The Influence of Acoustic Stimuli on “Walking Straight” Navigation by Blindfolded Human Subjects

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Abstract: Navigation of blindfolded sighted participants was tested in a 40-m free-space outdoor environment with and without external acoustic beacons. The common everyday observation about circling or veering from the straight line during walking without vision was tracked by means of a GPS device. 120 subjects participated from 19 to 83 years of age. Results are presented for normal walkings (no acoustic target), and for walkings with two different acoustic targets (click-train and white noise). This investigation supports the necessity of an external reference for walking in a straight course, furthermore, that different kind of acoustic stimuli can be used, and finally it serves for a comparative basis for further investigations with blind participants.

Keywords: localization, acoustics, blind, walking straight

1. Introduction

The common belief that people can not walk in straight line has origins in everyday life’s experience and also appearances in popular culture and literature. People walking in unfamiliar terrain where no external reference is visible often walk in circles or veer from the straight direct path. Humans, apparently, slip into circles when they can not see an external focal point, like a mountain top, the sun, or the moon. Investigations testing this phenomenon are easy to establish and non scientific approaches can be found on different websites, on YouTube or television shows.

On the other hand, properly and extensively prepared and executed scientific experiments are extraordinary. These mainly focus on the reason why it is so, trying to proof or disproof common explanations about this phenomenon. One belief is that the reason is anatomical difference between leg lengths or foot sizes: the size of the circle is depending on the length of one’s legs and on the size of the difference in length of the legs. One leg is slightly shorter than the other, usually the left leg, so walking will invariably be in a circle if one is blindfolded. The fact that following a straight line is also similarly difficult in case of blindfolded biking, swimming or car driving, these explanations can be hardly true. Furthermore, details such as brain dominance, surface unevenness, weather changes, handedness or footedness can influence the actual results [1]. The question also comes up if there could be any evolutionary advantage of the ability to walk straight without vision. Territorial instinct was suggested; however, blindfolded animals also veer or circle [2-5].

Another, mathematical point of view, suggests that there is only a single way to walk straight, but there are an infinite number of ways to walk other than straight so the probability of walking straight without feedback is essentially zero.

The first experimental results are as early as 1897, and these preliminary experiments also suggested biomechanical asymmetries [3, 6-11]. If vision is active, subjects update their current self-position and velocity of movement and the location of the target. The latest is sometimes constantly not visible, so target location has to be updated imaginarily. Visually directed walking is an action in which subjects try to walk without vision to a previously seen location (target). Here, subjects are forced to update the initially perceived target location (direction and distance) imaginarily based on velocity and without any external reference point.

A recent work tested the ability of humans to walk on a straight course through unfamiliar terrain in two different environments: a large forest and a desert [12]. Nine participants took walkings of several hours (captured via GPS) showing that they repeatedly walked in circles when they could not see the sun. When the sun was visible, participants sometimes veered from a straight course but did not walk in circles which are more a result of accumulating noise in the sensorimotor system than any biomechanical asymmetries or other general biases. Four walked in the forest on a cloudy day (all four walked in circles) and two on a sunny day followed an almost straight course. Three other in the Sahara desert veered from the course but did not walk in circles. The biomechanic differences (dynamic length strength, leg length etc.) were also measured and found to be too small for playing a significant role. Even different additional soles were added to test the role of biological asymmetries. This investigation included a small number of participants but a long monitoring time. In a former experiment same authors reported 3 out of 15 participants having a strong tendency to veer in one direction and walking in circles less than 20-m in diameter. It was very interesting that a recalibration by an external source, a touch from the experimenter, a turning or stopping could result in a straight walking path again from the given point on.

It was also reported that blindfolded people can walk quite accurately to previously seen targets up to about 25-metres [10-12]. In a follow-up study twenty healthy men were asked to walk as straight as possible to a target 60-m away at normal speed in an indoor environment [13]. The results revealed that all walked in a sinuous zig-zag line rather than a straight line. Periodicity and amplitude of the meandering differed from subject to subject. They explained the meandering movement primarily due to a slight structural or functional imbalance of the limbs, which produces a gait asymmetry, and only secondarily due to missing feedback from our sense of sight.

There is experimental evidence that perceived location is an invariant in the control of locomotion, by showing that different actions are directed toward a single visually specified location in space and that this single location, although specified by a fixed physical target, varies with the availability of information about the distance of that target [14]. Here, subjects viewed relatively close targets at 1.5-m, 3.1-m, or 6.0-m and then attempted to walk to the target with eyes closed and without any auditory cue using one of three paths. The participants stopped at about the same spatial location regardless of the path taken, providing evidence that action was being controlled by some invariant visually perceived location. This experiment included only 16 adults (20 – 31 years) and three short walking paths in an indoor environment without sound cues.

