Variability in the Length and Frequency of Steps of Sighted and Visually Impaired Walkers

Sarah J. Mason, Gordon E. Legge, and Christopher S. Kallie

Abstract: The variability of the length and frequency of steps was measured in sighted and visually impaired walkers at three different paces. The variability was low, especially at the preferred pace, and similar for both groups. A model incorporating step counts and step frequency provides good estimates of the distance traveled. Applications to wayfinding technology are discussed.

Sighted people often estimate distances by counting their steps (for example, to approximate the dimensions of a large room). Such estimates implicitly rely on the consistency of the length of one's steps. In wayfinding situations, where estimates of distance may be useful, people who are visually impaired (that is, those who are blind or have low vision) may not make use of step counting for several reasons: First, it is possible that the length of steps is less consistent for visually impaired people because of the use of mobility devices. Second, since walking speed affects the length of steps, accurate estimates of distance should take into account changes in walking speed. Third, it is often impractical to count steps accurately, given the concurrent cognitive demands of other activities. Ramsey, Blasch, Kita, and Johnson (1999) found that visually impaired cane users decreased the length of their stride when they had to concurrently complete an auditory task or anticipate a simulated drop-off. Finally, the practical value of estimates of distance relies on a map that converts these distances into useful information about the layout of the environment. In an unfamiliar environment, a person who is visually impaired rarely has access to a suitable map. In a familiar environment, he or she may conceivably memorize a cognitive map on the basis of step counts (for example, Dr. Walker's office door is on the left, 30 steps down the corridor from the main entrance).

Currently, there is wide interest in the development of assistive technology for wayfinding by people who are visually impaired. It has been demonstrated that signals from global positioning satellites (GPS) can be incorporated into wayfind-

Many thanks to members of the Minnesota Laboratory for Low Vision Research for their assistance, especially Rudrava Roy for writing the software program interfaced to the pedometer system and MiYoung Kwon for help in preparing the manuscript. We also thank Scott Kalpin for his helpful discussion and for supplying the computer-readable pedometer. This research was funded by Grant EY02857 from the National Institutes of Health and Grant H133A011903 from the National Institute of Disability and Rehabilitation Research.

ing technology for use outdoors (Loomis, Golledge, & Klatzky, 1998; Loomis, Golledge, Klatzky, Speigle, & Tietz, 1994). For instance, GPS-based software has been developed by the Sendero Group and runs on the BrailleNote refreshable braille notetaker (by Pulse Data HumanWare). This technology updates a position continuously, so there is no need to estimate distances by counting steps.

Because GPS signals are usually not available indoors, another method for tracking a pedestrian's position is necessary. Stable landmarks, such as the location of the elevators, or special-purpose markers, such as the Talking Signs Infrared Communications System (by Talking Signs), may provide information on one's position at key points in a building. Technology for estimating distance and direction from these landmarks could then be useful. As part of a larger project on indoor wayfinding technology at the Minnesota Laboratory for Low Vision Research at the University of Minnesota, we have been exploring technologies for estimating the distance and direction traveled by pedestrians who are visually impaired. A straightforward method for estimating distance would be to count steps with a computer-readable pedometer. If the step counts could be reliably converted into distance estimates and if the pedometer was interfaced to a computer-readable digital map of a building, then a pedestrian's current position in the building (computed as an estimated distance from a known landmark) could be determined. (More refined technology would be necessary to estimate the direction of travel. In buildings, however, direction is often highly constrained by the layout of corridors.)

In principle, such technology would take care of two of the problems just listed regarding step counting for the nonvisual estimation of distance: The technology, rather than the pedestrian, would count the steps and would convert the step counts into an estimated position on a map of the building. This article reports on the results related to the two remaining issues: How accurately can distances be estimated from step counts, and how is this accuracy affected by a person's walking pace?

Prior research has found that the length of the stride of healthy, sighted adults remains fairly consistent over time, especially at an individual's preferred walking pace. The participants in Sekiya, Nagasaki, Ito, and Furuna's (1997) study walked on a flat walkway with a freely chosen step rate at five different self-regulated speeds. The length of their strides was consistent (variable error < 4 centimeters, or 1.6 inches), particularly at the preferred walking speed (variable error < 2.5 centimeters, or 0.9 inch).

Although Danion, Varraine, Bonnard, and Pailhous (2003) did not find that the preferred walking speed necessarily minimized variation in the length of strides, they found that human gait was consistent. Their participants walked on a treadmill at 25 combinations of frequency and step length (imposed by the experimenter). The variability in the length of strides (expressed as a coefficient of variation, *SD*/*M*) was generally under 3%. Stride length was found to be most consistent at the frequency of 1Hz (60 strides per minute), more variable for shorter strides, and more consistent for longer strides.

