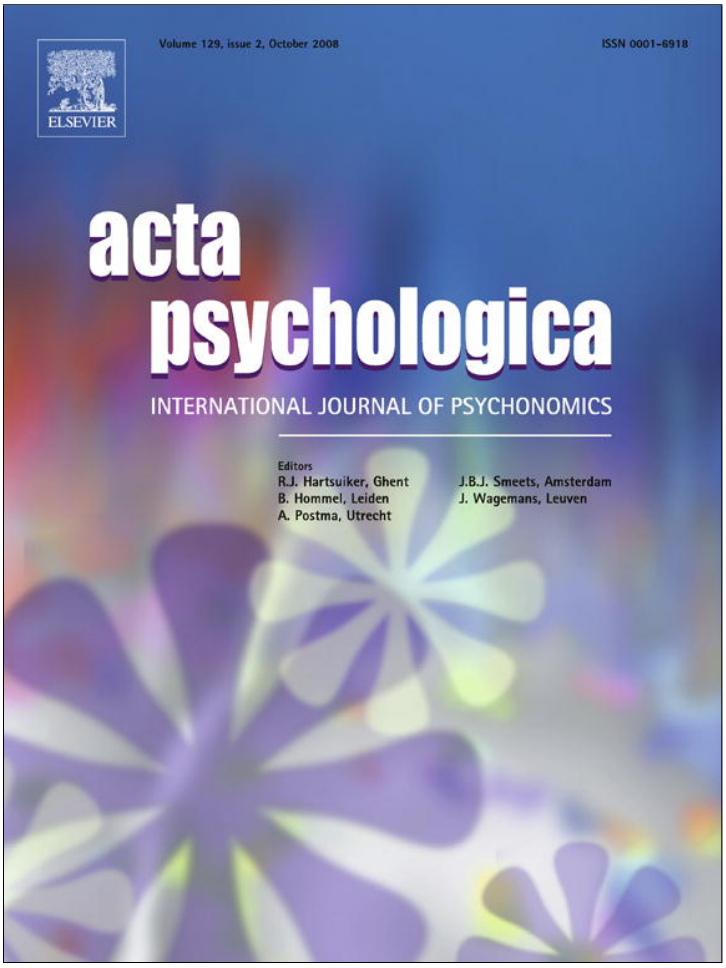
Volume 129, issue 2, October 2008
ISSN 0001-6918
ELSEVIER
acta psychologica
INTERNATIONAL JOURNAL OF PSYCHONOMICS
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Acta Psychologica 129 (2008) 234–242

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Exploring the process of progressive disorientation

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ARTICLE INFO

Article history:
Received 9 August 2007
Received in revised form 13 June 2008
Accepted 20 June 2008
Available online 8 August 2008

PsycINFO classification:
2320

Keywords:
Spatial cognition
Disorientation

ABSTRACT

While an increasing number of behavioral studies examining spatial cognition use experimental paradigms involving disorientation, the process by which one becomes disoriented is not well explored. The current study examined this process using a paradigm in which participants were blindfolded and underwent a succession of 70° or 200° passive, whole body rotations around a fixed vertical axis. After each rotation, participants used a pointer to indicate either their heading at the start of the most recent turn or their heading at the start of the current series of turns. Analyses showed that in both cases, mean pointing errors increased gradually over successive turns. In addition to the gradual loss of orientation indicated by this increase, analysis of the pointing errors also showed evidence of occasional, abrupt loss orientation. Results indicate multiple routes from an oriented to a disoriented state, and shed light on the process of becoming disoriented.

1. Introduction

One is said to be oriented if one can determine one's location and heading relative to the surrounding environment (Gallistel, 1990). Otherwise, by inference, one may be said to be disoriented. Past work has demonstrated that oriented participants can point to specific objects and landmarks in the surrounding environment with striking accuracy and precision, even without vision, and over considerable self motion (e.g., Loomis, DaSilva, Fujita, & Fukusima, 1992). Disoriented participants, on the other hand, exhibit essentially random behavior in such tasks (e.g., Wang & Spelke, 2000). Little has been done, however, to assess the process by which a person passes from an oriented to a disoriented state. The present study examined this process.

Two ways of becoming disoriented may be distinguished conceptually. While looking at pictures in an art museum, one might lose the sense of where the main entrance is. In this example, one remains oriented to the immediate environment (the room in which one stands) but loses track of the relationship between that environment and another, larger scale environment (the museum building as a whole). Issues specifically relevant to this way of becoming disoriented have been addressed in previous studies that examine relationships between different environmental representations (e.g., McNamara, Hardy, & Hirtle, 1989; Sholl, 2001; Wang & Brockmole, 2003). However, the current study focuses on the process of becoming disoriented with regard to one's immediate environment. For example, spinning in place while blindfolded, one completely loses track of one's surroundings relative to the body. While these two processes of becoming disoriented may share underlying mechanisms, they also differ in ways that are significant for the current study. Specifically, in the latter case, there is no ongoing visual input, and disorientation may occur more easily despite constant efforts to remain oriented.

We examined the situation in which a person seated in a swivel chair undergoes successive, passive rotations around a fixed point in the absence of visual and auditory input. Trials consisted of five clockwise turns, after each of which participants set a pointer to indicate a target and then indicated their confidence in this response. Our goals were (1) to document how performance in the pointing task (the behavioral indicator of orientation) decreased over successive rotations until accuracy reached objective criteria representing disorientation (no better than chance), (2) to examine the relationship between that performance and subjective perception of disorientation, and (3) to identify cases in which disorientation occurred abruptly, rather than gradually. Indices of constant and variable error were used as objective, behavioral measures of how well participants were oriented, while self reported confidence ratings provided a measure of the extent to which participants perceived themselves to be disoriented.

