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RESEARCH ARTICLE

The precision of locomotor odometry in humans

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Abstract Two experiments measured the human ability to reproduce locomotor distances of 4.6–100 m without visual feedback and compared distance production with time production. Subjects were not permitted to count steps. It was found that the precision of human odometry follows Weber's law that variability is proportional to distance. The coefficients of variation for distance production were much lower than those measured for time production for similar durations. Gait parameters recorded during the task (average step length and step frequency) were found to be even less variable suggesting that step integration could be the basis for non-visual human odometry.

Keywords Locomotion · Gait · Walking · Psychophysics · Distance perception · Time perception

Introduction

Imagine looking at a person about 10 m away, closing your eyes and then walking, without feedback, until you are standing right where they had been (before they stepped nimbly to one side). Most people who have not tried doing this think the task would be quite difficult, but a number of investigations have confirmed that humans are quite good at walking fairly accurately (without bias) to a distant target without visual feedback (Loomis et al. 1992; Rieser et al. 1990; Steenhuis and Goodale 1988; Thomson 1983). The ability to update one's location in space is probably an important aspect of normal human locomotion: fairly accurate open-loop walking has been demonstrated to distances of up to 27 m (Andre and Rogers 2006). Whereas the visual evaluation of distances between distant points is highly biased, Loomis et al. (1992) have clarified that egocentric distances are coded fairly accurately in vision. Little is known about the precision of non-visual human odometry, however, and the information used to control it. This paper intends to correct this.

Path integration refers to the process of keeping track of one's changing position in space. Odometry refers in particular to estimation of linear distance during path integration. Great progress has recently been made in the understanding of ant odometry. Desert ants are known to be able to integrate distance traveled when foraging so that they can return by dead-reckoning to their nest. They have even been shown to compute 3D ground distance, so that forcing ants to travel up and down hills does not throw off their distance along level ground (Wohlgemuth et al. 2001). Critically Wittlinger et al. (2006) shortened or lengthened ant legs and showed that this artificial change in step length produced errors in path length as predicted if ants were integrating step lengths by counting steps.

Two sources of non-visual information for human locomotion have received the most attention. One, the inertial information available even during passive self-motion, has proven to be of some utility (Israël and Berthoz 1989; Israël et al. 1997), but there is good reason to believe that it is dominated, during normal walking by locomotor information itself: Mittelstaedt and Mittelstaedt (2001) found that humans performing a travel-to-target task without feedback overestimated deviations from normal

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speed both when walking on a treadmill and when walking on solid ground, but underestimated deviations from normal speed when being passively moved. While theories of purely inertial odometry must depend on temporal integration, or even storage of velocity profiles (e.g., Berthoz et al. 1995), locomotor odometry might integrate units of distance (steps) directly.

Durgin et al. (2007) have shown that step frequency itself is treated as a primary cue to walking speed. Normally when humans are asked to walk at different speeds they maintain a constant ratio between step frequency and step length (Sekiya et al. 1996; Durgin et al. 2007). That is, to walk faster, most people will increase the length of each stride and decrease its duration by about the same proportion. This means that stride frequency is perfectly correlated with walking speed under normal circumstances. On a treadmill—especially one that varies its speed from trial to trial—the tight coupling between stride length and frequency can be broken. By using an immersive virtual environment to measure the visual speed that seemed appropriate to a given walking speed on a treadmill, Durgin et al. (2007) found that perceived locomotor speed was controlled by stride frequency: for a given treadmill speed, if participants inadvertently took shorter, more frequent, steps, they judged themselves to be moving faster than if they were taking longer, less frequent steps. This apparent assumption of a known (frequency-proportional) step size is not unlike the ant.

The evidence that speed is proportional to stride frequency is consistent with the evidence that locomotion in man and insect is coordinated by a system of coupled oscillators and that higher brain levels control this system with a descending signal that sets the period (1/frequency) of the stepping pacemakers (Gallistel 1980a, b). In the absence of feedback, this control system gives a purely feed-forward speed signal, the signal that sets pacemaker frequency. The odometric signal could be the integral with respect to time of this speed signal.

