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RESEARCH ARTICLE

The choice of intrinsic axis under multi-cue conditions

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Abstract
In the course of spatial representation, the choice of intrinsic axis depends on various spatial and non-spatial properties. The main purpose of the current study is to investigate how people choose the intrinsic axis in a virtual reality environment with spatial cues from different categories. Sixty-four participants (32 males and 32 females) each took part in one of two experiments. In each experiment, participants learned a layout comprising seven objects and viewed the scene through a head-mounted display from two perspectives. They then completed partial-scene-recognition tasks. Experiment 1 used objects lacking intrinsic orientations, and the directions of the symmetric axis (45°–315°) and the vertical side (0°–180°) of the mat were incongruent. Experiment 2 used avatars whose orientations were all aligned with the vertical mat side. Response patterns showed that the axis which was consistent with the initial learning perspective was chosen as the intrinsic axis in Experiment 1, while in Experiment 2, the 0°–180° axis was chosen. The results indicated that people would choose the intrinsic axis according to their original egocentric experience when there were two conflicting geometric cues of different categories, but if there were three geometric cues, the axis that was consistent with more cues was more likely to be chosen as intrinsic axis.

Keywords Intrinsic frame-of-reference system · Intrinsic axis · Virtual reality environment · Partial scene recognition

Introduction

Mou and McNamara (2002) developed intrinsic frame-of-reference system (IFoRs) theory, which emphasized the importance of IFoRs in spatial memory. It suggests that people learn and represent the locations of objects in a new scene by means of what is known as the intrinsic axis, which may or may not be the same as their viewing perspective, and that people can use this axis to construct an IFoRs. The IFoRs not only has an effect on spatial memory but also on spatial perception (Li et al. 2011). Many studies have focused on what clues in the environment can act as the intrinsic axis, for example, the symmetric axis (Mou et al. 2009), the edge of a presented scene (Kelly et al. 2013; Shelton and McNamara 2001; Sluzenski et al. 2011), the salient cues of the extrinsic environment (Li et al. 2009; Valiquette et al. 2007), the coincident orientations of objects in the scene (Li and Zhang 2011, 2012; Marchette and Shelton 2010), the similarity of some objects (Zhang et al. 2014), the object-centered reference system (Chen and McNamara 2011) and so on. It can be found that the selection of the particular axis or axes depend(s) on the spatial and non-spatial properties.

However, the establishment of an intrinsic frame of reference to represent the spatial scene has also been questioned by many experimental evidences and has shown some limitations. Richard and Waller (2013) suspected that participants in Mou and McNamara's (2002) study chose the intrinsic axes for not only the symmetry but also the orthogonality, so the coincidence of these two spatial characters helped people to use the direction different from the learning perspective to represent the environment. They showed that if these two characteristics were separated, people inclined to represent the environment according to the egocentric experience. Xie et al. (2017) also found that the establishment of the IFoRs in spatial memory was closely related to the egocentric experience, the regularity of the scene layout and the experimental instructions. These results indicated that only under some experimental conditions will the participants use the intrinsic reference system.

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The fact is that there are many co-occurring geometric cues in an environment and the spatial representations of environments would be complex. For example, Li and Su (2015) found that two cues of object orientation and symmetric axis were equally important for the establishment of the intrinsic axes, but the former cues had its limitations and instability. Kelly and McNamara (2008) discovered that when the intrinsic structure of the scene, that is, the axis of symmetry, conflicted with the external structure, participants used the experienced viewing point to represent the spatial scene. When the two were in agreement, the consistent direction was chosen as the IFoR in spatial memory. Besides, Tamborello et al. (2012) used "Two cannons" task and found that if there were multiple conflicting IFoRs based on the orientations of cannons, the participants seemed to prioritize processing of each IFoR by salience, and only one IFoR could be actively represented at a time. These studies showed that when two equally important environmental cues conflicted, people used the viewing point to represent the scenes. When cues were consistent, people would choose the environmental cues. Participants refer to one or more environmental cues to represent the spatial relationship between objects, but in the end, only one direction is chosen to establish the intrinsic frame of reference (IFoR).

