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Getting Completely Turned Around: How Disorientation Impacts Subjective Straight-Ahead

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Abstract

In manipulating a pointer to indicate subjective straight ahead (SSA), participants were more variable after a series of whole-body rotations in conjunction with external sensory blockade than after external sensory blockade alone. The variability of reported SSA did not increase consequent to a temporal delay matched to the time taken by the rotation procedure. The results suggest that an observer's egocentric reference frame is more complex and less stable than has previously been thought.

Keeping track of heading and position with respect to surrounding objects is a crucial ability for humans (and indeed many other organisms) as they move about an environment. In seeking to understand how an observer uses knowledge about object locations when tracking heading and position, theorists have drawn a distinction between egocentric and allocentric reference frames. In an egocentric reference frame, object locations are encoded relative to a reference system aligned upon the observer. In an allocentric reference frame, object locations are encoded relative to a reference frame defined by features of the environment rather than the observer (Klatzky, 1998).

Heading and position are tracked on the basis of information from external and internal sensory systems. Vision and audition are the most important of the external systems. Internal – *idiothetic* - sensory information can come from the vestibular, proprioceptive, or kinesthetic systems (Philbeck & Sargent, 2013). When external sensory input is minimal, heading and position must be tracked on the basis of primarily idiothetic information. This would be the case, for example, if one were walking through a forest in darkness. As would be expected, heading and position tend to be tracked less successfully under such conditions. In short, one tends to become disoriented with respect to the environment. Disorientation can have devastating consequences, as for example in aviation, hiking, or even navigation in once-familiar settings for patients with memory disorders. Thus, there is a pressing need to understand the process of tracking heading and position under minimal external sensory input.

Failures in the tracking of heading under minimal external sensory input have been studied with a *blind pointing task* in which participants learn the locations of a set of objects and then attempt to point to the objects from a central location, in the absence of visual and auditory input (Wang & Spelke, 2000). Of particular interest is the effect on performance of an *orientation challenge* comprising one or more full-body rotations. One can assess the effects of such a challenge by computing a signed angular *error score* for each response of each participant to each object in the set. For a given participant and object, *individual error* and *pointing error* are, respectively, the mean and standard deviation of the error scores across responses. For a given participant, *heading error* and *configuration error* are, respectively, the mean and standard deviation of the individual errors across objects. In response to increasing degrees of orientation challenge, the heading error for a group of participants tends to be distributed with increasing uniformity over the 360 degree range, implying that participants tend to become increasingly disoriented with respect to the objects in the set¹. The average pointing error across participants and objects tends to increase, implying that participants' knowledge of the locations of the objects tends to become less precise. Finally, the average configuration error across participants tends to increase, implying that participants' knowledge of the between-object location relationships tends also to become less precise (Holmes & Sholl, 2005; Mou, McNamara, Rump & Xiao, 2006; Sargent, Dopkins, Philbeck, & Arthur, 2008; Waller & Hodgson, 2006; Wang & Spelke, 2000; Wang, 2012; Xiao, Mou & McNamara, 2009).

The present study further explored the tracking of heading under minimal external sensory input. We were particularly interested in the role of the egocentric reference frame in this process. To an initial analysis, the egocentric reference frame would seem to be a simple, integrated, entity. As such, one would not expect this reference frame to be affected by manipulations that affect the observer's tracking of heading with respect to objects in the surrounding environment. In fact, past work has assumed that the egocentric reference frame is unaffected by such manipulations. In computing measures of pointing error, heading error, and configuration error, as were described earlier, researchers have assumed the stability of the egocentric reference frame in terms of which the locations of objects are stated. However, the egocentric reference frame is anchored in the body, which is composed of multiple parts. Thus, it is possible that the integrity of the egocentric reference frame is more precarious than has been thought.

The present study asked whether the egocentric reference frame is affected by manipulations that affect the observer's tracking of heading with respect to objects in the surrounding environment. To answer this question, we used a version of the blind pointing task in which participants were not required to point to any objects (as has typically been the case in past work showing an effect of orientation challenge on configuration error), but instead were simply asked to indicate *subjective straight ahead* (SSA). We asked how the signed angular

¹Wang & Spelke (2000) observed that heading error was uniformly distributed on a single trial in which participants were subjected to a series of clockwise and counter-clockwise rotations. Wang & Spelke characterized their participants as disoriented. Sargent, Dopkins, Philbeck, & Arthur (2008) observed that heading error became gradually more uniformly distributed across a series of trials on each of which participants were subjected to a single rotation. In the present context, it was not necessary that participants become completely disoriented as a result of our orientation challenges. It was merely necessary that the egocentric reference frame be stressed.