To our knowledge, no study on variability in the length of steps has been carried out using participants who are visually impaired. One could hypothesize that the lack of visual cues may increase variation in a visually impaired individual's walking pattern. Nakamura (1997) found that the length of the stride of adults who are blind who walked at their preferred pace was significantly shorter than that of sighted adults, possibly because of the need to integrate nonvisual input to walk safely. Considering that Danion et al. (2003) found sighted walkers' shorter strides to be more variable in length, there is a possibility that the short strides found in people who are visually impaired may also show increased variability. Studies on veering (for example, Guth & LaDuke, 1995) have concluded that people who are visually impaired often have difficulty maintaining a straight-ahead direction when walking; perhaps attaining a consistent step length may also prove difficult for them.

Experiment 1 consisted of 18 participants (6 sighted and 12 visually impaired) walking on a flat walkway 80 feet long. Eight trials were performed at each of three paces (slow, preferred, and fast), from which variability in the length and frequency of steps was calculated. Each participant then walked an additional eight trials at his or her preferred pace wearing a computer-readable pedometer, to test the pedometer's accuracy. Combining each participant's individual variability in step length with the pedometer's error rate gave us an estimation of the accuracy of a pedometer-based system for estimating walking distances.

Although prior studies, cited earlier, have measured strides (the distance between the placements of one foot), we chose to count steps (the distance in the forward direction between alternate feet). We chose this measure to maintain consistency with those parts of the experiment that used the pedometer, which counted steps, not strides.

Experiment 2 was conducted two months later, with four of the participants from Experiment 1. The participants were again asked to walk at a slow, preferred, and fast pace, but this time on walkways that were 20, 40, and 80 feet long. Experiment 2 had two aims. The first was to determine how reproducible each participant's mean step length was (especially at the preferred pace, at which a pedometer would be calibrated). The second was to compare the accuracy of two methods of estimating the distance traveled. Previous research has found that the relationship between length and frequency of steps is linear (Inman, Ralston, & Todd, 1981; Danion et al., 2003). Instead of calibrating a pedometer with an individual's preferred step length at the preferred pace, a more accurate way of estimating the distance traveled may be to calibrate by measuring the linear relationship between the length and frequency of steps for an individual. Distance would then be estimated from a linear equation that takes step frequency into account in estimating step length. For the four participants who returned for Experiment 2, we calculated their mean preferred-pace step length from Experiment 1 and the linear equation that best represented the relationship between the length and frequency of steps for each trial from Experiment 1. We then used both methods to estimate the distance traveled in Experiment 2, to compare the accuracy of each method.

Our overall aim was to compare the variability in the length and frequency of steps between participant groups and to answer the question, "Do participants who are visually impaired tend to show greater variability in walking patterns?" Other comparisons also interested us: Would the young visually impaired participants show more or less variability than the older visually impaired participants, and would the type of mobility device (dog guide or white cane) used by the participants be an influencing factor?

Experiment 1: Method

Participants

Of the 18 participants, 6 had typical vision (Snellen acuity 20/30 or better) and a mean age of 24.5 years, and 12 were visually impaired (with Snellen acuities ranging from 20/180 to total blindness). The visually impaired participants consisted of a younger group (Participants V1–V6, mean age 27.3 years) and an older group (Participants V7–V12, mean age 56.5 years). Four used dog guides, 4 used canes, and 4 used no mobility devices. All the visually impaired participants were independent and confident travelers (see Table 1 for characteristics of all the participants).

Design

The dependent variables that were measured were the time taken to walk the 80-foot length of hallway and the number of steps taken. The independent variable, manipulated by the experimenter, was the

Table 1
Characteristics of the sighted (S) and visually impaired (V) participants.

Participant	Age	Gender	Mobility device	Acuity	Diagnosis	Age of onset
Sighted						
S1	25	M	NA	20/20	NA	NA
S2	19	M	NA	20/20	NA	NA
S3	23	M	NA	20/20	NA	NA
S4	23	F	NA	20/20	NA	NA
S5	25	F	NA	20/20	NA	NA
S6	32	F	NA	20/30	NA	NA
Visually impaired						
V1	30	M	Dog	20/1500	Leiber's disease	Birth
V2	32	F	Cane	No vision	Congenital glaucoma	Birth
V3	26	F	None	20/180	Congenital aniridia	Birth
V4	24	F	Cane	20/1500	Optic nerve hypoplasia	Birth
V5	26	M	Dog	20/1200	Congenital glaucoma	Birth
V6	26	F	Dog	No vision	Diabetic retinopathy with glaucoma	18
V7	53	F	None	20/400	Optic atrophy	Birth
V8	62	F	Cane	No vision	Retinopathy of prematurity	Birth
V9	57	F	Cane	No vision	Retinopathy of prematurity	Birth
V10	57	F	Dog	No vision	Retinopathy of prematurity	Birth
V11	56	M	None	20/1000	Corneal vascularization secondary to Stevens-Johnson syndrome	6
V12	54	M	None	20/200	Macular degeneration	42

