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Retrieving Enduring Spatial Representations after Disorientation

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Abstract

Four experiments tested whether there are enduring spatial representations of objects' locations in memory. Previous studies have shown that under certain conditions the internal consistency of pointing to objects using memory is disrupted by disorientation. This disorientation effect has been attributed to an absence of or to imprecise enduring spatial representations of objects' locations. Experiment 1 replicated the standard disorientation effect. Participants learned locations of objects in an irregular layout and then pointed to objects after physically turning to face an object and after disorientation. The expected disorientation was observed. In Experiment 2, after disorientation, participants were asked to imagine they were facing the original learning direction and then physically turned to adopt the test orientation. In Experiment 3, after disorientation, participants turned to adopt the test orientation and then were informed of the original viewing direction by the experimenter. A disorientation effect was not observed in Experiment 2 or 3. In Experiment 4, after disorientation, participants turned to face the test orientation but were not told the original learning orientation. As in Experiment 1, a disorientation effect was observed. These results suggest that there are enduring spatial representations of objects' locations specified in terms of a spatial reference direction parallel to the learning view, and that the disorientation effect is caused by uncertainty in recovering the spatial reference direction relative to the testing orientation following disorientation.

People can reorient in a familiar environment after they temporally disengage from the environment, as in awaking after a nap. Phenomena such as these indicate that people have enduring spatial representations or cognitive maps of the surrounding environment. This claim was embodied in the classical models of human and non-human spatial memory (e.g., Gallistel, 1990; Tolman, 1948; O'Keefe & Nadel, 1978). This position is consistent with the discovery of place cells (e.g., Ekstrom et al., 2003; O'Keefe & Nadel, 1978) in human and non-human animals. Contemporary theories of spatial memory and navigation, however, have not reached agreement on whether people have enduring spatial representations of objects' locations (Burgess, 2006; Wang & Spelke, 2002; Zhang, Mou, & McNamara, 2011). The purpose of this study was to reconcile this disagreement.

Wang and Spelke (2000, 2002) proposed that people do not have precise enduring spatial representations of objects' locations although people might have precise enduring spatial

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representations of geometric shapes (e.g., shape of room). People depend principally on dynamic body-object vectors in spatial orientation and navigation. In particular, when one learns a layout of objects, he or she represents locations of individual objects with respect to his or her body and momentarily updates body-object vectors during locomotion. Presumably body-object vectors are specified in terms of the observer's body orientation, which changes as the person turns.

Mou, McNamara, and their colleagues (Mou, McNamara, Valiquette, & Rump, 2004; Mou, Xiao, & McNamara, 2008; Mou, Zhang, McNamara, 2009; Zhang, Mou, & McNamara, 2011) proposed that people have precise enduring spatial representations of objects' locations that are organized with respect to a fixed reference direction. In a newer version of this theoretical framework, Zhang, Mou, and McNamara (2011) proposed that when an individual learns a layout of objects, he or she represents an object's location in terms of his or her body (as a special object) and/or in terms of other objects. The body-object vectors and the interobject vectors are specified with respect to a reference direction that is a fixed component of the representation of the layout of the objects. The reference direction can be selected based on a variety of cues available to the observer (McNamara, 2003, for a review). Regardless of which cues are used to select the reference direction, the reference direction is stable and independent of the observer's locomotion unless the observer re-learns the layout from a new perspective (Kelly & McNamara, 2010; Shelton & McNamara, 2001). The fixed reference direction is analogous to the cardinal direction North in defining geographic information. When the direction of the conceptual north is established in the layout of the objects, it typically does not change when the observer changes his or her position and orientation. In addition to the enduring representations of body-object vectors (between the learning position and the location of an object) and interobject vectors, people also represent their learning orientation with respect to the same reference direction. The orientation defined with respect to a fixed reference direction was referred to as *allocentric heading* by Klatzky (1998). When a person only turns his or her body, body-object vectors and interobject vectors remain the same but the allocentric heading changes. The observer's new allocentric heading can be calculated by adding the turning angle and the represented original allocentric heading. When a navigator walks forward, the interobject vectors and the allocentric heading remain the same but the body-object vectors change. The new body-object vectors can be calculated by adding the locomotion vector between the current position and the original learning position and the represented body-object vectors. The vector between the current position and the original learning position can be calculated by a path integration mechanism (e.g., Wehner, Michel, & Antonsen, 1996). For example, it is the sum of the vector between the previous position and the original learning position and the vector between the current position and the previous position, as both of these vectors are defined with respect to a fixed reference direction in the environment.

These two models differ in whether spatial memory and navigation rely on a precise enduring representation of objects' locations. One piece of key evidence supporting Wang and Spelke's model was originally reported by Wang and Spelke (2000). In an influential study, Wang and Spelke reported that the internal consistency of pointing to objects in an irregular layout was disrupted by disorientation, and concluded that spatial orientation depended principally on dynamic self-to-object spatial relations. Wang and Spelke had participants learn locations of several objects in a room, and then point to objects with eyes open, after physically turning a small amount with eyes closed, and after being disoriented. The results showed that the configuration error, which is defined as the standard deviation across target objects of the mean signed pointing errors, was bigger in the disorientation condition than in the eye-closed locomotion condition. Wang and Spelke (2000; 2002) proposed that people do not have enduring spatial representations of objects' locations with respect to other objects' locations. They argued that if people had enduring representations of interobject vectors, configuration error should not increase after disorientation. Instead, people represent momentary body-object vectors, which are updated independently and dynamically during locomotion. Because body-object vectors are updated independently, the error of locating each object introduced during locomotion is independent. As a consequence, disorientation, which involves substantial locomotion, leads to an increase of the error of locating each object. They also reported that configuration error did not increase after disorientation when participants pointed to corners of a room, so they argued that people have an enduring representation of inter-corner spatial relations.

Several studies have shown that the disorientation effect does not occur in some circumstances. Waller and Hodgson (2006) reported that the disorientation effect was not evidenced when people pointed to objects based on extant knowledge of a familiar environment. In one experiment participants imagined themselves standing in their bedroom and then pointed to each of the objects in the bedroom. Participants then pointed to each object after physically turning a relatively small angle and after being disoriented. The results showed no disorientation effect. In contrast the disorientation effect was replicated when participants pointed to objects in a recently learned array in the lab. Interestingly, comparing the locomotion (eye-closed) condition across the environments with different familiarity (bedroom vs. lab), they found that configuration error was bigger in the familiar environment (i.e. bedroom) than in the recently learned array in the lab. They proposed that the disorientation effect occurs because enduring spatial representations are less accurate than transient spatial representations. Because transient spatial representations of the objects in the lab are disrupted after disorientation, people rely on the coarse enduring spatial representation and configuration error increases.

Holmes and Sholl (2005) failed to replicate the disorientation effect even when participants pointed to objects in a recently learned environment. They conjectured that the disorientation effect might depend on the precision of spatial representations formed during learning. In Holmes and Sholl's experiments, participants pointed to objects during learning with their eyes closed, which could have led to imprecise spatial representations. By way of contrast, participants in Wang and Spelke's experiments (2000) pointed to objects with their eyes open during learning, which might have produced precise representations of interobject spatial relations. Spatial attention during locomotion could have maintained these precise spatial representations. When spatial attention was disrupted by disorientation, precise representations of interobject spatial relations were susceptible to categorical bias (e.g., Huttenlocher, Hedges, & Duncan, 1991) with the direction of bias varying across objects. According to Holmes and Sholl, the disorientation effect occurred in Wang and Spelke's experiments because participants formed precise spatial representations, but did not occur in their own experiments because participants formed imprecise spatial representations.

