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Report

Walking Straight into Circles

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Summary

Common belief has it that people who get lost in unfamiliar terrain often end up walking in circles. Although uncorroborated by empirical data, this belief has widely permeated popular culture. Here, we tested the ability of humans to walk on a straight course through unfamiliar terrain in two different environments: a large forest area and the Sahara desert. Walking trajectories of several hours were captured via global positioning system, showing that participants repeatedly walked in circles when they could not see the sun. Conversely, when the sun was visible, participants sometimes veered from a straight course but did not walk in circles. We tested various explanations for this walking behavior by assessing the ability of people to maintain a fixed course while blindfolded. Under these conditions, participants walked in often surprisingly small circles (diameter < 20 m), though rarely in a systematic direction. These results rule out a general explanation in terms of biomechanical asymmetries or other general biases [1–6]. Instead, they suggest that veering from a straight course is the result of accumulating noise in the sensorimotor system, which, without an external directional reference to recalibrate the subjective straight ahead, may cause people to walk in circles.

Results

Normal Walking Trajectories

The ability of humans to maintain a fixed course in an unfamiliar environment, without the use of any navigational instruments, was tested in two different environments. Participants were instructed to walk as straight as possible in the direction indicated to them at the start of the experiment, and their walking trajectories were recorded via global positioning system (GPS). Six participants walked for several hours in a large, flat forest area with varying undergrowth density. Four of them walked on a cloudy day, with the sun hidden behind the clouds. These four all walked in circles, with three of them repeatedly crossing their own path without noticing it (Figure 1A). In contrast, the sun was visible when the other two participants performed the walking task. These two followed an almost perfectly straight course, except for during the first 15 min, when the sun was still hidden behind some clouds. These results suggest that the availability of a reliable external source of information about the direction of locomotion is critical for maintaining one's course through unfamiliar terrain.

Three other participants walked for several hours in the Sahara desert, in southern Tunisia. The two participants who walked during the heat of the day veered from the course that they were instructed to follow but did not walk in circles (Figure 1B). The third participant walked during the night, with the full moon initially visible. After the moon disappeared behind the clouds, he made several sharp turns, bringing him back in the direction from which he came.

Blindfolded Walking Trajectories

Although no empirical data in support of a tendency to walk in circles when lost have been published before, the common belief that people do so has spawned several explanations for this supposed behavior. According to one explanation, most humans (and animals in general) have a tendency to turn in one direction [6]. This tendency has been suggested to be mediated by hemispherical asymmetries in the dopamine system [1, 4, 5]. An alternative explanation focuses on biomechanical asymmetries, such as differences in leg length or leg strength [2, 3]. On this account, most humans would have one leg longer or stronger than the other, creating a small but constant bias in the opposite direction. These general biases should be most evident when visual information is lacking.

To test for a general directional bias, we measured blindfolded walking behavior in a large field. Participants walked blindfolded for a total duration of 50 min. They were instructed to keep walking straight in the direction indicated to them visually at the beginning of their walk. For most participants, the walking trajectories were highly random, and no overall bias was evident in the walking direction (Figure 2). The average bias in walking direction did not differ significantly from zero across participants [$T(14) = 0.21$, $p = 0.839$]. Only 3 out of 15 participants (KS, KB, and SM) showed a strong tendency to veer consistently in one direction, causing them to walk in circles most of the time. Most participants showed little overall bias but would occasionally make several small circles (e.g., FW in Figure 2C). The circles in which participants walked could be as small as 20 m in diameter, almost fitting within a basketball court.