Thirteen normal subjects were tested to walk blindfolded along circular paths instead of following a straight line [15, 16]. They were asked to walk completing two revolutions and to stop when they judged they had returned to the initial position with their head faced to the initial directions. Movements were recorded by 3D motion analyzing system which allowed to measure the total walked distance, the average radius of the trajectory, and the cumulative angle of rotation. Walked trajectories of young subjects were smooth, whereas those of older subjects tended to be polygonal. Young subjects overshot the ideal distance (6.6%) and ideal radius (9.5%), whereas they undershot the ideal angle (5.1%). There was no effect of circle size or condition on these variables. The performance of older subjects seemed to be affected by the concurrent mental task. Comparing the counter clockwise walk, the older subjects undershot the turning angle much more than the young subjects which suggest deficits in the vestibular function with aging. Lack of unilateral vestibular information seemed to have affected the circular walking trajectory. Normal participants consistently overshot the ideal radius independently of the condition and circle size, undershot the total angle and overshot total distance. A strong correlation was found between the errors in radius and total distance but not between distance and total angle. Principal components analysis suggested that radius and distance share a common source of errors while total angle produced independent errors. The results indicate that (a) circular trajectories can be generated starting from spatial and/or motor memory, without the aid of visual information; (b) the task needs some attentional control and does not involve simple automatic processing of afferent information; (c) different sensory information or different processing modes are probably involved in the estimation of the curvature and length of the walked path on the one hand, and of the total rotation angle on the other.

The ability to detect the distance walked when blindfolded sighted use only haptic information generated by the walking activity was investigated when participants walked a straight path until told to stop, turned, and attempted to return to their starting point [17]. Gait was varied or distorted. In all experiments the return distance was a linear function of the set distance, with some participants giving and some conditions resulting in remarkably sensitive performances. The magnitude of errors was a linear function of step length.

Research often focuses on medical points of view, effect of medication or damaged biological functions. Locomotion depends on an intact dopamine system that can be supplemented by medication [8, 18]. Levodopa is a dietary supplement and psychoactive drug found in herbs and is also used in the treatment of Parkinson's disease. This system seems to be functionally asymmetric, as evidenced by an asymmetric turning preference (right hemisphere). Using a double-blind procedure, the effect of levodopa on the number of veers when walking blindfolded along a straight line (20-m) in the middle of a corridor was tested in 40 healthy men. They found that (a) subjects veered less after levodopa than after placebo, and (b) improved straight-walking tendency was most prominent for the levodopa group which veered less often to the right side than the placebo group. These findings imply that spatial orientation skills improved under levodopa.

To investigate side preferences between different tasks within the same subject, 36 healthy research participants were investigated in (a) long-term spontaneous turning (number of 360 degree turns during 20 hours), (b) veering (lateral deviations during walking blindfolded straight forward) and (c) stepping (deviations while stepping blindfolded on a given spot) behaviour [8]. They observed a left-sided preference for long-term spontaneous turning behaviour and no significant side preference for veering and stepping behaviour. They also suggested that veering tendencies, which appeared equally pronounced in either direction, are under dopaminergic control as long as attention is directed towards extrapersonal space. Side preferences in lateralized whole-body movement tasks are thus neither comparable between tasks nor within subjects. Data indicate that, without being aware of the type of information being obtained, normal men and women rotate preferentially to the left or to the right during a routine day. Women had higher average rates of rotation than men. Males that were consistently right-sided (left-hemisphere dominant) for hand, foot and eye dominance rotated more to the right than to the left, whereas left-hemisphere dominant females rotated more to the left than to the right.