Note: NA = not applicable.

pace of walking: the participant's preferred pace, slow pace (72 steps per minute), and fast pace (144 steps per minute). To choose these particular paces, we started with Danion et al.'s (2003) slowest and fastest frequencies (76.8 and 151.2 steps per minute) and then modified them after testing them with the visually impaired members of our laboratory, reducing each slightly. The independent participant variables that were used for the analysis included age (younger versus older group), visual status (sighted versus visually impaired), and type of mobility device used (dog guide, cane, or none).

Procedure

An overview of the study was given to the participants, followed by an acuity test (when applicable). The participants read and signed a consent form that was approved by the University of Minnesota Institutional Review Board for the Use of Human Subjects, outlining the possible risks of participating in the study. An 80-foot track was marked with electrical tape in a quiet hallway (Elliott Hall, University of Minnesota). The participants were taken to the start point of the track and stood with their toes on the start line. For each trial, timing began when a participant began walking and stopped as he or she crossed the tape marking the end of the track. The experimenter also recorded the number of steps taken to walk the track.

Three walking speeds were used during the trials: the participant's preferred pace, slow pace (72 steps per minute), and fast pace (144 steps per minute). For the slow and fast paces, a metronome set the tempo for walking and remained audible for the duration of the trials. Although the participants were asked to keep as closely as possible to the beat, the experimenter emphasized that maintaining a natural walking style was more important than was staying exactly with the metronome. It was suggested to the participants that while walking at the slow pace, they should imagine strolling through a park and while walking at the fast pace, they should imagine walking quickly to catch a bus. The participants were urged to walk only at a speed that felt safe to them. If they did not feel comfortable walking at the fast pace set by the metronome, it was turned off, and they walked as quickly as they felt comfortable. (Note that the participants matched the metronome frequency fairly well; the mean slow pace maintained by the participants was 76.04 steps per minute, while the mean fast pace was 136.5 steps per minute. Two of the participants who were visually impaired asked to have the metronome turned off at the fast pace.)

Twenty-four trials were completed by each participant; 8 at each of the three paces. Before each set of 8 trials began, each participant was asked to walk up and down the hallway at the relevant speed to become accustomed to the required pace. If the participant used a mobility device in his or her daily life, the participant used the same device during the study. The experimenter walked a few paces behind, giving the participant plenty of room to walk in a natural manner. If anyone approached the participant during the trial, the participant was stopped and the trial was restarted.

After these trials were completed, a computer-readable pedometer was clipped onto the participant's waistband at the hip and connected via a cable to a laptop computer that was carried by the experimenter. The cable was long enough so that the participant's walking pace should not have been influenced by the experimenter's presence. Eight trials were performed at the participant's preferred walking pace: four with the pedometer clipped onto the participant's right hip and four with it clipped onto the participant's left hip. Two variables were measured: the number of steps taken to walk the 80-foot track, as recorded by the pedometer, and the number of steps taken to walk the same track, recorded by the experimenter. (The results of numerous pilot studies convinced us that the experimenter accurately and consistently counted the number of steps taken by the participants.)

Materials

The pedometer we used was an AME Micro Pedometer (V1.0), manufactured by Advanced Medical Electronics Corporation in Minneapolis, interfaced via a serial connection to a laptop computer carried by the experimenter. A software program written in Python script (by Rudrava Roy, University of Minnesota) kept track of the pedometer's step counts and converted these counts to an online estimate of the distance traveled by the pedestrian. This information was displayed on the laptop's screen for the experimenter.

Results of Experiment 1

The reader should keep the following points in mind when reviewing the results. First, the length of an individual's step on a given trial was computed as the distance walked (80 feet in Experiment 1) divided by the number of steps taken. For instance, if the participant took 40 steps to travel 80 feet, the step length was recorded as 2 feet. When we refer to the means and standard deviations of step lengths, we are referring to the means and standard deviations of these estimates across a number of 80-foot trials (eight trials in Experiment 1), not to measurements of individual steps within trials. Similarly, the frequency of steps was computed as the number of steps taken to walk 80 feet, divided by the total time.

Second, variability for each participant was calculated as a coefficient of variation (SD/M for the eight trials of each pace) and is expressed as a percentage. The percentage variability was found for each participant (within-subject variability), and then the overall means for each group were calculated using the appropriate participants. Third, note that the lengths of steps are stated in feet, and the frequencies of steps are stated in steps per minute.