Mou, McNamara, Rump, and Xiao (2006) reported that the disorientation effect was not observed when participants pointed to objects in a recently learned regular layout. In their fourth experiment, participants learned an irregular layout, in which objects were not lined up column by column, of 4 objects while standing amidst objects. Then, they pointed to objects at the original learning orientation (baseline), after turning 225° away (updating), and after disorientation. In all conditions, participants closed their eyes. In the disorientation condition, in order to prevent participants from adopting the original learning viewpoint subjectively, participants were asked to adopt a heading of 225° from their learning viewpoint by turning their body ("please turn left until you *believe* you are facing the candle.") The results showed that configuration error was bigger in the disorientation condition than in the updating condition. In their second experiment, participants learned a regular layout, in which objects were lined up column by column, of nine objects while standing at the edge of the layout. Then they pointed to objects in the above three conditions. The results showed that there was no disorientation effect. Mou, McNamara, Rump, and Xiao proposed that people are able to form a high fidelity enduring representations of interobject spatial relations when they learn a regular layout, whereas they form a low fidelity enduring representation of interobject spatial relations when they learn an irregular layout. After learning a regular layout people use high fidelity interobject spatial relations in both conditions of updating and disorientation leading to no disorientation effect. In contrast after learning an irregular layout people use high fidelity transient representations of self-to-object spatial relations in the updating condition and use low fidelity enduring representation of object-to-object spatial relations in the disorientation condition, as transient self-to-object spatial relations are disrupted by disorientation. Mou et al. also conjectured that the failure to obtain the disorientation effect in Holmes and Sholl's experiments (2005) occurred because the layout in their experiment was quite regular.

Xiao, Mou, and McNamara (2009) tested Mou et al.'s (2006) conjectures directly. In Experiments 1–4, Xiao et al. showed that there was a disorientation effect when participants learned an irregular layout, whereas there was no disorientation effect when participants learned a regular layout, regardless of participants' learning position (on the periphery of or amidst objects). In Experiments 5–8, they instructed participants who learned an irregular layout to pay attention to interobject spatial relations and those who learned a regular layout to pay attention to self-to-object spatial relations during locomotion. The results showed that there was a disorientation effect when participants who learned a regular layout were instructed to pay attention to self-to-object spatial relations during locomotion regardless of participants' learning position. However the instructions interacted with participants' learning position for an irregular layout. There was a disorientation effect when participants learned an irregular layout by standing amidst the objects and were instructed to pay attention to interobject spatial relations. There was no disorientation effect when participants learned an irregular layout on the edge of the layout and were instructed to pay attention to interobject spatial relations.

Xiao, Mou, and McNamara (2009) argued that participants represented both body-object and interobject vectors when they learned a regular layout and when they learned an irregular layout from its periphery. They hypothesized that participants primarily represented body-object vectors, and only minimally represented interobject vectors, when they learned an irregular layout while standing amidst the objects. Furthermore, one type of spatial relation (body-object or interobject) is primarily maintained and the other decays during locomotion, and this difference is modulated by the layout regularity. Participants maintained interobject vectors for a regular layout and maintained body-object vectors for an irregular layout. For a regular layout, participants relied on accurate interobject vectors in both updating and locomotion conditions leading to no disorientation effect. For an irregular layout, participants relied on accurate body-object vectors in the updating condition but relatively inaccurate interobject vectors in the disorientation condition, as the body-object vectors were disrupted by disorientation. Because inaccuracies in locating objects are independent across objects, more to the right for some objects but more to the left for other objects, the standard deviation of error is larger when the inaccuracy of locating each object is larger, leading to a disorientation effect. Participants were able to maintain the alternative spatial relations as instructed and the results of the disorientation effect changed accordingly with one exception. When participants learned an irregular layout by standing amidst it, they might not have been able to follow the instruction to use interobject vectors as those spatial relations were only minimally represented.

These studies have shown that the disorientation effect is not observed for a familiar environment, for a regular layout, or for an irregular layout when people learn it by standing outside of it and are instructed to maintain object-to-object spatial relations during locomotion. In other words, the disorientation effect seems to be limited to situations in which participants learn an irregular layout by standing amidst it. However, all prevailing explanations of the disorientation effect are still consistent with Wang and Spelke's (2000, 2002) original proposal. People have no or imprecise enduring spatial representations and precise transient spatial representations when they learn a layout of objects by standing amidst it. People dynamically update transient spatial representations during locomotion. These transient spatial relations are disrupted after disorientation and the imprecise enduring spatial representation have to be used. In this project, we proposed and tested a new explanation that was derived from theoretical model proposed by Mou and McNamara discussed above (e.g., Zhang Mou, & McNamara, 2011).

We propose, like Wang and Spelke (2000), that people primarily represent body-object vectors when they learn an irregular layout while standing amidst the objects. In contrast to Wang and Spelke, but consistent with Zhang, Mou, and McNamara (2011), we propose that people represent body-object vectors with respect to a spatial reference direction that is a fixed component of the spatial representation. We assume that when people learn an irregular layout by standing amidst it, the fixed reference direction is determined by the original learning viewpoint (e.g., Shelton & McNamara, 2001). We propose further that when people turn, they update their orientation (allocentric heading) with respect to the fixed spatial reference direction by keeping track of the reference direction. At a new testing orientation, the direction of a target object relative to the testing orientation is the difference between the bearing of the body-object vector relative to the fixed spatial reference direction and the testing orientation relative to the fixed spatial reference direction (See Figure 1). The testing orientation is participants' updated orientation in the updating condition, the one that they are instructed to adopt or that they adopt subjectively after disorientation (Mou, McNamara, Rump, & Xiao, 2006).

As illustrated in Figure 1, the signed systematic error (in contrast to the random error) in pointing to a target (e_{ij}) has two sources (which are assumed to be independent): the error in representing the body-object vector in terms of the spatial reference direction (η_i) and the error in identifying the spatial reference direction (Θ_{ij}). We hypothesize that the representations of body-object vectors are not disrupted by disorientation and that the variances of the represented error of the target directions with respect to the spatial reference direction (η_i) are comparable in the conditions of updating and disorientation. It is assumed, however, that the uncertainty in identifying the spatial reference direction relative to the testing orientation is higher in the disorientation condition than in the updating condition. In the disorientation condition, people are only able to use the testing orientation specified by the experimenter or adopted subjectively to identify the spatial reference direction because the vector between the body and the object indicating the testing orientation is represented with respect to the reference direction. Identifying the reference direction with respect to the testing orientation is the reverse of retrieving the testing orientation with respect to the reference direction and requires cognitive effort that has been well documented as orientation dependent performance (McNamara, 2003, for a review). Hence the uncertainty in identifying the spatial reference direction relative to the testing orientation is considerable. In the updating condition, the spatial reference direction can be identified from the test orientation but also spatial updating processes by which people keep track of the reference direction during locomotion. We assume that tracking of the reference direction during limited rotation is relatively accurate, so the uncertainty in identifying the spatial reference direction relative to the testing orientation is relatively small in the updating condition. Spatial updating processes cannot be used in the disorientation condition. Greater uncertainty in identifying the spatial reference direction relative to the testing orientation in the disorientation condition leads to larger variance of error in identifying the spatial reference direction (Θ_{ij}) across trials. Hence, the variance of the signed error in pointing to a target (e_{ij}) is larger in the disorientation condition than in the updating condition, producing the disorientation effect.

