VISUAL COGNITION, 2007, 15 (4), 402–419

Psychology Press
Taylor & Francis Group

Spatial updating during locomotion does not eliminate viewpoint-dependent visual object processing

Mintao Zhao

State Key Laboratory of Brain and Cognitive Science, Institute of Psychology, Chinese Academy of Sciences, Beijing, China

Guomei Zhou

State Key Laboratory of Brain and Cognitive Science, Institute of Psychology, Chinese Academy of Sciences, Beijing, and Department of Psychology, Chinese University of Hong Kong, China

Weimin Mou

State Key Laboratory of Brain and Cognitive Science, Institute of Psychology, Chinese Academy of Sciences, Beijing, China

William G. Hayward

Department of Psychology, University of Hong Kong, China

Charles B. Owen

Department of Computer Science and Engineering, Michigan State University, East Lansing, MI, USA

Two experiments were conducted to investigate whether locomotion to a novel test view would eliminate viewpoint costs in visual object processing. Participants performed a sequential matching task for object identity or object handedness,

---

Please address all correspondence to Weimin Mou, State Key Laboratory of Brain and Cognitive Science, Institute of Psychology, Chinese Academy of Sciences, Beijing, China. E-mail: mouw@psych.ac.cn or William G. Hayward – E-mail: whayward@hku.hk

This work was supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region (CUHK 4260/03H) to WGH and the "One-Hundred-Talent Plan" Fellowship of Chinese Academy of Sciences (CAS) and a grant from the National Natural Science Foundation of China (30470576) to WM. We are grateful to Dr David E. Irwin, Dr Michael Motes, and one anonymous reviewer for their helpful comments on a previous version of this manuscript. We are also grateful to the Virtual Reality Laboratory of Institute of Psychology, CAS for using its facility and space in collecting data.

http://www.psypress.com/viscog DOI: 10.1080/13506280600783658

using novel 3-D objects displayed in a head-mounted display. To change the test view of the object, the orientation of the object in 3-D space and the test position of the observer were manipulated independently. Participants were more accurate when the test view was the same as the learned view than when the views were different no matter whether the view change of the object was 50° or 90°. With 50° rotations, participants were more accurate at novel test views caused by participants' locomotion (object stationary) than caused by object rotation (observer stationary) but this difference disappeared when the view change was 90°. These results indicate that facilitation of spatial updating during locomotion occurs within a limited range of viewpoints, but that such facilitation does not eliminate viewpoint costs in visual object processing.

Observers often have more difficulty in recognizing a scene or object from a novel view than from a familiar view. This finding of viewpoint dependency has been observed by many studies of visual scene or object recognition (e.g., Diwadkar & McNamara, 1997; Hayward & Tarr, 1997; Hayward & Williams, 2000; Tarr, 1995; Tarr, Williams, Hayward, & Gauthier, 1998) and spatial knowledge processing (Mou, McNamara, Valiquette, & Rump, 2004; Reiser, 1989; Shelton & McNamara, 2001). However, Simons and Wang (1998, see also Simons, Wang, & Roddenberry, 2002; Wang & Simons, 1999) have criticized this type of research as being conducted in unnatural circumstances, i.e., presenting pictures or drawings of rotated objects to a stationary participant. They argued that the viewpoint problem in object recognition may be largely a function of the experimental apparatus.

Simons and Wang (1998) noted that spatial reasoning at a novel viewpoint was facilitated if participants locomoted to the viewpoint, which indicates a locomotion-induced updating of a spatial representation, (e.g., Farrell & Robertson, 1998; Mou, McNamara, et al., 2004; Reiser, 1989; Waller, Montello, Richardson, & Hegarty, 2002), and argued that facilitation of the locomotion should also be manifested in visual scene/object recognition. In particular, analogous to the results of Reiser (1989), viewpoint change costs might be eliminated if different views resulted from a participant's own locomotion. In a series of experiments, they used a natural scene change detection task, and found the predicted facilitation of recognition performance when novel views were caused by observer locomotion compared to novel views being caused by object rotation (Simons & Wang, 1998; Wang & Simons, 1999). Specifically, the cost of view changes was significant when the view change was caused by rotations of the display (observer stationary), whereas the cost of view change was little when the view change was caused by observer movement (display stationary). Simons and Wang (1998, p. 320) argued that, provided sufficient information is available, people can flexibly adjust or update their representations to achieve viewpoint-independent recognition.

However, other evidence indicates that performance costs associated with a change in viewpoint are not necessarily eliminated by locomotion induced spatial updating. For example, Burgess, Spiers, and Paleologou (2004) reported a viewpoint dependency effect as well as a spatial updating effect in scene change detection. Similar to Simons and Wang (1998), Burgess and his colleague had participants detect changes when the participant and the table (along with an additional phosphorescent landmark external to the array) were independently moved or were stationary. In contrast to Simons and Wang, they considered consistency between the test view and the learned view (visual snapshot) and consistency between the test view and the egocentric spatial representation of the array that was updated during the locomotion as separate variables (p. 151). They found that performance was facilitated by a match of test view and the updated egocentric spatial representation (spatial updating), but also by a match of study and test views (view-specific learning). In other words, although locomotion facilitated novel views, it did not eliminate the advantage of the experienced view over the novel view.