error in SSA responses varied with increasing amounts of orientation challenge. We considered two aspects of the error in SSA responses. The *bias* of SSA responses was the degree to which SSA responses were systematically incorrect in either a leftward or rightward direction. The *variability* of SSA responses was the degree to which SSA responses varied from trial to trial. We were particularly interested in the variability of SSA responses. Given that an orientation challenge increases the variability of pointing responses to objects, we thought it possible that such a challenge would increase the variability of SSA responses. We reasoned that, if an orientation challenge increased the variability of SSA responses, this would suggest that such a challenge decreased the stability of the egocentric reference frame. In pursuit of this intuition, we assessed the error in SSA responses following external sensory blockade, following external sensory blockade coupled with orientation challenge, and following external sensory blockade coupled with a temporal delay matched to the duration of the orientation challenge.

Experiment 1

Research with the traditional blind pointing task has demonstrated that pointing error and configuration error increase consequent to an orientation challenge. These results have been interpreted as reflecting the difficulty of updating multiple, egocentric object location codes during an orientation challenge (Wang, 2000; Wang, 2012; Wang, Crowell, Simons, Irwin, Kramer, Ambinder, et al., 2006; Wang & Spelke, 2000; however, see also Waller & Hodgson, 2006). Implicit in this interpretation is the assumption that the egocentric reference frame in terms of which object location is indicated remains stable in the face of such a challenge. In the preceding we suggested a rationale for questioning this assumption. Experiment 1 sought to test the assumption. The experiment assessed the bias and variability of SSA responses under differing degrees of orientation challenge.

In all conditions, participants reported SSA on each of twenty trials, donning a blindfold and hearing protectors before the first trial. In the Sensory Blockade (SB) condition, participants experienced no additional manipulations. In the Update (U) condition, participants were subject to an intermediate level of orientation challenge in addition to the external sensory blockade. Specifically, they experienced a single 90° rotation before responding on each trial. In the Orientation Challenge (OC) condition, participants were subject to a stronger orientation challenge in addition to the external sensory blockade. Specifically, they experienced multiple clockwise and counterclockwise rotations before responding on each trial.

Method

Participants—The sample comprised 10 females and 7 males with a mean age of 20.4 years. The following, in addition, was true for the samples in this and the other experiment of the study: the participants were right-handed, reported normal or corrected-to-normal vision, were undergraduate students at the George Washington University and received course credit in exchange for their efforts. The research was approved by the George Washington University Institutional Review Board and was performed in accordance with

the ethical standards of the 1964 Declaration of Helsinki. Written consent was obtained from all participants prior to testing.

Materials and Apparatus—All testing took place in a cylindrical chamber 3m in diameter. Participants were seated in a motorized rotating chair at the center of the chamber. A manual pointing device affixed to the chair was used to indicate SSA. This pointer was visually occluded during all pointing responses by a wooden board mounted to the chair. The pointer was mounted horizontally at the level of the subjects' midsection. The pointer's axis of rotation was offset by approximately 23 cm from the chair's axis of rotation. The pointer consisted of a 16 cm wooden manipulandum mounted to a polar scale graduated to the nearest degree (See Figure 1). Chair motion was remotely controlled using a computer located outside the experimental chamber. All rotations used in the experiment were capped at a maximum acceleration of 90 degrees/s/s and a maximum velocity of 90 degrees/s –these parameters allow for movements that are well above the vestibular threshold. For a more in-depth description of the apparatus and velocity profiles used here please see our previous work (Arthur, Philbeck, & Chichka, 2007).

Design—The experiment used a completely within-subjects design. Because the SB condition was intended as a baseline for the experiment this condition was always administered first so that participants would not be subject to lingering effects of manipulations applied in the U and OC conditions. The order of the U and OC conditions was counterbalanced across participants. All testing took place during a single one-hour-long testing session.

Procedure—The experiment comprised a pointer familiarization phase and an test phase. The pointer familiarization phase was implemented to minimize errors arising due to misunderstanding of the directions or previously demonstrated biases (Philbeck, Sargent, Arthur, & Dopkins, 2008). Participants were shown into the cylindrical experimental chamber and seated in the rotating chair with full vision. They then pointed in a random order (with no blindfold, but with the hand and the pointer occluded) to the four cardinal directions, which were identified as front, back, left, and right. Participants were required to point within 10 degrees of each direction relative to the pointer axis. Once four correct responses were recorded for a direction, that direction was no longer tested. If participants responded incorrectly for a direction, participants were shown (with vision of the pointer) the correct response for the direction in question.