This explanation is supported by some relevant empirical evidence. Recently Mou, Zhang, and McNamara (2009) demonstrated that indicating the original viewing direction in a test scene eliminated the commonly observed finding that detecting the position change of an object is easier when observers move to a new position than when the table rotates to a spatially identical position (e.g., Burgess, Spiers, & Paleologou, 2004; Simons & Wang, 1998; Wang & Simons, 1999). In one of their experiments, a stick was placed in the test scene to indicate the original viewing direction in both conditions of locomotion and table rotation. The results showed that the superiority of locomotion over table rotation disappeared. These results indicated that people updated their orientation with respect to the spatial reference direction determined by the original viewing direction. Without a stick to indicate the original viewing direction, participants identified the spatial reference direction more accurately in the locomotion condition using spatial updating than in the table rotation condition. Because objects' locations were represented with respect to the spatial reference direction participants located objects' locations more accurately when they identified the spatial reference direction more accurately. However this facilitative effect of locomotion was not necessary when the spatial reference direction was explicitly indicated by a stick in the table rotation condition, as confirmed by the results.

In summary, we propose that when people learn an irregular layout by standing amidst it, they represent body-object vectors with respect to a fixed spatial reference direction parallel to the learning direction. These representations of body-object vectors are enduring and not disrupted after disorientation. The disorientation effect occurs because people have greater uncertainty in identifying the spatial reference direction from the test orientation in the disorientation condition than in the updating condition. This proposal was derived from Mou and McNamara's reference direction model of spatial memory and navigation. In contrast, the prevailing explanations of the disorientation effect consistent with the dynamic spatial updating model proposed by Wang and Spelke (2000, 2002) claim that the disorientation effect occurred because there is no or imprecise enduring spatial representation in memory and precise transient spatial representations are disrupted after disorientation.

Our analysis leads to a prediction that could not be made by the prevailing explanations of the disorientation effect: If, after disorientation, participants are informed of the original viewing direction relative to their current orientation, they should recover the spatial reference direction, which was defined by the original viewing direction, relative to their current orientation and then there should be no disorientation effect as the uncertainty in recovering the reference direction relative to their current orientation should be comparable before and after disorientation. Note that participants' current orientation, as the term is used here, is not necessarily defined in the real room. The current orientation could be a subjective heading imagined by the participants after disorientation. For example, participants might imagine facing the original learning direction after disorientation without any idea of their actual heading in the real room. Four experiments tested this prediction. In two critical experiments (2, 3), participants were informed of their original viewing direction after disorientation. According to the hypothesis of this project, there would be no disorientation effect. Because the hypothesis is supported by the null effect of disorientation, measures were taken to assure that the null effect was not due to a Type II error.

Experiment 1 replicated Xiao et al.'s fourth experiment (2009) and as in that experiment, a disorientation effect was observed. In Experiments 2 and 3, participants were informed of their original viewing direction after disorientation, otherwise the materials, design, and procedure were identical to Experiment 1. The disorientation effects in Experiments 2 and 3 were not significant and the powers were .96 and .92 respectively for detecting the effect (4.14°) observed in Experiment 1 when employing the traditional .05 criterion of statistical significance. In Experiment 4, participants were informed of their test orientation. According to the hypothesis, there would be a disorientation effect. As predicted, the disorientation effect was observed, which provided another piece of evidence that the null effect in Experiments 2–3 was not due to the lack of power.

Experiment 1

Participants learned the locations of nine objects arrayed irregularly from a viewpoint amidst the objects. They stood at the learning position and were tested in the baseline, updating and disorientation conditions. The same layout and experimental procedure as in Xiao, Mou, and McNamara’s (2009) Experiment 4 were used. The aim of this experiment was to replicate the disorientation effect and also to determine the magnitude of the observed effect for subsequent power analyses. In the baseline condition, participants stood amidst the irregular layout and maintained their learning orientation (facing the scissors in Figure 2). In the updating condition, participants turned to face a new heading (ball or candle). In the disorientation condition, participants rotated until they were fully disorientated. Then they were asked to adopt a test perspective (candle or ball). As discussed in the Introduction, identifying the spatial reference direction (defined by the learning heading) relative to the testing orientation when the testing orientation and the learning heading were different is cognitively challenging (McNamara, 2003, for a review). This challenge can be eliminated or reduced in the updating condition because the spatial reference direction can be identified by spatial updating processes by which people keep track of the reference direction during locomotion. However this facilitative effect from the spatial updating process was not available in the disorientation condition. Hence the disorientation effect was expected.

Method

Participants—Twenty-four university students (12 male and 12 female) participated in return for monetary compensation.

Material, Design, and Procedure—The nine objects were placed in a cylindrical room 3.0 m in diameter constructed from a reinforced cloth and a black fabric. As illustrated in Figure 2, the configuration of the layout was the same as in Xiao, Mou and McNamara’s (2009) Experiment 4. A light was placed on the ceiling near the middle of the cylinder to illuminate the space. The floor was covered with gray carpet. The learning and testing location was the same and 1.2 m away from the hat as indicated in Figure 2. Participants’ learning orientation is also indicated in Figure 2.

Each test trial began with a warning signal (“start”) and then a target object was presented (e.g. “please point to the candle”). Trials were presented via wireless earphone controlled by a computer outside the cylinder. A joystick was used as the pointing apparatus.

The primary independent variable was the locomotion of participants just before the testing phase. In the baseline condition, participants stood amidst the irregular layout and maintained their learning orientation (facing the scissors). In the updating condition, participants turned to face a new heading (ball or candle). In the disorientation condition, participants rotated until they were fully disorientated. Then they were asked to adopt a test perspective (ball if they faced candle in the updating condition or candle if they faced ball in the updating condition). In each locomotion condition, there were 9 trials (one for each object) in each block, and 8 blocks of trials were included.

The primary dependent variable was configuration error as discussed in the Introduction and consistent with previous studies (Holmes & Sholl, 2005; Mou, McNamara, Rump, & Xiao, 2006; Waller & Hodgson, 2006; Wang & Spelke, 2000; Xiao, Mou, & McNamara, 2009). Other dependent variables were also measured as in Mou et al. (2006) and Xiao, Mou and McNamara (2009). The *signed pointing error* defined as the signed angular difference between the judged direction of the target object with respect to the test orientation (e.g., facing ball) and the actual direction of the target object with respect to the test orientation (e.g., facing ball); the *heading error,* defined as the mean of the means per target object of the signed pointing errors; the *configuration error,* defined as the standard deviation of the means per target object of the signed pointing errors; and the *pointing variability,* defined as the square root of the mean of the variances per target object of the signed pointing errors.

Before learning, participants were familiarized with the joystick in the preparation room, then they were blindfolded and led to the learning position by the experimenter. The blindfold was removed and the names of objects were provided by the experimenter. Participants learned the layout for 30 seconds before naming and pointing to each object with eyes closed. Each participant received 10 such learning-pointing sessions. Then they put on the wireless earphone and practiced pointing to objects with the joystick 5 times. After each practice, feedback and corrections were given if any absolute pointing error was more than 20 degrees. In the test phase, all participants received the same order of conditions: baseline, updating and disorientation. In the baseline condition, participants maintained their heading to scissors throughout the trials. In the updating condition, participants rotated 240 degrees by themselves (e.g. “please turn right until you are facing the candle”). Half of them turned right to face the candle and half of them turned left to face the ball. In the disorientation condition, participants rotated in place until stopped by experimenter (e.g. “stop and point to the ball”). Participants kept on rotating until the absolute error in pointing to the named object (e.g. ball) was larger than 90 degrees. This procedure assured that participants were fully disoriented. Then participants were required to adopt the test orientation, turning to face the ball if they faced candle in the updating condition (“please turn until you *believe* you are facing the ball”) or to face the candle if they faced the ball in the updating condition. Hence at test, participants subjectively assumed they were facing the ball or the candle although the physical direction of the ball or the candle was more than 90 degrees from their physical facing direction. We had participants adopt a subjective test orientation after disorientation for two reasons: First, this manipulation ensured that the test orientation in the disorientation condition was comparable to that in the updating condition. Second it could prevent participants from adopting the original learning orientation as their subjective test orientation. Mou et al. (2006, experiment 3) showed that without explicitly being asked to adopt a test orientation, half of the participants took the learning viewpoint as the test facing direction after disorientation and the disorientation effect was substantially reduced accordingly.