Mou, McNamara, et al. (2004; see also Mou, Biocca, et al., 2004) have also demonstrated the effects of both the spatial updating and view-specific learning on spatial reasoning. Participants, after learning a layout from a single viewpoint, performed better in judgements of relative direction (e.g., "imagine you are standing at X, facing Y, please point to Z") if (1) the imagined heading was the same as the actual heading, and (2) the imagined heading was same as the learned heading. The learned heading, imagined heading, and actual heading, respectively, in the spatial reasoning paradigm of Mou, McNamara, et al. are analogous to the learned view (snapshot), test view, and the view anticipated by the egocentric spatial representation that is updated during locomotion in the scene change detection paradigm of Burgess et al. (2004). Hence the actual heading effect is analogous to spatial updating and the learning viewing effect is analogous to view-specific learning.

Simons and Wang's (1998) finding that the viewpoint dependency of accuracy in scene change detection shown when participants were stationary, vanished when participants moved, can be interpreted in terms of the coexistence of the spatial updating effect and the viewpoint dependency effect. When participants stayed still, the familiar test view is supported by both spatial updating and view-specific learning, whereas a novel test view is not supported by either mechanism. Therefore, when participants stayed still, performance was better at the familiar (learned) view than at the novel view. In contrast, when participants moved, the familiar test view was supported by view-specific learning but not by the spatial updating, and the novel test view was supported by the spatial updating but not view-specific learning. Hence, a lack of effect of viewpoint change when participants moved could be the result of mutual costs rather than the viewpoint invariance of the spatial representation. The correct way to test viewpoint dependency of spatial representations is to compare the two views when both of them support spatial updating; in other words, to compare the performance at the experienced view when participants are stationary, with that at the novel view when participants moved. In fact, Burgess et al. (2004), Mou, Biocca, et al. (2004), and Mou, McNamara, et al. (2004) all reported that the performance for the experienced test view when participants were stationary was better than that for the novel test view when participants moved, suggesting that spatial representations are viewpoint dependent and that spatial updating during locomotion does not eliminate viewpoint dependency in scene recognition and judgements of relative directions.

The facilitation of locomotion to the different view has also been observed in object recognition. Simons et al. (2002) had participants view an object for 3 s and then make a same/different judgement to the target object from a different view caused by either object rotation or observer locomotion. Performance was better in the observer locomotion (object stationary) condition than in the object rotated (observer stationary) condition when responses to both distractor and target objects were analysed. However, this effect was mainly apparent in judgements of distractors; differences between conditions for target objects were very small. It is difficult to understand why the facilitation comes more from judgements of the distractor objects than target objects, because participants should not be able to update a representation of an object that they did not experience. Furthermore, the difference in viewpoint was not manipulated factorially with locomotion, which means that we do not know whether locomotion merely reduced or completely eliminated the effect of viewpoint change.

The questions of primary interest in the present study are (1) whether the facilitation from spatial updating observed in previous scene processing studies also occurs in processing individual objects and, more importantly, (2) whether such facilitation eliminates all performance costs due to a change in viewpoint. We tested the effects of spatial updating and viewpoint dependency on object recognition performance by orthogonally manipulating object rotation (object stationary or object rotated) and test view (same as or different from the learned view). In the object stationary condition, the tested view was anticipated by the spatial representation that was hypothesized to be updated by participants' locomotion, whereas in the object rotated condition, the tested view was not anticipated by the spatial representation that was hypothesized to be updated during locomotion. Hence the difference in performance between stationary and rotated objects reveals the effect of spatial updating during locomotion. Specifically, the difference at the novel test views between the stationary and rotated objects shows any facilitation of spatial updating during locomotion to the novel test view, whereas the difference for the experienced test view shows any interference from spatial updating to the experienced test view. In addition, differences between learned and test views show a basic viewpoint dependency effect. Of interest was whether we would find both a facilitation from locomotion for novel views and a viewpoint dependency effect; such a result would indicate that spatial updating, if found, does not eliminate viewpoint costs in object recognition.

The second goal of our present study was to test whether the facilitation of spatial updating during locomotion, if found, was affected by the angular distance of the locomotion. Almost all of the previous studies which demonstrated facilitation of spatial updating during locomotion on visual scene or object processing have used a relatively small angular displacement, that is, 50° or so (e.g., Burgess et al., 2004; Simons & Wang, 1998; Simons et al., 2002; Wang & Simons, 1999). It is unclear whether such facilitation would also occur for visual object processing when angular displacement was increased. We varied the angular displacement from 50° in Experiment 1 to 90° in Experiment 2.

