovach Computing Services, UK) to diagnose the cues that determined b_OP' and h' (Batschelet, 1981). For example, if the confidence interval of an observed mean direction (e.g., b_OP') includes the direction predicted by cue A, then it suggests the observed direction is based on cue A. When the confidence interval is not reliable because the combination of concentration of observed directions and the sample size is low, we will conclude that the estimated direction is undetermined. The Rayleigh test is widely used to test the null hypothesis that observed directions are uniform when we do not know the alternative direction. According to Batschelet,

the confidence interval test is more appropriate than the Rayleigh test in the current study as we have specific directions (e.g., predicted by self-motion cues) as an alternative to the null hypothesis of uniform directions. We have still reported the results of the Rayleigh test for readers who may be interested.

2.2 Results and Discussion

In the *no-piloting cue* condition, participants used self-motion cues to estimate their positions (Figure 3A) and headings (Figure 4A) (mean b_OP' = 20°, 95% CI [348° - 52°]; mean h' = 57°, 95% CI [36° - 78°]). The confidence intervals included the predictions from self-motion cues for both b_OP' and h', 25° and 50° respectively. The observed means of b_OP' and the predicted means of b_OP' based on self-motion cues were consistent. This finding indicates that participants were able to update the representations of their positions and headings using self-motion cues. It also confirms the validity of the least squares fitting method that calculated the observed position and heading estimations.

In the *displaced proximal landmark* condition, the estimated positions (Figure 3B) followed the displaced tower (mean b_OP' = 95°, 95% CI [63° - 126°]). The confidence interval included the prediction from the landmark (75°) but excluded the prediction from self-motion cues (25°). The estimated headings (Figure 4B) were close to what was predicted by self-motion cues (mean h' = 72°, 95% CI [57° - 87°]). The confidence interval excluded the prediction from self-motion cues (50°), although the lower boundary was close to the prediction.

In the *rotated distal scene* condition, critically, participants' position estimations (Figure 3C) were undetermined, as there was no reliable confidence interval for b_OP'. The estimated headings (Figure 4C) followed the rotated distal scenes (mean h' = 140°, 95% CI [121° - 159°]).

The confidence interval included the prediction from the landmark (150°) but excluded the

prediction from self-motion cues (50°).

In addition, the Rayleigh test showed that observed headings (h') were not uniform in any

of the three conditions, Rayleigh $Zs \geq 10.83$, $p < .001$. The observed bearings of estimated

positions (b_OP') were also not uniform in any of the three conditions, Rayleigh $Zs \geq 3.00$, $p \leq$

.05. Note that although the result of the Rayleigh test rejected the uniform distribution of b_OP'

in the rotated distal scene condition ($p = .05$), we still could not determine the direction of b_OP'

as there was no reliable confidence interval.

Most of these findings were consistent with the selective resetting hypothesis, which was

based on the findings when participants walked in a small space. One important exception was

that when participants saw rotated distal scenes, their position estimations were undetermined in

the current experiment, which is inconsistent with the prediction that participants' position

estimations followed self-motion cues when they saw rotated distal landmarks (Mou & Zhang,

2014). However, this finding can be explained by the locomotion-dependent selective resetting

hypothesis. According to this hypothesis, when people drive in a large-scale environment, path

integration updates heading estimates dynamically, but updates position estimates only when

required[3]. As discussed in the Introduction, path integration updates position representations only

when required because estimating positions while driving is a challenge. As a result, in the

current experiment, position representations in path integration had not been updated when

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[3] Continuous updating or updating only when required of positions could not be diagnosed by the
results in the no-piloting cue condition. Because there was no conflicting heading cue to interrupt
position estimation from path integration at the end of the outbound path, participants could still
use the moving distances and turning angle from self-motion cues to calculate their positions,
even if they updated positions only when required.

participants saw the rotated distal scenes which further interrupted the possible position estimation when required. Thus participants' position estimations did not follow self-motion cues and were undetermined.