The vestibulo-ocular reflex or oculovestibular reflex is a reflex eye movement that stabilizes images on the retina during head movement by producing an eye movement in the direction opposite to head movement, thus preserving the image on the center of the visual field. Findings from experimental data indicate that some aspects of vestibular perception are entirely independent of visual mechanisms, despite the observed influence of vision on velocity storage and the acknowledged role of vision in continuously recalibrating vestibular processing. Furthermore, balance, is the result of a number of body systems working together. Specifically, in order to achieve balance the (a) visual system, (b) ears (vestibular system) and (c) the body’s sense of where it is in space (proprioception) ideally need to be intact. In a study, the authors addressed whether the source of veering in the absence of visual and auditory feedback is better attributed to errors in perceptual encoding or undetected motor error [19]. Three experiments had the following results. No significant differences in the shapes of veering trajectories were found between blind and blindfolded participants; accuracy in detecting curved walking paths was not correlated with simple measures of veering behaviour; and explicit perceptual cues to initial walking direction did not reduce veering. The authors present a model that accounts for the major characteristics of participants’ veering behaviour by postulating three independent sources of undetected motor error: (a) initial orientation, (b) consistent biases in step direction, and, most important, (c) variable error in individual steps.

Blind participants’ behaviour was also tested showing a small amount of veering and indicating that they can walk better in a straight line [19-23]. However, informal and non scientific observations report opposite findings [24, 25].

During rehabilitation processes, prior to the walking straight task, different other enhancement exercises have to be practiced, such as localization of single sound sources (hand clap), turning (facing) to the direction of the sound source etc. Participants may use sound reflections, so results of indoor and outdoor test environments must be separated. If external acoustic beacon signals are applied, test environments and excitation signals have to be selected carefully. Broadband signals, such as white noise or pink noise can be detected and localized the best by human listeners [26, 27]. Furthermore, signals with higher frequency content are also better for auditory warnings from the same reason [28]. Click-trains are also preferred in localization tests and for everyday sounds for guidance of the blind (pedestrian crosswalks), for auditory displays etc. [29-33]. Increment of volume and duration also increase the localization performance: sound sources between 40-80 dB Sound Pressure Level (SPL) and signals exceeding 250 ms are localized the best [26, 34].

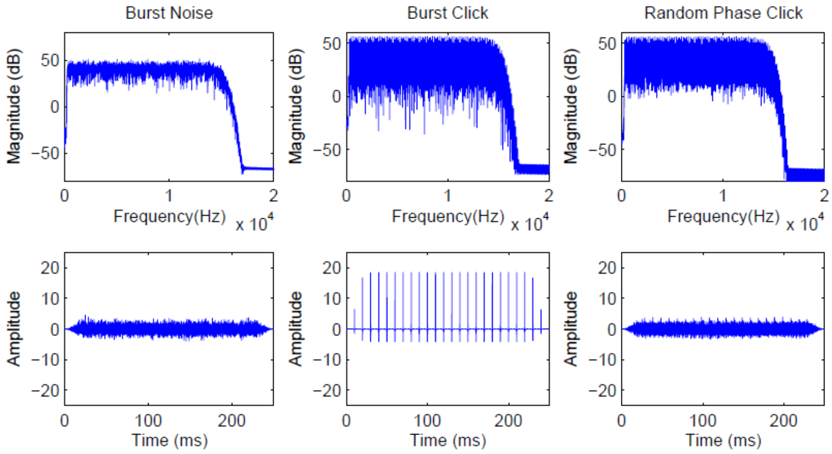

Figure 1. Typical spectra of excitation signals used for auditory experiments [35]. Time domain and frequency domain representations are shown for broadband burst noise (left), short paced click-train and a random phase click-train (right).

Click-trains, impulse sequences are different in contrast to individual clicks and impulses regarding localization of signals with different levels. Some results suggested that the performance difference observed between the localization of click-trains and noise might be related to the level of the stimulus (see Fig.1.) Results from burst click and random-phase click conditions show that even two stimuli with nearly identical spectral content can result in quite different levels of localization accuracy [35]. These differences are not limited to loud stimulus presentations. The usual assumption of higher level sounds (more than 70 dB) to be localized better is valid to noise signals and doubtful for different click or impulse trains.

The primary goal of our investigation is not to find answers and explanation for the reasons of veering and circling, but to test whether auditory feedback and acoustic beacons are enough reference for keeping walking paths straight, and, whether blind subjects are better or not in comparison with blindfolded sighted subjects (future work).

2. Experimental Setup

Our experiment was carried out in a free outdoor environment, on a concrete-surface handball court of 40-metres × 20-metres. The starting point was the base line (goal line) in the symmetry axis of the court and the target was the other base line 40-m ahead (Fig.2.). There were no reflecting surfaces, buildings near the court. A GPS tracker was used for recording time, distances and walking trajectories. Good weather conditions were also a requirement, mostly sunny or cloudy days without wind.