There were two different target conditions. In the Turn Beginning condition, participants set the pointer to indicate their heading at the beginning of the current turn. In the Home condition, participants set the pointer to indicate their heading at the beginning of the current *series* of turns, or trial. Performance in the Home

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doi:10.1016/j.actpsy.2008.06.005

condition reflects perception of all previous turns in a given trial. This allowed us to observe how well participants were oriented with regard to the remembered environment. Performance in the Turn Beginning condition reflects perception of the most recent (current) turn only. In this case, memory for the target direction need not be maintained over successive turns. Therefore, decreases in pointing performance consequent to successive rotations in this condition may reflect, specifically, decreases in the capacity for *perceiving* those rotations. In order to consider mechanisms by which this decrease in perceptual capacity might occur, the following discussion briefly details the processes by which blind rotations are perceived.

In the absence of visual and auditory input, perception of passive, whole body rotation occurs primarily through a process called path integration. Path integration is based, at least in part, on velocity and acceleration signals, arising from the vestibular apparatus and somatosensory systems, which may be integrated (doubly-integrated in the case of acceleration signals generated by the vestibular apparatus) over time to provide an estimate of change in position (Etienne, Maurer, & Séguinot, 1996; Loomis, Klatzky, Golledge, & Philbeck, 1999). The current study does not provide a rigorous assessment of these vestibular and somatosensory systems. However, factors that may contribute to the accuracy and precision of path integration processes, either directly, or through these "lower level" systems, will be considered in light of current results.

Confidence ratings were examined for trends across the different conditions in order look at the subjective aspect of the process of becoming disoriented. Confidence ratings were also important in achieving goals (2) and (3) above. Linear correlations between confidence ratings and performance allow us to consider how trustworthy subjective assessments of orientation may, or may not be. Is orientation with regard to the environment accessible to cognitive inspection? Finally, confidence ratings were used in the analysis to show that occasional *abrupt* loss of orientation occurred in conjunction with *gradual* loss of orientation. Toward this end, we sought to identify cases in which both pointing performance and confidence were particularly low and to then demonstrate that the deterioration in performance in those cases had no antecedents on prior turns. This analysis was included in the interest of conducting a comprehensive, if not exhaustive, examination of how we pass from an oriented to a disoriented state.

There were two different Turn Size conditions. In one, all of the turns on a given trial were 70° in size. In the other, all of the turns on a given trial were 200° in size. This manipulation was of secondary interest, undertaken in the service of generalizeability. We chose the 70° turn as representative of a modest-sized turn and the 200° turn as representative of a larger, potentially more challenging, turn.

2. Method

Participants completed a single session lasting approximately 1 h. The session consisted of a Pointer Training Phase, in which participants learned how to use the pointer, and a Test Phase, in which the experimental manipulations occurred.

2.1. Participants

Twenty-one George Washington University undergraduates participated in this study in exchange for course credit. Demographic information for one participant was lost (experimental data were retained). Of the remaining 20 participants, 16 were female, and 4 were male. The mean age was 20 years (range: 17–22). None of the participants reported being left-handed.

2.2. Apparatus

The experiment took place in a 5 × 7 m room. During the Pointer Training Phase, the room was lit by overhead fluorescent lights. During the Test Phase, the room was lit by a string of dim Christmas lights mounted in a circle above the participant; this served to minimize directional illumination cues that might otherwise be visible underneath the blindfold. The swivel chair in which participants sat was situated in the center of a circular aperture in a square table (1.52 m square × 76 cm tall). The aperture was marked with a 360° scale, according to which the chair was oriented at 0° when it faced the north wall of the experimental chamber.

A pointing device was mounted horizontally on the chair in participants' median sagittal plane, at approximately the level of the abdomen (see Fig. 1). The pointer's axis of rotation was offset 23 cm from that of the chair. The pointer itself was a thin rod extending 16 cm from its axis of rotation. A 360° scale, graduated to the nearest degree, lay underneath the rod. The pointer was oriented at 0° when it was perpendicular to the front of the chair.

2.3. Procedure

Prior to testing, participants were alerted to the fact that the pointer's center of rotation was offset from that of the chair. Participants were instructed to use their preferred hand to set the pointer.

2.3.1. Pointer Training Phase

On each trial, participants sat in the chair, viewed a small (5cm tall) bottle of correction fluid, which was placed on the perimeter of the table at one of 15 positions (45°, 70°, 90°, 115°, 140°, 160°, 170°, 180°, 190°, 200°, 220°, 245°, 270°, 290°, and 315° measured in a clockwise direction from straight ahead), and aimed the pointer at the bottle. The chair was oriented at 0° ("home") throughout this phase, although participants were allowed to turn their head and torso to look at the bottle when it was located behind them. Participants were instructed to set the pointer so that an imaginary line passing through the pointer would also pass through the bottle. Participants had full visual and auditory access during pointer training. A response was scored as correct if the pointer was aimed within ±3° of the bottle. After each incorrect response, the correct pointer direction was demonstrated to the participant. Once a position had elicited three correct responses without an intervening

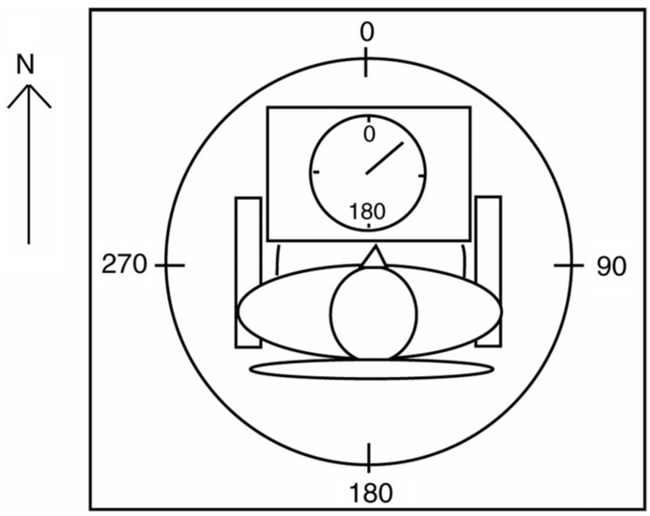

Fig. 1. Schematic overhead view of rotation table and pointing device (not to scale).

incorrect response, it was considered "passed" and tested no more. Positions were tested in random order until all were passed. Participants were required to meet these criteria to establish a common baseline proficiency in using the pointer.