EXPERIMENT 1

In Experiment 1 we used a virtual reality system to examine the spatial updating effect and the viewpoint dependency effect on judgements of object identity and handedness. Participants observed an object from one view, and after a short interval, during which participants moved or did not move to a new viewing position and objects were stationary or rotated, were shown the test object. There were two main independent variables: (1) Whether or not the test object was presented from the same view as that previously learned, and (2) whether or not the test object was rotated. The corresponding relations between participants' locomotion and the main independent variables are illustrated in Table 1. Both object rotation and observer locomotion resulted in a view displacement of 50°, as an approximate

TABLE 1
The corresponding relations between participants' locomotion and the main independent variables: Test view (same or different) and object rotation (stationary or rotated)

	Same view	*Different view*
Object stationary	Observer stationary	Observer locomoted
Object rotated	Observer locomoted	Observer stationary

replication of previous studies (e.g., Simons & Wang, 1998; Simons et al., 2002). If locomotion-induced spatial updating facilitates object recognition at a novel view, we would expect participants to perform better at the novel view when the test object was stationary than when the test object was rotated. If there was an effect of viewpoint change, we would expect participants to perform better when the test view was the same as the learned view than when the test and learned views were different.

In order to ensure generalizability of the results, two different tasks of visual object processing were used, one requiring *identification* of an object, and the other requiring a judgement of object *handedness* (that is, whether an object is mirror-reflected). When objects are rotated by up to 90° in 3-D space between presentations, both judgements show viewpoint change costs in performance that are generally a linear function of the size of the viewpoint change (Hayward, Zhou, Gauthier, & Harris, in press; Shepard & Metlzer, 1971; Tarr, 1995).

Method

Participants. Thirty-two university students (16 males and 16 females, with normal or corrected-to-normal visual acuity) were recruited in Beijing in return for monetary payment.

Apparatus. The experiment was conducted using a fiducial-based video see-through virtual reality system (Owen, Tang, & Xiao 2003). The system consists of a light (about 5.5 oz) glasses-like i-visor DH-4400VPD head-mounted display (HMD, Personal Display Systems, Inc., California) with a small video camera attached, and a group of four fiducials printed on a paper on the top of a round table (50 cm in diameter, 70 cm high). The HMD supplied identical images to both eyes at a resolution of 800×600 pixels and a field of view (FOV) of 31° diagonally for each eye. The virtual objects were rendered with an ATI Radeon X300 graphics accelerator, updating the graphics and display at 60 Hz. The virtual objects were presented on the origin of the coordinates (superimposed at the centre of the table), which was defined by the groups of fiducials and could be recognized by the video camera mounted on the HMD. Whenever the participants looked at the direction of the centre of table, the virtual objects (or the red arrow when the object was covered) would be seen at the centre of the FOV through the HMD.

Two chairs were placed to serve as the location of learning and testing such that (1) the distance between the chair and the centre of the table was 1 m, and (2) the lines connecting the centre of the table and the midline of the two chairs constituted a 50° angle (see Figure 1). The apparatus was placed in a $6\text{ m} \times 6\text{ m}$ laboratory with each wall covered by homogeneous black curtains.

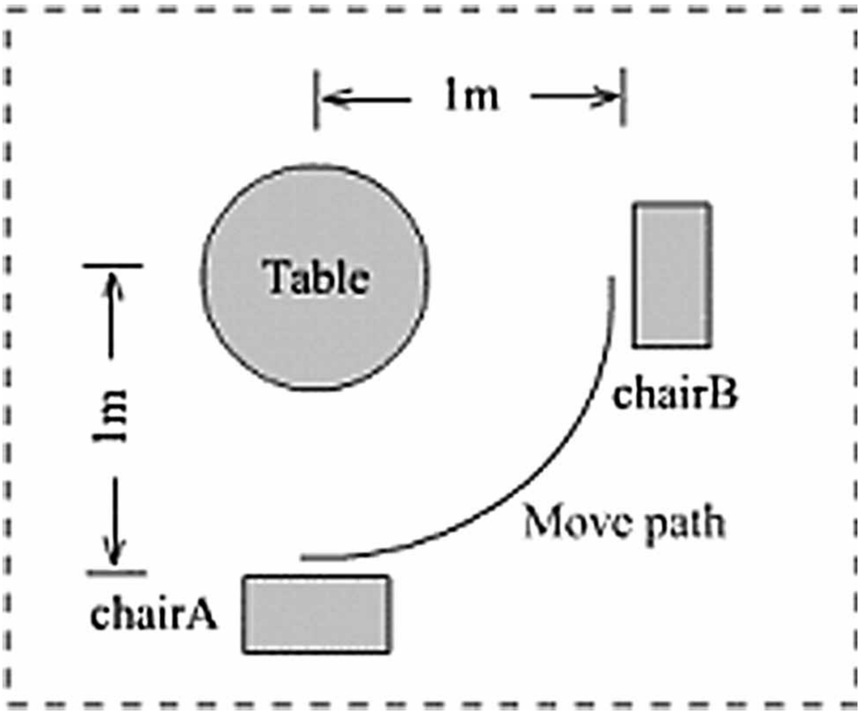

Figure 1. Experimental setup in Experiments 1 and 2.

Materials and design. Eight novel three-dimensional virtual objects were created using the commercially available 3-D MAX software (Autodesk, Inc., California) based on the objects used by Gauthier et al. (2002) and Tarr (1995). All of the objects were asymmetrical across the sagittal, frontal, and horizontal planes, and shared a long vertical component (21 cm), which had a short "foot" block (9 cm) at the bottom; in the learned view they were rotated slightly (20°) in the z-axis. The reflected version of each of the eight objects (enantiomorphs) was generated by reflecting the object at upright through the sagittal plane (reversing left and right, but not front and back). The same components were visible across both object rotation and locomotion conditions, so that the object had the same parts visible across viewpoint changes as proposed by Biederman and Gerhardstein (1993). Examples are shown in Figure 2.