Results and Discussion

The dependent variables were analyzed in repeated measures analyses of variance (ANOVAs) with one term for locomotion condition. Locomotion condition was a within-participants variable. The results on configuration error were reported in detail. The results on other measures were reported in Tables 1–2 as they may be interesting to some readers. The relatively small heading errors occurred because participants adopted a subjective test orientation after being fully disoriented (as described previously) and the heading errors were scored relative to the direction participants *believed* they were facing, and not relative to objects’ *real* positions in the room.

Configuration error is plotted in Figure 3 as a function of locomotion condition. As shown in the figure, the main effect of locomotion condition was significant, $F(2, 46) = 21.77$, $p <$.

01, *MSE* = 27.17. Pairwise comparisons showed that configuration error was smaller in the baseline condition than in the updating and disorientation conditions, *ts* (46) ≥ 3.82, $p < .01$. Configuration error was smaller in the updating condition than in the disorientation condition (20.66° vs. 24.80°), $t(44) = 2.76$, $p < .01$.

Experiment 1 successfully replicated the disorientation effect. The effect of disorientation, 4.14°, would be used as the predicted effect in the power analyses in the following experiments in which the null effect was observed.

Experiment 2

In Experiment 2, after disorientation, participants were asked to imagine that they were facing the original learning direction and then turned their body to adopt the test orientation. Participants should be able to imagine that they were facing the original learning direction after disorientation by directly retrieving the enduring representation of their original learning orientation (i.e., facing the scissors). This assumption was supported by Experiment 3 of Mou, McNamara, Rump, and Xiao (2006). In that experiment, participants were not explicitly asked to adopt a specific test orientation. The results showed that half of the participants took their learning viewpoint as the test facing direction after disorientation and the disorientation effect was substantially reduced accordingly.

In the current experiment, after adopting the imagined original learning direction as their subjective heading, participants should be able to recover the reference direction, which is parallel to the original learning direction and is the same as their subjective heading, and retrieve the directions of the objects with respect to the recovered reference direction. Participants should also be able to keep track of the recovered reference direction defined by this imagined original learning direction while they turned their body to face the direction they believed to be the testing orientation (e.g. facing ball), even though this facing direction might not be the actual testing orientation in the room. Under these conditions, then, participants should be able to identify the spatial reference direction relative to the testing orientation (i.e., the facing direction participants believe to be the testing orientation) in the disorientation condition with the same degree of certainty as when they identify the spatial reference direction relative to the updated testing orientation in the updating condition. If the disorientation effect occurred because of the uncertainty in identifying the spatial reference direction from a test orientation that was different from the learning orientation in the disorientation condition, the manipulation should remove the disorientation effect. In contrast if the disorientation effect occurred because there are no or less accurate enduring representations after disorientation, the manipulation should not remove the disorientation effect.

Method

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

Materials, Design and Procedure—The materials, design, and procedure were the same as Experiment 1 except for the disorientation condition. After disorientation, they were instructed to imagine facing the learning direction (“imagine you are facing the scissors now”) and to rotate toward the object in the testing direction (e.g., “then turn to face the ball”).

Results and Discussion

The dependent variables were analyzed in repeated measures analyses of variance (ANOVAs) with one term for locomotion condition. Locomotion condition was a within-participants variable. The results on configuration error were reported in detail. The results on other measures were reported in Tables 1–2.

Configuration error is plotted in Figure 4 as a function of locomotion condition. As shown in the figure, the main effect of locomotion condition was significant, $F(2, 46) = 27.06$, $p < 0.01$, $MSE = 16.76$. Pairwise comparisons showed that configuration error was smaller in the baseline condition than in the updating and disorientation conditions, $ts(46) \geq 6.26$, $p < .01$. The difference between the latter two conditions was not significant, $t(46) = 0.21$, $p > .05$. The power of the experiment to detect an effect of the magnitude observed in Experiment 1 (4.14°) was .96 using the traditional .05 criterion of statistical significance.

In Experiment 2, configuration error did not increase in the disorientation condition relative to the updating condition. The disorientation effect was observed in the previous experiment of the current study and Experiment 4 of Xiao et al. (2009), using the same materials, design, and procedure except for the reorientation manipulation in the disorientation condition in the current experiment. Furthermore the failure to obtain the disorientation effect is unlikely due to the type II error. The probability of failure to detect the disorientation effect of 4.14° when employing the traditional .05 criterion of statistical significance is .04 as the power is .96. Hence the failure of obtaining the disorientation effect should be attributed to the manipulation of reorientation in the current experiment. Experiment 2 provides the first demonstration that the disorientation effect will disappear if participants directly retrieve the original viewing direction and then turn to face the testing orientation relative to the retrieved original viewing direction after disorientation.

Experiment 3

In Experiment 3, after disorientation, instead of imagining that they were facing the original viewpoint, participants turned to adopt the testing orientation and were explicitly instructed by the experimenter where the original viewing direction was. The aim of Experiment 3 was to provide convergent evidence that if participants could identify the original viewing direction after disorientation, the disorientation effect would disappear. We still expected that the uncertainty in locating objects in the disorientation condition would be larger than in the baseline condition. The extra error was expected to come from the inconsistency between the test body orientation and the learning orientation in the disorientation condition. Although participants knew explicitly the direction of the learning orientation with respect to their test orientation and could retrieve the bearing between the target object and their body with respect to the reference direction defined by the learning orientation, they still needed to redefine that bearing to one specified in terms of their body orientation to make the pointing response. This extra computational process was not necessary in the baseline condition as the test orientation was the same as the learning orientation. Hence retrieval of the bearings in terms of the learning viewpoint from the test body orientation was harder in the disorientation condition than in the baseline condition. Participants also needed to retrieve the bearings in terms of the learning viewpoint from the test body orientation in the updating condition. The uncertainty was therefore expected to be comparable in the disorientation condition and in the updating condition, both larger than that in the baseline condition.

Method

Participants—Twenty-four university students (12 male and 12 female) participated in return for monetary compensation.

Materials, Design and Procedure—The materials, design, and procedure were the same as Experiment 1 except for the disorientation condition. After participants were disorientated, the experimenter stood at the object position in the testing direction (e.g., ball) and informed participants to adopt the testing orientation ("please turn to face to me"). Participants were not informed that they were facing in the testing orientation. After participants turned to face the experimenter, the experimenter moved and stood at the object position in the learning direction (i.e., scissors) and informed the participants where the original learning direction was ("I'm standing at the scissors, please point to the scissors"). Participants were then required to point to objects in the previous experiments.

Results and Discussion

The dependent variables were analyzed in repeated measures analyses of variance (ANOVAs) with one term for locomotion condition.