2.3.2. Test phase

Each of the trials in this phase began with the chair oriented at 0° ("home"). At the start of each trial, participants oriented themselves with respect to the experimental chamber, put on a blindfold and hearing protectors and underwent 5 clockwise turns (70° or 200° in magnitude, depending on the condition). After each turn, participants set the pointer to indicate a previous heading and then indicated their confidence in this pointer response.[1] Confidence was indicated on a 7 point scale, in which 1 indicated highest confidence and 7 indicated lowest confidence. Approximately 5 s passed between the end of the rotation and the pointing response. Overall, about 20 s passed between rotations within a trial.

The Test Phase included two different Target conditions. In the Turn Beginning condition, participants were instructed to set the pointer to indicate their heading at the beginning of the current turn. In the Home condition, participants were instructed to set the pointer to indicate their heading at the beginning of the current trial ("home"). However, after running 11 participants, it was observed that one participant had clearly misunderstood instructions regarding the difference between the Home and Turn Beginning conditions. Because of this, the procedure was changed slightly as follows. For all subsequent participants, the first two trials ("Filler" trials for which the data were not analyzed) were completed without the blindfold and hearing protectors. This change was made to clarify the instructions for the different Target conditions and reveal any participants that misunderstood, before any experimental data were collected. The order of the Target conditions was counterbalanced across participants.

Fifteen trials were administered in each Target condition block of the Test Phase. The trials were of four types. In the 70° experimental trials all turns were 70° and in the 200° experimental trials all turns were 200°. Filler trial type *F*1 consisted of consecutive turns of 70°, 200°, 70°, 110°, and 40° and filler trial type *F*2 consisted of consecutive turns of 40°, 110°, 200°, 200°, and 70°. Filler trials were included in order to control instruction compliance, and to expose participants to turns of different magnitudes. In order to maximize the degree to which each response reflected ongoing perception, we wanted to discourage participants from developing categorical responses for 70° and 200° turns. The Test Phase consisted of the following sequence of trial types: *F*1, *F*2, 70, *F*1, 200, 200, 70, 70, 200, *F*1, 200, 70, 200, *F*2, 70. This is one of many possible arrangements that result in neither experimental trial type having a disproportionately greater chance of occurring earlier or later in the testing sequence. For participants 12–21, who completed the first two filler trials with unrestricted vision and hearing, the Filler trials were moved up in the trial order as follows: *F*1, *F*1, *F*2, 70, 200, 200, *F*1, 70, 70, 200, *F*2, 200, 70, 200, 70. This change ensured that all participants would complete at least one (Filler) trial with blindfold and hearing protectors before the first experimental trial.

Participants removed the blindfold and hearing protectors between trials (on which they wore them) and rested briefly, but were not allowed to view their last pointer response. Three experimenters administered the Test Phase. Two experimenters executed the rotations, attempting to impose a bell-shaped velocity profile, with rapid, monotonic accelerating and decelerating phases and a minimum of jerky starts and stops. Typical velocity profiles produced by experimenters instructed in this way were recorded with an infrared video tracking system (Optotrak, Waterloo) by Philbeck, Behrmann, and Loomis (2001). The peak angular velocity varied from about 40° to 90° per second, depending on the rotation magnitude. Experimenters in the current experiment were trained by the third author (who worked on both studies) to produce velocity profiles similar to those used in the previous work. A third experimenter recorded the pointer responses and the magnitude of accidental over- and under-rotations. The latter information was used to adjust the pointer data to reflect the rotation that was actually administered on each turn. This experimenter also returned the pointer to 0° after each response so that responses were always made from 0°.

Because participants were trained with full vision, and subsequently blindfolded during experimental trials, an ancillary experiment was conducted in order to examine how depriving participants of vision might affect the accuracy and precision of pointing responses, even without rotation. Six (5 female and 1 male), right handed George Washington University undergraduates participated in exchange for course credit. The mean age was 21 years (range: 20–22). Each participant was trained as described above and then underwent two experimental trials, one with full vision, and one with blindfold and hearing protectors, the order of which was counterbalanced across participants. In each trial participants were instructed to point to four targets (0°, 90°, 180°, and 270°), five times each, in random order. These targets were chosen because, as part of the body scheme, they have 'sharp' internal representations (Haun, Allen, & Wedell, 2005), and therefore the effects of factors such as memory decay or perceptual demands should be minimal. Mean constant (signed) error was .3° in the full vision condition, and −1.5° in the blindfolded condition. Mean variable error, calculated as within subject standard deviation across repeated responses to the same target, was 1.9° in the full vision condition, and 4.8° in the blindfolded condition. These results suggest that at best, only a small percentage of the error that was observed in the current data set may be explained by the fact that the subject-pointer operating function appears to deteriorate somewhat in the absence of vision and with reduced hearing.

3. Data analysis

First, analyses of variance (ANOVA) including the two experimental factors of interest: (1) Target, (Home and Turn Beginning), and (2) Turn Number (1–5) were run for each of the three dependent variables (constant error, variable error, and confidence rating) separately for data from the two Turn Size conditions (70° and 200°). Second, analyses were conducted in order to show objective evidence that participants reached the state of complete disorientation. Third, correlations were calculated between accuracy (or precision) and confidence rating. Finally, an analysis was conducted in order to identify cases in which orientation may have been lost abruptly, rather than gradually. For the sake of continuity, a description and the results of these last two analyses are presented together at the end of the results section. Unless specified, all measures described below were calculated separately for each subject, for each level of Turn Size and Turn Number.