Mou et al. (2008) proposed an experimental paradigm called partial scene recognition (PSR) for the research about IFoRs, which was modified from the whole-scene-recognition task. Whole scene recognition has been widely used in studies on viewpoint dependence, a closely studied phenomenon related to the egocentric system, indicating that participants' performance of spatial memory and recognition tasks is better for experienced perspectives than for novel ones (Shelton and McNamara 1997). In a PSR task, participants are asked to recognize triplets consisting of objects from the learned scene and then judge whether the relative positional relationship of these three objects is the same as the one in the learned scene. By this paradigm, researchers have found that the response time was shorter when the line between any two objects in the triplets was parallel to or consistent with the intrinsic axis than other triplets presented (Rump and McNamara 2013). The PSR paradigm also found that the response from an experienced perspective was faster than a new one and has disassociated the viewpoint dependence and intrinsic axis dependence successfully (Mou et al. 2008).

The above studies showed that many cues could be selected as intrinsic axes and explored the interaction of different cues. One problem with these studies was that no more than two environmental cues were provided in experimental materials, such as Tamborello et al. (2012) only focused on the orientations of two cannons, so there was only one category of geometric cue. Kelly and McNamara (2008) only explored the impact of two clues on the IFOR. The clues in the actual environment are very complex, so what would happen if two or more different categories of geometric cues coexist? Two experiments were designed to answer this question. Experiment 1 used seven objects lacking intrinsic orientations on a square mat, where the direction of symmetric axis and the vertical side of the mat were incongruent. Experiment 2 used avatars whose orientations were all aligned with the vertical mat side. That is to say, besides the learning perspective, there were two and three geometric cues in Experiment 1 and 2, respectively. In each experiment, two learning perspectives, along the symmetric axis and along the vertical mat side, were used to disassociate the effect of viewpoint (Mou et al. 2007), and then a PSR paradigm was used to discover people's choice strategy of intrinsic axis under multi-cue conditions through the comparison of response time patterns. The hypotheses of the study were that when there were two equally significant cues in the scene, the egocentric viewpoint was chosen as the intrinsic axis. When the third significant clue was added to the scene and was consistent with the vertical edge of the mat, the direction containing more clues was used for spatial representation.

Experiment 1

Method

Participants

Thirty-two graduate students (16 males and 16 females) between the ages of 22 and 25 years from Nanjing Normal University participated in the study. All reported that they had normal or corrected-to-normal eyesight without apparent color vision deficiency. The IRB of Nanjing Normal University approved the study, and all participants volunteered to take part in the experiment. Each participant received 15 CNY (about 2.5 USD) as compensation.

Materials and design The study included two phases of learning and testing. Both phases were conducted in a circular space that was surrounded with black curtains in order to minimize distractions from the environment. Figure 1 illustrates the placement of learning materials in Experiment 1. Seven objects with no clear orientation were of different colors and shapes and were placed on a white square mat.

The direction from Object 6 to Object 2 was defined as 0°, and all other angles were subsequently defined counterclockwise. The 45° direction was defined by Object 7 to Object 1. The 0°–180° axis was parallel to the vertical side of the mat, and the 45°–225° axis served as the symmetric axis of the scene.

The testing phase was comprised of 96 trials. In each trial, an image of three of the seven objects from the