Configuration error is plotted in Figure 5 as a function of locomotion condition. As shown in the figure, the main effect of locomotion condition was significant, $F(2, 46) = 14.46$, $p < .01$, $MSE = 20.28$. Pairwise comparisons showed that configuration error was smaller in the baseline condition than in the updating and disorientation conditions, $ts(46) \geq 4.00$, $p < .01$. The difference between the latter two conditions was not significant, $t(46) = 1.12$, $p > .05$. The power of the experiment to detect a disorientation effect of the magnitude observed in Experiment 1 (4.15°) was .92 using the traditional .05 criterion of statistical significance.

In Experiment 3, configuration error did not increase in the disorientation condition compared with the updating condition. The null disorientation effect is unlikely due to the type II error. The probability of the type II error is .08 as the power is .92. Experiment 3 provided the second demonstration that the disorientation effect will disappear if participants can identify the original viewing direction after disorientation accurately.

Experiment 4

The previous experiments demonstrated that identifying the original learning viewpoint after disorientation can remove the disorientation effect. These experiments cannot rule out the possibility that any reorientation information (e.g., information about location of any object) can remove the disorientation effect, which undermines our proposal that the uncertainty in identifying the spatial reference direction after disorientation leads to the disorientation effect. In Experiment 4 of this project, participants were explicitly told the testing orientation by the experimenter.

Method

Participants—Twenty-four university students (12 male and 12 female) participated in return for monetary compensation.

Materials, Design and Procedure—This experiment was the same as Experiment 3 except for the disorientation condition. As in Experiment 3, after participants were disorientated, the experimenter stood at the object position in the testing direction and asked participants to turn to face that direction ("I'm standing at the ball, please turn to face to me"). Unlike Experiment 3, participants were not then informed the original learning direction.

Results and Discussion

The dependent variables were analyzed in repeated measures analyses of variance (ANOVAs) with terms for locomotion condition.

Configuration error is plotted in Figure 6 as a function of locomotion condition. As shown in the figure, the main effect of locomotion condition was significant, $F(2, 46) = 17.48$, $p < .01$, $MSE = 30.25$. Pairwise comparisons showed that configuration error was smaller in the baseline condition than in the updating and disorientation conditions, $ts(46) \geq 3.27$, $p < .01$. Configuration error was smaller in the updating condition than in the disorientation condition, $t(44) = 2.63$, $p < .01$.

Experiment 4 showed that indicating the test orientation is not enough to remove the disorientation effect and undermined the possibility that any reorientation information can remove the disorientation effect.

General discussion

The aim of this project was to investigate whether there are precise enduring spatial representations of objects' locations especially when people learn an irregular layout of objects by standing amidst it. Wang and Spelke (2000, 2002) originally proposed that there are no precise enduring spatial representations of objects' locations[1]. Spatial navigation relies on the dynamical updating of body-object vectors during locomotion. By contrast, Mou and McNamara (e.g., Mou, McNamara, Valiquette, & Rump, 2004; Zhang, Mou, & McNamara, 2011) proposed that enduring body-object vectors, interobject vectors, and their learning orientation are represented with respect to a fixed reference direction. During locomotion, people calculated new body-object vectors and new orientation by adding the translation and rotation information to the enduring representations.

The disorientation effect was originally reported by Wang and Spelke (2000) to support the conjecture that precise enduring spatial representations of objects' locations did not exist. The disorientation effect when people learn an irregular layout while standing in the middle of it was replicated in several follow-up studies (Mou, McNamara, Rump, & Xiao, 2006; Waller & Hodgson, 2006; Xiao, Mou, & McNamara, 2009; Sargent, Dopkins, Philbeck, & Modarres, 2008; but see Holmes & Sholl, 2005). There are two alternative explanations of the disorientation effect. The prevailing explanation consistent with Wang and Spelke's model is that people form precise, transient body-object spatial representations but do not form or form imprecise, enduring spatial representations when they learn an irregular layout by standing amidst it. The transient spatial representations are updated during locomotion, but are disrupted by disorientation, which forces people to use imprecise enduring spatial representation after disorientation (Mou, McNamara, Rump, & Xiao, 2006; Waller & Hodgson, 2006; Wang & Spelke, 2000; Xiao, Mou, & McNamara, 2009; but see Holmes & Sholl, 2005). The alternative explanation proposed in this paper is more consistent with Mou and McNamara's model. This explanation stipulates that people represent enduring body-object vectors (which may or may not be precise) when they learn an irregular layout and these vectors are specified with respect to a fixed spatial reference direction parallel to the learning direction. When people locomote, they update their orientation with respect to the spatial reference direction. Disorientation does not disrupt body-object vectors but instead interferes with the ability to recover the spatial reference direction relative to the testing orientation, thereby adding error to pointing judgments and causing the disorientation effect.

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[1] Wang (2011) stated that there is an enduring viewpoint dependent spatial representation that might be used after disorientation.

The findings of this project support the second of these two explanations. Participants in Experiments 2 and 3 were given the original learning direction after disorientation by being asked to imagine that they were facing the learning direction before turning to face the testing orientation or by being told the learning direction at the testing orientation. The results showed that informing participants of the learning direction after disorientation removed the disorientation effect. The null effect of disorientation is unlikely due to a Type II error as the probability of a Type II error is .04 and .08 in Experiments 2 and 3 respectively. According to the explanation advanced here, when participants were given the learning direction explicitly, the uncertainty in identifying the spatial reference direction from the testing orientation was removed or reduced greatly, and as a consequence, variability in error in pointing to objects did not increase relative to the updating condition. The standard explanation has difficulty accommodating these findings. If people do not have precise enduring spatial representations, there is no mechanism by which the disorientation effect can be removed by providing participants with information about the learning viewpoint. The present findings suggest that people do have enduring body-object vectors represented in terms of a fixed spatial reference direction and that the greater uncertainty in identifying the spatial reference direction relative to participants' testing orientation after disorientation causes the greater variance of the error in locating objects across trials.

Using the model illustrated in Figure 1, we can roughly estimate the contributions to the uncertainty in pointing from the different sources if we assume that the contributions are independent. The configuration error is around 15° in the baseline condition, which is consistent across all experiments. The configuration error in the updating is around 20°, which is consistent across all experiments. The configuration error in the disorientation condition when participants explicitly knew their learning orientation is also around 20° consistently in Experiments 2 and 3. The configuration error in the disorientation condition when participants did not know their learning orientation is also 25° consistently in Experiments 1 and 4. We may attribute the uncertainty in the baseline condition (15°) to the error in representing the body-object vector in terms of the spatial reference direction (η_i). We may attribute the increased uncertainty ($\sqrt{(25^2-20^2)}\approx 15°$) in the disorientation condition when participants did not know the learning orientation relative to the updating condition to the error in identifying the spatial reference direction (θ_{ij}). We may also attribute the increased uncertainty ($\sqrt{(20^2-15^2)}\approx 13°$) in the updating condition and the disorientation condition when participants knew the learning orientation compared to the baseline condition to the cost in computing the bearing of the target with respect to a new testing orientation (this term is not included in the model in Figure 1 for simplicity)[2].

The findings of this project provide novel empirical evidence for and extend the model of spatial memory proposed by Mou, McNamara and their colleagues (e.g., Mou & McNamara, 2002; Mou, McNamara, Valiquette, & Rump, 2004; Mou, Zhang, & McNamara, 2009; Zhang, Mou, & McNamara, 2011). There are two unique claims in this model and both claims were supported by the findings of this project.