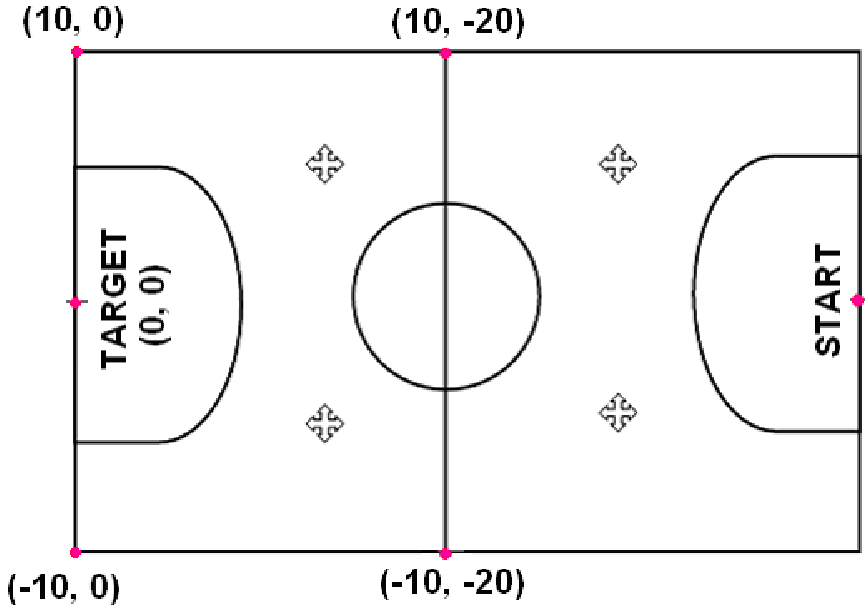

Figure 2. Layout of the handball court used for the experiment. The task was to follow the straight course from the start to the target (40-metres). A coordinate system was applied on the court and deviations were measured in space (metres, as indicated) and time. Walking trajectories were recorded via GPS tracker.

The number of participants was 120, 65 females and 55 males from 19-years of age up to 83. Test signals were white noise and 1 kHz click-train. The latter is a looped 200-ms 1 kHz sinusoidal burst followed by a 200-ms silence. These signals were played back on a Discman in CD quality, amplified and radiated by a loudspeaker standing in the target position at 1,1 meters height. Sound pressure level of the sound source was 90 dB at 6-metre distance. Control measurements of the SPL indicated that the outdoor environment is almost a free-field condition, where doubling the distance between sound source and listener results in a 6 dB decrease of the SPL.

The experiment was conducted as follows. After registering the personal data (gender, age, handendess) a detailed explanation of the procedure was given. Subjects held the

GPS tracker in the hand and faced the target. Without any auditorial feedback they tried to walk blindfolded toward it with the experimenter behind them to avoid any damages or injuries (Fig. 3 and 4). The waking ended if the subject reached the other goal line (in ideal case the target) or walked off the court on the sides. The next run included the same task but with the auditory target active: first the click train, followed by the white noise signal. At the end, the first run without sound was repeated to check whether any learning or adaptation processes are present or not. One run lasted about 40-70 seconds. The deviation in metres and the time elapsed were recorded, furthermore, the GPS logger tracked the trajectories in a 1 Hz temporal and 1-metre spatial resolution for calculating the total walking distances. Results were collected in a spreadsheet and GPS logs were processed using different software environments (Fig. 5-9).

Figure 3. Initialization of the experiment at the starting point. During visually directed walking subjects try to walk blindfolded to a prevoisusly seen location, in this case, a straight walking course of 40-metres with or without auditory stimulus.

Figure 4. The loudspeaker mounted on a stand as target sound source in the middle of the goal (left) and the procedure of blindfolded walking secured by the experimenter on the handball court (right).