3.1. Pointer task

The object of the analysis was to examine constant error and variable error as a function of Turn Number and Target condition. The raw data were the pointer readings that participants produced, which ranged from 0° to 359°. For each response, *raw error* was

[1] Approximately 20 s passed between successive turns. It was assumed that 20 s is ample time for the semicircular canal fluids to settle and for the vestibular system to recover normal function. Thus, no effects of dizziness were considered.

calculated by subtracting the correct response (calculated differently in different cases, as below) from the observed pointer reading.

3.1.1. Constant error

In order to establish a measure of constant error that may be analyzed using linear statistics, circular data must be mapped onto a linear scale. This was done by adjusting (up or down in increments of 360) the *raw error* for a given response so that it was within ±180 of zero. Calculating error in this way results in positive clockwise errors and negative counter-clockwise errors. So, for example, if the correct response for a given condition was 10° and the observed pointer reading was 350°, the constant error would be −20°.

For the Turn Beginning condition, the correct response after each 70° and 200° clockwise turn was 290° (360 − 70 = 290), and 160° (360 − 200 = 160), respectively. In the Home condition, correct response, and thus constant error, was calculated two different ways. *Cumulative error* was calculated relative to the actual target heading (Home) in order to determine how well a participant was oriented with regard to the environment. *Incremental error* was calculated relative to the pointer reading observed on the previous turn (or zero on the first turn of a trial). For example, for a given participant and trial, if the observed pointer reading on turn n in the 70° condition was 155°, the correct pointer reading for turn $n + 1$ would be 85° (155 − 70 = 85). Thus *incremental error* measures the error accumulating over each isolated turn in the Home condition, allowing reasonable comparison to performance in the Turn Beginning condition. For both Turn Beginning and Home conditions,*mean error* for a given participant was the average of the constant errors across trials, for a given combination of the different levels of Turn Number and Turn Size.

3.1.2. Variable error

The circular statistic *angular deviation* was used to index the variable error in the pointer readings (Batschelet, 1981). *Variable error* was the within participant variability of responses across trials for a given combination of the different levels of Turn Number, Turn Size, and Target.

3.2. Confidence task

The raw data were the confidence ratings that participants produced. Analyses were conducted on the mean confidence ratings across trials for a given combination of the different levels of Turn Number, Turn Size, and Target.

3.3. Results

The data for the aforementioned participant who did not follow instructions were removed prior to analysis, as were the data for one additional participant, who despite changes made to clarify the instructions, still expressed confusion about them. Both excluded participants received full credit for their participation.

3.4. Pointer task

3.4.1. Constant error

For the Home condition *incremental error* is analyzed here; *cumulative error* will be examined subsequently. Figs. 2a and 2b present the mean error in the pointer data for the 70° and 200° conditions as a function of Turn Number and Target. The grand mean for signed error across all conditions and participants was −9.8°. Statistical analyses are summarized in Table 1. Mean error varied as a function of Turn Number in the 70° condition, with the most interesting component of the effect being an increasingly

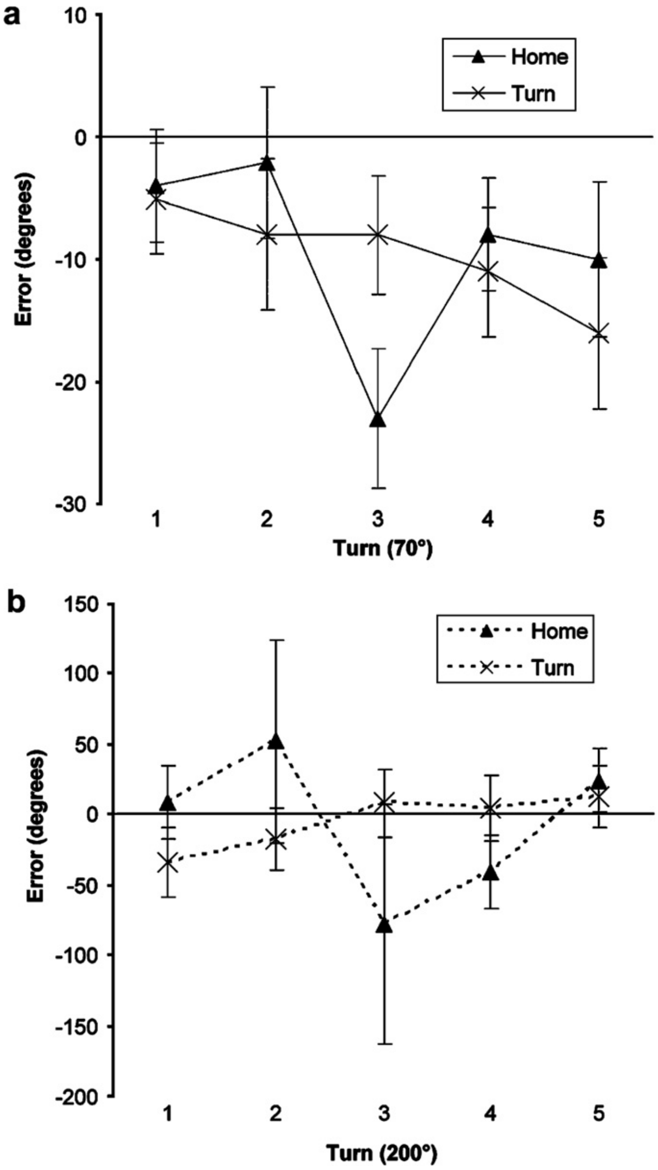

Fig. 2. *Mean error* (signed) for the 70° and 200° conditions (respectively) as a function of Turn Number and Target. Error bars are the standard errors of the mean. Positive error results from responses that are too far in a clockwise direction, and negative error results from responses that are too far in a counter-clockwise direction. *Mean error* is plotted separately for the 70° and 200° conditions because of the large difference in scale.

