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Body- and Environment-Stabilized Processing of Spatial Knowledge

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In 5 experiments, the authors examined the perceptual and cognitive processes used to track the locations of objects during locomotion. Participants learned locations of 9 objects on the outer part of a turntable from a single viewpoint while standing in the middle of the turntable. They subsequently pointed to objects while facing the learning heading and a new heading, using imagined headings that corresponded to their current actual body heading and the other actual heading. Participants in 4 experiments were asked to imagine that the objects moved with them as they turned and were shown or only told that the objects would move with them; in Experiment 5, participants were shown that objects could move with them but were asked to ignore this as they turned. Results showed that participants tracked object locations as though the objects moved with them when shown but not when told about the consequences of their locomotion. Once activated, this processing mode could not be suppressed by instructions. Results indicated that people process object locations in a body- or an environment-stabilized manner during locomotion, depending on the perceptual consequences of locomotion.

Keywords: spatial updating, body-stabilized spatial processing, environment-stabilized spatial processing

Effective navigation requires people to keep track of objects in the environment that are stationary and objects in the environment that move with them. For instance, when a person shops in a supermarket, goods on the shelves are stabilized with respect to the environment but change positions with respect to the body, whereas goods in a shopping cart are stabilized with respect to the body but change positions with respect to the environment as the person pushes the cart. Accordingly, the human cognitive system may have two kinds of processes for handling the locations of objects. Processing the locations of objects in an environment-stabilized way requires, among other things, that people update their orientation with respect to the objects during locomotion, whereas processing the locations of objects in a body-stabilized way requires that people maintain their (approximate) orientation with respect to the objects during locomotion.

The existence of environment-stabilized spatial processing finds extensive empirical support in research on spatial updating (e.g., Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Rieser, 1989; Simons & Wang, 1998; Wraga, Creem, & Proffitt, 2000). This research has shown that as people locomote in an environment, they update their heading with respect to the layout of the objects. This updating process is difficult to ignore (e.g., Farrell & Robertson, 1998).

By contrast, there are relatively few behavioral studies that can help us to understand body-stabilized spatial processing (Mou, Biocca, et al., 2004; Waller, Montello, Richardson, & Hegarty, 2002; Woodin & Allport, 1998). Results of these studies suggest that body-stabilized processing can be induced by appropriate perceptions (e.g., participants see virtual objects move with them) or by instructions (e.g., participants are told to imagine a simple path moving with them). Possible limitations of these studies are that learning and testing occurred in virtual environments (e.g., Mou, Biocca, et al., 2004) or that the studies used simple four-segment paths (e.g., Waller et al., 2002).

This study investigated spatial processing of objects during locomotion in a real environment with relatively complex layouts. We attempted to answer three questions: First, does body-stabilized spatial processing of real objects occur in a relatively complicated layout? Second, under what conditions is body-stabilized processing activated? Third, can body-stabilized processing be ignored once it has been activated? Although introspection suggests that body-stabilized spatial processing must occur in daily activities, a convincing empirical demonstration is desired. Furthermore, the second and third questions have not been answered by prior research. The answers to these questions are theoretically important, because they are informative about the different ways in which people track locations of objects during locomotion and about whether activation of either processing mode is obligatory or is subject to cognitive interpretation.

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Participants in five experiments learned the locations of nine objects from a single viewpoint (e.g., facing the candle or the ball in Figure 1) on a turntable that rested on a floor. In the testing phase, they either remained stationary or turned to a new heading (i.e., candle or ball) while blindfolded. At both actual body headings, they made pointing judgments from the imagined heading that corresponded to the current actual body heading and the imagined heading that corresponded to the other actual body heading. The experiments therefore independently manipulated the angular difference between the learning view and the imagined heading (learning minus imagined, or L-I) and the angular difference between the actual body heading and the imagined heading (A-I; e.g., Mou, McNamara, Valiquette, & Rump, 2004). These manipulations are illustrated in Figure 2. The learning heading is indicated by the dashed arrow. The two actual body headings at testing are indicated by the head–nose icons. The imagined headings are indicated by the solid arrows.