First, Mou and McNamara's model stipulates that there is a fixed reference direction in spatial memory (at least for enduring spatial representations). The reference direction, once selected, is a stable component of the representation and typically is not altered as people locomote (see Shelton & McNamara, 2001, for situations in which reference directions are altered). Other models either do not claim there is a reference direction in spatial memory or claim that a reference direction is fixed to participants' orientation as they locomote (e.g., Easton & Sholl, 1995; Sholl & Nolin, 1997; Wang & Spelke, 2000, 2002). This project provided new evidence that reference directions are fixed in the environment in spatial

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[2] We are grateful to one anonymous reviewer for the suggestions to add this analysis.

memory. Otherwise it is difficult to understand why information about the learning viewpoint would improve the consistency in locating objects. In the present experiments, reference directions were selected using egocentric cues (i.e. the learning orientation). The fact that egocentric cues were used to select reference directions does not imply that the reference direction itself is egocentric. In Mou and McNamara's model, fixed reference directions (a type of allocentric reference direction) are selected using egocentric and nonegocentric cues, including external frames and layout geometry (e.g., Greenauer & Waller, 2010; Mou, Xiao, & McNamara, 2008; Shelton & McNamara,2001).

The original model proposed by Mou, McNamara, Valiquette, and Rump (2004) did not cast an important role for body-object vectors in enduring spatial memories. Mou, Xiao, and McNamara (2008) speculated that body-object vectors could be represented with respect to an allocentric reference direction but did not have direct evidence for this hypothesis. This project suggests that body-object vectors are also represented with respect to a fixed reference direction extending the model of Mou and McNamara.

The second unique claim in the model of Mou and McNamara is that during locomotion, people update their body-object vectors and their allocentric heading with respect to the spatial reference direction that is selected at learning, and then compute objects' location with respect to their new location and orientation as needed (Mou, McNamara, Valiquette, & Rump, 2004; Zhang, Mou, & McNamara, 2011). We are not aware of any other models that specify that people update with respect to a fixed reference direction although it was proposed that non-human animals might use a fixed reference direction during navigation (e.g., Gallistel, 1990; Wehner, Michel, & Antonsen, 1996). Wang and Spelke (2000) argued that people update all body-object vectors dynamically (see also Wang et al., 2006). Hodgson and Waller (2006) argued that people form enduring, long-term memory representations of the layouts at learning and reconstruct spatial information about the layouts as needed (i.e., offline updating). This is very similar to Mou and McNamara's model except that Mou and McNamara speculated that people update with respect to a fixed spatial reference direction that has been used to represent objects' locations.

The notion that people update their orientation with respect to the originally selected spatial reference direction can explain the results of the present experiments. Participants can identify the spatial reference direction relative to their current orientation accurately in the updating condition because of spatial updating with respect to the reference direction during locomotion. This facilitative effect of locomotion is not available in the disorientation condition. Uncertainty in locating the spatial reference direction relative to their testing orientation after disorientation creates greater variability in the errors of pointing to objects, the disorientation effect. The disorientation effect is eliminated when the spatial reference direction is identified explicitly after disorientation; in effect, explicit identification replaces spatial updating as a means to locate the originally selected spatial reference direction. This set of findings is challenging to explain unless one assumes that people update their orientation with respect to the original spatial reference direction.

There is another study indicating that people update with respect to a fixed reference direction (Mou, Zhang, & McNamara, 2009). As discussed in the Introduction, Mou, Zhang, and McNamara demonstrated that the facilitative effect of spatial updating during locomotion for position change detection disappeared when participants were explicitly informed of the original viewing direction in the table rotation condition. This demonstration indicated that participants kept track of the spatial reference direction parallel to the viewing direction during locomotion. Participants could identify the spatial reference direction more accurately in the locomotion condition than in the table rotation condition without the explicit indication of the original viewing direction. Hence there was facilitative effect of locomotion. This facilitative effect of locomotion was not necessary when the original viewing direction was explicitly indicated in the table rotation condition. Mou, Zhang, and McNamara's experiments and the current experiments differ dramatically in terms of learning durations, testing tasks, and so forth. In spite of these differences, the studies provided converging evidence that people keep track of the fixed spatial reference direction during locomotion. Furthermore, both studies implicated that reorientation and maintaining orientation might rely on identifying the spatial reference direction (Kelly, McNamara, Bodenheimer, Carr, & Rieser, 2008). The more accurately people can identify the spatial reference direction, the more accurately they can reorient to the environment.

The new explanation of the disorientation effect proposed in this paper should not be generalized to circumstances in which the disorientation effect was not present. In particular, we are not claiming that people primarily represent body-object spatial relations with respect to a fixed reference direction when people learn a regular layout (Mou, McNamara, Rump, & Xiao, 2006; Xiao, Mou, & McNamara, 2009). Instead when people learn a regular layout, they represent both body-object and interobject vectors with respect to a fixed spatial reference direction. The represented interobject spatial relations can be used to locate objects after disorientation and remove the disorientation effect. It is still not clear how people combine representations of the interobject vectors and representations of the body-object vectors to determine an object's location (Cheng, Shettleworth, Huttenlocher, & Rieser, 2007). Future studies are needed to address this issue.

A different version of the uncertainty hypothesis was tested in previous studies (Mou et al., 2006; Waller & Hodgson, 2006; Wang & Spelke, 2000). According to this uncertainty hypothesis, the uncertainty in pointing to an individual object (i.e. pointing variability) might increase after disorientation and thus might lead to the higher configuration error after disorientation although the configuration of the objects might not be disrupted after disorientation. This hypothesis was disconfirmed by findings that the configuration error still increased after disorientation even when the contribution of the pointing variability to the configuration error was removed statistically. This hypothesis was also undermined by the finding that the configuration error increased after disorientation but the pointing variability was constant across disorientation (e.g. Experiment 4 in the current study).

The uncertainty hypothesis proposed in the current study does not predict that the disorientation effect on pointing variability should be observed when the disorientation effect on configuration error is observed. According to the uncertainty hypothesis of the current study after disorientation people have greater uncertainty about the reference direction (defined by the original learning direction in the current study) relative to their testing heading. This uncertainty contributes to the pointing error when people map the target direction with respect to the reference direction (i.e. the original learning direction) onto an egocentric frame of reference determined by the testing heading to make the pointing response. This uncertainty should be applicable to all objects and thus increase the configuration error. However it is plausible that people might maintain representations of the egocentric directions of the targets longer than one trial and use these representations to point to the same objects presented again. Hence the uncertainty of identifying the reference direction (i.e. the original learning direction) relative to the testing heading might have less influence on the variance of within-object pointing error than on the variance of across-object pointing error, especially when the same objects are tested multiple times, as they were in the current study. This conjecture implies that when there is no disorientation effect on the variance of across-object pointing error, there will be no disorientation effect on the variance of within-object pointing error. Hence the current uncertainty hypothesis predicts that when there is no disorientation effect on configuration error (i.e. the variance of across-object pointing error), there should be no disorientation effect on pointing variability (i.e. the variance of within-object pointing error). The results of the current study showed that there was no disorientation effect on pointing variability or on configuration error in Experiments 2 and 3. There was a disorientation effect on configuration error in both Experiments 1 and 4. There was a disorientation effect on pointing variability in Experiment 1 but a significant disorientation effect on pointing variability was not observed in Experiment 4. In fact the pointing variability did increase numerically although it was not significant in Experiment 4. These findings are therefore consistent with the uncertainty hypothesis proposed in the current study.