Without visual or auditory input providing an external directional reference, our blindfolded participants had to rely on body cues such as vestibular information and proprioception to sense their walking direction. Humans are able to walk blindfolded to a previously seen target quite accurately at short distances (up to 20 m) by using these body cues [7–10]. Both blindfolded and blind people show a small amount of veering when instructed to walk straight for a short distance [11–14]. For larger distances, however, theoretical considerations suggest that these cues cannot be used as an inner compass because of the accumulation of sensory noise [15, 16]. In fact, even when people do not walk in circles, they should still be limited in the distance that they can cover on average without an absolute directional reference. The reason for this

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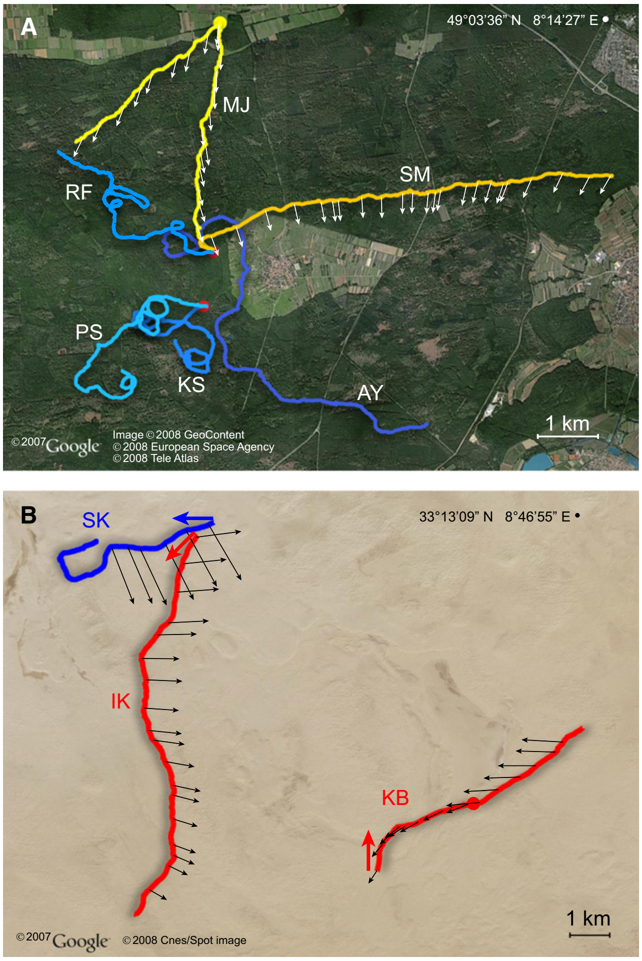

Figure 1. Normal Walking Trajectories

(A) Bienwald forest (Germany). Participants began walking from two different starting positions (red dots). They were instructed to walk as straight possible in the direction indicated to them at the beginning of the experiment (northwest for KS and MJ; west for the others). Four participants walked on a cloudy day (blue trajectories); when SM and MJ walked, the sun was visible, except for during the first 15 min (yellow trajectories). For the two yellow trajectories, white arrows indicate the direction of the solar azimuth at 10 min intervals (length proportional to the angle of solar incidence). MJ walked out of the forest; he was instructed to turn around (yellow circle) and follow a new southwest course. PS and MJ walked for 3.5 hours; the other participants walked for 4 hr.

(B) Sahara desert (Tunisia). IK and KB walked during the day (red trajectories); SK walked at night (blue trajectory). Red and blue arrows indicate start positions and directions. Black arrows indicate the direction of the solar (IK and KB) or lunar (SK) azimuth in 10 min intervals (length proportional to the angle of solar/lunar incidence; for SK, azimuth is only shown for the period during which the moon was visible). KB walked for 3.5 hr (with a long pause halfway; red circle), IK walked for 3 hr, and SK walked for 2.5 hr.

Satellite imagery is from Google Earth; azimuth and elevation data are from http://aa.usno.navy.mil.

is that with increasing path length, the trajectory will start to drift more and more from the intended direction in a random fashion. Analysis of our blindfolded walking data confirms this. Within a few minutes of walking, the average displacement (across all participants) from the starting point leveled off to an asymptotic value (~100 m), and the variance in position increased equally in both the intended direction of walking and the orthogonal direction (Figures 3A and 3B). This implies that, on average, people will not travel much more than 100 m from their starting point when using only body cues to guide their walking direction, regardless of how long they walk. Without the use of an external directional reference, humans (like any animal) are not able to maintain a fixed course.