To further test this conjecture, Experiment 2 modified the *rotated distal scene* condition. Participants were instructed to keep track of the origin of the path (O) while driving (He & McNamara, 2017; Wiener et al., 2011). In addition, after driving, they were asked to point to the origin of the path before the rotated distal scenes were presented. We assume that people use both position and heading representations to estimate the origin of the path (Mou & Zhang, 2014). Thus, participants had to update their position estimates before pointing to the origin. As a result, this instruction forced them to produce their position representation using self-motion cues before they saw the rotated distal scenes. Therefore, their position estimations would follow self-motion cues.

3. Experiment 2

3.1 Method

3.1.1 Participants

Twelve university students (six men and six women) participated in the experiment to fulfill a partial requirement for an introductory psychology course. Before the experiment, all participants signed the consent form approved by the University of Alberta Research Ethics Board. Twelve participants were tested following the number of participants used in each cue condition of Experiment 1.

3.1.2 Design and Procedure

This experiment used the *rotated distal scene* condition in Experiment 1, with two modifications. First, participants were instructed to keep track of the origin of the path while driving. Second, when participants finished driving in the testing position, they were asked to point to the origin before viewing the rotated distal scenes. We termed this condition the *rotated distal scene & instruction* condition.

3.2 Results and Discussion

Consistent with our conjectures, the participants' position estimations (Figure 3D) followed self-motion cues (mean b_OP' = 30°, 95% CI [359° - 62°]). The confidence interval included the prediction from self-motion cues (25°). As in Experiment 1, participants' heading estimations (Figure 4D) followed the rotated distal scenes (mean h' = 138°, 95% CI [121° - 156°]). The confidence interval included the prediction from the landmark (150°) but excluded the prediction from self-motion cues (50°). In addition, the Rayleigh test showed that observed headings (h') were not uniform, Rayleigh Zs =13.45, $p < .001$, and the observed bearings of estimated positions (b_OP') were not uniform, Rayleigh Zs = 5.56, $p < .01$.

4. General Discussion

There are two important findings in the current study. First, when the proximal landmark (i.e., tower) reappeared at the testing position, participants' position estimations followed the displaced proximal landmark. When the distal scenes reappeared with a 100º rotation, participants' heading estimations followed the rotated distal scenes. Second, when the displaced proximal landmark reappeared, participants' heading estimations followed self-motion cues. When the rotated distal scenes reappeared, the participants' position estimations depended on whether participants were instructed to keep track of the origin of the path during locomotion. In

particular, their position estimations followed self-motion cues with such instruction but were undetermined without such instruction.

The current findings significantly strengthen the selective resetting hypothesis. The results, together with the previous studies (Mou & Zhang, 2014; Zhang & Mou, 2017), indicate that regardless of the travelling modes (walking or driving) and the scale (small or large) of the environment, a displaced proximal landmark determines people's position estimations, whereas rotated distal scenes determine their heading estimations. These findings suggest that different piloting cues (i.e., heading cues or position cues) selectively reset the headings or positions estimated by path integration.

However, one finding in the current study strikingly differed from those in Mou and Zhang's (2014) study and questioned the selective resetting hypothesis. In Mou and Zhang's study, when rotated distal cues reappeared, participants' position estimations followed self-motion cues (2014). By contrast, in Experiment 1 of the current study, when rotated distal scenes reappeared, participants' position estimations appeared to be random (undetermined). This novel finding undermined one important claim of the selective resetting hypothesis. According to the selective resetting hypothesis, path integration dynamically updated participants' position representations as well as their heading representations. Therefore, both position and heading representations should have been updated in path integration before the rotated distal landmarks reappeared. As a consequence, participants' position estimations should have followed self-motion cues regardless of the locomotion mode. These predictions are inconsistent with the findings in Experiment 1.

