Step Frequency and Perceived Self-Motion

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There is a discrepancy between the ability to correctly match the gains of visual and motor speed in virtual reality (VR) when walking on solid ground and the failure of this ability when walking on a treadmill. Moreover, this discrepancy has been found to interact with effects of the structure of the visual environment. The authors used a high-fidelity treadmill VR system to reproduce the high interactivity of normal walking in wide-area VR. Under these conditions, it was found that gain matches in a richly structured near environment differ by only about 10% in treadmill VR from matches in wide-area VR and that trial-to-trial variations in step frequency predicted changes in perceived locomotor speed. Gait differences resulting from treadmill walking (which are shown not to be a product of wearing a head-mounted display), apparently lead to an overestimation of motor speed on treadmills. When the near visual environment represented an empty hallway, additional errors were present that could be accounted for by known illusions in the perception of visual speed during self-motion. A study of normal gait at different speeds measured by head-tracker is reported as evidence of other possible sources of perceptual estimates of locomotor speed in normal walking.

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1. INTRODUCTION

Human perception of self-motion is thought to be based on a combination of signals, including those that arise from within the body (e.g., vestibular, motor, and proprioceptive information) and those that arise from without as a result of self-motion (optic flow, auditory flow, and haptic flow) [e.g., Mergner and Rosemeier 1998]. How these various sources of information get combined is not well understood. Some authors have suggested "domination" of one set of signals by another. For example, Lishman and Lee [1973] found that when visual information was pitted against inertial information (i.e., against the sensory consequences of actual accelerations of the observer's body, including vestibular signals), compelling visual information seemed to override the inertial information. However, domination may be regarded an extreme form of normal cue combination. Modern theories of cue combination suggest

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that more precise and reliable cues should (and do) receive more weight when combined [Ernst and Banks 2002], and that, when conflicts are too large, discrepant cues may be vetoed. In this paper we will consider locomotor cues to self-motion, in particular, and how these might interact with inertial information (such as that available from the vestibular otoliths). On the face of it, locomotor speed should be computed from the product of step frequency and step length. However, the sensory information available for estimating these two variables may be differentially reliable [Terrier and Schutz 2003]. We will argue that, at least on treadmills, step-frequency tends to dominate step-length information in determining the perceived speed of self-motion. We will further consider that the perception of step length may normally be linked to inertial signals that could be able to help estimate deviations in step length during walking on solid ground.

It is a somewhat surprising to most people that if they are asked to walk blindfolded to a visually previewed target at distances of 3 to 20 m, they are fairly accurate at doing so and demonstrate no systematic bias when walking at normal speed [Loomis et al. 1992; Rieser et al. 1990; Thomson 1983]. This implies that self-motion perception from the combination of locomotor and inertial signals is well calibrated. Mittelstaedt and Mittelstaedt [2001] have argued that in the absence of visual feedback, motor estimates dominate inertial ones. They based this observation on similarities between the signs of errors in the perceived distance of treadmill walking and real walking (without visual feedback) when walking speed was varied. That is, when walking without visual feedback on treadmills and on solid ground, people stopped short of the previewed goal when they were walking faster than normal, but overshot it when walking slower than normal. These errors may be contrasted with the signs of errors in perceived speed induced by speed differences during passive self-motion. In the passive case, they overshot the target when being pushed faster than normal and undershot it when being moved at a slower rate. Because treadmill and active walking are both self-controlled, whereas passive transport is not, these results could be recast, however, as an underestimation of deviations from normal speed in the passive case (in the absence of internal control parameters) and an overestimation of deviations from normal speed in the active case (where internal control parameters are being used to produce the deviations). That is, it may be difficult to generalize from passive self-motion to the case of inertial information received as feedback to internally controlled actions. Nonetheless, as we will argue below, inertial signals during self-motion are, indeed, likely play a secondary role in the estimation of self-motion. Indeed, we will suggest that step frequency, in particular, may serve as a very strong cue to locomotor speed.

Although step frequency may seem an unlikely candidate for estimating locomotor speed, it turns out to be an unbiased estimator of locomotor speed for most walkers on solid ground. This is because walkers normally adjust step frequency as a function of speed [Greive and Gear 1966]. Indeed, most adjust both step frequency and length in equal measure when they change speed [Sekiya et al. 1996; Terrier and Schutz 2003]. Thus, the two sources of information are, in some sense, redundant. We will suggest that the dominant role of step frequency in perceiving the speed of self-motion may result in part from reduced noise in the estimation of frequency relative to that in estimating step length.