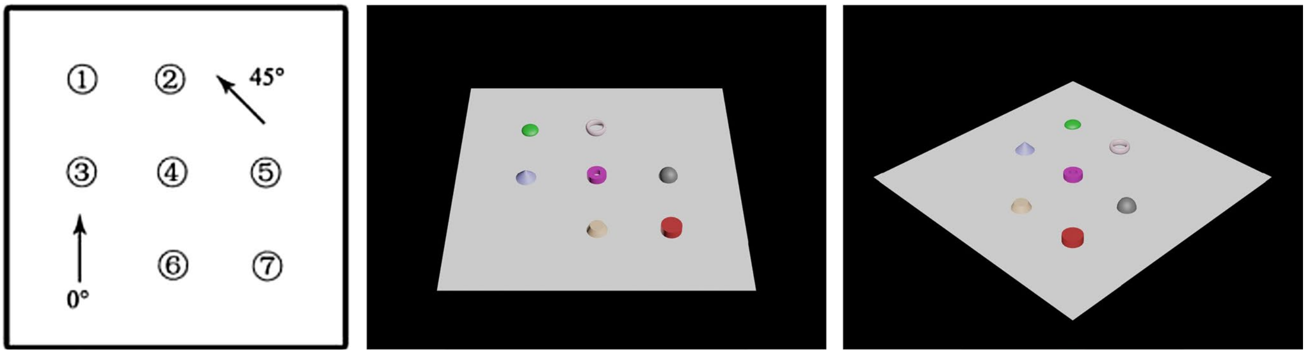
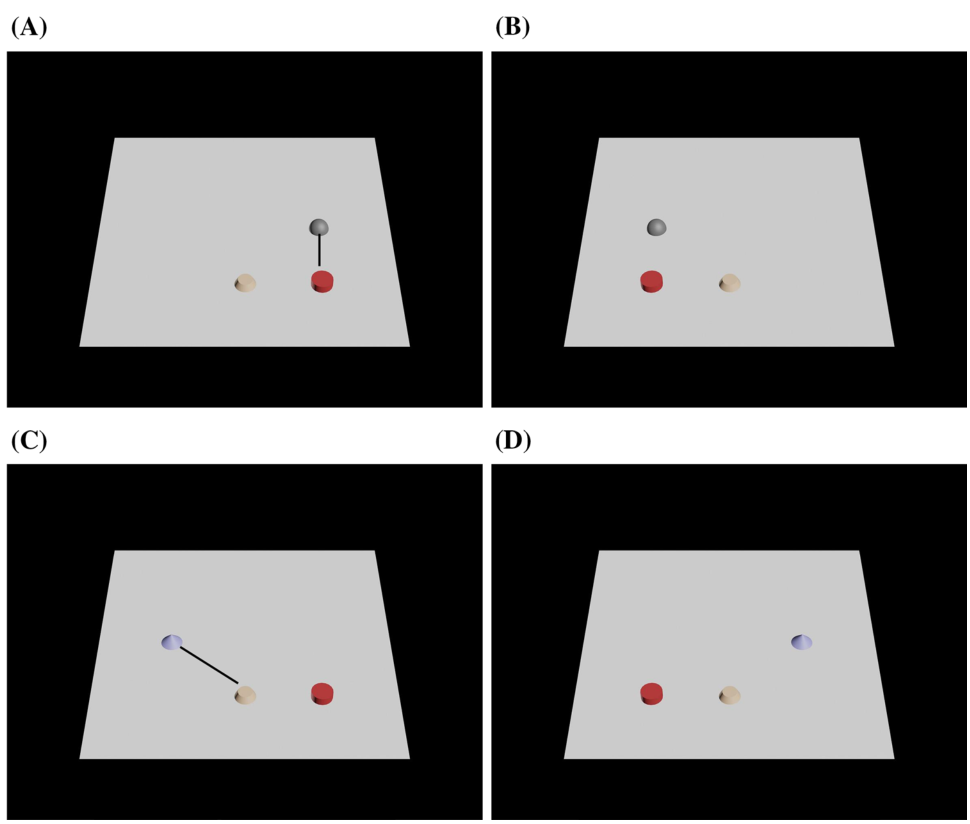