The locomotion-dependent resetting hypothesis, however, could explain the discrepancy in Mou and Zhang's findings (2014) and in Experiment 1 of the current study. According to this

hypothesis, when people walk, path integration updates their position and heading representations continuously. In contrast, when people drive, path integration updates their heading representations continuously, but updates their position representations only when participants are required to do so. This difference occurs because updating position representations is more complex than updating heading representations. One possible reason is that calculating position representations requires the input of heading representations, but not vice versa. The complexity in updating position representations, relative to updating heading representations, might be unnoticeable when people walk but might be significant when people drive. Historically, humans have much more experience walking than driving. Furthermore, walking provides people with richer idiothetic cues than driving does. In addition, walking is much slower than driving. Therefore, it makes sense that position representations would be updated continuously for walking but only when required for driving. In particular, when the rotated distal landmark reappeared, participants in Mou and Zhang's study had obtained position representations in path integration, whereas participants in Experiment 1 of the current study had not produced position representations in path integration. We assumed that seeing the rotated distal landmark interrupted the process of calculating positions when participants were required to do position estimation. That is why participants' position estimations followed self-motion cues in Mou and Zhang's study but did not follow self-motion cues and were undetermined in Experiment 1 of the current study.

The speculation that the random (i.e. undetermined) position estimations in the *rotated distal scene* condition of Experiment 1 resulted from updating of position representations only when required was further supported in Experiment 2 of the current study. In Experiment 2, participants were instructed to keep track of the origin of the path (He & McNamara, 2017;

Wiener et al., 2011). The result showed that participants' position estimations followed self-motion cues when the rotated distal scenes reappeared, replicating the findings in Mou and Zhang's (2014) study. As discussed in the introduction, people need to know their positions and headings before they estimate their home locations. That explains why, in Experiment 2, participants updated their position estimations when they kept track of the origin of the path while driving. Path integration had produced the position estimation before the rotated distal scene reappeared. Thus, the participants' position estimations followed self-motion cues.

Although the rotated distal landmark led to random (undetermined) position estimates, the displaced proximal landmark did not lead to random heading estimates while driving. The locomotion-dependent resetting hypothesis provides an explanation. According to this hypothesis, path integration updates heading representations continuously whether people drive or walk. In the current study, heading representations in path integration had been updated before the displaced proximal landmark reappeared. Consequently, participants' heading estimations followed self-motion cues.

We acknowledge that the two kinds of updating (continuous updating and updating only when required) distinguished in the locomotion-dependent resetting hypothesis were inspired by the idea that individuals can have two spatial updating mechanisms while walking (e.g., Loomis et al., 1999). According to Loomis et al. (1999), individuals could continuously update the homing vector during locomotion (*continuous updating*). Individuals could also maintain the shape of the path during locomotion. They calculate the homing vector at the end of the path (*configural updating*). Extending this original idea, the current study's findings suggest three new insights.

First, the two spatial updating mechanisms in the previous studies focus on whether the homing vector is calculated continuously or only when required (He & McNamara, 2017; Wiener et al., 2011). By contrast, in the locomotion-dependent resetting hypothesis, the two spatial updating mechanisms focus on whether participants' positions are calculated continuously or only when required. In the current study, during the test, participants pointed to buildings. Their position estimations were calculated with their response with regard to the directions of the buildings. Participants' responses to the home location were not collected or used to calculate their position estimations. As a consequence, participants should have updated their positions with respect to many locations in the environment rather than the home only. This suggests that updating (continuous or not) is about vectors between people's positions and several important locations in the environment. The homing vector might be just one of these vectors.

Second, the previous studies found that the two spatial updating mechanisms were selected by instruction. In Wiener et al.'s study (2011; see also He & McNamara, 2017 and Experiment 2 of the current study), participants could be instructed to update only at the end of the outbound path (e.g., by paying attention to the shape of the path) or continuously during locomotion (e.g., by keeping track of the origin of the path). The current study further shows that two spatial updating mechanisms could be selected by the locomotion mode, as the locomotion-dependent resetting hypothesis suggests. Participants who walked updated positions continuously (Mou & Zhang, 2014), whereas participants who drove updated positions only when required (Experiment 1 of the current study). There might be other ways to activate the two spatial updating mechanisms. Future studies may test whether the complexity of the outbound path can also activate these two updating mechanisms. For example, if participants walk on a more

complicated path with more legs (e.g., Kelly et al., 2008), position estimations might also be updated only when required (Loomis et al., 1999).