The eight novel objects were randomly divided into two sets of four objects. For each participant, one of the sets was used in the *locomotion* condition while the other was used in the *no locomotion* condition. For handedness judgements, a distractor was a reflected version of the learned

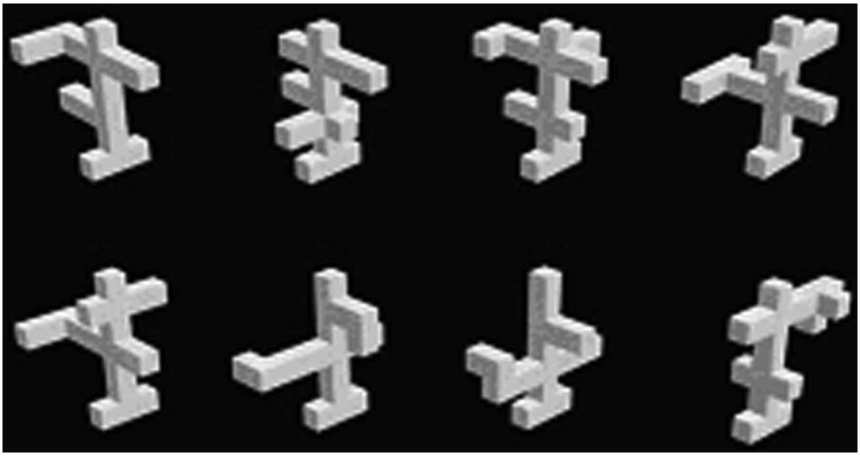

Figure 2. 3-D models used in Experiments 1 and 2.

object itself; for identification judgements, the distractor was a reflection of another object in the same object sets. This manipulation made the learned objects and the test objects in different tasks identical.

We used a 2 (task: Handedness vs. identification judgement) $\times$ 2 (participants' locomotion: Judgement at original location vs. at new location) $\times$ 2 (object rotation: Rotated vs. stationary) mixed design. Note that the main independent variables, test view and object rotation, need to be derived from the above design (see Table 1). Task was manipulated between participants while the rotation of the object and the locomotion of participants were manipulated within participants. The sets of objects, the order of locomotion (locomotion or no locomotion first), and participant gender were counterbalanced across participants in each task. Locomotion was blocked and the sequence of test trials in each block for each participant in each task was randomized.

As a consequence, each task had a total of 32 standard trials (half were target trials and half distractor trials) which were divided into two blocks, one for locomotion and the other for no locomotion. In each locomotion condition, there were 16 trials, produced by 4 viewed models $\times$ 2 types of probed models (distractor or target) $\times$ 2 test views.

Procedure. A sequential matching paradigm was used for both handedness and identity judgement tasks. Participants were run individually and were randomly assigned to one of the tasks.

Each trial consisted of three stages: Learning, locomotion, and testing, as shown in Figure 3. In the learning phase, the participant first stood in front

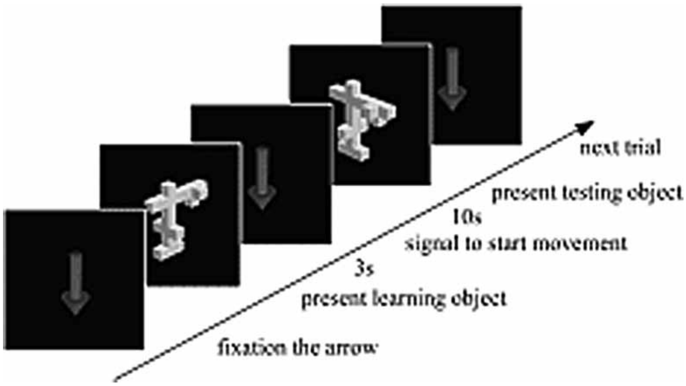

Figure 3. Sequence of presenting stimuli in a trial.

of chair A and looked through the HMD at the centre of the table. A red vertical arrow pointing to the centre of the table was presented to indicate the location of the forthcoming object, and the participant was instructed to pay attention to the location of the red arrow vocally via the earphone of the HMD. Immediately after instruction, the learning object was presented against a black colour background for 3 s. Upon disappearance of the object, another red arrow was displayed and the participant was instructed via the earphone to either "go to another chair" or "go half and back" (according to the predetermined block order). Participants then had 10 s from the end of learning to complete the locomotion. When the 10 s locomotion duration was over, a test object (either the original object or a distractor) was presented by replacing the red arrow, and was shown either from the same view as the initial display or from a different view. For the handedness judgement task, participants were asked to determine whether the test object was same as or a reflection of the learned object, regardless of the rotation in depth. For the identity judgement task, participants determined whether the test object was the same as or different from the learned object regardless of the rotation in depth. Participants pressed the left button (for target) or the right button (for distractor) of a mouse to make a response. They were instructed to respond as accurately as they could without sacrificing response speed.