We used the effect of the distance between the actual body heading and the imagined heading (actual heading effect) to determine whether participants had used body-stabilized or environment-stabilized processing. If participants had been successful in using body-stabilized spatial processing when they turned, there should be no actual heading effect. To understand why, one should first consider the L-I = 0° conditions (see Figure 2). In the A-I = 0° condition, pointing should be easy, because participants would be pointing to objects from the same heading from which the participants had learned them. In the A-I = 120° condition, performance should be just as good, because participants would have successfully imagined the array turn with their bodies. Now consider the L-I = 120° conditions. In the A-I = 0° condition, participants turned 120° and therefore should have had in mind the array as it appeared from the learning heading, but the test trials required them to imagine a heading that differed 120° from the learning heading. Performance should suffer as a result (e.g., Mou, McNamara, et al., 2004). In the A-I = 120° condition, participants did not turn but were asked to point to objects from an imagined heading that differed 120° from the learning heading. Performance should suffer to the same extent. Overall, therefore, there should be no effect of the magnitude of the difference between the actual and imagined headings. On the other hand, if participants used environment-stabilized processing, performance should be better when the actual and imagined headings were the same than when they were different, which would create an actual heading effect.

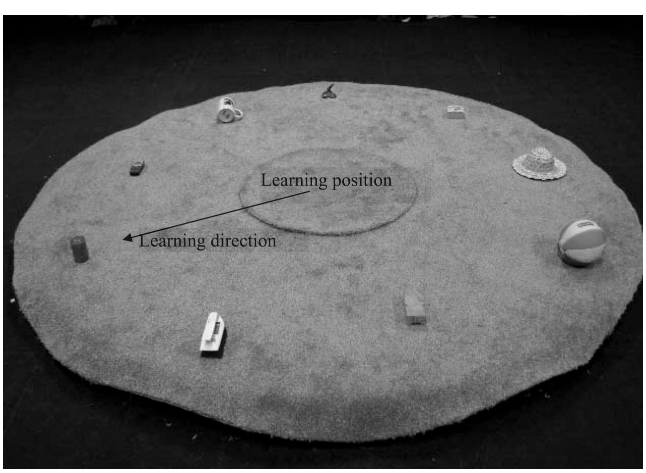

Figure 1. Layout of objects used in all experiments. The turntable had two parts: an inner part that was not rotatable and an outer part that was rotatable by the experimenter. Participants stood in the middle of the turntable, and objects were placed near the outer edge of the turntable.

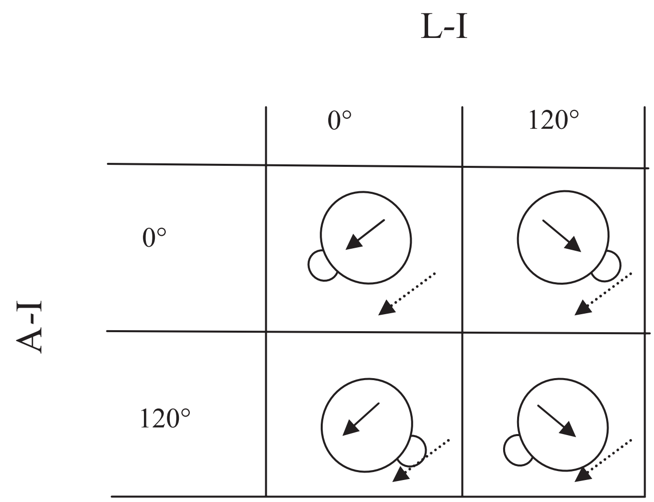

Figure 2. Design of the experiments. Head–nose icons indicate actual body headings at testing; solid arrows indicate imagined headings at testing; dashed arrows indicate the learning heading. L-I = learning-imagined; A-I = actual-imagined.

Experiment 1

In this experiment, the turntable remained stationary when participants turned their bodies. Participants were asked to imagine all of the objects moving with them as they turned but were never informed that the turntable was rotatable.

Method

Participants. Twenty-four undergraduates (12 women and 12 men) participated in return for monetary compensation.