Third, the previous theories hypothesized that people might represent the configuration (i.e., shape) of the path through the configural updating mechanism (e.g., Loomis et al., 1999; Wiener et al., 2011). However, the random position estimations in the *rotated distal scenes* condition in Experiment 1 indicated that at least while driving, the length of travel legs and the turning angle are still separately represented as a cognitive graph (Warren, Rothman, Schnapp, & Ericson, 2017) and have not been integrated into an enduring representation of the path shape, a cognitive map (Loomis et al., 1999). If an enduring representation of the path shape has been formed, the rotated distal scene should not impair it. Thus, participants should be able to use the enduring representation of the path shape to calculate the position, producing a position estimation that is consistent with self-motion cues rather than a random position estimation as indicated by the result. In future studies, we may test whether participants who are instructed to form an enduring representation of a path shape will show random position estimations when they see a rotated distal scene like in the *rotated distal scenes* condition in Experiment 1. It is possible that being instructed to pay attention to the shape of the path (Wiener et al., 2011) while driving can lead to an enduring representation of the outbound path, which participants can use to calculate their positions even when they see the rotated distal landmark.

We acknowledge that the findings of the current study are based on navigation in immersive environments without constant coherence between inertial cues and visual cues. Participants in the current study, with a tracked HMD, could move their head to change their views during driving. Therefore, inertial cues and visual cues were coherent while the car was moving forward within streets. However, when the virtual car turned across streets, the visual

information indicated the turn whereas inertial cues did not, disrupting the coherence between inertial cues and visual cues. Thus, although driving a virtual car in an immersive virtual environment added some inertial cues compared to driving in a non-immersive virtual environment (e.g. tele-operating a vehicle or a drone), it was still not the same as driving in real environments. Previous studies showed that humans recalibrated the inertial information in terms of the visual information when the relations between inertial and visual cues changed systematically (e.g. Viaud-Delmon, Ivanenko, Berthoz, & Jouvent, 1998). In addition, hamsters relied less on inertial information in homing when both inertial and visual information were available even after they had briefly been rotated on a rotating platform in darkness (Etienne, Teroni, Hurni, & Portenier, 1990). These findings suggest that human and non-human animals are very sensitive to incoherence between inertial and visual information. We speculate that participants while driving across streets relied on the visual turning angle less the turning angle from their inertial cues to calculate the turning angles as participants in the No-piloting cue condition were accurately in estimating their headings. Future studies may test the locomotion-dependent selective resetting hypothesis in a driving stimulator providing constantly coherent inertial cues to understand resetting in real-life driving.

5. Conclusion

In conclusion, when people drive in a large-scale immersive virtual environment, the rotated distal scenes and the displaced proximal landmark selectively reset the heading and position estimations. Path integration uses self-motion cues to update position and heading estimates. Heading updating is continuous, but position updating may require more cognitive effort to work continuously. These results, together with the findings in previous studies (Mou &

Zhang, 2014; Zhang & Mou, 2017), support the locomotion-dependent selective resetting

hypothesis.

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Appendix derivation of homing error = position error – heading error (i.e. b_ PO' – b_PO = (b_OP' - b_OP) – (h' - h)) (see Figure A1)

We assume that this participant uses the represented spatial relations between the origin (O), the estimated testing position (P'), and the estimated testing heading (h') in his or her spatial memory to judge the relations between replaced location of the origin (O'), the testing position (P), and the testing heading (h) during response. Hence the relations between the elements in the memory (O, P', h') should be the same as the relations between the elements in the response (O', P, h).

We obtain

$$h' - b\_OP' = h - b\_O'P \qquad (A1)$$

All headings (h and h') and bearings (i.e. b_AB) are defined as the angular distance from a fixed allocentric direction in the environment. We further define the clockwise direction as the positive direction to specify an angular distance. As signed angles belong to real numbers, all the mathematical principles for read numbers should be applied to headings and bearings.