Before the experimental trials, participants were trained to be familiar with the locomotion procedure, and were then given eight practice trials (four with locomotion and four without locomotion, with objects not used in the rest of the experiment) to be familiar with the tasks in the virtual reality system. All participants were informed before each experimental block whether they needed move to another chair or only go halfway and then back to the original chair to make judgements.

Results

The mean latencies of correct responses for target trials, as well as the accuracy for target trials, were computed for each participant under each condition and were then submitted to three-way ANOVAs, with task (handedness vs. identity judgement) as a between-participants factor, and test view (same as learned vs. different from learned) and object rotation (object stationary vs. object rotated) as repeated-measures factors. Averaged accuracy and latency across participants under each condition are illustrated in Figure 4.

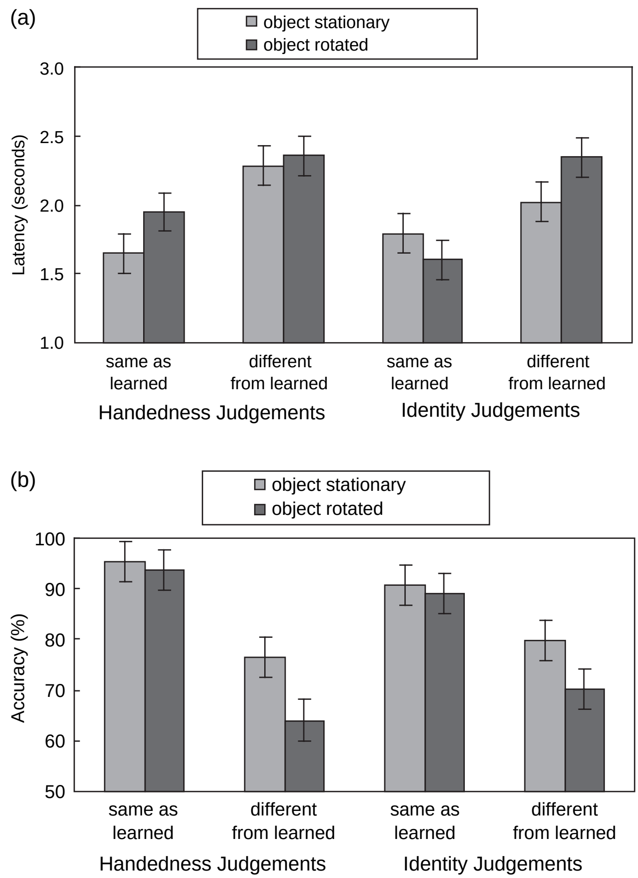

Figure 4. Response latency (a) and accuracy (b) as a function of task, test view, and object rotation in Experiment 1. (Error bars are confidence intervals corresponding to ± 1 standard error as estimated from analysis of variance.)

The three-way ANOVAs revealed a significant main effect of test view in terms of response latency, $F(1, 30) = 38.61$, $p < .001$, $MSE = 0.21$, and accuracy, $F(1, 30) = 32.84$, $p < .001$, $MSE = 0.037$, and a significant main effect of object rotation in terms of accuracy, $F(1, 30) = 5.86$, $p < .05$, $MSE = 0.016$. Interpretation of the main effects is modified by the significant interaction between test view and object rotation in terms of accuracy, $F(1, 30) = 4.19$, $p < .05$. No other effects or interactions reach statistical significance.

When the test view was the same as the learned view, whether the object was stationary or rotated had no effect on judgements, ts < 1, in latency and accuracy. However, when the test view was different from the learned view, participants' judgements were more accurate when the object was stationary than when the object was rotated, $t = 2.61$, $p < .05$ in accuracy, with the same pattern in latencies though not significant. Participants' performance when test and learned views were the same was always better than their performance when test and learned views differed, regardless of whether the object was stationary or rotated, ts > 2.71, ps < .05 in latency and ts > 3.24, ps < .01 in accuracy.

Discussion

When the test view was different from the learned view, performance was more accurate when the object was stationary than when the object was rotated, showing facilitation of spatial updating during locomotion to the novel view. This result is consistent with previous findings that participants were significantly more accurate in object and scene recognition when the novel view was caused by their own locomotion than when it was caused by the object rotating. However, there was no such effect of spatial updating when learned and test views were identical, suggesting that the observers may be able to ignore spatial updating information when the test view was the one they experienced at learning in visual object processing. This finding is inconsistent with the claim that spatial updating during locomotion cannot be ignored (e.g., Farrell & Robertson, 1998). Because of the various methodological differences between this study and Farrell and Robertson's, including the task (visual recognition in this study and judgements of relative direction in Farrell and Robertson's) the environment (a virtual reality in this study and a real environment in Farrell and Robertson's), and the remembered target (an object in the study and an array of objects in Farrell and Robertson's), the reason for this difference in findings needs more systematic investigation.

In addition, Experiment 1 also showed a robust effect of test view change even when the test view was supported by the spatial updating effect in the object stationary condition. Although locomotion facilitated the novel view, with better performance when the test object was stationary than when the test object was rotated, performance was still better at the experienced test view when participants were stationary than at the novel test view when participants moved to a different viewpoint. This result indicates that the viewpoint dependency effect in object recognition is reduced, but not eliminated, by spatial updating during active locomotion.