External cues to walking direction could be used to recalibrate the direction estimate based on body cues, reducing the drift caused by accumulated sensory noise. In our blindfolded walking experiment, there were two different events that may have provided such external cues. First, participants did not walk blindfolded for 50 min continuously. Instead, they walked in separate trials of 5 or 10 min, interspersed with 1 min of walking with vision to the starting point of the next trial. If the visual input did not affect the perceived walking direction while walking blindfolded, the change in walking direction at the end of a trial should be strongly correlated to that at the beginning of the next trial. However, our data show that this was not the case ($r = -0.09$, $p = 0.348$; see Figure 3C). Instead, if participants deviated strongly from a straight line at the end of a trial, they tended to start the next trial by walking more or less straight again (indicated by a negative correlation between the direction change at the end of a trial and its difference with the direction change at the start of the next one: $r = -0.81$, $p < 0.001$; see Figure 3D).

The second opportunity for external references to influence the perceived walking direction occurred when a participant walked off the field. In that case, he or she was turned around by the experimenter while still blindfolded and instructed to continue walking in a straight line. Although the turning did not give absolute directional information, it may have reset the internal estimate of walking direction. Our data show that this was indeed the case. If participants showed a strong deviation from straight ahead just before being turned around, they tended to walk more straight after turning (again indicated by a negative correlation between direction change just before the turn and its difference with the direction change after the turn: $r = -0.58$, $p < 0.001$; see Figure 3D). However, this recalibration was weaker than that after walking with vision ($z = 3.38$, $p < 0.001$), causing the change in walking direction before and after turns to be still significantly correlated ($r = 0.34$, $p < 0.001$; see Figure 3C). From our data, we cannot determine whether this partial recalibration was caused by being touched by the experimenter, by the act of turning itself, or by stopping and then starting to walk again.

Biomechanics

The large variability in curvature of the blindfolded walking trajectories and the absence of a consistent bias in most participants suggest that biomechanical asymmetries did not play an important role [14]. This conclusion was supported by further tests on the effect of biomechanical asymmetries. We measured dynamic leg strength for 11 of the 15 participants in the blindfolded walking experiment. Differences in leg strength between the two legs were expressed in the ratio of the left and right leg for maximum torque in flexion and extension at the knee. These ratios did not correlate with the mean direction bias during blindfolded walking ($r = -0.16$, $p = 0.65$ and $r = -0.40$, $p = 0.23$, respectively; see Figure S1A available online). Leg length is difficult to measure reliably without radiology [17]. Participant KB had his legs X-rayed for this study (they differed by less than 1 mm in length), but it was not feasible to do this for the other participants as well. Instead, we manipulated leg length by adding soles of different thickness (±12 mm) to the feet. Participants were again asked to walk as straight as possible while blindfolded.