Fig. 1 Materials of learning phase in Experiment 1. The left picture shows the layout of the learning scene. Each participant studied the scene from two perspectives, 0° and 45°, respectively. The learning order was balanced among the participants. The middle and the right pictures are 0° and 45° view of the learning scene

learning phase was presented to the participants. Following the experimental design used by Mou et al. (2008), 12 triplets were selected and divided into two types: those that lay along the 0°–180° axis (type 1) and those along the 45°–225° axis (type 2). Triplets along the 0°–180° axis mean that two of the three objects are in line with the 0° axis. Triplets along the 45°–225° axis mean that two of the three objects coincide with the 45° axis. The triplets of type 1 used in the experiment were 1–2–3, 1–3–5, 2–3–4, 3–5–7, 4–5–6 and 5–6–7, and the type 2 were 1–2–5, 1–4–5, 2–3–5, 3–4–7, 3–5–6 and 3–6–7. The two sets of triplets were non-overlapping, that is to say, triplets along the 0°–180° axis did not contain any two objects along the 45°–225° axis, and vice versa. Figure 2 shows two types of triplets that lay along the 0°–180° and 45°–225°, respectively. Each triplet was presented from eight directions (0°–315° in 45° increments), and 96 images were generated in total. In the test phase, the orientation of the table top varied in the test phase, that is, the test stimuli were generated by capturing images from a virtual camera rotating around the array on the table top (see supplementary materials for more details). Half of these images were randomly assigned as targets, and

Fig. 2 Examples of testing stimuli in Experiment 1. The four pictures show the triplets at 0° viewing perspective. **a** The triplet along 0°–180° axis; **b** the mirror image of picture **a**, i.e., the distractor; **c** the triplet along 45°–225° axis; **d** the mirror image of picture **c**



the others were rotated into mirror images as distractors. The distractors can be understood as placing the targets on the front side of the plane, and the triplets seen from the back of the plane are distractors. So there would be no objects outside the original object scene in all trials. The distractors have been used in previous experiments by the authors and indicated to be effective in the PSR paradigm (Fig. 3).

The virtual learning scene was produced by Autodesk 3Ds Max 2012. In the learning phase, participants studied the scene by wearing the helmet-mounted display (HMD, NVISer SX60, NVIS Company, Reston, VA), which supplied identical pictures to both eyes at a resolution of 1024 by 768 pixels. In the testing phase, the stimuli were presented using E-prime 2.0 software on a Dell desktop computer. The dizziness of the participants after wearing the HMD for a long time will affect the accuracy of completing the tasks (Papadakis et al. 2011). That is why the testing phase used a computer display instead of a virtual reality set.

The experiment used a two-factor mixed design. The between-subjects independent variable was the learning order of the two perspectives (Group A vs. Group B). Participants were divided into two approximately homogenous groups based on their sex and age; each group consisted of 16 participants (8 men, 8 women). Group A learned the scene from 0° first and then from 45°, while Group B learned in reversed order. The within-subjects independent variable was triplet type (along 0°–180° axis vs. along 45°–225° axis). The dependent variables were response time and accuracy.

Procedure

Learning phase

The participants were led into the experimental room with opaque curtains. The experimenter explained the process and the concept of positive image and mirror

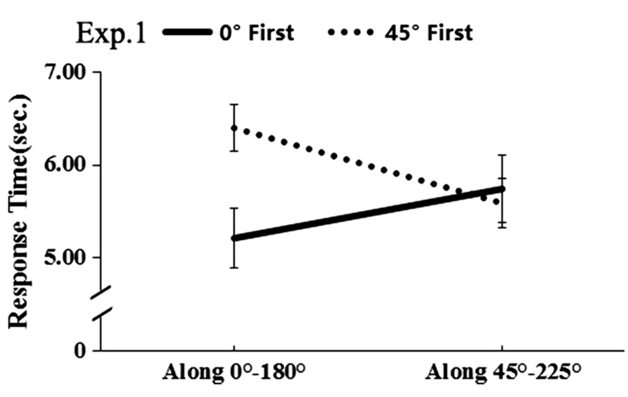


Fig. 3 Response times under different experimental conditions in Experiments 1 (error bars represent ± 1 SE)

image. Then, the participants sat in front of the computer and the experimenter helped them to wear the HMD until they could clearly see the scene layout. The movement of the head would not affect the scene observed in the field of vision, so the participants were free to move their heads.