It seems, then, that the human locomotor system provides a metric of speed that can be used to do distance tasks, but is this mediated by the perception of time, or is distance integrated more directly? Do humans integrate the expected step lengths themselves, for example, as ants seem to do? To study this question we sought to measure the variability of performance at distance walking and compare it to time perception. In a first experiment, we measured variability in the production of distances between 4.6 and 18 m of walking without sensory feedback from vision or audition. As we will report, the coefficient of variation (CV) for this task is impressively low; its magnitude suggests that time perception is not involved.

In a second experiment, we extended our investigation for distances of up to 100 m and compared CVs for this task with CVs for time perception of similar intervals. We report that the CV for conscious distance production is much lower than that for conscious time perception. Details of our data suggest that the distance task is accomplished by means of step integration.

Experiment 1: CV measured for human odometry

Loomis et al. (1992, 1993) reported that for distances of up to 12 m, error variability in walking, without visual feedback, to a visually previewed target was proportional to the distance. It is unclear, however, which portion of the variability was due to the visual estimate of the distance and which portion to the locomotor production of the distance. To determine how precisely subjects can replicate locomotor distances, we will be computing the CV for a task in which subjects attempt to repeatedly walk out the same distance without visual guidance or feedback. Because we are not concerned with accuracy, but only with precision, the distance will be demonstrated to them by telling them, on the first walk, when to stop; moreover, feedback will be provided to them after each attempt to reproduce the distance so as to minimize calibration drift. This will allow us to measure intrinsic variability in the production/perception of locomotion distance under fairly ideal conditions.

Method

Participants

Subjects were three volunteers (2 men, 1 woman), including the third author, who all gave informed consent. The experiments reported here were approved by local ethics committees in accordance with ethical standards laid down in the 1964 Declaration of Helsinki.

Location and equipment

The Southwest corridor of the Rutgers Athletic Center on Livingston Campus was used during off-hours. The corridor is 50 m long, 5 m wide, and 2.6 m high. A taut guideline was stretched between two supports 40 m apart, so that subjects would not veer but could not get useful feedback about their forward location from the line itself. Each subject wore a plush blindfold and listened to synthesized white noise through headphones. Starting and ending points for each of three distances (4.57, 9.14, and 18.29 m) was marked on the floor. Walking distance errors were measured to the nearest inch (2.54 cm).

Procedure

To begin a set of 20 trials, a subject (wearing blindfold and earphones) was told to walk, while holding onto the line, until told to stop. The subject then replicated the initial distance after turning back to face the initial starting position, and was given verbal feedback about how far or short he or she had gone in inches. While walking, subjects were instructed to repeat the word "the" with each step as a means of preventing them from counting steps; however, one subject confessed to having counted steps inadvertently at the shortest distance, so this data was excluded from analysis. Each subject completed one session of 20 trials for each of the three distances.

Analysis

We used F tests to compare the variances in log distance traveled across target conditions. Weber's law states that discriminability is proportional to magnitude. In a magnitude production task, Weber's law can be interpreted as asserting that the variability in distance produced, $\sigma(d)$, is proportional to mean distance produced, $\bar{d}$. The CV is the constant of proportionality: $\sigma(d) = (CV)\bar{d}$. Equivalently, Weber's law asserts that the variability in log distance for a given target is a constant (i.e., $\sigma(\log d) = k$) independent of the target (hence of $E(\log d)$, the mean of the logs of the distances walked). The constancy of the standard deviation of the log of the distances walked implies the constancy of its square, the variance. Thus, if Weber's law holds, then F ratios formed from pairs of these variances at different target distances will not depart significantly from an expectation of 1: $\mathrm{E}(\sigma^2(\log(d_1))/\sigma^2(\log(d_2))) = 1$, where d_1 and d_2 are sets of observed distances run at two different target values. If this is found to be the case (that is, if the variances do not appear to differ significantly), then the CV may be computed from the average of the standard deviations of the logarithms of several such sets $(\overline{\sigma}(\log(d)))$ by the formula: $CV = \exp(\overline{\sigma}(\log(d))) - 1$. Consistent with the assumptions of this analysis, Shapiro–Wilk Normality tests found fewer violations of normality in log-transformed data than in untransformed data in the experiments reported in this paper, though the statistical conclusions of the paper would not differ if the CVs were instead computed based on untransformed data.