EXPERIMENT 2

In Experiment 1, we found facilitation of locomotion when making handedness and identity judgements at a novel view. Most previous studies have used rotations of about the same size as that used in Experiment 1 (e.g., Burgess et al., 2004; Simons & Wang, 1998; Simons et al., 2002; Wang & Simons, 1999). In order to know whether spatial updating provides a general benefit across all viewpoints or whether such benefits only occur across a restricted range of viewpoints, in Experiment 2 we replicated Experiment 1 almost exactly, except that both the rotation of the object and the locomotion of the participant around the object were increased to 90°. If the facilitation observed in Experiment 1 is a general benefit, we should see a similar effect in Experiment 2. On the other hand, if the previous finding occurs only within a limited range of viewpoints we might fail to replicate the locomotion advantage for the novel view.

Method

Participants. Sixty-three university students from Beijing (32 males and 31 females, with normal or corrected-to-normal visual acuity) were recruited in return for monetary payment. None of them had participated in Experiment 1.

Apparatus and materials. The same apparatus and materials as in Experiment 1 were used in the current experiment with the following two exceptions: (1) The two chairs that served as the learning and testing locations were separated by 90° as measured from the centre of the table, and (2) the learning view of the object was 45° rotated along the z-axis counterclockwise from the standard version for the same reason described in the method section of Experiment 1.

Design and procedure. The design and procedure were identical to Experiment 1, except that the two views were separated by 90°.

Results

As in Experiment 1, three-way ANOVAs were conducted on (correct response) latencies and accuracy for target trials. Task was a between-participants factor, and test view and object rotation were within-participant factors. Averaged accuracy and latency across participants under each condition are illustrated in Figure 5.

The three-way ANOVAs revealed a significant main effect of test view in terms of response latency, $F(1, 61) = 71.02$, $p < .001$, $MSE = 0.49$, and accuracy, $F(1, 61) = 79.90$, $p < .001$, $MSE = 0.035$. The main effect of object rotation was not significant in terms of either latency or accuracy, $Fs < 1$. There was no significant interaction between test view and object rotation.

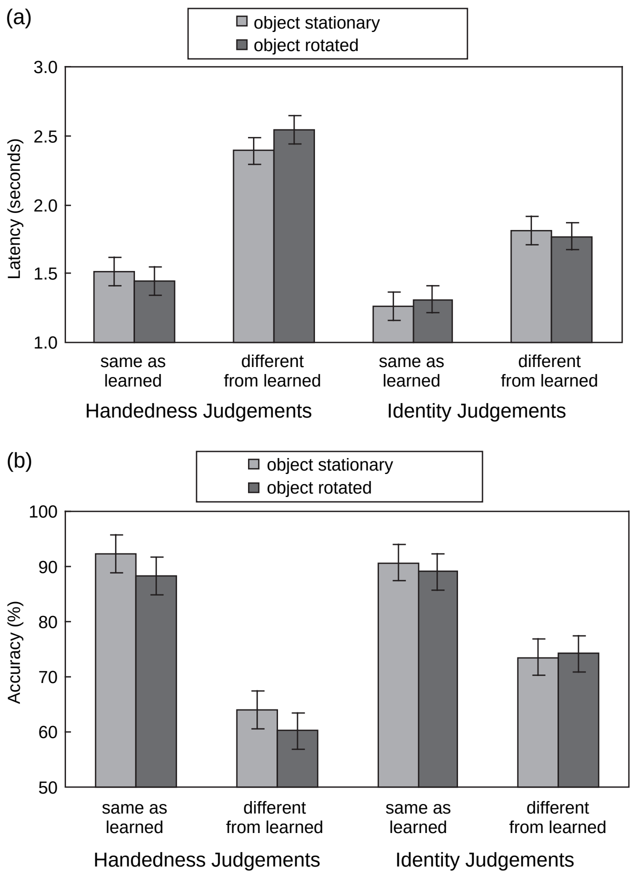

Figure 5. Response latency (a) and accuracy (b) as a function of task, test view, and object rotation in Experiment 2.

The main effect of task was reliable in terms of response latency, $F(1, 61) = 10.10$, $p < .01$, $MSE = 1.24$, showing reliably better performance for identity judgements than for handedness judgements. The test view by task interaction was also reliable in terms of response latency, $F(1, 61) = 7.22$, $p < .01$, and accuracy, $F(1, 61) = 4.66$, $p < .05$. Specifically, the difference between tasks came mainly when there was a difference between test and learned views. Performance between the tasks did not differ when test and learned views were identical, $t\text{s} < 1.75$, $p\text{s} > .05$ for both latency and accuracy, whereas when test and learned views differed, performance was better in the identity judgement than in the handedness judgement, $t\text{s} > 2.20$, $p\text{s} < .05$ for both latency and accuracy. Therefore, viewpoint change costs were larger for the handedness task than for the identity task. No other effects or interactions were reliable.

Discussion

Unlike Experiment 1, in Experiment 2 we did not find a benefit of active locomotion to the novel view. Neither the main effect of object rotation nor its interaction with any other variables reached statistical significance. In other words, the facilitation of locomotion to the novel view found in Experiment 1 disappeared in the current experiment. On the other hand, Experiment 2 revealed a strong cost of viewpoint change between learned and test views in both object processing tasks. Consistent with Experiment 1, this viewpoint-dependent performance was not affected by the participants' active locomotion.