Table 1
Analyses of variance for constant error (mean error, across trials)

Source	df	*F*/*MSE*	*p*	df	*F*/*MSE*	*p*
	70° Turn Size			200° Turn Size		
Turn Number	4	3.60	.01	4	3.54	.01
Error	72	416		72	1030	
Linear trend component	1	5.77	.03	1	9.39	.007
Error	18	630		18	692	
Target	1	2.79	.122	1	5.64	.029
Error	18	2383		18	3701	
Turn Number × Target	4	2.84	.03	4	1.97	.108
Error	72	619		72	821	
Linear trend component	1	4.33	.052			
Error	18	1291				

negative mean error as a function of Turn Number. Mean error also varied as a function of Turn Number in the 200° condition, with the most interesting component of the effect being an increasingly positive mean error as a function of Turn Number. In the 200° condition, mean error was more negative in the Home condition than the Turn Beginning condition. In the 70° condition, mean error did not vary as a function of Target. In the 70° condition, the effects of Turn Number and Target interacted in the mean-error data. However, the linear component of this effect was not significant. In the 200° condition, the effects of Turn Number and Target did not interact in the mean-error data.

3.4.2. Variable error

Fig. 3 presents the mean (across participants) *angular deviation* (variable error) in the pointer data for the 70° and 200° conditions as a function of Turn Number and Target. The grand mean for variable error across all conditions and participants was 34°. Statistical analyses are summarized in Table 2. *Angular deviation* varied as a function of Turn Number in both Turn Size conditions. Specifically, *angular deviation* increased with increases in Turn Number in both conditions. *Angular deviation* was greater in the Home than in the Turn Beginning condition for both Turn Size conditions, but the difference was significant only in the 200° condition. The interaction of Turn Number and Target in the *angular deviation* data was significant for both Turn Size conditions. Also, the linear component of this interaction effect was significant in both Turn Size conditions. That is, the linear trend in the effect of Turn Number was greater in the Home than in the Turn Beginning condition.

3.5. Confidence task

Fig. 4 presents the mean confidence ratings for the 70° and 200° conditions as a function of Turn Number and Target. Statistical analyses are summarized in Table 3. Confidence rating varied as a function of Turn Number in both Turn Size conditions. Specifically, confidence decreased with increases in Turn Number in both conditions. Confidence rating did not significantly vary as a function of Target in either Turn Size condition. The effects of Turn Number and Target interacted in the confidence data for both Turn Size conditions. Of greatest interest here, the linear trend in the effect of Turn Number was greater in the Home than in the Turn Beginning condition, marginally so in the 70° condition, and significantly so in the 200° condition.

To assess, objectively, whether the current study captured the state of full disorientation we examined *cumulative error* scores (calculated relative to the actual target direction) in the Home

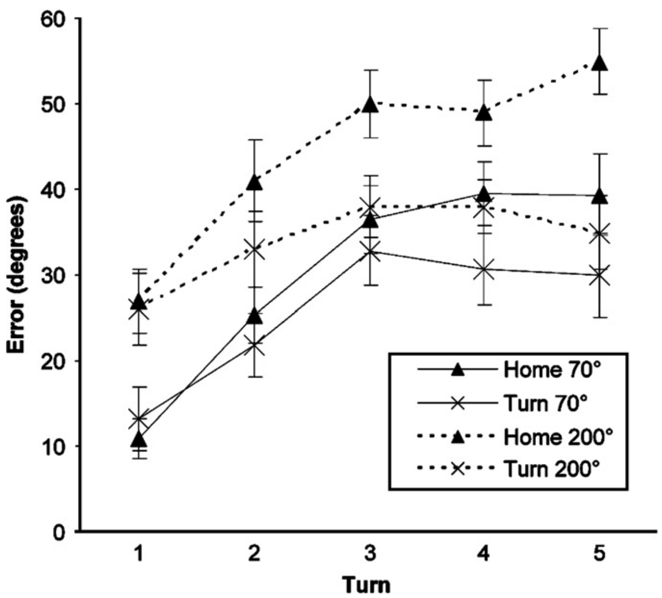

Fig. 3. Mean *angular deviation* for the 70° and 200° conditions as a function of Turn Number and Target. Error bars are the standard errors of the mean.

Table 2
Analyses of variance for variable error (angular deviation)

Source	df	*F/MSE*	*p*	df	*F/MSE*	*p*
	70° Turn Size			200° Turn Size		
Turn Number	4	16.63	<.001	4	11.46	<.001
Error	72	235		72	197	
Linear trend component	1	34.06	<.001	1	3.94	<.001
Error	18	358		18	177	
Target	1	2.66	.121	1	9.56	.006
Error	18	373		18	551	
Turn Number × Target	4	2.62	.042	4	2.78	.033
Error	72	83		72	157	
Linear trend component	1	6.40	.021	1	9.6	.006
Error	18	125		18	161	

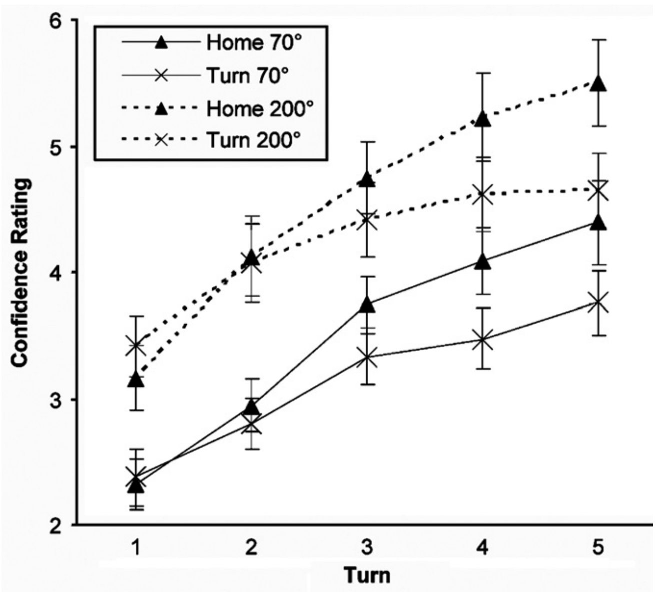

Fig. 4. Mean confidence ratings for the 70° and 200° conditions as a function of Turn Number and Target. Error bars are the standard errors of the mean. (Recall that 1 = highest confidence, and 6 = lowest confidence.)