Results

The estimates of the individual CVs are shown for each distance in Table 1. Excluding the case where conscious step counting contaminated (enhanced) performance, seven within-subject pairwise F tests (with Bonferroni correction) found no significant differences in CV by distance, consistent with the assumption that in the logarithmic domain, the variances at different target distances are the same (Weber's law). The overall mean CV was 0.080 (SD = 0.015).

Table 1 CVs for walking a previously walked distance in Experiment 1

Subject	Target Distance (m)		
	4.6	9	18
CRG	0.097[a]	0.066	0.107
DG	(0.034)[b]	0.080	0.068
KV	0.069	0.083	0.068

[a] CV = ratio computed from standard deviation of log distances

[b] Value excluded from analysis. Subject reported counting steps

Discussion

The precision of walking a known distance under the conditions tested was fairly constant across the distances tested here. Based on prior studies of time perception (e.g. Rakitin et al. 1998), it would appear that the precision of distance production is better than that of timing by a factor of between 1.5 and 2. If distance estimation is substantially more precise than timing estimation, then timing could not have been the mechanism for the distance estimation. It is notable that step counting led to enhanced performance in the one cell where a subject reported using it suggesting that the odometer does not provide as much precision as verbal step counting would.

Experiment 2: CVs for distance and time perception

Although the results of the previous experiment strongly suggest that locomotor distance production is more precise than is thought to be true of time perception, the methods employed differed sufficiently from most time perception studies that we sought to measure the precision of distance perception and time perception in the same individuals performing essentially the same task with the same kind of feedback structure. We also sought to extend the range of distances and times to intervals well beyond the distances used in previous studies.

If odometry is accomplished by direct integration of estimated step lengths (perhaps estimated by step frequency), then gait parameters like step length, step frequency, and their ratio would need to be quite stable. We therefore additionally measured basic gait properties to determine whether, as expected, these gait properties would show sufficient stability to explain the precision of odometry.

Method

Participants

Subjects were three student members of the Swarthmore perception laboratory (2 men, 1 woman), including the second author, who all gave informed consent.

Design

We measured CVs for spatial intervals of 12.5, 25, 50, and 100 m, and temporal intervals of 13, 25, 50, and 100 s. The time perception task was done indoors, while seated, whereas the distance perception task was done outdoors, but the basic design was identical in both cases. Two initial instances of the to-be-produced extent were provided as in Experiment 1. Ten practice production trials then followed (with feedback for each trial) and then, for the three shorter extents, there were 50 experimental trials with feedback. For the longest extent, there were only 25 experimental trials. The reduction in the number of trials at the longest distance was to avoid fatigue, because the total duration of the experiment for these extents already exceeded an hour and the cumulative distance walked in this condition alone was about 2.5 km. The order in which various extents were completed was varied between subjects. All subjects completed all distance tasks before doing the time tasks.

Location and equipment

Straight portions of the Swarthmore College outdoor track were used for the distance task. A taut guideline was stretched over a distance of 160 m for the longest distance, and over 120 m for the shorter distances. Subjects gripped a lightweight plastic sleeve that slid easily along the guideline. Subjects wore earplugs (NR 31) to minimize auditory localization information, as well as a blindfold. Distance errors of up to 2 m were measured using a tape measure. Longer errors were measured to the nearest cm using a laser measuring device pointed at a white board mounted at the intended stopping point (a white board was mounted at each end of the walking extent).

In addition to the measurement of distance, a video record was kept of up to 1 h of each walking session so that the number of steps taken, and the duration of each walk could be recorded later. For one subject (JND), three of these video records were damaged and could not be recovered. One other video session for subject MA was also lost because of equipment failure.