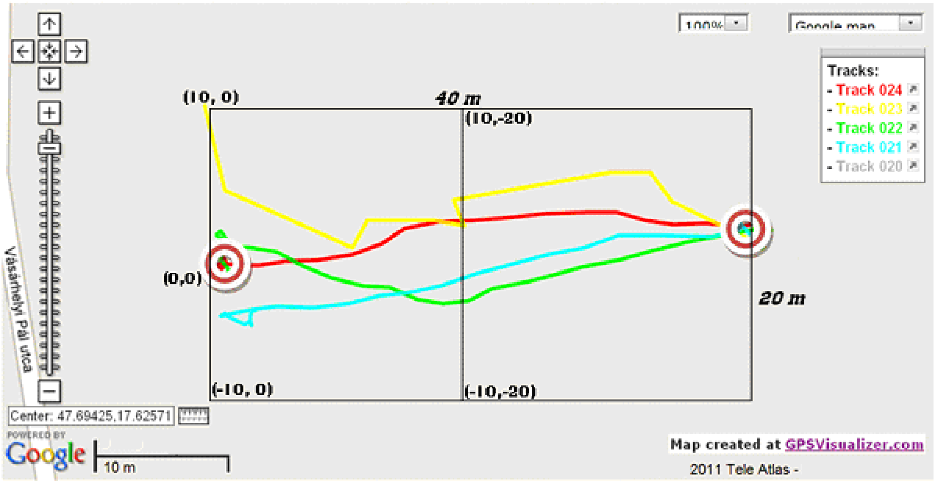

Figure 5. Visualization method using the GPSVisualizer based on the GPS logs and Google Maps. For a better mapping and visualization, pictures were edited and simplyfied (see Figures 7-9).

3. Results

Results of the measured X and Y coordinates corresponding to the deviation to the target are the basis for evaluation. If a subject reached to the loudspeaker to be able to touch it, the task was completed successfully. Measured results can be evaluated based on maximum, minimum, mean values and standard deviation.

Table 1 shows the results of the first walkings without sound, based on the results including all 120 trials. This is the reason why the minimum values can be as low as 17 seconds and 18 metres of total walking distance corresponding to a participant who walked off the court on the right side 28 metres before the target base line. Negative X-values indicate left from the target, negative Y-values indicate walking off the court on the side (not reaching the base line). Table 2 shows the same for those only who reached the base line.

Table 1. Results of the first walking experiment without sound for all 120 participants. Maximum, minimum, mean values and standard deviation are shown respectively. Differences in metres are shown along both axes as well as total distance covered.

	Time (sec)	**Difference (X, m)**	**Difference (Y, m)**	**Distance (m)**
MAX	76	10	0	46
MIN	17	-10	-28	18
MEAN	36,22	0,26	-4,05	40,13
SD	9,45	7,60	6,36	4,72

Table 2. Results of the first walking experiment without sound for the participants who reached the base line (67 subjects). Maximum, minimum, mean values and standard deviation are shown respectively. Differences in metres are shown along both axes as well as total distance covered.

	Time (sec)	**Difference (X, m)**	**Difference (Y, m)**	**Distance (m)**
MAX	76	10	0	46
MIN	21	-10	0	40
MEAN	38,01	-0,71	0	41,93
SD	8,79	4,87	0	1,66

The absence of auditory stimuli means that people walk blind and deaf that usually the case is in such experiments if we test the ability of keeping the straight line. Figure 6 shows the exit points on the court for all participants and trials. 67 subjects (56%) reached the base line (within ±10-metres left or right on the X-axis), including those who ended up in the corner. 11% reached the loudspeaker and another 6% were within ±1 metre (Table 3).