Our results also showed larger viewpoint costs for handedness judgements than for identity judgements, which is generally consistent with previous results (Gauthier et al., 2002; Hayward et al., in press). When taken in conjunction with the results of Experiment 1, as well as from the earlier studies, these results suggest that handedness judgements, requiring a more specific discrimination of a particular object, become differentially harder than identity judgements at 90° rotations (Experiment 2) but not at smaller (Experiment 1) rotations. However, as in Experiment 1, the qualitative results concerning benefits of observer locomotion were not affected by the type of task.

GENERAL DISCUSSION

The results of the present study indicated that visual object processing at a novel view was facilitated if the novel view was caused by participants' locomotion, but that such facilitation was confined to a small change in viewpoint. In Experiment 1, when the angular disparity between views was 50°, the facilitation of locomotion to novel views was observed (as revealed with better performance at the novel view when the object was stationary than when the object was rotated); this result is consistent with studies of scene change detection (e.g., Simons & Wang, 1998; Wang & Simons, 1999; see also Burgess et al., 2004) and novel object recognition (Simons et al., 2002). Recognition performance when a novel test view was caused by participants' own locomotion was about 11% higher in response accuracy compared to novel views that were caused by object rotation. When the viewpoint disparity increased to 90°, however, the facilitation from locomotion was eliminated. Participants' recognition performances for novel test views caused by object rotation and observer locomotion were essentially identical (Figure 5). Therefore, the present study suggests that, for visual object processing, the facilitation on the novel view from locomotion is affected by the size of the viewpoint disparity.

Our results also indicated that facilitation from locomotion, when found, did not eliminate the viewpoint-dependent effect found in visual object processing (Hayward & Tarr, 1997; Hayward & Williams, 2000; Tarr, 1995; Tarr et al., 1998) and scene processing (Burgess et al., 2004; Mou, McNamara, et al., 2004). In both experiments of the present study, participants' performance is reliably better for learned views when participants stayed still than for novel views when participants moved to the novel viewpoint. These findings are consistent with the findings of Burgess et al. (2004) and Mou, McNamara, et al. (2004) in scene processing. For example, Mou, McNamara, et al. (2004) showed that both the actual heading (equivalent to view anticipated by the updated spatial representation in the object stationary condition) and the learned view affected participants' performance on spatial reasoning simultaneously, and that spatial updating did not eliminate orientation (viewpoint) dependency.

Simons and Wang (1998, see also Simons et al., 2002; Wang & Simons, 1999) have proposed an egocentric updating process model to account for locomotion-based facilitation in scene change detection and object recognition. In their model, viewer-centred representations were formed after a brief single view, and were then continuously updated during participants' movements. When participants moved to a new position, the representation was modified by the updating process to correspond to their current perspective.

Mou, McNamara, et al. (2004) proposed in their allocentric updating model that the spatial representation of objects' locations, as well as the representation of location and orientation of the observer, is organized with respect to an allocentric frame of reference (e.g., intrinsic frames of reference inside the layout) rather than with respect to the observer. During locomotion the observer only updates his/her location and orientation with respect to the allocentric frame of reference and then the location of any object with respect to the observer can be accessed by computation.

The spatial updating effect (facilitation in performance when the tested view was consistent with the updated spatial representation during locomotion in the object stationary condition) observed when participants moved 50° in Experiment 1 could be well explained by both egocentric and allocentric models because both models propose that observers update their object representations during locomotion. However neither model can well explain why the spatial updating effect was not observed when participants moved 90° in Experiment 2. There are two possible explanations: First, when participants move without seeing the object, the locomotion systems of participants cannot update their location and orientation accurately to a level that the spatial updating effect can be observed; second, during locomotion, participants update their location and orientation very accurately; however, they could not successfully generalize the object representation formed at the learned view to the viewpoint of 90°, because the process of spatial updating was not robust enough to support such a large change in viewpoint. Hence, the participants had to reconstruct the representation from this novel viewpoint when they saw a different view of the target object. Future studies are needed to test these two possibilities.

The test view effect (better performance when the test view was the same as the learned view) could be explained by the egocentric updating model with an assumption that the updating of a viewer-based representation involves errors when participants move to a viewpoint 50° away. In contrast, the allocentric updating model can explain the test view effect if we assume that the object representation in an intrinsic or object-centred frame of reference was analogous to the spatial representation of locations in an allocentric frame of reference, and that such an intrinsic frame of reference plays an important role in visual object processing (Palmer, 1999; Rock, 1973). The allocentric model claims that spatial updating changes the observer's orientation with respect to the intrinsic frame of reference but does not change the salient direction of the intrinsic frame of reference, which is usually parallel to the egocentric learning view; just as spatial updating does not eliminate orientation dependency in spatial reasoning, spatial updating does not eliminate orientation (viewpoint) dependency in object recognition. We acknowledge that the data in this study are not able to differentiate these two models, but argue that the data give several constraints to both models. It appears that new experimental paradigms are needed to differentiate these two models (e.g., Mou, Xiao, & McNamara, 2006).