For the timing task, subjects (in a quiet lab environment) wore noise-canceling headphones as well as the earplugs and blindfold. A custom-designed computer program provided auditory start and end signals, accepted start and end key press responses, and provided feedback using a computer voice played through the headphones at sufficient volume to be easily audible through the earplugs. The voice reported whether the response was early or late and by how many seconds (produced duration was recorded in ms).

Procedure

The basic procedure for the distance task was similar to that of Experiment 1 except that two instances of the target distance were initially walked out and then ten practice trials followed so that the subject could become familiar with both the procedure and with the required distance. There were then 50 test trials (25 for the longest distance). Because the absolute errors were expected to be quite large on some trials, one experimenter normally remained at each end of the walking area (this was particularly necessary for the longer distances). They quietly marked the stopping location, provided approximate feedback to the subject about the amount of over- or under-shoot, escorted the subject to the starting position for the next trial and, once the subject was on their way, measured and recorded the amount of error. This procedure allowed the production of distances to be efficiently self-paced by the subjects.

For the timing task, the entire procedure was conducted by the computer with minimal supervision from an experimenter. Verbal feedback concerning signed error in seconds was automatically provided by the computer at the termination of each trial. The start of the next trial was self-paced by the subject who would press one button to start the trial and a second button once he or she felt that the allotted time had elapsed.

Sessions of each extent in each task were normally done on different days. Subjects in the distance task were instructed not to count steps, or in any other way attempt to artificially measure distance, but rather to try to stop the trial when they felt that the intended spatial extent had been completed. Similar instructions were given for the timing task. Subjects were not required to do any distracter task to prevent step-counting, but all reported that they had successfully resisted any urge to count steps and that no counting strategies were employed in the timing task either.

Table 2 CVs for distance and time production in Experiment 2

Subject	Target distance (m)				Target time (s)			
	12.5	25	50	100	13	25	50	100
JND	0.155	0.108	0.122	0.077	0.201	0.256	0.205	0.185
KDS	0.131	0.111	0.108	0.088	0.261	0.289	0.226	0.218
MA	0.125	0.097	0.112	0.097	0.228	0.182	0.202	0.190