Equation A1 can be rewritten as

$$h' - h = b\_OP' - b\_O'P \qquad (A2)$$

Therefore,

$$b\_OP' - b\_OP - (h' - h) = b\_OP' - b\_OP - (b\_OP' - b\_O'P)$$

$$= b\_O'P - b\_OP$$

We obtain

$$b\_OP' - b\_OP - (h' - h) = b\_O'P - b\_OP \qquad (A3)$$

Because b_AB = b_BA -180, we rewrite Equation A3 as

$$b\_OP' - b\_OP - (h' - h) = b\_PO' - 180 - (b\_PO - 180)$$

$$= b\_PO' - b\_PO$$

We obtain

$$b\_PO' - b\_PO = b\_OP' - b\_OP - (h' - h) \text{ or homing error = position error – heading error}$$

Figure A1.

A hypothetic participant while standing at the testing position (P) with the testing heading (h) points to the location of the origin (O). Suppose that the judged location of O is O'. The angular error of homing is b_ PO' – b_PO. b_AB refers to a bearing from positions A to B relative to an horizontal allocentric reference direction in the environment. Suppose that this participant's estimates of his or her testing position and heading are P' and h'. The angular error of heading is h' – h. Both h and h' are specified by the angular distance from the allocentric reference direction. The angular error of position is b_OP' - b_OP. As derived in the Appendix, homing error = position error – heading error. Position errors and heading errors cannot be dissociated with the measured homing errors. If this participant also learns an addition location X and then replaces X in the position of X', then position errors can be measured by (b_OX – b_PO) – (b_O'X'– b_PO') (see Mou & Zhang (2014) for derivation) and heading errors can also be measured given the measured position errors and homing errors (heading error = position error – homing error).
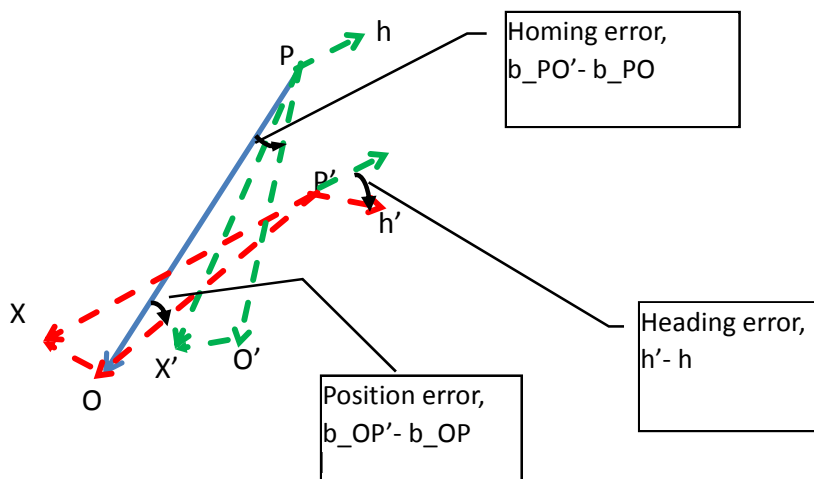
Table 1. Similarities and differences between the selective resetting hypothesis and the locomotion-dependent selective resetting hypothesis on when path integration updates position and heading estimates using self-motion cues and whether landmarks reset position and heading estimates from path integration. Differences are highlighted in red.

	Selective resetting hypothesis	Locomotion-dependent selective resetting hypothesis
Updating heading representations using self-motion cues	Continuously	Continuously
Updating position representations using self-motion cues	Continuously	Only when required
Resetting heading representations by rotated distal landmarks	Yes	Yes
Resetting position representations by displaced proximal landmarks	Yes	Yes

Table 2. Cues that were available to determine the bearing from the origin (O) to the testing position (P) (in short, b_OP') and the estimated testing heading (h'), cues that would be used according to the selective resetting hypothesis and the locomotion-dependent selective resetting hypothesis (predicted), and the cues that were indeed used to determine b_OP' and h' (observed) in different experimental conditions. The first three conditions were used in Experiment 1 and the last condition was used in Experiment 2. Note that the selective resetting hypothesis and the locomotion-dependent selective resetting hypothesis have a similar prediction on which cue would determine b_OP' and h' except for b_OP' in the rotation distal scene condition (highlighted in red). The former predicts that the b_OP' would be determined by the self-motion cue whereas the latter predicts that the estimated position would not be determined by self-motion cues and might be undetermined.