The participants learned two pictures of the virtual learning scene captured from two perspectives. The angle between the line of participants' viewing point and the center of the scene and the horizontal plane was 45°. The learning time varies greatly among individuals. In order to ensure that all participants are able to remember all objects in the scene, there were no constraints on learning time. Once they reported that they had memorized the first picture, the experimenter would switch to the second picture. After learning, there would be a task to test the learning results of the participants. The participants were presented with a scene with one plane but no objects. There was position information on the plane that was represented by the numeric number. The task of the participants was to recall and dictate the objects in each position. The criterion for learning was to recall the scene three times correctly after removing the helmet.

Test phase

Each participant seated before the testing computer, facing the screen with his or her right hand on the mouse. The distance between the participants and the screen was 1 m, and the participants' visual angle was about 12°. The participants clicked the left button to indicate that relative positional relationship of these three objects is the same as the one in the learned scene (target) and the right button to indicate that it is not (distractor). Participants were asked to click as quickly as possible without sacrificing accuracy. Each stimulus disappeared immediately after the response, and the next one appeared without delay. After the participants understood the test operation, the experimenter turned off the light source to eliminate all spatial cues outside the experimental scene.

All data were analyzed using IBM PASW Statistics Version 18. In the interest of brevity, accuracy data were used to screen the results and only the correct response times to targets were included in tests of the effects of the two independent variables.

Results and discussion

The mean accuracy rate was 88.2% for all trials. The average accuracy of target stimulus is 92%. A 2 (learning order) × 2 (triplet type) mixed ANOVA revealed a significant interaction between the two variables (F(1, 30) = 76.71, p < .01, η_p^2 = 0.72). A simple effect analysis was conducted to interpret the interaction effect. For Group A, participants responded to triplets along 0°–180° axis (M = 5.21 s, SD = 1.28) more quickly than triplets along 45°–225° axis (M = 5.75 s, SD = 1.46), F(1, 30) = 24.28, p < .01. For Group B, the situation was completely opposite. Participants responded to triplets along 45°–225° axis (M = 5.59 s, SD = 1.25) more quickly than triplets along 0°–180° axis (M = 6.40 s, SD = 0.99), F(1, 30) = 55.64, p < .01. There was no significant main effect of learning order (F(1, 30) = 1.48, p > .05) or triplet type (F(1, 30) = 3.02, p > .05) (Table 1).

In Experiment 1, there were two types of geocentric cues which were inconsistent, the symmetric axis (45°–225°) of the scene layout and the vertical side (0°–180°) of the mat. With this incongruence, participants inclined to represent the scene in terms of the initial visual experience. Although participants had learned from both the symmetric axis and the characteristic axis of the external environment, the viewpoint effect still appeared. The results indicated that these two cues played the same role in the process of choosing the intrinsic axis, and they did not effect spatial representation when they were co-occurring and inconsistent.

Table 1 Response time and accuracy rates across learning order (and triplet type)

Learning order	0° First		45° First	
Triplet type	0°–180°	45°–225°	0°–180°	45°–225°
Response time (ms)	5212	5747	6396	5590
Accuracy rate (%)	91.1	92.5	93.4	92.1

Experiment 2

Method

Participants

Thirty-two graduate students (16 males and 16 females) between the ages of 22 and 28 years from Nanjing Normal University participated in the study. All participants did not take part in the Experiment 1 in order to avoid learning effects. All reported that they had normal or corrected-to-normal eyesight without apparent color vision deficiency. The IRB of Nanjing Normal University approved the study, and all participants volunteered to take part in the experiment. Each participant received 15 CNY (about 2.5 USD) as compensation.

Materials, design and procedure Materials, design and procedure were identical to Experiment 1 with one exception. In Experiment 2, the learning materials were seven avatars that were all dressed differently and had different hairstyles. The orientation of avatars was 180° and parallel to the vertical side of the mat. The layout of learning scene is shown in Fig. 4.