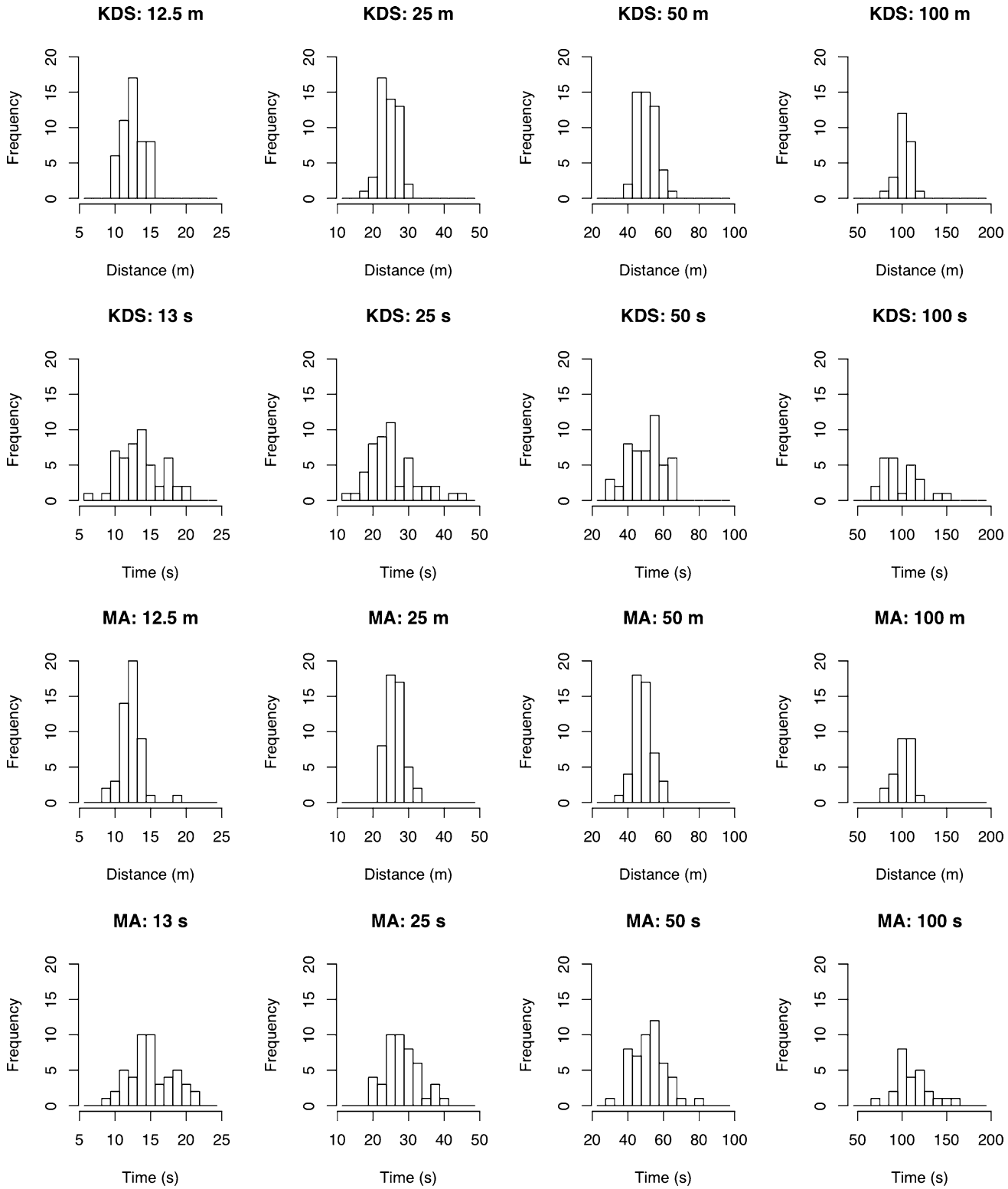


Fig. 1 Histograms of distance and time productions in Experiment 2 for subjects MA and KDS. Corresponding distance and time productions are shown on the same scales. Note that the range of values for each histogram extends from half the target distance/time value to twice the target value

Results

CVs for each session of each task are shown in Table 2. Eighteen within-subject pairwise *F* tests conducted to check for equal variance across different distances found only one reliable difference (with Bonferroni correction), which was between the shortest and longest distances for subject JND. We suspect that nearby noises present during the conduct of the longest distance may have inadvertently provided some localization information. No reliable differences were found among variances for the different time intervals.

Twelve *F* tests comparing variances from distance and time production (for each subject at each comparable extent) were all significant at the level of $p < .001$, satisfying Bonferroni corrections in all cases. The overall mean CV for distance (0.111, SD = 0.021) is clearly about half that for time (0.220, SD = 0.033). Histograms of distance and time productions are shown for two subjects in Fig. 1.

Analysis of gait parameters

Using videos to extract number of steps taken and the duration of each trial allowed us to compute CVs for these two parameters (Table 3) in the same manner as for distance and time, as well as to compute an average step length and an average step frequency for each trial so that the variability in these gait parameters could also be quantified (Table 4). Whereas Table 5 shows that the CVs for the number of steps taken on each trial ($M = 0.101$, SD = 0.017), and for the duration of walking on each trial ($M = 0.110$, SD = 0.019) are similar to the CVs for distance walked (both are correlated with distance and with each other), as shown in Table 6, the CVs for average step length are much lower ($M = 0.030$, SD = 0.013) as are the CVs for average step frequency ($M = 0.033$, SD = 0.015), as confirmed by *F* tests (with Bonferroni correction) for the eight comparisons available in each case. The overall CVs for time, distance and the various gait parameters are summarized in Fig. 2. The trial-to-trial stability of gait suggests that, like ant odometry, human odometry can capitalize on fixed information about gait parameters by using (unconscious) step accumulation to estimate distances traversed.