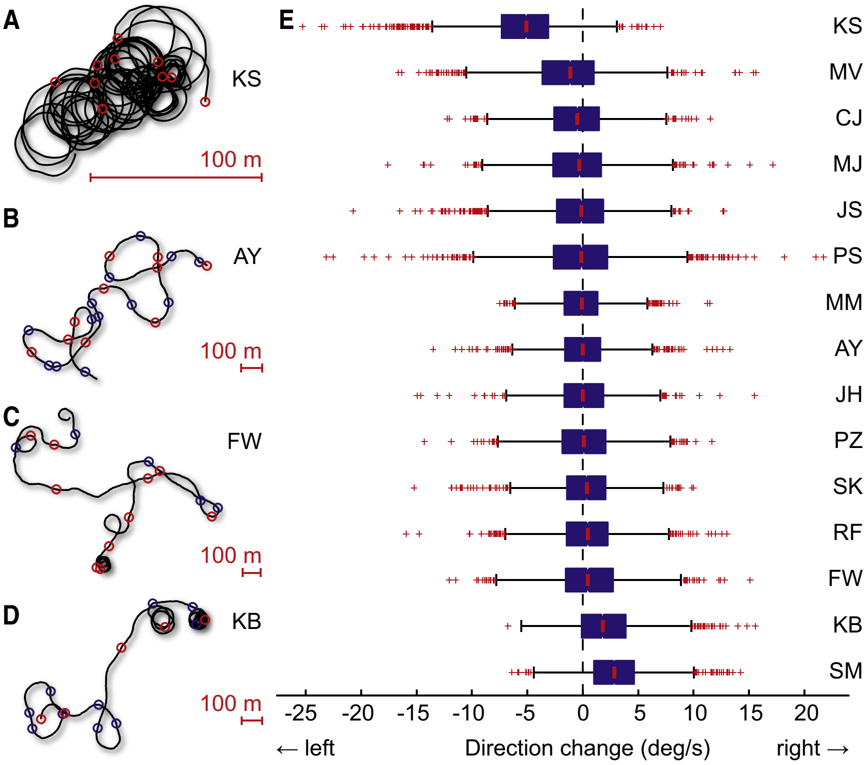

Figure 2. Blindfolded Walking

(A–D) Individual trajectories for four participants. Trial starts are indicated by open red circles; blue circles show where participants were stopped and turned around when they reached the end of the field. Trajectories from different trials were aligned and pasted together in post-processing.

(E) Individual distributions of the change in walking direction for all 15 participants. Participants walked without vision in five trials of 10 min each (MV, JS, PS, JH, SK, and KB) or in ten trials of 5 min each (other participants), with 1–2 min breaks with vision in between. Box-plot whiskers represent 1.5 times the interquartile range; red crosses indicate outliers. Participants are shown sorted according to their median direction change.

This manipulation did not have a systematic effect on veering (Figure S1B).

Discussion

The belief that people who get lost end up walking in circles is widespread and often alluded to in both literature (e.g., Mark Twain, *Roughing It* [1872]; Leo Tolstoy, *Master and Man* [1895]; J.R.R. Tolkien, *The Lord of the Rings: The Two Towers* [1954]) and films and television (e.g., *Laurel & Hardy: Beau Hunks* [1931], *The Flight of the Phoenix* [1965], *The Blair Witch Project* [1999]). Our data provide the first empirical evidence that humans actually do tend to walk in circles when traversing unfamiliar terrain without reliable directional references. If such directional references such as landmarks or the solar azimuth are present, people are able to maintain a fairly straight path, even in an environment riddled with obstacles, such as a forest.

With the sun visible, participants exhibited little systematic deviation from straight ahead in their trajectories, even though the solar azimuth changes substantially in the course of a few hours (white and black arrows in Figure 1). If they had used the position of the sun without compensating for this change in azimuth, participants would have followed a more curved trajectory. Their actual trajectories deviated little from a straight line (especially in the forest), suggesting that participants were able to at least partially compensate for the change in solar azimuth. Other animals, such as honey bees [18] and pigeons [19, 20], have been shown to possess this ability as well. Compensation may be based on an internal clock, or on the use of additional visual cues (e.g., local landmarks, optic flow) to maintain a fixed course. Rather than using the sun itself, participants may have used the shadows cast by it to orient themselves, because they rarely looked up to the sun. Veering was more pronounced in the desert than in the forest (when the sun was visible). This may have been caused by the larger changes in solar azimuth in the desert or by the availability of additional visual cues in the forest. Taken together, these results reinforce the importance of having reliable visual cues for navigation, such as easily recognizable landmarks, the sun, or the moon.