Prior to the test phase, the experimenter defined SSA to the participant as straight ahead from the participant, that is - the direction in which the participant was facing or heading in the chamber, regardless of what that direction might be. More concretely, the experimenter explained SSA as a directional ray starting in the middle of the participant's torso and extending outward in the direction of the participant's heading. Prior to the first trial in all conditions, the participant donned a blindfold and hearing protectors. On each trial in the SB condition, the participant used the pointer to indicate SSA. Each SB trial lasted approximately 5 seconds². On each trial in the U condition, the participant was rotated 90 degrees clockwise and then used the pointer to indicate SSA. The participant was then rotated back to the starting heading. Each U trial lasted approximately 7 seconds. On each

trial in the OC condition, the participant experienced an orientation challenge and then used the pointer to indicate SSA. The orientation challenge was similar to that used by Sargent, Dopkins, Philbeck, and Chichka (2010). The challenge included seven sequential rotations: 200 degrees clockwise (C), 100 degrees counterclockwise (CC), 40 degrees CC, 100 degrees C, 90 degrees CC, a filler rotation, and finally a return to the starting heading. The filler rotation was either 60 degrees CC, 120 degrees C, 120 degrees CC, or 210 degrees C (randomly selected with replacement across trials). Thus, although participants were always rotated back to the same starting heading after the orientation challenge, the magnitudes of the last two rotations in the set differed across trials. This was intended to discourage participants from assuming that they were always being moved back to the same heading, an assumption we reasoned might lessen the effect of the orientation challenge. Each OC trial lasted approximately 25 seconds. In all conditions, the participant manipulated the pointer with the right hand to indicate SSA. After each trial in all conditions the experimenter turned the pointer so that it pointed toward the center of the participant's abdomen. Thus, the participant had to move the pointer on every trial. After the last of the 20 trials in each condition, the participant was allowed to raise the blindfold.

Results

SSA error was assessed as follows: pointing responses that fell to the left and the right of zero degrees (i.e., the physical straight-ahead direction) were coded as negative and positive respectively. To assess the bias and the variability of reported SSA in the three conditions, we calculated the mean and the standard deviation, respectively, of each participant's SSA error for each condition. The mean of SSA error differed across conditions, $F(2,30) = 4.30$, $MSe = 5.24$, $p < .05$ (See Figure 2). The effect of condition on mean SSA error did not vary as a function of the order in which the U and OC conditions were administered, $F(2,30) < 1$. Planned comparisons showed that mean SSA error was more negative in the Orientation Challenge condition than in the Sensory Blockade condition, $t(16) = 2.90$, $p < .01$, $d = .70$, and that mean SSA error did not differ in the Update and Sensory Blockade conditions, $t(16) = .64$, $p = .53$, or in the Update and Orientation Challenge conditions, $t(16) = 1.91$, $p = .17$.

The standard deviation of SSA error also differed across conditions, $F(2,30) = 6.18$, $MSe = .39$, $p < .01$ (See Figure 3). The effect of condition on the standard deviation of SSA error did not vary as a function of the order in which the U and OC conditions were administered, $F(2,30) < 1$. Planned comparisons showed that the standard deviation of SSA error was greater in the Orientation Challenge condition than in the Sensory Blockade condition, $t(16) = 2.92$, $p < .01$, $d = .71$, and greater in the Update condition than in the Sensory Blockade condition, $t(16) = 3.04$, $p < .01$, $d = .74$. On average, the standard deviation of SSA error was greater in Orientation Challenge condition than in the Update condition but the difference was not statistically significant, $t(16) = 1.66$, $p = .12$.

To find out how the bias of reported SSA varied with time on task in each condition, we examined the way signed SSA error varied as a function of trials in the task. Signed SSA error did not vary as a function of trials in the Sensory Blockade, $F(19,304) = 1.03$, $MSe =$

²This estimate reflects an average calculated across five representative trials.

10.56, $p = .43$, Update, $F(19,304) = 1.40$, $MSe = 12.78$, $p = .12$, or Orientation Challenge conditions, $F(19,304) < 1$. To find out how the variability of reported SSA varied with time on task in each condition, we computed the absolute difference between each participant response and the participant's mean response and then examined the way this absolute SSA error measure varied as a function of trials in the task. The measure did not vary as a function of trials in the Sensory Blockade, $F(19,304) = 1.37$, $MSe = 5.35$, $p = .14$, Update, $F(19,304) = 1.39$, $MSe = 4.71$, $p = .13$, or Orientation Challenge conditions, $F(19,304) = 1.37$, $MSe = 5.32$, $p = .14$.