Results and discussion

The mean accuracy rate was 88.4% for all trials. The average accuracy of target stimulus is 91%. A 2 (learning order) × 2 (triplet type) mixed ANOVA revealed a significant main effect of triplet type (F(1, 30) = 19.75, p < .01, η_p^2 = 0.40), indicating that participants responded to triplets along 0°–180° axis (M = 5.10 s, SD = 1.94) more quickly than triplets along 45°–225° axis (M = 5.83 s, SD = 2.62). The main effect of learning order (F(1, 30) = 1.65, p > .05)

Fig. 4 Materials of learning phase in Experiment 2. The middle and the right pictures are 0° and 45° view of the learning scene. Each participant studied the scene from two perspectives, 0° and 45°, respectively, and the learning order was balanced among participants

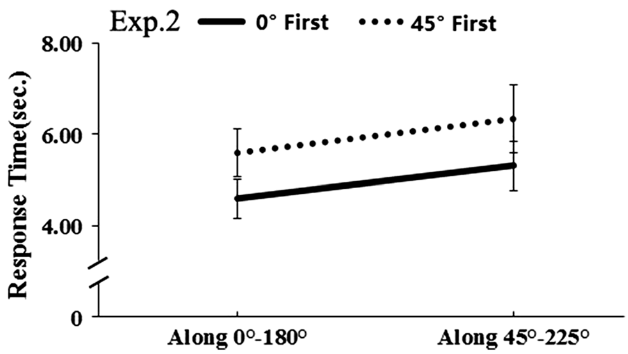


Fig. 5 Response times under different experimental conditions in Experiments 2 (error bars represent ± 1 SE)

Table 2 Response time and accuracy rates across learning order (and triplet type)

Learning order	0° First		45° First	
Triplet type	0°–180°	45°–225°	0°–180°	45°–225°
Response time (ms)	4596	5314	5594	6347
Accuracy rate (%)	95.3	93.5	85.5	88.5

and the interaction between learning order and triplet type ($F(1, 30) = 0.01$, $p > .05$) were not significant (Fig. 5).

The difference between Experiment 1 and 2 was that the materials were composed of avatars with orientations in Experiment 2. Furthermore, this orientation (0°–180°) which was parallel to the vertical side of the mat was identical with the external environmental cues. In this case, participants consistently chose 0°–180° axis to construct the IFOR. The results indicated that people used direction that contained more clues for spatial representation and the initial learning perspective had no significant impact (Table 2).

General discussion

The purpose of this study was to explore how the participants represent spatial scenes under multiple environmental cues. The results of two experiments indicated different strategies in the choice of intrinsic axis under two-cue and three-cue conditions. In Experiment 1, the symmetric axis of the objects' layout was inconsistent with the environmental geometric cues. The initial viewing perspective was selected as IFoRs. In Experiment 2, the "Object Orientation" cue was added and consistent with the environmental cues. Consequently, the strategy of the participants changed to select the direction containing more clues as the intrinsic axis.

The Experiment 1 aimed at exploring how the subjective visual experience, the structure of the objects' layout and the environmental cues affect the spatial memory simultaneously. There was a significant interaction between the learning order and triplet type. When participants learned from the 0° perspective first, they chose the 0°–180° axis as their intrinsic axis. Conversely, when they learned from the 45° perspective first, the 45°–225° axis was IFoRs. The results indicated that the initial egocentric experience affected the choice of intrinsic axis. This is consistent with the results of Kelly and McNamara (2008), that is, when there were two incongruent geometric cues in the scene, participants constructed their IFoRs according to the axis that is aligned with their first experienced view. Furthermore, according to Shelton and McNamara's (2001) definition, the symmetric axis and the side of the mat both qualify as local geometric cues, so there should be no significant relative saliency difference between them. The possibility of choosing the axis of symmetry or the side of the mat as intrinsic could be considered equal.