Table 3
Analyses of variance for confidence ratings

Source	df	*F/MSE*	*p*	df	*F/MSE*	*p*
	70° Turn size			200° Turn size		
Turn number	4	51.83	<.001	4	48.14	<.001
Error	72	.36		72	.45	
Linear trend component	1	67.49	<.001	1	70.86	<.001
Error	18	1.07		18	1.11	
Target	1	3.57	.075	1	2.47	.133
Error	18	1.62		18	2.34	
Turn number × Target	4	3.28	.016	4	3.61	.010
Error	72	.26		72	.38	
Linear trend component	1	4.21	.055	1	5.47	.023
Error	18	.78		18	.89	

condition. For a given condition in which participants are disoriented, these error scores, across participants, should be randomly distributed around the circle. Following Wang and Spelke (2000), the X^2 test described by Batschelet (1981) was used to test for random distribution of error scores. The circle was divided into six, 60° regions and individual *cumulative error* scores were categorized according to the region into which they fell. Disorientation would be indicated by a condition in which each of the six regions contained an equal number of individual error scores. Thus, rejecting the null (each region contains an equal number of individual error scores) would suggest that participants were not disoriented. Because we were concerned with the ability of our manipulation to produce full disorientation *at some point* during the five rotations, we examined the data from the final turns (5) of each trial, where disorientation was most likely. Running the X^2 test on Turn 5 of each trial separately failed to show that the distributions of errors differed from uniform. However, this was uninformative because the number of participants included in the analysis (19) was too small to conduct a valid X^2. Therefore, the test was run on the categorized *cumulative error* scores for Turns 5 of all trials at once, resulting in 95 cases.[2] Results for the 70° condition showed that the distribution of error scores differed from uniform (X^2 (5) = 36.31, $p < .0001$). However, for the 200° condition, results failed to show that the distribution of error scores differed from uniform (X^2 (5) = 4.22, $p = .52$) providing evidence that disorientation occurred.

We next examined correlations between accuracy (and precision) and confidence rating. Because, on our scale, high confidence was rated as 1 and low confidence as 7, positive correlation actually indicates a negative relationship between confidence rating and absolute error. For constant error (*cumulative error* was used in the Home condition), linear correlations were calculated across turns and trials for each subject, separately for the different levels of Target, and Turn Size. The grand mean across all correlations was .02. None of the mean correlations (across participants) for the different levels of Target, and Turn Size approached the critical strength (.37) at which a one tailed t-test with 23 degrees of freedom, alpha = .05, would suggest a correlation differing significantly from zero. Visual inspection of the data revealed no clear trends across the different levels of Target, and Turn Size. For variable error, the calculation of which collapses across trials, correlations were not done separately for the different levels of Target, and Turn Size because of the low n (5) that would have been available for each correlation. The grand mean across correlations for all participants was .39. A one tailed t-test with 18 degrees of freedom, alpha = .05, shows that this correlation is significantly greater than zero.

Finally, we conducted an analysis on data from the Home condition seeking to identify cases in which disorientation occurred abruptly, and to examine the occurrence of such cases across conditions. Each individual pointer response made in the Home condition represented one case in this analysis. Obviously, the criterion for disorientation used in the analysis above (randomly distributed errors across participants) cannot be used to identify individual responses that might reflect disorientation. Instead, responses were said to meet criteria for disorientation if the associated error was larger than the mean error associated with random responding. Recall that each raw cumulative error score was adjusted so that it was bounded by ±180, and so absolute *cumulative error* scores would be distributed between 0 and 180. Therefore, the case of disorientation would be characterized by a mean absolute *cumulative error* of 90°. Therefore, responses over ±90° from the target (as measured by *cumulative* error) were considered to have met the criterion indicating disorientation. Because we conceived of instances of abrupt disorientation as including objective *and* subjective elements, we also identified cases in which confidence was below average (calculated across trials for the corresponding Participant, Turn Number, and Turn Size). From amongst cases meeting both criteria above, we identified as 'breakdown' cases, those on which *incremental* error also was over ±90°. This eliminated cases in which the large *cumulative* error had accumulated gradually, over several turns. So in these 'breakdown' cases, error relative to the actual target was larger than the mean error associated with random responding, confidence was relatively low, and error relative to the target direction indicated on the previous turn was also larger than the mean error associated with random responding.

Forty-one of the 950 cases that occurred on Home trials met the 'breakdown' criteria. Across trials, for the 70° level of Turn Size, there were 0, 2, 2, 4, and 0 'breakdown' cases occurring on turns 1–5, respectively. For the 200° level of Turn Size, there were 10, 5, 5, 6, and 7 such cases occurring on turns 1–5, respectively. An ANOVA showed that the number of 'breakdown' cases occurring across participants varied as a function of Turn Size, $F(1, 49) = 14.92$, $MSe = .838$, $p < .001$. Specifically, more 'breakdown' cases occurred during the 200° turns than during the 70° turns. There was no significant effect of Turn Number, or Trial.