Fourth, comparisons among the following groups were made using an independent samples *t*-test: sighted and visually impaired; sighted and young visually impaired; young visually impaired and older visually impaired; men and women; and dog users, cane users, and those who used no mobility device. An alpha level of 0.007 was selected, on the basis of a Bonferroni correction of a *p*-value of .05 for seven comparisons. Pairwise tests of this sort were conducted, rather than an omnibus analysis of variance (ANOVA), because we did not have a crossed design suitable for an ANOVA.

Mean lengths and frequencies of steps

The male participants had significantly longer step lengths at the fast pace (M = 2.86 feet) than did the female participants (M = 2.44 feet, t [16] = 3.402, $p < .005$). There were no other significant group dif-

Table 2
Variability in the length and frequency of steps at three paces: Coefficient of variation (percentage).

Variability	Walking pace		
	Slow: *M* (*SE*)	Preferred: *M* (*SE*)	Fast: *M* (*SE*)
Step length	2.74 (0.31)	1.94 (0.13)	2.02 (0.12)
Step frequency	1.96 (0.17)	2.05 (0.18)	2.42 (0.19)

Note: Variability is expressed as the percentage coefficient of variation (*SD/M*). $N = 18$.

ferences in either the length or frequency of steps.

Variability in the length and frequency of steps

Taking the mean of all 18 participants, we found that the variability in both the length and frequency of steps was low (see Table 2 for the means and standard errors). The variability in step length was the lowest at the preferred pace ($M = 1.94\%$, $SE = 0.13\%$), while the variability in step frequency was the lowest at the slow pace ($M = 1.96\%$, $SE = 0.17\%$). When we compared the variability among the groups, we found no significant differences. We also compared the variability between the sighted and functionally blind participants (that is, removing the participants with low vision from the analysis) and again found no significant difference.

Accuracy of the pedometer

Table 3 displays the percentage of step-detection errors (error rates) from the pedometer when it was worn on the right hip and the left hip and an overall average. Error rates are shown for both the sighted and visually impaired participants plus an overall average. No significant differences in error rates were found between the sighted and visually impaired groups or among the dog users, cane users, and those who used no device (when the pedometer was worn on the right hip or left hip or for the overall average). The error rates indicate an overestimation because the pedometer picked up extraneous movement. Note that the pedometer was more accurate when it was worn on the right hip. We will return to this difference in the Discussion section.

Relationship between length and frequency of steps

For the four participants who later returned for Experiment 2, the step length (x-axis) and step frequency (y-axis) for each trial were plotted, plus the straight line that best fit the data. The linear equations describing the lines were used in Experiment 2 as an alternative method to predict the distance traveled. Figure 1 displays the graphs,

Table 3
Accuracy of the pedometer (percentage).

Participant group	Pedometer location		
	Right hip	Left hip	Mean
Sighted group	4.55	7.90	6.23
Visually impaired group	2.70	13.79	8.24
Combined mean for both groups	3.31	11.82	7.57

Notes: Values show the percentage overestimate of the pedometer's step count compared to the experimenter's step count. $N = 18$.

linear equations, and correlation coefficients for each of the four participants. (Note that the r^2 value is low for Participant S5 because she unexpectedly decreased the length of her step at the fast pace.)

Experiment 2: Method

Participants and procedure

Four participants from Experiment 1 returned after approximately two months to participate. Two were sighted (Participants S3 and S5), and two were visually impaired (V9 and V11).

The same hallway was used in this experiment as in Experiment 1. Three tracks were marked on the floor: 20 feet, 40 feet, and 80 feet. The participants were asked to walk these tracks at one of three paces: slow, preferred, or fast. This time, the metronome was not used to set the slow