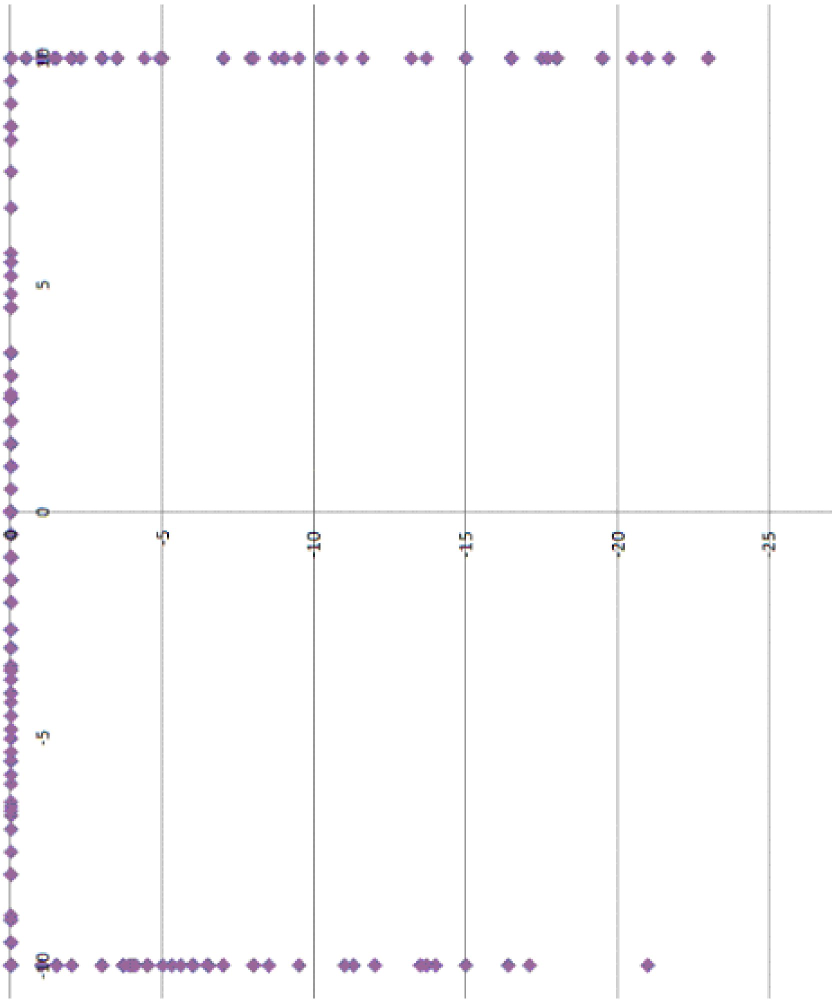

Figure 6. Exit points on the court based on all trials during the first walking in absence of auditory stimuli. Some exit points overlap if there were participants who left the court at the same point, so actual number of dots are less than 120 in this figure.

Table 3. Results of the first walking experiment without sound. 67 out of 120 (56%) reached the base line. All together 17% could reach the target or were at least within ±1 metre. 11% reached the target and 4% left the court in the left or right corner.

	Within 1-metre	**1-5 metres**	**5-10 metres**	**Sum**
RIGHT	2%	11%	5%	18%
LEFT	4%	11%	8%	23%
TARGET				11%
CORNER				4%
SUM				56%

All together 92 participants executed the test with repetition. At the first try, only 5 reached the target (5%), and another 46 reached the base line (50%). At the second try, these numbers increased to 12 (13%) and 56 (60%) respectively. Here, males performed better: 28% more reached the base line at the second time, whereas, this was only 11% more for females. Figure 7 shows walking trajectories plotted based on the GPS logger.

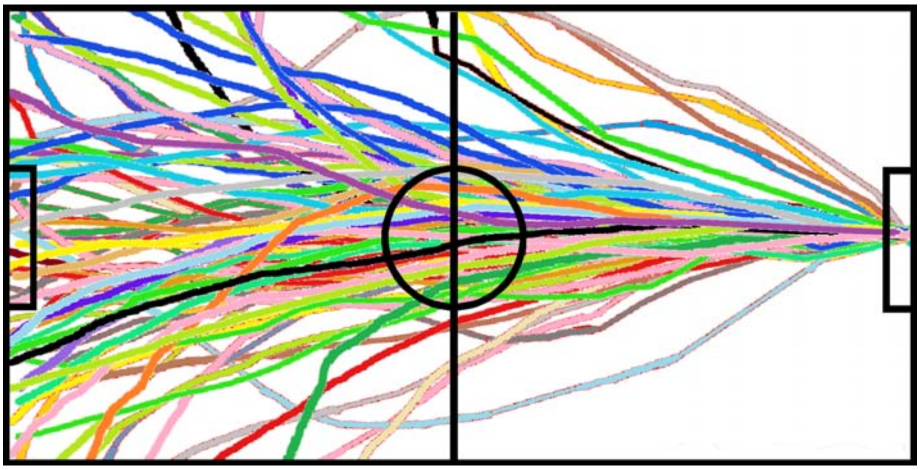

Figure 7. Walking trajectories based on GPS tracking during the first try without sound. Because there was only a moderate improvement during the second try, this latter is not shown. Compare with Figures 8 and 9.

The same experiment was repeated using acoustic beacons. Tables 4 and 5 show the results for click-train and white noise stimuli respectively. Furthermore, Figures 8 and 9 show the GPS log data similarly to Figure 7. Because there were only two and one subjects who failed to reach the base line, Y-coordinates in Tables 4 and 5 are not statistically relevant.

Table 4. Results of the walking experiment following a click-train stimulus. Maximum, minimum, mean values and standard deviance are shown respectively. Differences in metres are shown along both axes as well as total distance covered.

	Time (sec)	**Difference (X, m)**	**Difference (Y, m)**	**Distance (m)**
MAX	95	3,1	-12	42
MIN	21	2,5	-1	31
MEAN	43,54	0,03	-6,50	40,68
SD	12,44	0,46	3,88	1,02

Table 5. Results of the walking experiment following a white noise stimulus. Maximum, minimum, mean values and standard deviance are shown respectively. Differences in metres are shown along both axes as well as total distance covered.