Materials and design. Experiments were conducted in an empty square space (6 × 6 m) surrounded with a black fabric and carpeted with a black mat. The objects were placed on a round turntable (diameter = 2.2 m; see Figure 1) in the middle of the room. The turntable had two parts: The inner part (diameter = 0.8 m) was not rotatable, and the outer part was designed to be rotatable if the experimenter removed blocks from under the turntable and turned the turntable. Both parts were covered by gray carpet. Participants stood in the middle of the inner part, and objects were placed on the outer part during the experiment. Participants could not determine that the outer part was rotatable by its appearance. The configuration of nine objects was approximately circular (diameter = 1.8 m). Objects were distributed evenly around a circle and were separated by 40°. Objects did not share any obvious semantic associations. The direction of the scissors from the center of the layout was aligned with the room.

Each test trial (e.g., "Imagine you are facing the candle. Please point to the hat.") required participants to point to a target object (hat) from an imagined facing direction (candle). Participants pointed with a joystick held in their hands.

The design is illustrated in Figure 2. The designs for participants who faced the candle and participants who faced the ball during the learning phase were identical. We describe only the design for the participants who faced the candle during learning. The independent variables were (a) the angular difference between the learning heading and the imagined heading at the time of test (L-I) and (b) the angular difference between the actual body heading at the time of test and the imagined heading at the time of test (A-I). Participants had two actual body headings at the time of test: the same as the learning heading or 120° different from the learning heading. At each actual body heading, participants had two imagined headings: the same as the learning view or 120° from the learning view. Both variables were manipulated within participant. At each actual body heading, participants had 16 trials (pointing to each of the other eight objects except the imagined facing object at each imagined heading) in a random order.

The dependent measures were response latency, measured as the time from presentation of the name of the target object to the pointing response, and angular error of the pointing response, measured as the absolute angular difference between the judged pointing direction and the actual direction of the target. In this and the following experiments, angular error was not as sensitive to the actual heading effect as was pointing latency, but generally there were no accuracy–latency trade-offs. Thus, we used the actual heading effect in latency as the main indication that the participant had used environment-stabilized spatial processing.

Procedure. Participants were randomly assigned to each combination of learning view (candle vs. ball) and the order of actual heading conditions (facing the learning view first or turned 120° away from the learning view first), with the constraint that each group contained an equal number of men and women.

Participants were trained to point from imagined headings that were the same as or different from their actual body heading. The experimenter then escorted them to the experiment room. Participants were blindfolded while being escorted into the experiment room and to the learning position to prevent any experience from a viewpoint other than the assigned one.

When participants were standing on the learning position and facing the learning direction, the blindfold was removed. They were allowed to study the layout for 30 s and then were required to name and point to the objects with their fingers with eyes closed. Participants had 10 of these study–test sequences. Each of them was then given a joystick and a wireless earphone. Participants were asked to hold the joystick in front of their waist and in a fixed orientation with respect to their bodies. They had another five study–test sequences, except that they pointed with the joystick to the object that was named via earphone. All participants were able to point to all of the objects accurately (error $<20°$) with the joystick.

After participants were blindfolded, they adopted the first actual body heading. Participants always stood at their learning position but turned their body if the actual body heading was different from the learning direction. They were required to turn their body slowly and to imagine all of the objects moving with them with the same angle (e.g., "Please turn left slowly and imagine every object moving with you, which means during your turning the candle will be always in front of you."). The participants were stopped by the experimenter when they were facing the correct direction but were never informed of the direction.

Each test trial initiated by the experimenter began with the imagined heading (e.g., "Imagine you are facing the candle."). Participants pulled the trigger after they had a clear image of their facing direction. The target object immediately followed (e.g., "Please point to the ball."). Participants were asked to point with the joystick as quickly as possible without sacrificing accuracy. After finishing all of the 16 trials, they adopted the second actual body heading and repeated the same 16 trials.

Results

Pointing latency is presented in Figure 3A, and angular error is presented in Table 1 as a function of the angular distance between the actual body heading and the imagined heading and the angular distance between the learning heading and the imagined heading. Means for each participant and each condition were analyzed in repeated-measures analyses of variance, with terms for the A-I = 0° and A-I = 120° conditions and for the L-I = 0° and L-I = 120° conditions.