Conditions	Available cues		Predicted cues		Observed cues	
	b_OP'	h'	b_OP'	h'	b_OP'	h'
No-piloting cue	self-motion cues	self-motion cues	self-motion cues	self-motion cues	self-motion cues	self-motion cues
Displaced proximal landmark	self-motion and landmarks	self-motion cues	landmark	self-motion cues	landmark	self-motion cues
Rotated distal scene	self-motion cues	self-motion and landmarks	self-motion or undetermined	landmarks	undetermined	landmarks
Rotated distal scene & instruction	self-motion cues	self-motion and landmarks	self-motion cues	landmarks	self-motion cues	landmarks

Table 3. Predicted bearings of the estimated testing position (b_OP') and the estimated testing heading (h') based on self-motion cues or landmarks, and the observed b_OP' and h' in different experimental conditions. The predicted b_OP's and h's consistent with the observed b_OP's and h's are underlined.

Conditions	Prediction from self-motion cues		Prediction from landmarks		Observed circular mean (length of mean vector, r)	
	b_OP'	h'	b_OP'	h'	b_OP'	h'
No-piloting cue	**<u>25º</u>**	**<u>50º</u>**	Not applicable	Not applicable	20º (.48)	57º (.67)
Displaced proximal landmark	25º	**<u>50º</u>**	**<u>75º</u>**	undetermined	95º (.48)	72º (.79)
Rotated distal scene	25º	50º	undetermined	**<u>150º</u>**	undetermined	140º (.71)
Rotated distal scene & instruction	**<u>25º</u>**	50º	undetermined	**<u>150º</u>**	30º (.48)	138º (.75)