There are a number of studies of spatial memory and spatial reasoning using the judgements of relative directions that show that the advantage of locomotion occurs over a wide range of angular disparities (Farrell & Robertson, 1998; Mou, McNamara, et al., 2004; Reiser, 1989; Waller et al., 2002). For example, Mou, McNamara, et al. (2004), found that participants updated their location and orientation when they turned 225°. Why did the advantage of locomotion not occur when participants moved to a viewpoint of only 90° in Experiment 2 of this study? There are at least three possible explanations. First, in Mou, McNamara, et al., participants' locomotion was a simple rotation, but in this study, participants' movements were a simultaneous rotation and translation for which spatial updating might be more complicated. Second, a room-sized layout was used in Mou, McNamara, et al., but a table-size object was used in this experiment; the errors in spatial updating might have a relatively larger impact in a smaller scale of space. Third, it is possible that, compared to visual recognition, judgements of relative direction are more robust to the errors inherent in the process of spatial updating. Future studies are needed to test these possibilities.

In summary, the present study demonstrates that spatial updating during locomotion facilitates visual object processing at novel views in similar ways to those shown for visual scene processing. However, this facilitation is not as robust as has been previously thought and was restricted to specific conditions: First, the facilitation of spatial updating during locomotion could not be generalized to a larger angular disparity of 90°, and, second, the facilitation of spatial updating during locomotion did not eliminate viewpoint costs in visual object processing. Object representations appear to be viewpoint dependent even when participants' locomotion is taken into consideration.

REFERENCES

Biederman, I., & Gerhardstein, P. C. (1993). Recognizing depth-rotated objects: Evidence and conditions for three-dimensional viewpoint invariance. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 1162–1182.

Burgess, N., Spiers, H. J., & Paleologou, E. (2004). Orientational manoeuvres in the dark: Dissociating allocentric and egocentric influences on spatial memory. *Cognition*, *94*, 149–166.

Diwadkar, V. A., & McNamara, T. P. (1997). Viewpoint dependence in scene recognition. *Psychological Science*, *8*, 302–307.

Farrell, M. J., & Robertson, I. H. (1998). Mental rotation and the automatic updating of body-centered spatial relationships. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*, 227–233.

Gauthier, I., Hayward, W. G., Tarr, M. J., Anderson, A. W., Skudlarski, P., & Gore, J. C. (2002). BOLD activity during mental rotation and viewpoint-dependent object recognition. *Neuron*, *34*, 161–171.

Hayward, W. G., & Tarr, M. J. (1997). Testing conditions for viewpoint invariance in object recognition. *Journal of Experimental Psychology: Human Perception and Performance*, *23*, 1511–1521.

Hayward, W. G., & Williams, P. (2000). Viewpoint dependence and object discriminability. *Psychological Science*, *11*, 7–12.

Hayward, W. G., Zhou, G., Gauthier, I., & Harris, I. (in press). Dissociating viewpoint costs in mental rotation and object recognition. *Psychonomic Bulletin and Review*.

Mou, W., Biocca, F., Owen, C. B., Tang, A., Xiao, F., & Lim, L. (2004). Frames of reference in mobile augmented reality displays. *Journal of Experimental Psychology: Applied*, *10*, 238–244.

Mou, W., McNamara, T. P., Valiquette, C. M., & Rump, B. (2004). Allocentric and egocentric updating of spatial memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *30*, 142–157.

Mou, W., Xiao, C., & McNamara, T. P. (2006). Spatial memory of briefly-viewed desktop scenes. *Manuscript in preparation*.

Owen, C. B., Tang, A., & Xiao, F. (2003). *ImageTclAR: A blended script and compiled code development system for augmented reality*. Paper presented at the international workshop on Software Technology for Augmented Reality Systems, Tokyo, Japan.

Palmer, S. E. (1999). *Vision science: Photons to phenomenology*. Cambridge, MA: MIT Press.

Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*, 1157–1165.

Rock, I. (1973). *Orientation and form*. New York: Academic Press.

Shelton, A. L., & McNamara, T. P. (2001). Systems of spatial reference in human memory. *Cognitive Psychology*, *43*, 274–310.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, *171*, 701–703.

Simons, D. J., & Wang, R. F. (1998). Perceiving real-world viewpoint changes. *Psychological Science*, *9*, 315–320.

Simons, D. J., Wang, R. F., & Roddenberry, D. (2002). Object recognition is mediated by extraretinal information. *Perception and Psychophysics*, *64*, 521–530.

Tarr, M. J. (1995). Rotating objects to recognize them: A case study on the role of viewpoint dependency in the recognition of three-dimensional objects. *Psychonomic Bulletin and Review*, *2*, 55–82.

Tarr, M. J., Williams, P., Hayward, W. G., & Gauthier, I. (1998). Three-dimensional object recognition is viewpoint dependent. *Nature Neuroscience*, *1*, 275–277.

Waller, D., Montello, D. R., Richardson, A. E., & Hegarty, M. (2002). Orientation specificity and spatial updating. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *28*, 1051–1063.

Wang, R. F., & Simons, D. J. (1999). Active and passive scene recognition across views. *Cognition*, *70*, 191–210.

Manuscript received November 2005
Manuscript accepted April 2006
First published online June 2006