Discussion

Using the same procedures and individuals for both time and distance tasks we find that variability at producing a spatial extent by walking is less than the variability in estimating a comparable interval of time by a factor of between 1.5 and 2. Gait parameters from video recordings of the walking task suggest that very stable walking parameters within a given session may play a role in facilitating human odometry because average step length and step frequency are much less variable than distance production. Presumably, variability is added by the integration processes and by the decision processes involved in stopping.

Table 3 Mean number of steps taken (with standard deviations) in Experiment 2

Subject	Target distance (m)			
	12.5	25	50	100
JND	–	–	–	130 ± 9.18
KDS	19.9 ± 2.17	36.1 ± 3.57	74.6 ± 6.99	145 ± 11.9
MA	–	36.2 ± 3.91	65.7 ± 6.81	149 ± 17.1

Table 4 Mean walking durations (with standard deviations) in Experiment 2

Subject	Target distance (m)			
	12.5	25	50	100
JND	–	–	–	72.5 ± 6.31
KDS	11.4 ± 1.31	19.7 ± 2.06	42.7 ± 4.07	80.1 ± 6.77
MA	–	19.8 ± 2.60	36.7 ± 4.23	81.3 ± 9.63

Table 5 CVs for number of steps taken (left) and for walking duration (right) in Experiment 2

Subject	Target distance (m)				Target distance (m)			
	12.5	25	50	100	12.5	25	50	100
JND	–	–	–	0.071	–	–	–	0.086
KDS	0.113	0.103	0.095	0.085	0.120	0.109	0.097	0.087
MA	–	0.113	0.108	0.121	–	0.136	0.120	0.128

Table 6 CVs for average step length (left) and average step frequency (right) in Experiment 2

Subject	Target distance (m)				Target distance (m)			
	12.5	25	50	100	12.5	25	50	100
JND	–	–	–	0.025	–	–	–	0.038
KDS	0.043	0.023	0.018	0.016	0.054	0.024	0.014	0.018
MA	–	0.043	0.048	0.020	–	0.048	0.042	0.029

General discussion

In two experiments we have shown that humans, when asked to reproduce a distance by walking without visual or auditory feedback, perform this task with a precision that far exceeds their ability to reproduce a temporal interval of a similar magnitude. Like the honeybee (Cheng et al. 1997) human odometry follows Weber's law that discriminability