In point latency, the main effect of L-I distance was significant, $F(1, 23) = 34.61$, $MSE = 3.44$, $p < .001$. The main effect of A-I distance was significant, $F(1, 23) = 8.86$, $MSE = 3.01$, $p < .01$. The interaction between L-I and A-I distances was not significant, $F(1, 23) = 0.51$, $MSE = 1.41$, $p > .05$.

In pointing error, the main effect of L-I distance was significant, $F(1, 23) = 52.21$, $MSE = 80.07$, $p < .001$. The main effect of A-I distance was not significant, $F(1, 23) = 0.21$, $MSE = 130.63$, $p > .05$. The interaction between L-I and A-I distances was not significant, $F(1, 23) = 0.87$, $MSE = 41.09$, $p > .05$.

Discussion

Participant pointing latency was shorter when the actual and imagined headings were the same than when they were different. This result indicates that although participants were asked to imagine the objects stabilized with respect to their body, they were not able to ignore that the objects on the turntable were stabilized with respect to the environment; that is, they still used environment-stabilized spatial processing. This finding is consistent with that of Farrell and Robertson (1998) but not consistent with the findings of Mou, Biocca et al. (2004) and Waller et al. (2002).

The second important finding was that the pointing latency was shorter and the pointing error was smaller when the imagined heading and the learning heading were the same than when they were different. This result indicates that people represented the locations of the objects with respect to a frame of reference selected at the learning view. This finding is consistent with the claim of Mou, McNamara, et al. (2004) that spatial memory is orientation dependent and that spatial updating does not change the pattern of orientation dependence.

Experiment 2

Our goal in this experiment was to determine whether participants could use body-stabilized spatial processing if they per-