In Experiment 1, two groups of participants observed the same scene in accordance with different orders. Group A learned the scene from 0° first and then from 45°, while Group B learned in reversed order. According to previous studies (Liu et al. 2012, 2014), people first established an intrinsic frame of reference to encode the spatial scene. Participants obtained the scene information in first experienced view and identified all the objects before memorizing the distribution. However, when they transferred to the second perspective, the scene was only rotated by 45°. The new scene cues may be noticed by participants, but it was not strong enough to motivate people to modify the spatial representation they had already formed. Therefore, most people only reconfirmed the layout and the extent of processing cognitive resources was completely different from that of the first perspective. Consequently in Experiment 1, it took participants more time to finish learning task in the initial view. As a result, the learning order had a significant impact on choosing the intrinsic axis. When the two equal and contradictory geometric cues interacted with the egocentric experience, the initial perspective experience had a significant effect.

However, a completely different result was found in Experiment 2. The 0°–180° axis was chosen as the intrinsic axis very consistently. Participants also had different first impressions on the scene due to different initial experienced view in learning phase. Group A (learned from 0° first and then 45°) initially obtained the richest cues of the whole scene, including not only the characteristic axes of the external environment but also the orientation information of the materials. Therefore, participants would take initiative to represent the scene and simply consolidated the previously formed scene after shifting to a new perspective. In the view of 45°, most of them immediately reported that learning tasks had completed, indicating that their previous spatial memories were already well established. While Group B (learned from 45° first and then 0°) saw the profile image of the seven avatars, but compared to the symmetric axis of the layout, participants would be more likely to imagine that they observe the scene from the front. After converting the learning perspective, they updated initial impression formed before. According to the results of data analysis, they consistently chose the 0°–180° axis as intrinsic axis. Experiment 1 had proved that the external environment and the symmetric axis played the same role in spatial representation. Thus, after the orientation clue was added, there was a strong spatial cue in the direction of 0°, as a result that participants ignored the initial egocentric experience and chose this perspective to construct IFoRs. To sum up, the consistent information of the avatars' coincident orientation and the side of the mat resulted in the participants' representing the scene according to the 0°–180° axis. In this situation, the symmetric axis was neglected entirely in the course of IFoR construction.

The avatars' coincident orientation as a new factor added in Experiment 2 was more obvious than any other oriented objects. Chen and McNamara (2011) studied the object-centered reference systems in spatial memory. They discovered that merely replacing the oriented human avatars with the animal models resulted in nonsignificant results. It can be seen that avatars' orientation has a stronger role in spatial memory. Besides, the information conveyed by a person's front and back was different. On the one hand, the most important part of a person is the face which can provide information on emotions, expressions, appearance and so on. On the other hand, there will be more details on the front of the dress, such as patterns and buttons. Furthermore, the orientation is consistent with the direction that people communicate with each other in daily life. When people only have information on the back of others, people will try to get more information about others face to face. Therefore, instead of using geometric objects but using avatars, all the avatars were oriented in the coincident direction, and the orientation angle was set to 180°, which was an easy perspective to observe the front of the objects. The orientation clue became the prominent factor to affect the construction of IFoRs. In addition to the saliency of the orientation, the previous studies have shown that object orientation factor has limitations and uncertainties, and the different properties of the orientation will have different effects. For example, the angle and salience of the objects' orientation affected the role of the object orientation in the spatial representation (e.g., Li and Su 2015; Li et al. 2017). Because of the special properties of the avatars' orientation, further experiment could dissociate the effect of the intrinsic axis of the avatars from other environmental axes to make the conclusions more convincing. For instance, the direction of the avatars is independently aligned and/or aligned with each one of the two environmental axes in separate experimental conditions.

In conclusion, people tend to choose the intrinsic axis according to their original egocentric experience when there are two conflicting geometric cues of different categories, but if there are three geometric cues, the direction that is consistent with multiple cues is more likely to be taken as the intrinsic axis.

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Compliance with ethical standards

Conflicts of interest All the authors declare that they have no conflict of interest.

Ethical approval The study was supported by the IRB of Nanjing Normal University. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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