Figure 1. Snapshots of the first-person view in each experimental phase in Experiment 1 across conditions: the study phase (A), the driving phase (B), the testing phase in the no-piloting cue condition (C), the testing phase in the displaced proximal landmark condition (D), and the testing phase in the rotated distal scene condition (E)
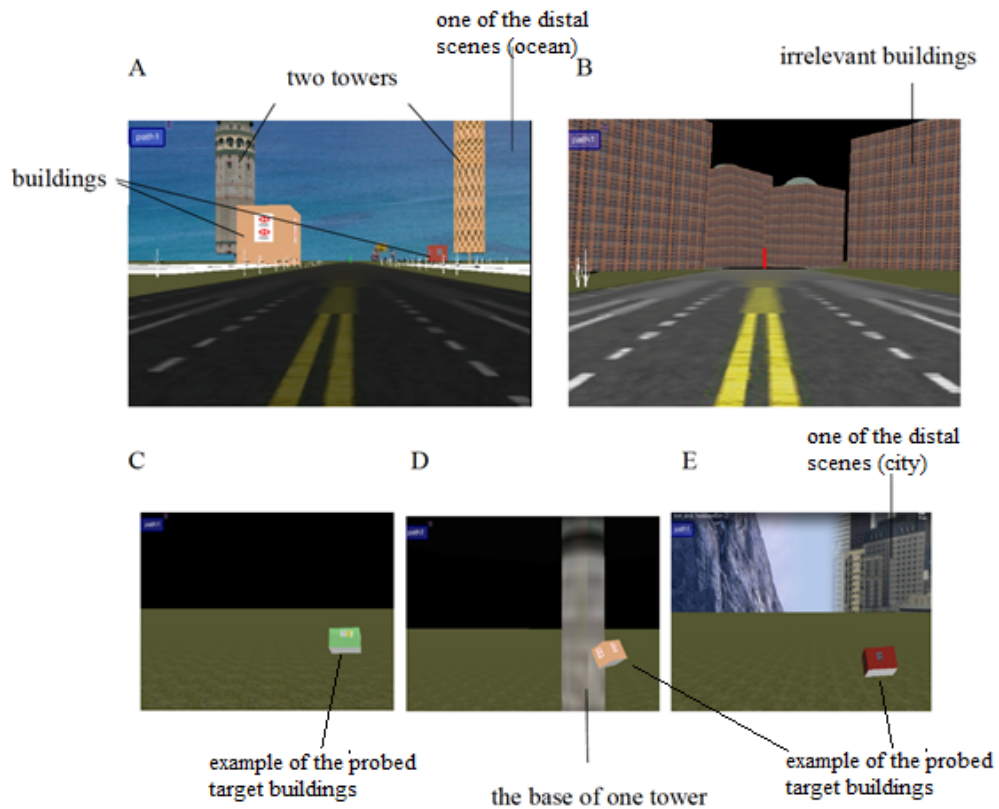
Figure 2. Schematic diagram of the experimental set-up. **(A)** The study phase across all conditions. The triangles represent the two study viewpoints (S and O). Length of SO = 200 m. The squares represent the two proximal landmarks (towers 1 and 2). Ocean, forest, city, and mountain represent the distal scenes. All four scenes instead of words were presented. Five dots represent target buildings. **(B)** No-piloting cue condition. O is the origin of the path. T is the turning point. P is the testing position. h is the testing heading (equivalent to the direction of TP). P' is the estimated position and h' is the estimated heading. According to the selective resetting hypothesis, P' and h' are predicted by self-motion cues and are the same as P and h. **(C)** Displaced proximal landmark condition. Tower1 was displaced from L to P during the test. According to the selective resetting hypothesis, P' is reset by the displaced landmark and is the same as L, and h' is predicted by the self-motion cues and is the same as h. **(D)** Rotated distal scene condition. Distal scenes were rotated 100° during the test. According to the selective resetting hypothesis, h' is predicted by the rotated distal scenes and is 100° from h, and P' is predicted by the self-motion cues and is the same as P. Lengths: OT = TP = TL =100 m. Bearings with respect to the direction from O to T: b_TP = 50°, b_OL = 75°, b_OP = 25°.
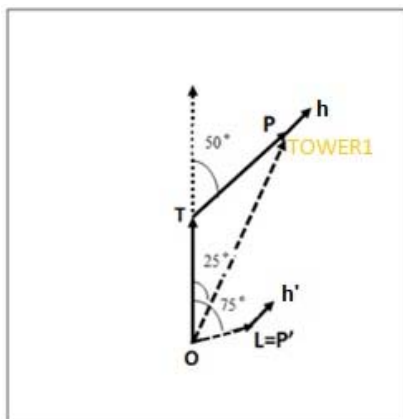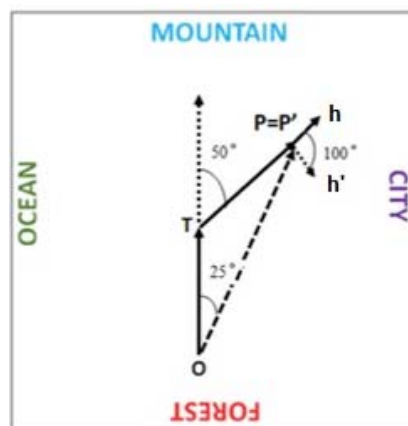
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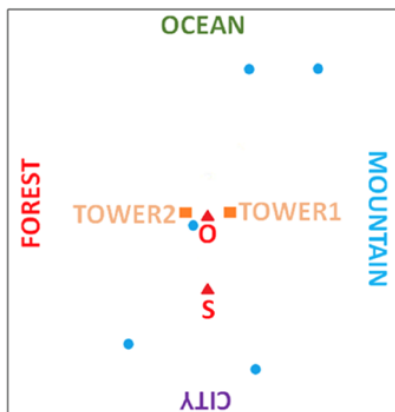
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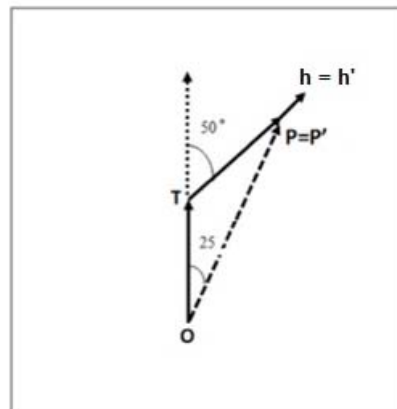
C.