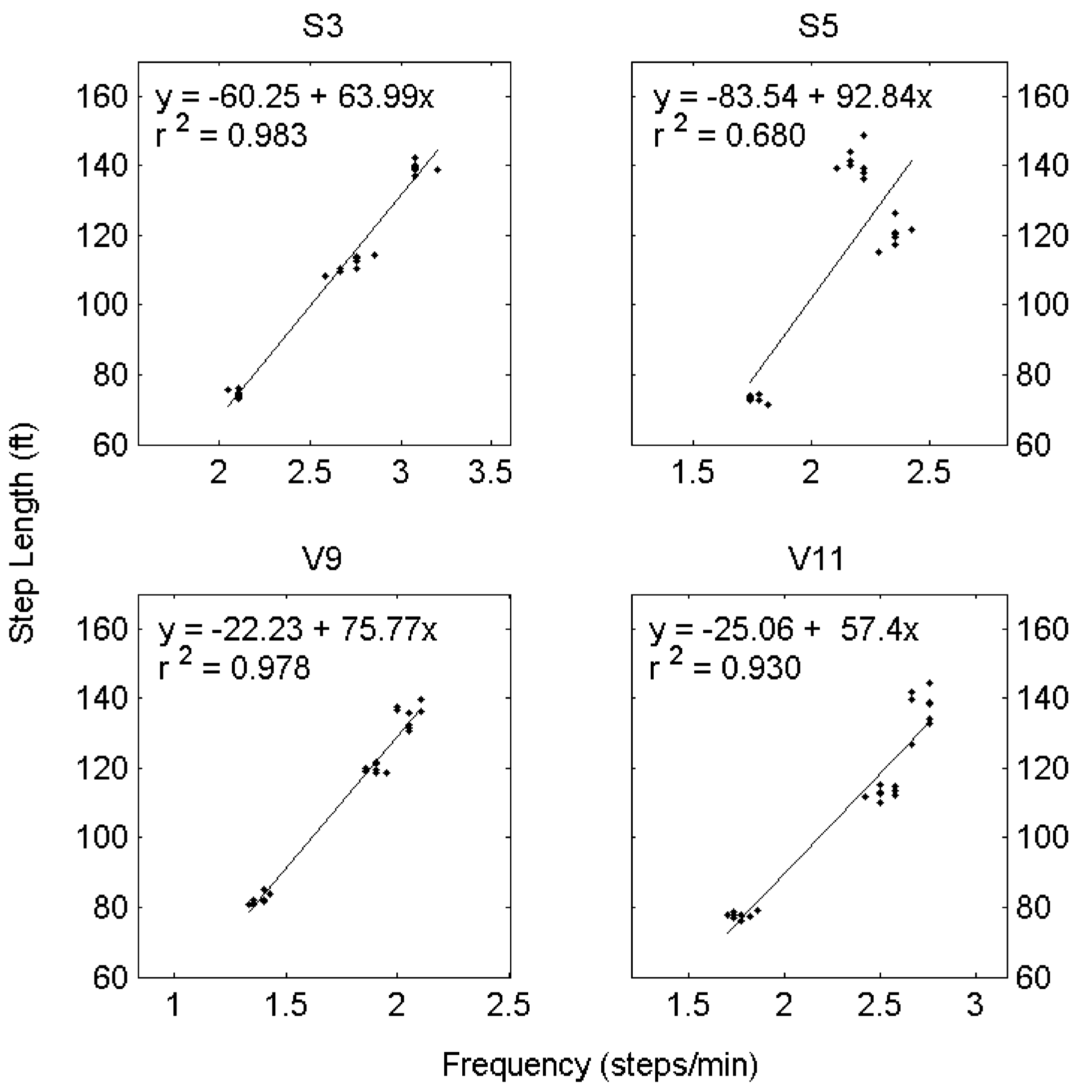

Figure 1. Graph depicting the relationship between the length and frequency of steps for the four participants in Experiment 2.

and fast paces; the participants chose their own interpretation of these paces. In the 36 trials that were completed, each combination of distance and speed was repeated four times. Trials were arranged in six blocks; each block was at one of the three speeds and included two trials at each of the three distances. The six blocks were arranged in a different order for each participant so as to minimize the effects of order. As in Experiment 1, the experimenter recorded the number of steps and the time taken to walk the track.

Results of Experiment 2

Repeatability of the length and frequency of steps over time

The mean percentage changes (from Experiment 1 to Experiment 2, calculated as absolute differences) in the length and frequency of steps at the three paces for the four participants were calculated. The overall mean percentage change for the entire group was as follows. At the slow pace, the percentage change was comparatively high (step length: 8.5%, frequency: 23.3%). At the preferred and fast paces, the percentage changes were lower: preferred pace (length: 5.4%, frequency: 5.2%) and fast pace (length: 5.5%, frequency: 6.7%).

Variability in step length

As in Experiment 1, the variability in the length of steps was calculated as a coefficient of variation (*SD*/*M*). The overall variability in the mean step length (plus *SE*) for each walking pace is listed here for the 20-, 40-, and 80-foot distances, respectively: slow pace (4.1% [1.600], 3.1% [0.11], and 2.9% [0.007]); preferred pace (4.6% [0.016], 5.8% [0.013], and 3.4% [0.006]); and fast pace (3.2% [0.018], 2.0% [0.011], and 1.9% [0.010]).

From these data, we were able to assess whether the percentage of the variability in the length of steps was constant with the distance or whether it increased or decreased as the participants walked farther. An inspection of the data suggested a trend toward decreasing variability with increasing distance. However, an ANOVA showed that the variability in step length did not vary significantly with distance. We conclude that for our participants and for the range of distances that we tested, there was no systematic change in the percentage of variability across distances. Stated another way, the variability in the number of steps required to cover a given distance scales in proportion to the distance.