	Time (sec)	**Difference (X, m)**	**Difference (Y, m)**	**Distance (m)**
MAX	73	0,5	-10,6	41
MIN	23	0,5	-10,6	31
MEAN	41,18	0,50	-10,60	40,84
SD	10,20	0	0	0,98

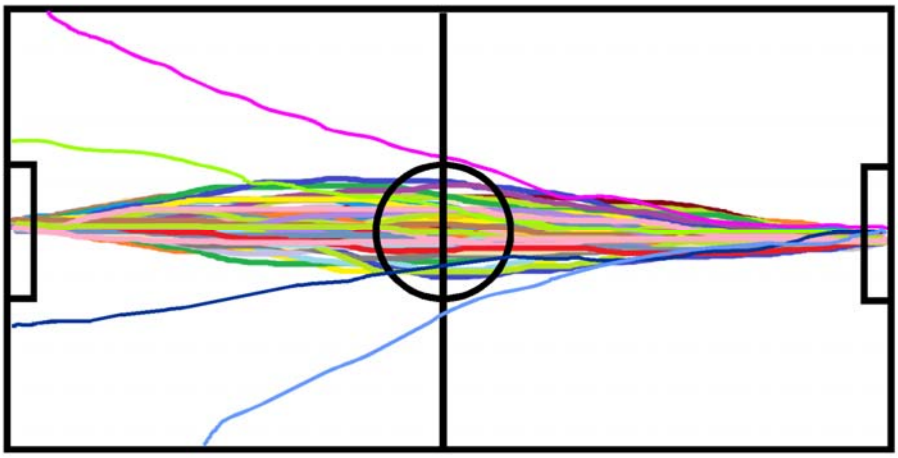

Figure 8. Walking trajectories based on GPS tracking in case of the click-train excitation.

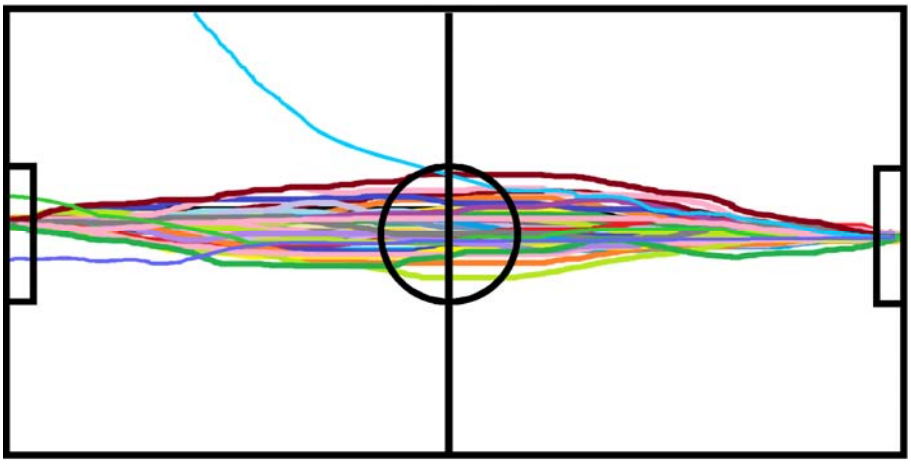

Figure 9. Walking trajectories based on GPS tracking in case of the white noise excitation.

4. Discussion

Results of this experiment supports former findings about the fact that blindfolded humans can not keep a straight walking path without external reference. People veer from the straight path after several meters of walking. Sighted, blindfolded participants reported a „depressing feeling" during walkings without sound and they were surprised how low they performance first was and if they evolved or not during the test, furthermore, how much help sound provided. Note, that in case of outdoor experiments good weather conditions are required; especially wind can literally blow sound waves away.

Data in Table 1 revealed that there is no real side preference of veering: the mean calculated based on the deviations to the left or to the right in metres is only 0,26 along the X-axis and only 4-metres along the Y-axis; however, standard deviations are as large as 7,6 and 6,36-metres. All together 11% reached the target without sound and an additional 6% were within ±1 metre despite of veering. This result is better than we expected. From those who did not reach the target, 31% were on the right and 42% on the left side of it. Figure 6 also shows this kind of symmetry of exit points between the right and left side of the court. Subtracting results of participants who got off the court before the base line shows little differences in results: decreased values of standard deviations (Table 2). Although it was suggested that handedness (or footedness) can be related to the direction of circling and veering, our results did not reveal anything to support this. We had only 12 (10%) left handed subjects who veered as randomly as right handed subjects and there were no clear tendencies of the direction of veering.