Discussion

This experiment assessed the bias and the variability of reported SSA under conditions that posed differing degrees of orientation challenge. In all conditions participants were subject to external sensory blockade. In the Update and Orientation Challenge conditions participants in addition underwent, respectively, a 90 degree rotation and multiple clockwise and counter-clockwise rotations. The study produced two findings. 1) The mean of SSA error was more negative when participants were subjected to multiple rotations than when participants were only subjected to external sensory blockade. 2) The standard deviation of SSA error was larger when participants were subjected to a 90-degree rotation or multiple rotations than when participants were only subjected to external sensory blockade.

It is not clear what to make of the fact that SSA error was more negative when participants experienced multiple rotations as well as external sensory blockade than when they only experienced external sensory blockade. Under our coding system, this implies that multiple rotations shifted SSA to the left. One possibility is that the liquid in participant semicircular canals retained residual movement in one direction following the rotations that were participants experienced. Another possibility is that the rotations induced response 'inertia' and consequent under-turning of the pointer. Under our procedure, the pointer always pointed to the participants' abdomen at the beginning of a trial and participants always turned the pointer with their right hands. Under these conditions, the pointer was most naturally turned in a clockwise direction to SSA (although we did not systematically monitor this). Thus, if the rotations had induced response inertia and consequent under-turning of the pointer, SSA would have been shifted to the left³.

Of greater interest is the finding that the standard deviation of SSA error was larger when participants experienced one or more rotations as well as external sensory blockade than when they only experienced external sensory blockade. This result suggests that the stability of a participant's egocentric reference frame decreased consequent to the rotations. However, these results prompt a follow-up question. The most notable difference between the Update/Orientation Challenge conditions and the Sensory Blockade condition lay in the rotations to which participants were subjected. Confounded with this difference, however, was a difference in the amount of time that had passed, at each SSA report, since the most recent viewing of the experimental environment. Our favored Body Rotation interpretation holds that the stability of the egocentric reference frame decreased consequent to the

³We thank Eric Hodgson for suggesting the bias analysis and the interpretation that we have offered for the results of that analysis.

rotations that participants experienced in the absence of external sensory input. An alternative Time Passage interpretation holds that the stability of the egocentric reference frame decreased consequent to the simple passage of time in the absence of external sensory input. Experiment 2 sought to pit the Body Rotation interpretation against the Time Passage interpretation. The experiment focused on the manipulation from the Orientation Challenge condition as this produced the strongest effect in Experiment 1.

Experiment 2

The experiment assessed the bias and the variability of reported SSA following external sensory blockade, following orientation challenge, and following a delay matched to the time taken by the orientation challenge. In all conditions, participants reported SSA on each of twenty trials, donning a blindfold and hearing protectors prior to the first trial. In the Sensory Blockade (SB) condition, participants experienced no additional manipulations. In the Orientation Challenge (OC) condition, participants were in addition subject to multiple clockwise and counterclockwise rotations before responding on each trial, as in Experiment 1. In the Delay (D) condition participants were required to wait 20 seconds, the time taken by the multiple rotations, before responding on each trial.

The Time Passage interpretation predicted that the variability in reported SSA would be greater in the OC and D conditions than in the SB condition, and that the differences between the OC and SB conditions and between the D and SB conditions would be of similar magnitude. The Body Rotation interpretation predicted that the variability in reported SSA would be greater in the OC condition than in the SB condition but that the variability in reported SSA would not differ in the D and SB conditions.

Participants

The sample comprised 26 females and 6 males with a mean age of 19.7 years. A power analysis indicated that this sample size had a power of .95 to reveal an SSA variability effect of the sort observed in the contrast between the Sensory Blockade and Orientation Challenge conditions of Experiment 1.

Materials and Apparatus

The materials and apparatus were identical to those of Experiment 1.

Design

The experiment used a completely within-subjects design. The SB condition was administered first for 21 participants. In addition, to test for the possibility that our results reflected order effects in the administration of the SB condition, the condition was administered last for 11 participants. The order of the OC and D conditions was counterbalanced across all participants. All testing took place during a single one-hour-long testing session.