Use of a linear equation to predict the distance traveled

Two methods were used to calibrate for the length of steps in estimating the distance traveled in the Experiment 2 trials on the basis of data that were recorded for each participant in Experiment 1.

Calibration Method 1 (simple). The mean preferred step length from Experiment 1 was multiplied by the number of steps taken in each trial in Experiment 2 to estimate the distance that was traveled.

Calibration Method 2 (linear). A linear equation was calculated for each participant that best represented the relationship between the length and frequency of steps for each trial in Experiment 1. Using this equation, the frequency of steps in each trial in Experiment 2 was used to select the appropriate step length. This step length, together with the number of steps taken, was used to estimate the distance that was traveled.

Table 4 and Figure 2 compare the percentage errors in the calculation of distance using both methods, with Method 2 (linear) depicted by triangles in Figure 2, showing the smallest percentage error at all the walking paces.

Discussion

Our primary aim was to study the length and frequency of steps for the participants who were visually impaired and to compare the results to those for the sighted participants. Would the visually impaired participants show greater variability in their walking patterns? Would any subgroup within the visually impaired group show marked differences from the rest of the group?

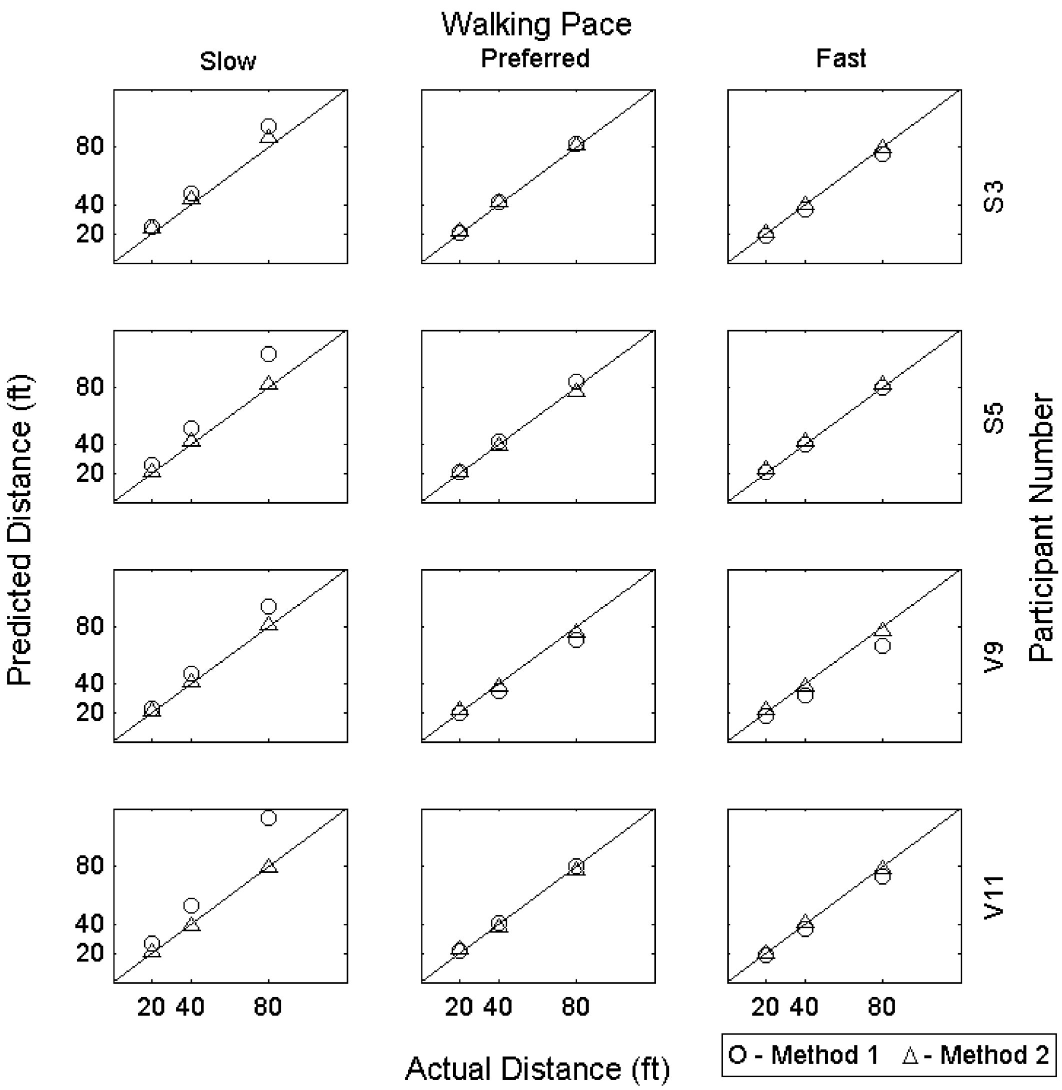

Figure 2. A comparison of the accuracy of distance prediction using Method 1 (simple) and Method 2 (linear) for the four participants in Experiment 2 at each of the three walking paces. The diagonal lines represent a perfect prediction of distance; the closer the symbols are to this line, the more accurate the prediction.