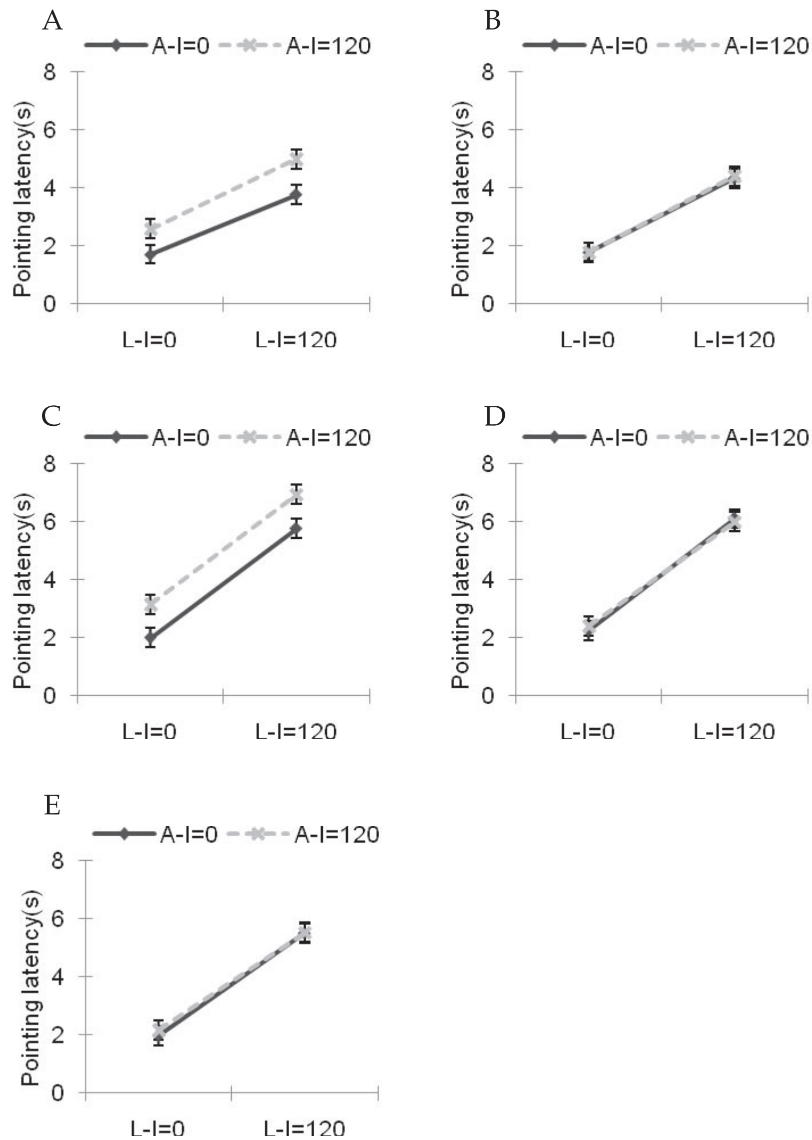

Figure 3. Pointing latency as a function of actual minus imagined (A-I) distance and learning minus imagined (L-I) distance in (A) Experiment 1, (B) Experiment 2, (C) Experiment 3, (D) Experiment 4, and (E) Experiment 5. Error bars are confidence intervals corresponding to ±1 standard errors, as estimated from the analysis of variance.

ceived that the turntable was rotatable. Participants were shown that the turntable was rotatable after they had learned the layout and were informed that the experimenter would turn the turntable at the same speed and in the same direction as they turned their body.

Method

Participants. Twenty-four undergraduates (12 women and 12 men) participated in return for monetary compensation.

Materials and design. Materials and design were the same as in Experiment 1, except that the blocks under the outer part of the turntable were removed, so the outer part of the turntable could be turned smoothly by the experimenter.

Procedure. Procedure was the same as in Experiment 1, except that after participants learned the locations of the objects, the experimenter revealed that the turntable was rotatable by turning it 20° clockwise and 20° counterclockwise. The experimenter informed participants that the turntable would be turned at the same speed and in the same direction as they turned their bodies.[1] Participants were asked to imagine all objects moving with them as they turned.

[1] The same results were found in another experiment when the experimenter did not turn the turntable as participants turned their bodies.

Table 1
Mean (and Standard Deviation) Angular Error (in Degrees) as a Function of Actual-Imagined (A-I) Distance and Learning-Imagined (L-I) Distance in the Experiments

	A-I = 0		A-I = 120	
Experiment	L-I = 0	L-I = 120	L-I = 0	L-I = 120
1	16.72 (8.11)	31.14 (10.48)	19.01 (9.66)	30.99 (13.67)
2	15.84 (4.48)	28.28 (10.33)	16.33 (6.01)	30.04 (12.21)
3	16.84 (5.96)	29.64 (13.38)	16.58 (8.09)	30.66 (12.48)
4	19.03 (4.45)	31.53 (10.62)	22.18 (10.27)	33.20 (8.64)
5	15.89 (4.16)	28.24 (9.52)	16.64 (7.33)	28.18 (13.58)

Results and Discussion

In pointing latency (see Figure 3B), the main effect of L-I distance was significant, $F(1, 23) = 58.62$, $MSE = 2.73$, $p < .001$. The main effect of A-I distance was not significant, $F(1, 23) = 0.05$, $MSE = 0.60$, $p > .05$. The interaction between L-I and A-I distances was not significant, $F(1, 23) = 0.05$, $MSE = 0.91$, $p > .05$.

In angular error (see Table 1), the main effect of L-I distance was significant, $F(1, 23) = 45.04$, $MSE = 91.1$, $p < .001$. The main effect of A-I distance was not significant, $F(1, 23) = 0.76$, $MSE = 39.81$, $p > .05$. The interaction between L-I and A-I distances was not significant, $F(1, 23) = 0.31$, $MSE = 31.27$, $p > .05$.

The actual heading effect observed in Experiment 1 was not observed in Experiment 2. This finding indicates that participants used body-stabilized spatial processing after they had perceived the layout was stabilized with respect to their body. The learning view effect observed in Experiment 1 was also observed in Experiment 2.

Experiment 3

This experiment investigated whether verbal instructions could activate body-stabilized spatial processing. After learning the layout of objects, participants were informed by the experimenter (but did not visually perceive) that the turntable was rotatable. They were informed, as in Experiment 2, that the experimenter would turn the turntable at the same speed and in the same direction as they turned their bodies. Participants were required to imagine all objects moving with them when they were turning, as in the previous experiments.

Method

Participants. Twenty-four undergraduates (12 women and 12 men) participated in return for monetary compensation.

Materials, design, and procedure. Materials, design, and procedure were the same as in Experiment 2, except that participants were verbally informed (but were not shown) that the turntable was rotatable.