Procedure

The experiment comprised a pointer familiarization phase and a test phase. The pointer familiarization phase was essentially as in Experiment 1⁴. The test phase was as in Experiment 1 for the SB and OC conditions. The D condition was the same as the SB condition except that participants waited 20 seconds on each trial before reporting SSA.

Results

SSA error was computed as in Experiment 1. To assess the bias and the variability of reported SSA in the three conditions, we calculated the mean and the standard deviation, respectively, of each participant's SSA error for each condition. Whereas the mean of SSA error did not differ across conditions, $F(2,56) = 1.87$, $MSe = 8.85$, $p = .16$ (See Figure 4), the standard deviation of SSA error differed across conditions, $F(2,56) = 3.48$, $MSe = .66$, $p < .05$ (See Figure 5). The effect of condition on the standard deviation of SSA error did not vary as a function of the order in which participants performed the SB and other two conditions, $F(2,56) < 1$, the order in which participants performed the D and OC conditions, $F(2,56) = 1.46$, $MSe = .66$, $p = .24$, or the interaction of the effects of the order in which participants performed the SB and other two conditions and the order in which participants performed the D and OC conditions, $F(2,56) = 1.95$, $MSe = .66$, $p = .15$. Planned comparisons showed that the average standard deviation was greater in the Orientation Challenge condition than in the Sensory Blockade condition, $(t(31) = 2.45, p < .05, d = .43)$, and greater in the Orientation Challenge condition than in the Delay condition, $(t(31) = 1.86, p < .05 \text{ (one-tailed)}, d = .33)$. However, the average standard deviation did not differ statistically in the Sensory Blockade and Delay conditions, $(t(31) = 1.18, p = .25)$.

To find out how the bias of reported SSA varied with time on task in each condition we examined the way signed SSA error varied as a function of trials. Signed SSA error decreased as a function of trials in the Orientation Challenge condition, $F(1,31) = 7.56$, $MSe = 49.24$, $p < .01$, and the Delay condition, $F(1,31) = 8.35$, $MSe = 23.35$, $p < .001$ but signed SSA error did not vary as a function of trials in the Sensory Blockade condition, $F(19,589) = 1.02$, $MSe = 12.49$, $p = .43$. To find out how the variability of reported SSA varied with time on task in each condition we again computed the absolute difference between each participant response and the participant's mean response and then examined the way this absolute SSA error measure varied as a function of trials in the task. The measure decreased as a function of trials in the Sensory Blockade, $F(1,31) = 7.14$, $MSe = 4.02$, $p < .01$, and Delay conditions, $F(1,31) = 6.22$, $MSe = 4.70$, $p < .01$, but did not vary as a function of trials in the Orientation Challenge condition, $F(19,589) = 1.49$, $MSe = 5.91$, $p = .08$.

Discussion

The experiment sought evidence against the Time Passage interpretation of the results of Experiment 1. Toward that end the experiment sought to disconfirm the interpretation's prediction that the variability of reported SSA would be greater in Orientation Challenge and Delay conditions than in Sensory Blockade condition. In fact the variability of reported SSA

⁴During the pointer training phase the eleven participants who experienced the SB condition last were only required to point to the front.

was greater in the Orientation Challenge than in the Sensory Blockade condition but not greater in the Delay than in the Sensory Blockade condition. In addition, the variability of reported SSA was greater in the Orientation Challenge than in the Delay condition. These results suggest that the differences in SSA variability that were observed in Experiments 1 and 2 reflected the full-body rotations that were administered. The simple passage of time may have caused an increase in SSA variability in Experiment 2 but this increase was not detectable given the statistical power available. The fact that the power was adequate to reveal an effect of orientation challenge in two experiments indicates that an effect of the passage of time, if one exists, is not the only effect in play.

We also observed effects of orientation challenge and the passage of time on mean SSA error. In the Orientation Challenge and Delay conditions, SSA error became more negative across trials. This result may reflect the same response ‘inertia’ as was suggested in explanation of the results of Experiment 1. Orientation challenge and the passage of time under sensory blockade may have induced under-turning of the pointer that increased in magnitude across trials. (Notice that, under this account, orientation challenge and the passage of time had similar effects on the bias of SSA and different effects on the variability of SSA. Notice also that the residual vestibular movement account that was suggested for the SSA error results of Experiment 1 is not considered here because it would not be applicable to the results in Delay condition).

Finally, our measure of absolute SSA error decreased across trials in the Sensory Blockade and Delay conditions. This may reflect a learning effect. Participants may have learned over trials in these conditions to reduce SSA error variability. Because the same effect was not observed in Experiment 1 we will not consider it further.