D.

Figure 3. Observed and predicted bearing from the origin to the estimated testing position (b_OP') relative to the first street (from O to T). (A) No-piloting cue condition. (B) Displaced proximal landmark condition. (C) Rotated distal scene condition. (D) Rotated distal scene & instruction condition. Each blue dot indicates one observed b_OP' of one path of one participant. (The signs of b_OP' for the left-turning path are flipped.) The solid black line indicates the circular mean observed b_OP'. The black arc indicates the 95% circular confidence interval of the mean observed b_OP'. The red arc indicates no reliable confidence interval of the mean observed b_OP'. The dotted red line indicates the predicted b_OP' following self-motion cues (25°). The dashed green line indicates the predicted b_OP' following the proximal landmark (75°) in the displaced proximal landmark condition (B).
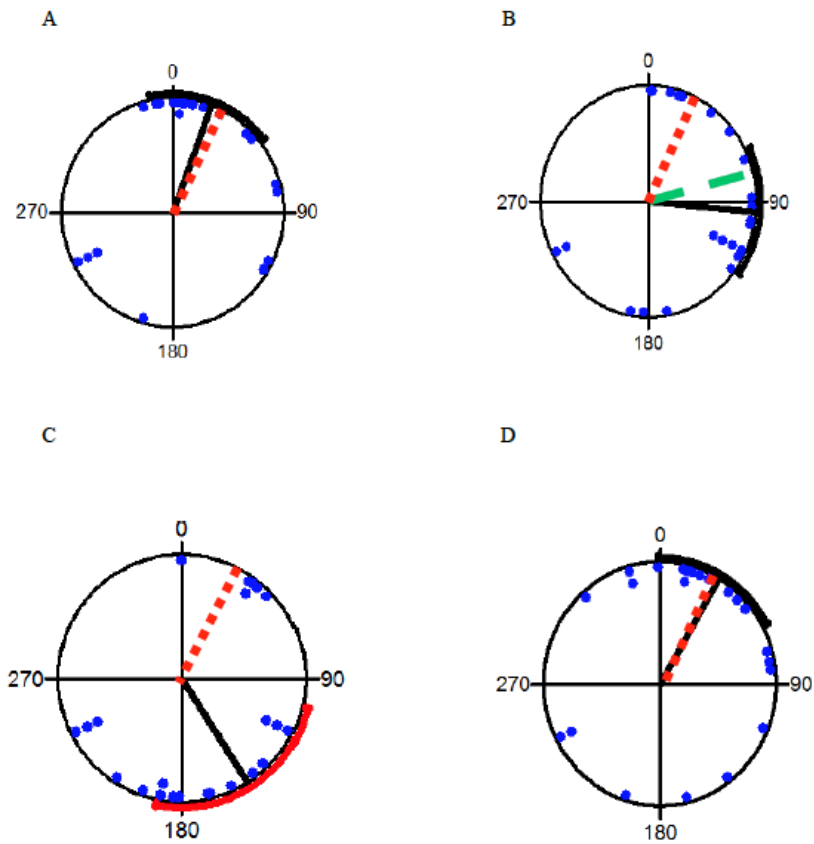
Figure 4. Observed and predicted testing headings (h') relative to the first street (from O to T). (A) No-piloting cue condition. (B) Displaced proximal landmark condition. (C) Rotated distal scene condition. (D) Rotated distal scene & instruction condition. Each blue dot indicates one observed h' of one path of one participant (the signs of h' for the left-turning path are converted by flipping the sign). The solid black line indicates the circular mean observed h'. The black arc indicates the 95% circular confidence interval of the mean observed h'. The dotted red line indicates the predicted h' following self-motion cues (50°). The dashed green line indicates the predicted h' following the rotated distal scenes (150°) in the rotated distal scene condition and in the rotated distal scene & instruction condition (C and D).