4. General discussion

In this study we sought initial insight into the process by which a person passes from an oriented to a disoriented state, with respect to the immediate environment. We sought to challenge participants' capacity to remain oriented with a task in which they experienced sequences of rotations without visual and auditory input. This study was effective in demonstrating a gradual decrease in the ability to point to specific target headings across successive turns in this task. Both variable error and absolute constant error in the pointer responses increased with successive turns. The Turn Number manipulation was evidently effective in challenging participants' ability to remain oriented, and by the final turns performance across participants in the 200°, Home condition met established criteria indicating that full disorientation had occurred. Although participants became increasingly less confident of their pointer responses over successive turns, error and confidence were not highly correlated on a trial by trial basis. Finally, in addition to the gradual loss of orientation described above, cases in which disorientation seems to have occurred abruptly were identified as well.

The analysis showing that criteria for disorientation were met by the final turns of the 200°, Home condition is noteworthy for several reasons. First, it provides evidence that the current study included the state of full disorientation. Second, it suggests that in the current paradigm, a considerable amount of passive, blind rotation (five, 200° turns) is necessary to induce such a state. Of course, the rotation acceleration rates are important factors in the accuracy of the signals generated by the vestibular system, which is insensitive to very low rates. Considerably slower rates than those used here would likely result in full disorientation occurring sooner. Finally, it is worth noting that when *incremental error* (accruing only over the most recent turn) was analyzed, performance did *not* reach criteria for disorientation by the final turns of the 200°, Home condition. This indicates that even in a state of full disorientation, participants were able to perceive ongoing rotations with some degree of accuracy.

[2] Error scores for a given subject on separate trials were considered independent cases for this analysis. Given that we set out to show that disorientation occurred, this assumption was conservative. Any tendency for a given participant to produce consistent errors across trials would increase the probability of a significant X^2, and thus decrease our chances of showing disorientation.

The process of becoming disoriented with respect to the immediate environment may be examined further in light of current results. Consider the results for trials on which participants were required to indicate what their heading had been at the beginning of the current turn (Turn Beginning condition). Variable error on these trials increased with successive turns regardless of whether the turns were 70° or 200° in magnitude. Participants were required on these trials to report their perception of the current turn. So, while we have shown that the capacity for perceiving turns never totally broke down, this result implies that it did *decrease* with successive turns.

Previous research indicates possible mechanisms by which this decrease in perceptual capacity might occur. For example, Barr, Schultheis, and Robinson (1976) showed that visual preview boosted the gain of the vestibular ocular reflex (VOR) occurring in subsequent blind rotation. Using a paradigm similar to that used in the current study, Arthur, Philbeck, and Chichka (2007) showed that visual preview resulted in more precise pointing responses after blind rotations. Thus, in the current study, processes involved in the perception of blind rotation may benefit more from signals (e.g., eye movements) related to the VOR on initial turns than on later turns due to the relative recency of visual preview. Rieser (1999) has suggested that stored environmental representations might support imagined visual flow, which could contribute to path integration processes and thus to the maintenance of orientation over blind motion. Current results may reflect the deterioration of the stored visual and spatial information that supports imagined visual flow, or more generally, environmental flow. (See Arthur, et al. for a more comprehensive discussion of the role of stored environmental representations in the deterioration of perceptual abilities over blind rotation.)

Alternatively, current results may reflect deteriorating contributions from vestibular and somatosensory systems that are independent of stored environmental information. Future research involving more rigorous controls would be informative in this regard. For example, eye movement, and head on neck movement might be controlled in order to better isolate the contribution of vestibular signals to perception of blind rotation. The importance of stored visual information in explaining the observed decrease in perceptual capacity might be bolstered if that decrease could be specifically tied to eye movement.

Consider next the results for trials on which participants were required to indicate what their heading had been at the beginning of the current trial (Home condition). Why might variable error in this condition have been higher over all, and increased more dramatically across turns than in the Turn Beginning condition? One possible factor is that the egocentrically defined direction of the target was constant within trials of the Turn Beginning condition, but varied in the Home condition. It is quite possible that this egocentric consistency results in lower variable error. This possibility could be explored by including experimental trials that comprise series of turns of different sizes, and thus varying egocentric target directions. Another possible factor arises if we consider that the target direction in the Home condition was constant with regard to an allocentric, or environmentally defined frame of reference. Because the target remains fixed relative to the environment in the Home condition, it seems reasonable that the task would be performed by the common process of attempting to maintain orientation relative to salient environmental cues, such as a representation of the surrounding room (e.g., Hermer & Spelke, 1994; Shelton & McNamara, 2001). The Turn Beginning condition however, may favor processes that rely relatively less on intact environmental representations, and more directly on vestibular and somatosensory signals. For example, participants might use the pointer to simply "undo" the most recent turn based on immediate sensory signals. Thus, greater error in the Home than the Turn Beginning condition might reflect a greater dependence on eroding environmental representations in the Home condition.

Other possible explanations of why error was greater in the Home than the Turn Beginning condition arise depending on how the difference between the two conditions is conceptualized. We may reasonably equate the processes contributing to angular self motion updating over each individual turn in the Home and Turn Beginning conditions if we assume that participants are continuously updating and maintaining the single target heading only (Fujita, Loomis, Klatzky, & Gollege, 1990; Müller & Wehner, 1988). In this conception, the representation of the target heading would have no associated trace of the history of rotation, or at least none extending further back than the most recent turn. However, Loomis et al. (1993) have shown evidence that over blind navigation, humans do not simply update a single homing vector (the distance and relative direction from themselves to their starting positions) but that they also construct a record of the path traveled. If a similar "rotation history" is encoded in the current study, it seems reasonable that such encoding would be more difficult in the Home condition, as the relevant history involves the entire series of turns rather than just the most recent. To the degree that this history is relied upon in providing pointing responses then, the greater degree of complexity involved in updating, maintaining and retrieving this history in the Home condition might result in a greater degree of pointing error. This explanation suggests that the complexity of integrating an increasing amount of self motion history may also play a role in the process of becoming disoriented.