General Discussion

Research with the traditional blind pointing task has demonstrated that pointing error and configuration error increase consequent to an orientation challenge, implying that knowledge of the locations of the objects in an ensemble becomes less precise consequent to such a challenge. The present study asked whether knowledge of the egocentric reference frame similarly becomes less precise consequent to an orientation challenge. The experiments used a version of the blind pointing task in which participants reported subjective straight ahead (SSA) rather than the positions of objects. In both of the experiments, reported SSA was more variable following an orientation challenge in conjunction with external sensory blockade than following external sensory blockade alone.

The mechanism underlying these results is unclear. The orientation challenge may have decreased the stability of motor control. Alternatively, the orientation challenge may have induced changes in body posture. Another possibility is that the orientation challenge disrupted memory for the relative location of different body parts.

Regardless of the specific mechanism involved, we suggest that the results speak to the nature of the egocentric reference frame, implying that the frame is more complex and less stable than has been thought. In order to locate SSA relative to the egocentric reference frame, an observer presumably must integrate signals related to different parts of the

proprioceptive system (finger, arm, torso, etc.) with one another, and with the motor system, to yield a coherent reference frame. The present results suggest that an orientation challenge may disrupt this process of integration.

It is possible that the orientation challenge procedure resulted in instability in body posture and/or motor control. This raises the possibility that the SSA instability we have observed comes about purely at the motor output stage, without affecting the egocentric reference frame that is presumably constructed “upstream”. While we acknowledge that this is a possibility, in this domain, the distinction between the underlying representation (of SSA and the egocentric reference frame that it is based on) and motor output is very difficult to disentangle, both conceptually and empirically. Going further, the efferent and afferent signals that make motor control possible may themselves form important inputs to the construction of the egocentric reference frame. Thus, even if the body posture changes as a result of the disorientation procedure, these postural changes might be sensed and integrated into the egocentric reference frame and contribute to its instability. From this perspective, postural and motor control instability elicited by the orientation challenge procedure could be seen as potential mechanisms for the egocentric reference frame instability that is our favored interpretation.

An important question concerns the relationship between the present SSA error effect and the pointing error and configuration error effects that have previously been observed. The argument of the previous paragraph suggests that an orientation challenge may increase the variability of SSA in roughly the same way that such a challenge increases configuration error. When increases in configuration error have been observed consequent to an orientation challenge, the configuration error increases have been held to reflect the perturbation of independent egocentric vectors corresponding to objects in the environment (Wang, 2012; Wang, Crowell, Simons, Irwin, Kramer, Ambinder, et al., 2006; Wang & Spelke, 2000). In the same way, increases in the variability of SSA error may reflect the perturbation of independent components of the egocentric frame. By the same token, an increase in pointing error consequent to an orientation challenge may reflect the same perturbation of the egocentric frame as does the present increases in SSA variability, with the increase in pointing error being larger because of the difficulty of integrating the egocentric frame and the target of the pointing.

In any case, one practical implication of our findings is that more care must be taken, with measures such as pointing error, configuration error, and heading error, to adjust for instability in the egocentric reference frame. The size of our SSA effect relative to the error effects that have been observed in past studies implies that such effects cannot be completely explained in terms of instability in the egocentric reference frame (Wang and Spelke, 2000). Nonetheless, a portion of such effects can probably be explained in this way.

An important question for future research is the degree to which the increases that we have observed in the variability of SSA depend on the passive nature of the movement that we administered in our orientation challenge. Future work should ask whether similar increases in SSA variability occur when orientation is challenged in the course of active movement (as when one becomes disoriented in the course of exploring a new environment).

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Figure 1.
Rotating chair used in Experiments 1 and 2.

Figure 2.

Experiment 1: Vertical bars represent the mean across participant means for SSA error in each condition. Error bars give SEM. “**” denotes a reliable difference between conditions at $\alpha < .01$.

Figure 3.

Experiment 1: Vertical bars represent the mean across participant standard deviations for SSA error in each condition. Error bars give SEM. “**” denote reliable differences between conditions at $\alpha < .01$.

Figure 4.

Experiment 2: Vertical bars represent the mean across participant means for SSA error in each condition. Error bars give SEM.

Figure 5.

Experiment 2: Vertical bars represent the mean across participant standard deviations for SSA error in each condition. Error bars give SEM. “*” denote reliable differences between conditions at $\alpha < .05$.