Table 4
Mean percentage error in estimates of distance for the four participants in Experiment 2.

	Walking pace		
Method	Slow	Preferred	Fast
Method 1 (simple)	25.84	14.38	7.97
Method 2 (linear)	5.84	5.58	5.59

Note: Values show the comparison between Methods 1 and 2 at three walking paces.

Measures of the length and frequency of steps

The only significant difference between the participant groups for either the length or frequency of steps was gender. The men had significantly longer step lengths at the fast pace, probably because they were generally taller and could extend their step length at faster frequencies, whereas the women reached a step-length ceiling. Unlike our findings, Nakamura (1997) found that the blind participants in his study had shorter stride lengths and slower walking speeds than did the sighted participants. He suggested that the "slow, guarded gait" of the blind participants might have been due to anxiety that was associated with walking without their customary devices. We found no significant difference between the stride length of the visually impaired and sighted participants, possibly because all the participants in our study were confident travelers who were using their usual mobility devices.

Variability in the length and frequency of steps

Taking the mean for all the participants (both those who were sighted and those who were visually impaired) into account, we found that the variability in both the length and frequency of steps was low. For step length, our results mirrored those of Sekiya et al. (1997) for sighted participants. In our study, the least variability was found at the preferred pace (M = 1.94%). However, little variability was found at either the slow or the fast pace (M = 2.74% and 2.02%, respectively). Considering that the participants were allowed to walk freely at their preferred pace, variability of less than 2% would seem to indicate that human walking is highly consistent in a controlled indoor environment. Likewise, the overall variability in the frequency of steps was low, with the least variability found at the slow pace (M = 1.96%) and increasing slightly at the preferred (M = 2.05%) and the fast (M = 2.42%) paces. Although the participants walked under controlled conditions to ensure safety, walking in a corridor (rather than on a treadmill or in a virtual environment) helped create as natural an environment as possible from which to interpret these results.

Comparing variability between the groups

No significant differences between the groups were found. We acknowledge that our participant groups were small and that Type II errors could be possible. We did note that those who used dog guides showed slightly more variability at the slow pace that appeared to confuse the dogs. However, since no significant differences were found, we conclude that under these experimental conditions, the participants who were visually impaired walked as consistently as did the sighted participants and that their mobility devices did not appear to affect the variability.

Accuracy of the pedometer

The pedometer manufacturer indicated that the pedometer should be accurate to within 10%, and our results support this claim. When we combined the results from both the visually impaired and sighted groups and for the measures taken from both hips, we found that the overall accuracy was 7.57%. For 15 of the 18 participants, the pedometer gave a more accurate step count when it was worn on the right hip. Although unconfirmed, there is a possibility that the cable extending from the pedometer to the laptop was more prone to interference from the participant's swinging arm when the pedometer was worn on the left hip because the cable extended from the right side of the laptop. If we used data collected from the right hip only, accuracy improved to 3.31%. Since step-count errors were due to the pedometer picking up extraneous movement, errors would give an overestimation in the steps taken and therefore the distance traveled. For example, in the 80-foot hallway, a 3.31% overestimation would give a pedometer readout of approximately 82.6 feet. Individual variability in the length of steps at the preferred pace (M = 1.94%) over the same distance would result in an over- or underestimation of approximately 1.6 feet. Combining the pedometer error with individual variability over 80 feet would still place an individual within approximately 4.5 feet of his or her target destination. In most cases, this accuracy would be adequate to find the correct door to a room on a long corridor. This simple example, derived from our data, shows that estimates of distance, based on pedometer tracking, could be a useful component of indoor wayfinding technology. We recognize that these results apply to the particular pedometer that we used for our study and might not generalize to other pedometer designs. Also, if this style of pedometer was incorporated into a travel device, it would be necessary to discount spurious counts that were registered when the participants turned or shifted their weight from foot to foot. This might be done by some automatic detection scheme or by giving the user a Pause button.