Results showing a decrease in confidence over successive rotations, as more time passes and more motion occurs without intervening perceptual support, are not surprising. Results showing greater decreases in confidence over turns in the Home than in the Turn Beginning condition also make sense. In the Home condition, over the course of any given turn (other than the very first), the uncertainty that would accrue to the target heading would be added to that already associated with the target heading previously indicated. Alternatively, in the Turn Beginning condition, the target heading may be established with greater certainty prior to each turn (as "forward"), and whatever uncertainty accrues over the turn would thus be added to a lower "baseline uncertainty".

In the current study, the correlation between confidence and accuracy, examined across participants on a trial by trial basis was not strong. The correlation between confidence and *constant* error was very close to zero (.02). This result appears to provide experimental evidence that there is little relationship between phenomenological and de facto disorientation. However, a significant, if not overwhelming correlation *was* observed between confidence and *variable* error (−.39). It is impossible to determine, based on the current study, whether lower confidence may have caused greater variable error, been caused by other factors that also caused greater error, or both. Further research is needed to clarify the complex relationship between confidence and pointing performance.

Regarding constant error (*incremental error* in the Home condition), there was a significant effect of Turn Number for both Home and Turn Beginning conditions. Notably, constant error was increasingly negative with successive turns for 70° trials, and increasingly positive with successive turns for 200° trials. In other words, over successive rotations, 70° turns were increasingly *over*estimated, while 200° turns were increasingly *under*estimated. This pattern makes sense when we remember that the average Turn Size across the entire study was 135°. Thus, participants responded as if both turn sizes were closer than they actually were to the mean Turn Size for the study as a whole. This apparent regression to the mean phenomenon, or range effect, which has been observed in previous work (e.g., Klatzky et al., 1990; Poulton, 1977), may have become increasingly apparent over successive turns because of the simultaneously decreasing influence of other factors which might have contributed to more veridical estimations of Turn Size (e.g., environmental flow). The relationship between sensory uncertainty and magnitude of the range effect is considered in some depth by Jurgens and Becker (2006). It is unclear, in the present case, whether this phenomenon reflects a cognitive level response bias formed as a result of experience with the range of turn sizes used in the current study, or a tendency occurring in lower level perceptual processing whereby small turns are actually perceived as larger than they are, and large turns as smaller, regardless of the actual mean of the turns (Klatzky, Beall, Loomis, Golledge, & Philbeck, 1999). In any case, to guard against the former possibility, Turn Size might be included as a between subjects factor in future efforts.

Beyond revealing this apparent range effect, the constant error data from this study are somewhat less informative regarding tendencies humans may have to over- or underestimate blind rotation as they become increasingly disoriented.[3] Prior research has provided some evidence that blindfolded participants tend to underestimate whole body rotations (Blouin, Gauthier, & Vercher, 1995, 1995, 1997). However, subsequent work by Mergner, Nasios, Maurer, and Becker (2001) has shown that such apparent rotation misperceptions can vary depending on a number of variables such as (a) how perception of the rotation is assessed (e.g., pointing, eye movement, target adjustment), (b) target eccentricity, (c) the relative involvement of retinal, orbital and neck afferent signals, and critically, (d) the rate of acceleration (the vestibular apparatus has high-pass frequency characteristics and is insensitive to very low accelerations).

Another goal of the study was to show that occasional abrupt failures in pointing performance occurred in conjunction with the gradual decrease in performance. The study was also effective in this respect. We identified a small number of instances in the Home condition in which performance was very poor and showed that the large error observed in these instances did not accumulate gradually over previous turns. Thus, our results suggest two routes from the oriented to the disoriented state. On one hand, one may gradually lose the capacity to localize objects in the surrounding environment. The analysis showing that performance *across participants* did not reach criteria for disorientation until the final 200° turns of the Home condition suggests that this gradual route to disorientation was most common, at least in the particular circumstances of this paradigm. On the other hand, one may abruptly lose that capacity. As expected, results showed that this occurred far more frequently in the 200° than in the 70° Turn Size condition. However, unexpectedly, the incidence of such abrupt losses of orientation did not increase with successive turns, wherein perceptual demands had accumulated and visual support was more remote. This raises the possibility that increasing perceptual demands and decaying visual memory are not always the primary causes of abrupt disorientation. Non-spatial cognitive processes may also be a factor. For example, all or some of the abrupt losses of orientation observed here may have resulted from lapses in attention. It is also possible that confidence in the coupling between heading direction and a deteriorating environmental representation reaches a critical minimum at which point the old coupling is abandoned and a new one is adopted arbitrarily, or on the basis of real or imagined perceptual cues. Finally, abrupt losses of orientation were *not* concentrated in the condition in which disorientation appears to have occurred across participants (the final 200° turns of the Home condition). This supports the conclusion that the two routes to disorientation, gradual and abrupt, are distinct.

To sum up what we have learned about the process of becoming disoriented, first, over whole body rotation, in the absence of visual and auditory input, the ability to perceive that rotation gradually decreases. However, the ability to perceive that movement relative to egocentrically consistent targets decreases less dramatically than the ability to perceive that movement relative to allocentrically consistent targets. Possible mechanisms in the loss of orientation were discussed in light of these results. Second, while correlations between confidence and degree of objective orientation are very weak in this paradigm, there is a significant correlation between confidence and precision of responses. Finally, we have shown evidence for occasional abrupt losses of orientation, suggesting an alternative route to disorientation that may involve different mechanisms. Future studies involving disorientation may benefit from the preliminary steps, taken here, towards unpacking this complex topic.

[3] Analyses of constant error also produced a result for which we have no ready explanation. In the 70° condition, the effects of Turn Number and Target interacted in the *mean error* data. Because the linear component of the interaction was not significant, it is difficult to know what to make of this result.

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