The last issue we need to address is why in Experiment 4, participants were not able to identify the spatial reference direction accurately after disorientation using their testing orientation. This result is consistent with the orientation dependency in retrieving spatial relations that has been well documented (McNamara, 2003 for a review). Participants usually have more difficulty in pointing to objects at the headings that are oblique to their learning viewpoint than at the headings parallel or orthogonal to their learning viewpoint. In this project, participants' testing orientation after disorientation was misaligned with (i.e., neither parallel nor orthogonal to) the learning direction. The difficulty in identifying the learning direction at the testing orientation is likely caused by the same mechanisms that cause orientation dependency in perspective taking tasks. This analysis can also be used to explain why the disorientation effect appeared even when participants were reoriented by turning on the light that was mounted on one side of the ceiling in Experiment 5 of Wang and Spelke (2000). It is very likely that participants in their experiment did not represent body-object vectors with respect to the direction determined by the position of the light. Instead other cues in the environment (e.g., the door) might be more salient to determine a reference direction. If the position of the light did not directly indicate the reference direction, then the disorientation effect would still occur.

In conclusion, this study showed that disorientation did not disrupt the internal consistency of pointing to objects using memory if participants accurately identified the original learning direction after disorientation. This finding indicates that the disorientation effect is caused by greater uncertainty in identifying the reference direction defined by the original learning direction after disorientation, not by disruptions to spatial memories, and therefore, supports the claim that there are enduring spatial representations of objects' locations in memory even when people learn an irregular layout by standing amidst it.

Acknowledgments

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Highlights

- Disorientation effect appeared when people did not know the learning direction
- Disorientation effect disappeared when participants knew the learning direction
- Disorientation effect was due to the imprecise recovery of reference direction

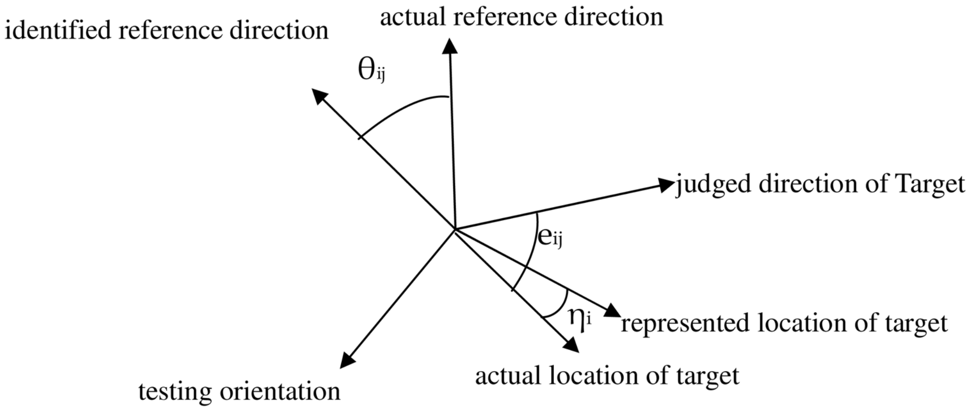

Figure 1.
Model of pointing to objects using spatial memory

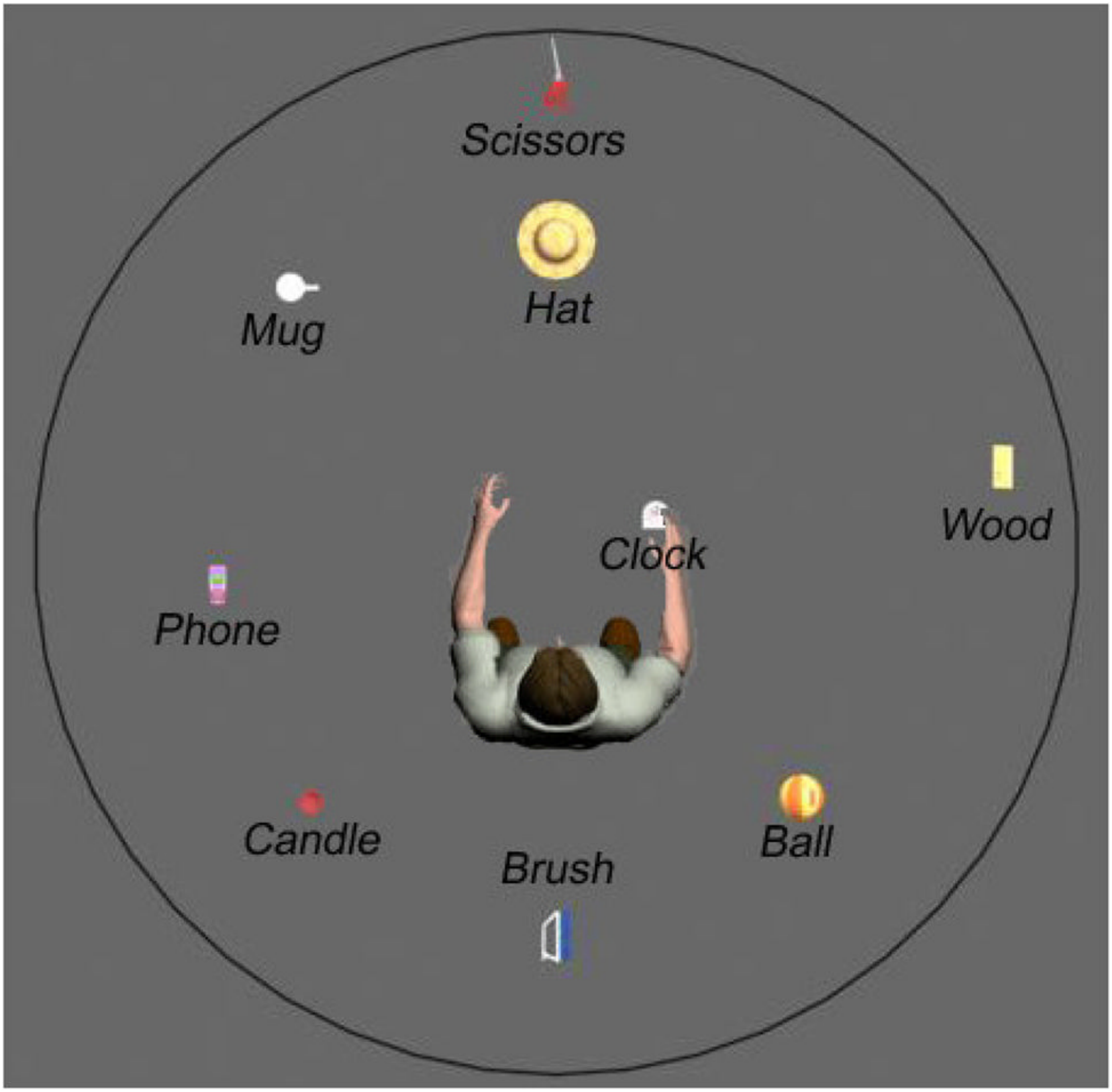

Figure 2.
Layout of objects used in Experiments.