Biomechanical asymmetries do not explain the direction into which people veer when walking blindfolded, let alone when walking with vision. In fact, participant KS, who had the strongest directional bias while walking blindfolded (Figure 2A), veered into the opposite direction in the forest (Figure 1). We also failed to find a correlation with functional asymmetries such as handedness or footedness (only participant MJ reported to be left dominant for hand and foot). One reason for the lack of correlation between veering behavior and asymmetries [21, 22] may be that the body adapts to them by using visual and other sensory information to calibrate the motor system. Therefore, it is unlikely that these asymmetries play a significant role when people walk in uneven terrain with visual feedback about the direction in which they are walking.

A striking feature of both the blindfolded walking trajectories (Figure 2) and the forest trajectories with cloudy weather (Figure 1A) was that in most trajectories, periods of seemingly random behavior were interspersed with systematic circling. In the forest, this may have been a result of differences in the availability of local landmarks and/or obstacles that had to be circumvented. Local landmarks, such as a tree that stands out, may help a person to walk straight for a short period of time. In contrast, obstacles may induce a curved path, especially if someone tends to pass obstacles more to one side than the other. During blindfolded walking, however, no such variable external factors were present. The fact that participants often walked in circles instead of following a random zigzag path suggests that the veering from straight ahead was caused by a change in their subjective sense of straight ahead rather than by random noise in either the sensory input or the motor output. The recorded walking trajectories show exactly the kind of behavior that would be expected if the subjective sense of straight ahead were to follow a correlated random walk [23]. With each step, a random error is added to the subjective straight ahead, causing it to drift away from the true straight ahead (see Figure S2 for an example). As long as

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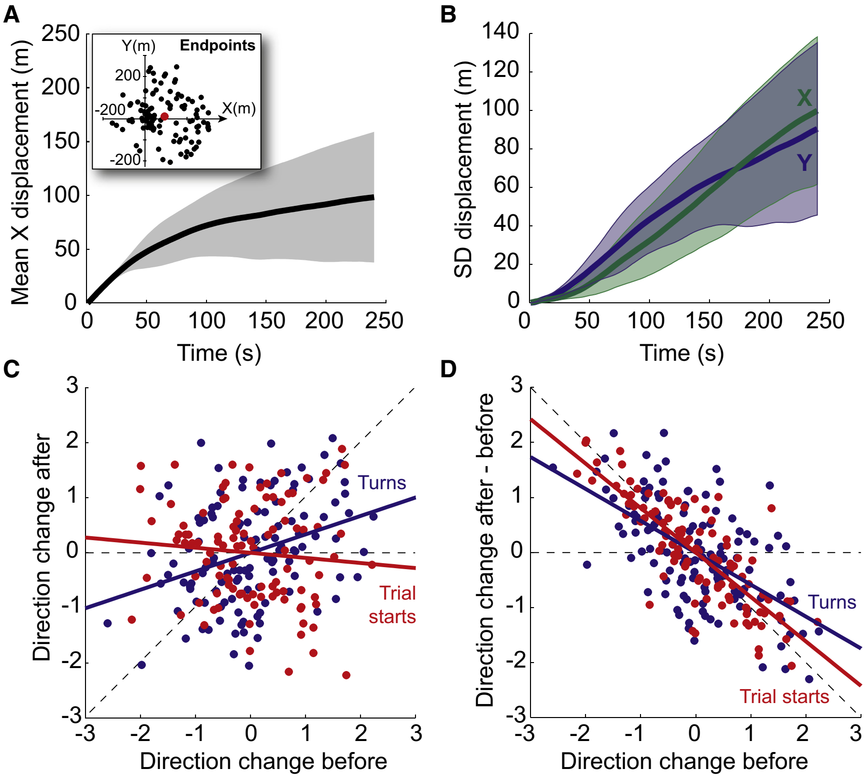

Figure 3. Noise Accumulation and Recalibration

(A) Mean displacement in the initial walking direction X plotted against time since trial start. Inset shows endpoints of individual trials after 240 s (red dot indicates the average endpoint).