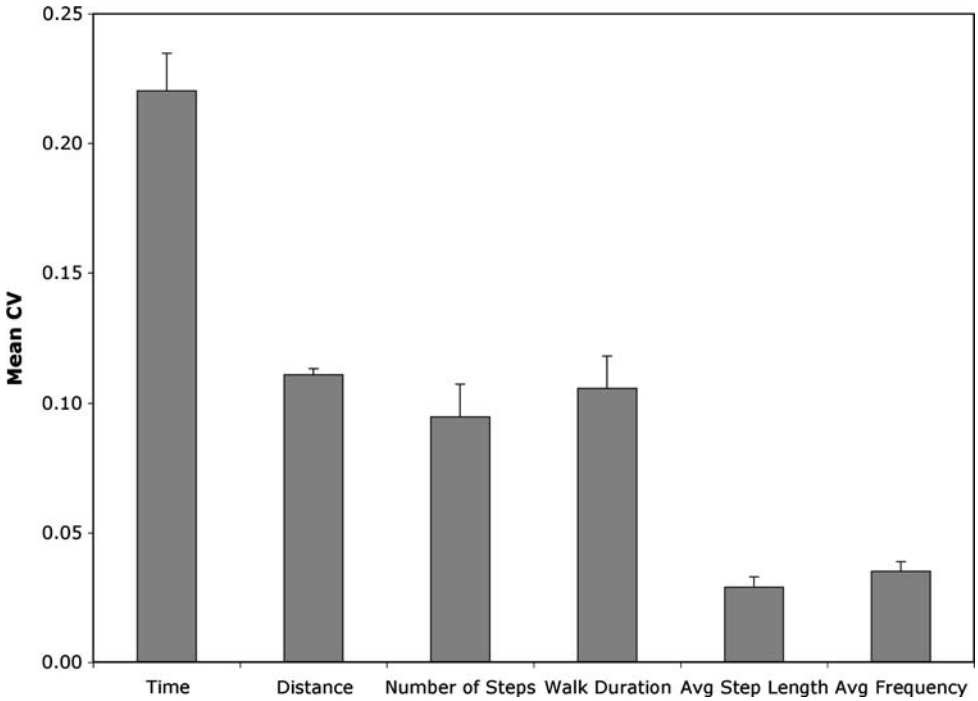


Fig. 2 Average CVs from Experiment 2 for time production and distance production are compared to average CVs for number of steps, walking duration, average step length, and average step frequency. The relative stability of basic gait parameters suggests that direct integration of steps may underlie the precision of distance production. *Error bars* represent between-subject standard errors of the means

is proportional to absolute magnitude. Like the ant, humans may depend on fairly fixed gait variables.

Glasauer et al. (2007) have shown that concurrent mental arithmetic distorts (reduces) the perception of produced locomotor distance in a manner consistent with reductions in the perception of temporal magnitude. However, our results do not favor a temporal metric for locomotor distance perception because the precision of distance production is greater than that of time production. It is possible that interference from concurrent cognitive tasks affects magnitude integration generally rather than temporal integration specifically.

Although it remains a possibility that the rhythmic activity of walking improves time-keeping, the direct integration of distance per unit step seems more parsimonious than using steps to keep time for the purpose of integrating velocity. A recent study of human odometry from optic flow has also argued for spatial rather than temporal integration (Lappe et al. 2007). It thus seems possible that a common spatial integration process may underlie both visual and non-visual odometry. Whereas we might expect that CVs for passive self-motion of similar distances would resemble those for temporal intervals, step-wise inertial contributions to locomotor odometry may derive from the periodic inertial signals associated with head accelerations during walking (Durgin et al. 2007), which could serve as error feedback. It remains to be seen whether the perception of passive self-motion without vision may also involve spatial, rather than temporal integration as is more commonly supposed (for example Berthoz et al. 1995).

For most humans there is normally a visual component to odometry, but the present results demonstrate the precision of non-visual odometry. How are the two connected? Several studies have investigated recalibration of human locomotor odometry based on visual feedback. Rieser et al. (1995) had subjects walk on a treadmill at one speed while that treadmill was pulled through a parking lot at a slower speed. Following adaptation in which a fast biomechanical speed was provided with very slow visual speed, subjects overshot previewed targets when they tried to walk to them without visual feedback. The odometry system was evidently underestimating distance traveled as a result of adaptation. But human odometry is also recalibrated by non-visual feedback (Ellard and Wagar 2008). For example, simply hopping on a treadmill with eyes closed will produce a leg-specific overshoot when attempting to hop to a visually-previewed target (Durgin et al. 2003). Durgin et al. (2005b) argued that treadmill running for as little as 1 min without visual feedback alters the odometer because of non-visual sensory information on treadmills about the lack of real motion through space (e.g., haptic information indicating that one is staying in one place with respect to the treadmill).

Conversely, the proprioceptive and vestibular signals from locomotion have been shown to modify the perception of visual flow (see Durgin et al. 2005a for a review), and there is evidence that the precision of optic flow discrimination may actually be enhanced by these modifications (Durgin and Gigone 2007). For a motor context to enhance sensory discrimination requires that the

motor context be a stable predictor. The present study has provided further evidence that this is the case for human locomotion.

The facts that sighted humans are fairly accurate when walking without vision to visually-previewed targets and that they quickly recalibrate this non-visual odometry indicate that even when vision is present, a non-visual odometer is providing an internal estimate of displacement through space. Considering that humans are often using their visual systems for tasks other than odometry as they walk, it may be that non-visual odometry is a basic part of human navigation and that this is why we are normally so well calibrated when walking without visual feedback.

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