Results and Discussion

In pointing latency (see Figure 3C), the main effect of L-I distance was significant, $F(1, 23) = 35.12$, $MSE = 9.79$, $p < .001$. The main effect of A-I distance was significant, $F(1, 23) = 10.44$, $MSE = 3.14$, $p < .01$. The interaction between L-I and A-I distances was not significant, $F(1, 23) = 0.003$, $MSE = 2.00$, $p > .05$.

In pointing error (see Table 1), the main effect of L-I distance was significant, $F(1, 23) = 37.40$, $MSE = 115.92$, $p < .001$. The main effect of A-I distance was not significant, $F(1, 23) = 0.07$, $MSE = 50.94$, $p > .05$. The interaction between L-I and A-I distances was not significant, $F(1, 23) = 0.09$, $MSE = 108.99$, $p > .05$.

The actual heading effect was observed in Experiment 3, just as it was in Experiment 1. This result indicates that verbal instructions about turntable rotation were not sufficient to allow participants to use body-stabilized spatial processing. The learning view effect was observed, as in the previous experiments.

Experiment 4

Experiments 2 and 3 showed that perceiving the rotation of the turntable with the objects was critical to the activation of body-stabilized spatial processing. Our purpose in Experiment 4 was to determine whether participants could still use body-stabilized spatial processing if they had seen the empty turntable rotate before the objects were placed on it.

Method

Participants. Twenty-four undergraduates (12 women and 12 men) participated in return for monetary compensation.

Materials and design. Materials and design were the same as those in Experiment 2.

Procedure. Procedure was the same as that in Experiment 2, except that before (rather than after) participants learned the locations of the objects, the experimenter showed them that the turntable (without objects on it) was rotatable by turning it 20° clockwise and 20° counterclockwise. After that, participants put on blindfolds and the experimenter placed all the objects on the turntable. Then participants removed their blindfolds to learn the locations of the objects.

Results and Discussion

In pointing latency (see Figure 3D), the main effect of L-I distance was significant, $F(1, 23) = 55.71$, $MSE = 5.96$, $p < .001$. The main effect of A-I distance was not significant, $F(1, 23) = 0.015$, $MSE = 5.96$, $p > .05$. The interaction between L-I and A-I distances was not significant, $F(1, 23) = 0.34$, $MSE = 1.47$, $p > .05$.

In pointing error (see Table 1), the main effect of L-I distance was significant, $F(1, 23) = 37.68$, $p < .001$, $MSE = 80.76$. The main effect of A-I distance was not significant, $F(1, 23) = 2.62$, $p > .05$, $MSE = 33.5$. The interaction between L-I and A-I distances was not significant, $F(1, 23) = 0.59$, $p > .05$, $MSE = 63.00$.

The results of Experiment 4 showed that, for participants, perceiving rotation of the turntable, even when it contained no objects, was sufficient to activate body-stabilized spatial processing. The learning view effect was also observed.

Experiment 5

Our purpose in Experiment 5 was to determine whether the activation of body-stabilized spatial processing could be inhibited by verbal instructions. After participants had learned the layout, they were shown that the turntable was rotatable and were informed that the experimenter would turn it as they turned their body. However, participants were instructed to ignore rotation of the turntable when they were turning.

Method

Participants. Twenty-four undergraduates (12 women and 12 men) participated in return for monetary compensation.

Materials and design. Materials and design were the same as in Experiment 2.

Procedure. Procedure was the same as in Experiment 2, except that participants were required to use environment-stabilized spatial processing when they were turning (e.g., "Please turn left slowly and imagine every object staying in its original position, which means after you stop turning, you will not face the candle anymore.").

Results and Discussion

In pointing latency (see Figure 3E), the main effect of L-I distance was significant, $F(1, 23) = 64.25$, $MSE = 4.44$, $p < .001$. The main effect of A-I distance was not significant, $F(1, 23) = 0.36$, $MSE = 0.81$, $p > .05$. The interaction between L-I and A-I distances was not significant, $F(1, 23) = 0.17$, $MSE = 0.90$, $p > .05$.