The fact that people during long term veering end up walking in circles instead of walking a zig-zag paths suggests that veering is caused by a change in their subjective sense of straight ahead and this small random error accumulates step by step. When this error is small, people can maintain the straight path, when deviation is large, veering becomes circling. 40-metres of distance in our case seemed to be long enough to veer after a short distance already and some trajectories indicate that circling in a relatively small radius is also present. Sinusoid veering, meandering, zig-zag paths during the first trial were not significant.

Although the external reference is usually a visual point, auditory signals can also be used with accuracy. There is no significant difference between the results using white noise and click-train stimuli. Only one subject veered ostentatiously in case of white noise, and four using the click train. Some minor differences in arrival time were also observed, but no obvious tendency for the benefit of the either of them. In case of the click-train, 96% reached the target and in case of white noise it was 97%. Almost any kind of sound source could serve as external reference instead of vision, however, broadband signals and high sound pressure levels are recommended. Based on the participants' comments, the click-train signal was easier to follow after half of the distance covered by walking, as long white noise was easier to follow before reaching half of the distance. Trajectories show that around half of the distance (20-metres) is the veering effect the largest, creating an almost symmetrical figure (Fig. 8 and 9). This does not mean that participants use the sound source for reference after this point only, because veering tendencies are decreased already shortly after the start, indicating that participants listen actively and try to follow the sound source from the beginning. This is done by equalizing the sound pressure levels between the two ears: trying to keep the interaural intensity and time difference low by facing the sound source. Sound sources in the front of the listener (in the median plane) cause almost the same sound pressure levels in the two ears that was the main localization cue for the participants. This localization procedure also takes time so subjects walk slowly: walkings can last as long as 73-95 seconds. On the other hand, the mean time for the first try was only 36 seconds due to two reasons, (a) people often walk shorter distances as they walked off the court; (b) they do not use any external reference, so they do not need time for localizing the sound source. Interestingly, this value increased only up to 38 seconds in case if we calculate it only based on the results of the 67 subjects who reached the base line.

The time needed for the repeated task without sound as well as the deviation in metres could indicate learning processes during the experiment. 90% of the participants who did not reach the base line on the other side and got off the court, in the repeated walking were within ±5-metres from the target (without sound). First, only 55% reached the base line, at the second try, it was 73%. Examining the data and walking trajectories we can not report a clear evidence of learning during this experiment. Either it was too short for training or this ability can not be learned and improved at all. Learning processes could be only detected in accuracy of reaching the target and not in time, because subjects walk in different speeds independent of their spatial accuracy. The minor improvement can be due to some kind of adaptation to the experiment (in which people knew the direction they veered first and tried to compensate, however, sometimes this resulted in overcompensating and thus, veering in the other direction).

Detecting of the walking distance during blindfolded walkings has been also in focus of other research projects [15, 36-38]. It was interesting to see in our experiment how participants began to walk slower (even wanted to stop) about 6-8 metres from the sound source, because they feared to collide. The SPL level at this distance was about

85-90 dB that suggests correlation with everyday life's experience: sources this loud are too near and it is dangerous to get closer. This phenomenon will be investigated deeper in the current research with blind participants. All these may indicate that hearing loss could affect these tasks, but we had only one subject who had a damaged left ear and there was no significant error in his performance.

Our current investigation – induced by former results - partly focuses on children's behaviour and navigation ability in terms of walking straight and determination of distances during blindfolded walking [39, 40]. Furthermore, localization ability of blind persons is in focus, including free-field environments and virtual reality [41].

5. Summary

An experimental setup was installed in an outdoor environment to test the influence of auditory beacon signals (targeting a sound source) on the ability of keeping a straight walking path of blindfolded sighted participants. 120 participants' walking trajectories were recorded via GPS tracker and veering from the straight line was measured in space and time. Results showed that missing external reference results in veering shortly after couple of metres, supporting former results. 17% of the participants could reach or were within ±1 metre without using external auditory cues. There were no side preferences for veering and trajectories showed an almost symmetrical spatial distribution to the walking path. Furthermore, simple auditory beacon signals, such as clicks and broadband noise can serve as external reference, resulting in that almost all participants were able to approach the sound source without serious veering based on sound source localization (96-97%). Future work includes further testing with blind subjects for comparison.

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