(B) Mean standard deviation of the position in the initial walking direction X (green) and the orthogonal direction Y (blue). Shaded areas indicate the standard deviation across participants.

(C) Change in walking direction after the start of a new trial (red) or after being turned around at the edge of the field (blue) plotted against the direction change just before the discontinuity. Direction change data were first transformed into z scores for each individual participant and then aggregated across all participants. A consistent change in walking direction before and after a trial start or turn would result in the data points lying on the positive diagonal. The colored lines in (C) and (D) show the best fitting straight lines.

(D) Difference between the change in walking direction before and after the discontinuity, plotted against the direction change just before the turn or trial start. If participants completely recalibrated at trial starts and after turns, the data points would lie on the negative diagonal.

the deviation stays close to zero, people walk in randomly meandering paths. When the deviation becomes large, it results in walking in circles. This implies that circles are not necessarily an indication of a systematic bias in the walking direction but can be caused by random fluctuations in the subjective straight ahead resulting from accumulating noise. As long as no information about the absolute direction is available for recalibration, the internal estimate of straight ahead becomes increasingly unreliable.

This drift in the subjective straight ahead may be the result of accumulating noise in all components of the sensorimotor system. The vestibular system, for example, is known to be easily biased in one direction or the other. Asymmetric vestibular stimulation, by caloric or galvanic stimulation, has been shown to cause people to veer from a straight path [24, 25]. Similarly, vestibular disorders affect the amount of veering during blindfolded walking [26, 27]. Alternatively, the drift from straight ahead might originate in the motor system. It has been suggested that hemispheric differences in the dopaminergic neurotransmitter system cause systematic veering from a straight path [5]. However, it is unclear whether the timescale on which these neurotransmitter levels fluctuate corresponds to that of the changes in veering behavior observed in our experiments. Regardless of the source of the veering behavior, our blindfolded walking data show that veering is not the result of a constant directional bias but is more likely to be caused by random changes in the subjective sense of straight ahead. When walking with vision (Figure 1), visual information can be used to recalibrate the subjective straight ahead, making the trajectories less curved. In addition, vision allows for the use of cognitive strategies, such as the use of landmarks.

Our results show that humans tend to walk in circles when no external directional references are available. If such cues (e.g., the solar azimuth) are present, people are able to maintain a fixed course. However, in emergency situations, where one's life depends on the ability to navigate through unfamiliar terrain and reach safety, emotional state (panic) and social factors (group dynamics) may cause these cues and more cognitive navigation strategies to be disregarded, making people walk in circles even in the presence of reliable directional cues. Ironically, in the age of ubiquitous navigation systems in airplanes, cars, and even mobile phones, we are only beginning to understand how humans navigate through their environment, exploring uncharted terrain. Our results here show that the seemingly simple act of walking in a straight line actually involves a complex interplay of various sensory modalities, the motor system, and cognition.

Experimental Procedures

Walking trajectories were recorded via GPS at 1 Hz (5 Hz for the leg length manipulation experiment). The area used for the forest experiment (Bienwald in western Germany) was selected based on its size (large enough to walk in a constant direction for several hours) and its minimal changes in elevation. The desert terrain in Tunisia was selected because of the absence of visible landmarks (mountains, trees, manmade structures), the scarcity of vegetation, and the presence of sand dunes, which prevented participants from being able to constantly see the horizon. The blindfolded walking experiment and the leg length manipulation experiment were conducted on an airstrip with a large grass field and a concrete runway. Leg strength was measured at the Department of Sports Medicine of Eberhard Karls University Tübingen with an isokinetic test device.

Supplemental Data

Supplemental Data include Supplemental Experimental Procedures and two figures and can be found with this article online at http://www.cell.com/current-biology/supplemental/S0960-9822(09)01479-1.

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