In angular error (see Table 1), the main effect of L-I distance was significant, $F(1, 23) = 29.4$, $MSE = 116.53$, $p < .001$. The main effect of A-I distance was not significant, $F(1, 23) = 0.05$, $MSE = 54.34$, $p > .05$. The interaction between L-I and A-I distances was not significant, $F(1, 23) = 0.09$, $MSE = 45.82$, $p > .05$.

The actual heading effect was not observed. This finding indicates that participants could not ignore the activation of body-stabilized spatial processing after they had perceived that the layout was stabilized with respect to their body. The learning view effect was observed, as in the previous experiments.

General Discussion

Participants in the present experiments were able to employ body-stabilized spatial processing in a real environment with relatively complex layouts of objects. Body-stabilized processing was activated by what people were shown rather than by what they were told about the consequence of their locomotion. This mode of processing could not be inhibited once it had been activated. This project also replicated the finding that spatial updating is automatic, in the sense that it could not be ignored (e.g., Farrell & Robertson, 1998).

Environment-stabilized processing and body-stabilized processing must complement each other during locomotion. The prior perception of the consequences of locomotion with respect to a specific object recruits, exclusively and automatically, the spatial processing consistent with that perception. For example, when a shopper perceives that a shopping cart is moving with him or her while it is being pushed through the aisles, body-stabilized processing is recruited to track the cart, whereas perceiving the same cart in the cart array will recruit environment-stabilized processing. Because these modes of processing are invoked automatically, people seldom realize consciously that different modes of spatial processing are used to track objects attached to their bodies as opposed to objects stabilized in the environment. Although these examples and the present experiments address the role of visual perception, other perceptual modalities should also play a role.

An important consequence of the automatic recruitment of body- and environment-stabilized spatial processing is that cognitive resources can be allocated to other tasks during locomotion. For example, attention can be focused on tracking the movements of other objects and actors. It is reasonable to assume that these two types of spatial processing develop through perceiving the consequences of locomotion (e.g., Rieser & Pick, 2007). Many objects stay put when a person locomotes from place to place, whereas other objects, namely those attached to the body in some way, move with the person. These relations hold throughout development. The ability to classify such objects efficiently and assign them to appropriate spatial processing systems would provide a sound foundation for efficient navigation.

Another important property of the mechanisms used to track object location is that the spatial processing of an object is inherited by objects attached to that object. Experiment 4 of this study showed that perceived rotation of the empty turntable activated body-stabilized processing of the objects subsequently placed on the turntable. This feature is also ecologically important. People know that a shelf is stationary in the environment and can therefore use environment-stabilized processing to track all the goods on the shelf. People also know that a shopping cart they push moves with the body, so they can use body-stabilized processing to track all the objects in the cart. This analysis may explain why verbal instructions to use a body-stabilized virtual reality system can activate body-stabilized spatial processing, as reported by Mou, Biocca et al. (2004, Experiment 3). Participants automatically used body-stabilized spatial processing for their head-mounted display (HMD). They may also use body-stabilized spatial processing for the virtual objects displayed on the HMD, if they are explicitly instructed that the virtual objects will move with the HMD.

It is unclear why participants in Waller et al.'s (2002) experiment could be instructed to use body-stabilized processing but participants in this project could not (see also Farrell & Robertson, 1998). Differences in materials may account for the inconsistent findings. The layouts used in our own and in Farrell and Robertson's experiments differed from the four-segment paths used by Waller et al. in that they contained more objects, did not have objects connected by paths, and were viewed from an internal rather than an external viewpoint. Additional experiments are needed to determine which of these differences may account for the different findings.

Another important finding in this study is that, in all experiments, an effect of the learning heading was observed. This finding confirms that spatial updating during locomotion does not alter the spatial reference directions in memory established at the time of learning and indicates that such spatial memories are allocentric (e.g., Mou, McNamara, et al., 2004). The learning-heading effect was observed when object locations were processed in a body-stabilized manner and in an environment-stabilized manner, showing that the mechanism of tracking object locations is independent of the spatial reference systems used in long-term memory.

In summary, this study provides clear evidence that there are two kinds of spatial processing involved in tracking locations of objects during locomotion, that the activation of each kind of spatial processing is determined by the perception of the consequences of locomotion, and that such activation is automatic, in the sense that it cannot be ignored.

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