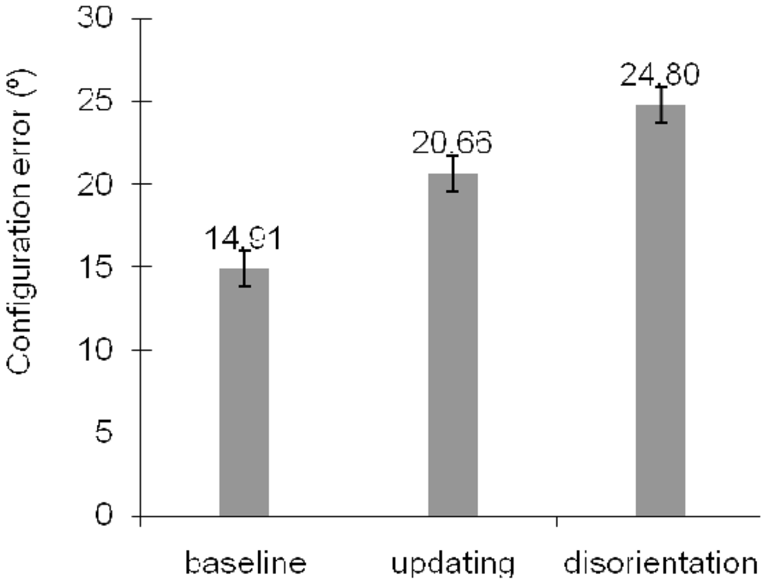

Figure 3.

Configuration error as a function of locomotion condition in Experiment 1. (Error bars are ±1 standard error, as estimated from the analysis of variance.)

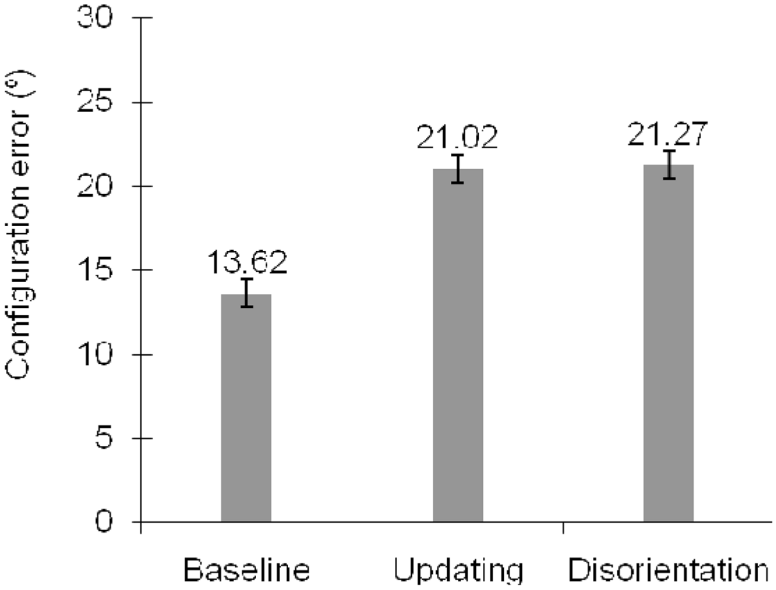

Figure 4.

Configuration error as a function of locomotion condition in Experiment 2. (Error bars are ±1 standard error, as estimated from the analysis of variance.)

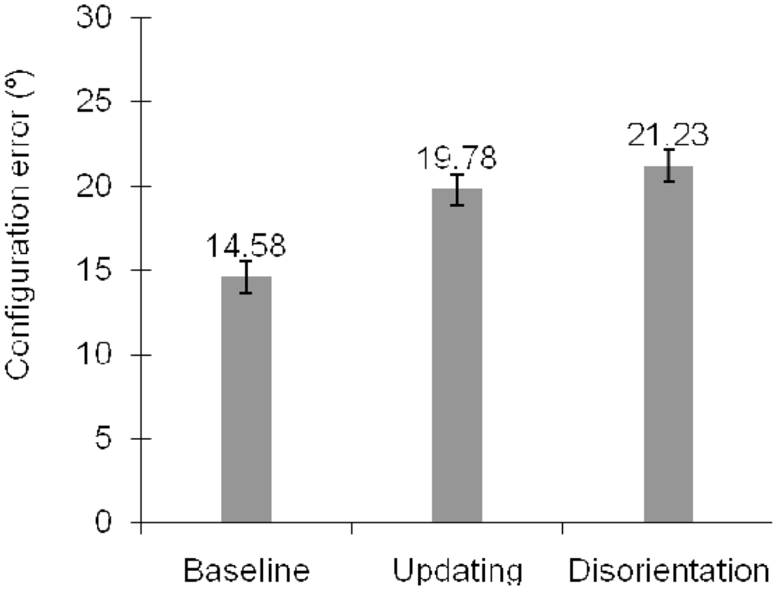

Figure 5.
Configuration error as a function of locomotion condition in Experiment 3. (Error bars are ±1 standard error, as estimated from the analysis of variance.)

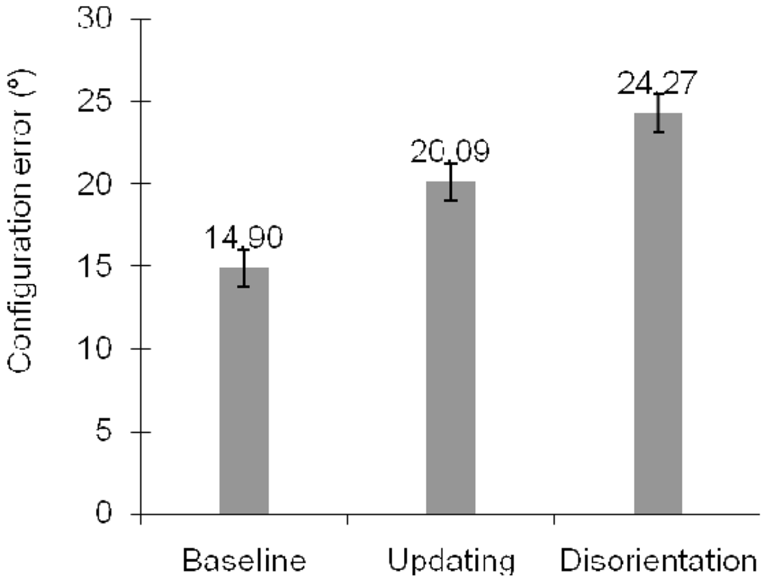

Figure 6.

Configuration error as a function of locomotion condition in Experiment 4. (Error bars are ±1 standard error, as estimated from the analysis of variance.)

Table 1

Means (and Standard Deviations) of pointing variability as a function of locomotion condition for each experiment

Exp	Locomotion condition			Comparison
	B	**U**	**D**	
1	10.61 (5.29)	15.60 (4.05)	19.36 (8.52)	B<U; B<D; U<D
2	9.85 (2.23)	13.58 (3.24)	13.65 (3.53)	B<U; B<D; U = D
3	9.54 (2.77)	16.22 (5.61)	15.47(4.11)	B<U; B<D; U = D
4	10.95 (3.38)	14.88 (4.10)	16.19 (6.44)	B<U; B<D; U = D

Note: n = 24 in all experiments. B = Baseline; U = Updating; D = Disorientation. In comparison “<” refers to significantly smaller at .05 level; “=” refers to no significantly difference at .05 level.

Table 2

Means (and Standard Deviations) of Absolute heading error as a function of locomotion condition for each experiment

Exp	**Locomotion condition**			**Comparison**
	B	**U**	**D**	
1	3.83 (3.16)	13.51 (9.03)	22.08 (20.75)	B<U; B<D; U<D
2	3.90 (3.35)	16.20 (11.11)	23.15 (11.54)	B<U; B<D; U<D
3	5.11 (4.32)	15.89 (9.63)	19.75 (12.81)	B<U; B<D; U = D
4	4.76 (3.70)	17.70 (13.69)	21.81 (17.10)	B<U; B<D; U = D

Note: n = 24 in all experiments. B = Baseline; U = Updating; D = Disorientation. In comparison “<” refers to significantly smaller at .05 level; “=” refers to no significantly difference at .05 level.