Repeatability of the length and frequency of steps over time

How stable are the characteristics of walking over time? We addressed this question by bringing back four participants after two months to take part in Experiment 2. At the preferred pace, the percentage changes for both the length and frequency of steps from Experiment 1 to Experiment 2 were slightly higher than 5%, higher than the estimated variability of about 2% from Experiment 1. However, even in the trials in Experiment 2, we noted somewhat higher within-subject variability for the length of steps at the preferred pace: a mean of 4.6% in Experiment 2 versus a mean of 1.94% in Experiment 1. This difference was probably due to differences in the experimental design; in Experiment 1, all the trials of a single pace were conducted as a block, whereas in Experiment 2, the trials of different walking paces were interspersed. Considering that each trial would exert some influence on the next, it is not surprising that individual variability in the length and frequency of steps increased. However, over the 80-foot hallway, even a 5% error rate would result in only a 4-foot over- or underestimation of the distance traveled.

Variability in the length of steps over different distances

During Experiment 2, we collected data from three different distances and walking paces and could calculate whether the variability in the length of steps was constant with distance or whether it increased or decreased. As was noted in the Results of Experiment 2, it appears that variability decreased slightly as the distance increased, although an ANOVA showed that the variability in the length of steps did not vary significantly with distance and therefore that the error in this case was generally a fixed percentage of the distance that was walked. So if the percentage error is constant with distance (absolute error proportional to distance), we would expect approximately an 8-foot error for a trip of 160 feet in a long hallway.

Use of a linear equation to predict the distance traveled

Before an individual uses a pedometer to estimate the distance traveled, he or she must calibrate it with his or her average (preferred) step length. When walking at a preferred pace, this step length may provide a viable figure from which to estimate distance when it is multiplied by the number of steps taken. However, when walking at a slow or a fast pace, this figure would over- or underestimate the distance traveled because of the variation of the length of steps with the frequency of steps. Considering that most participants showed a strong linear relationship between the length and frequency of steps, we wondered whether accounting for frequency in the step-length calibration would provide a substantially better indicator of the distance traveled, especially at the slow and fast paces. Our results from Experiment 2 showed that this was the case. We conclude that a system that records both step counts and step frequency, together with a linear calibration model, makes substantially better predictions of the distance traveled than does a system that relies on step counting alone.

Conclusions

Our results support those of prior studies, indicating that human gait (as described by the length and frequency of steps) appears to be consistent across trials and days, typically close to a 5% variability or less. We also conclude that, in general, persons who are visually impaired show no greater variability than do sighted persons when walking in a controlled indoor environment, such as a corridor. Finally, using the linear relationship between the length and frequency of steps provides an improved method for estimating the distance that is traveled.

References

Danion, F., Varraine, E., Bonnard, M., & Pailhous, J. (2003). Stride variability in human gait: The effect of stride frequency and stride length. *Gait and Posture, 18,* 69–77.

Guth, D., & LaDuke, R. (1995). Veering by blind pedestrians: Individual differences and their implications for instruction. *Journal of Visual Impairment & Blindness, 89,* 28–37.

Inman, V. T., Ralston, H. J., & Todd, F. (1981). *Human walking*. Baltimore, MD: Williams & Wilkins.

Loomis, J. M., Golledge, R. G., & Klatzky, R. L. (1998). Navigation system for the blind: Auditory display modes and guidance. *Presence: Teleoperators and Virtual Environments, 7,* 193–203.

Loomis, J. M., Golledge, R. G., Klatzky, R. L., Speigle, J. M., & Tietz, J. (1994). Personal guidance system for the visually impaired. *Proceedings of the First Annual ACM/SIGGAPH Conference on Assistive Technologies* (pp. 85–91). New York: Association for Computing Machinery.

Nakamura, T. (1997). Quantitative analysis of gait in the visually impaired. *Disability and Rehabilitation*, *19,* 194–197.

Ramsey, V. K., Blasch, B. B., Kita, A., & Johnson, B. F. (1999). A biomechanical evaluation of visually impaired persons' gait and long-cane mechanics. *Journal of Rehabilitation Research and Development, 36,* 323–332.

Sekiya, P. T., Nagasaki, H., Ito, H., & Furuna, T. (1997). Optimal walking in terms of variability in step length. *Journal of Orthopaedic & Sports Physical Therapy, 26,* 266–272.

Sarah J. Mason, B.A., *research assistant, University of Minnesota; 75 East River Road, Minneapolis, MN 55455; e-mail: <mason058@umn.edu>.* ***Gordon E. Legge, Ph.D.,*** *Distinguished McKnight University Professor, Department of Psychology, and director, Minnesota Laboratory for Low Vision Research, University of Minnesota; e-mail: <legge@umn.edu>.* ***Christopher S. Kallie, B.A.,*** *graduate research assistant, University of Minnesota; e-mail: <kallie@umn.edu>. Address all correspondence to Dr. Legge.*