Prior evidence of the possible dominance of step frequency for locomotor speed perception comes from the work of Prokop et al. [1997]. Participants were asked to walk at constant speed on self-driven treadmill (position sensing was used to adjust the treadmill speed so as to keep the walker in a fixed location as he or she walked). When subjected to sinusoidal oscillations in simulated optic flow rate, participants' walking speeds oscillated in phase with the visual input. This locomotor speed variation was limited entirely to changes in step length, however, without any fluctuation in step frequency. Prokop et al. [1997] argued that visual speed and step length were trading off in the perception of perceived speed, but it is also possible that perceived step length was being directly recalibrated by the visual signals. That is, walkers in that experiment seemed to treat step frequency as the variable that was to be kept constant to maintain constant motor speed while (unconsciously) allowing step-length adjustments to react to time-varying visual signals as if for purposes of error correction.

1.1 Two Kinds of Error in Speed Judgments

The perception of self-motion is a very complex phenomenon because of the contingencies that exist among the various kinds of sensory and motor information that signal self-motion. These contingencies provide motivation for the various kinds of information to interact, as in recent reports of speed subtraction: The correlation between walking speed and optic flow is so tight that the perceived speed of visual flow while walking is subtractively reduced—as predicted by models of coding efficiency [Barlow 1990; Durgin et al. 2005b]. That is, the same visual flow field will look slower when viewed while walking than while standing and even nonlocomotor rhythmic actions can produce weak reductions in perceived speed of flow [Pelah and Thurell 2001]. This perceptual subtraction has been shown to have the advantage of enhancing perceptual discrimination of expected speeds during walking (those appropriate to walking) [Durgin and Gigone 2004]—at the cost of rendering low visual speeds more difficult to discriminate. There is evidence that these speed subtractions seem to apply more to the flow from distant objects—especially the ground plane [Durgin et al. 2005b], though this has not been thoroughly tested.

Recently, a second type of speed error has been discussed; it has been reported that when people were asked to *match* visual speed (presented in a head-mounted display, or HMD) to locomotor speed (on a treadmill), the visual speed was set too high—by as much as 40% [Banton et al. 2005; Durgin et al. 2005a]. At present, however, it is unclear whether this "gain-matching" error is because of the subtractive reduction in visual speed, an error in perceived locomotor speed, difficulty in relating the two perceptually, distortions from VR itself (such as compression of perceived distance), or some combination of these. Banton et al. [2005] attributed the problem to a reduced field of view in the HMD that restricted lamellar flow. They found that people gave more accurate matches when looking to the side. However, Banton et al. [2005] confounded direction of gaze with environmental structure: There were near objects off to the side in their virtual environment. Durgin et al. [2005b] found that during treadmill walking, speed subtraction (based on judgments of visual speed itself) also disappeared when sideways gaze revealed a near wall, but was full strength (about 15% of walking speed on treadmills) when sideways gaze revealed a ground plane. Their data suggest, however, that visual subtraction effects can only account for a 15% error on treadmills and much larger errors are typically reported.

Moreover, it would seem likely that people should be calibrated by their massive experience of walking such that visual speed subtraction would be irrelevant to judgments of locomotor-relative visual speed. Consider that Pelah and Barlow [1996] reported that after running on a treadmill with eyes open, the perceived speed of visual flow when walking seemed unnaturally high. This observation implies that judgments relating perceived visual speed to one's own motor activity are normally fairly well calibrated inasmuch as people are sensitive to departures from normal. However, the possibility that subtraction applies primarily to the ground plane may be quite relevant here. In most locomotor contexts there is near structure available off the side so subtraction may not be playing much of a role.

1.2 The Trouble with Treadmills

Although some of the data of Durgin et al. [2005a] are quite consistent with the idea that gain match errors are because of speed subtraction (in particular, the data collected during normal walking on solid ground), their treadmill data have seemed to contradict the idea. We present here a quantitative argument, based on data collected in two different paradigms using similar virtual environments. Speed subtraction while walking on solid ground is approximately double that found on treadmills at similar speeds, representing a reduction by about 30 to 35% of walking speed [Durgin et al. 2005b]. Durgin

Table I. Gain-Matching Results[a] from Durgin et al. [2005a]

	Cluttered Hall	Empty Hall	All
Treadmill walking	1.36 ± 0.07 ($N = 5$)	1.46 ± 0.20 ($N = 4$)	1.40 ± 0.09 ($N = 9$)
Walking on floor	1.05 ± 0.06 ($N = 13$)	1.34 ± 0.08 ($N = 14$)	1.19 ± 0.06 ($N = 27$)

[a] Mean gain ratio (visual/motor speed ± standard error of the mean) judged "accurate" as a function of substrate (treadmill or floor) and visual environment (cluttered or empty); all data are from subjects exposed to only one world and surface (i.e., only the first block if they did more). Data are averages of PSEs estimated for each participant from at least 36 forced-choice trials. A gain ratio of 1 would be geometrically accurate.

et al. [2005a] reported that when walking on solid ground in an empty (virtual) hallway, people set visual speeds about 34% too high, whereas when they walked in a cluttered virtual hallway, with lots of near-space structure, they set the visual gain only about 5% too high, though gaze was forward. Apart from the added 5% overestimation in both conditions (which is a common error in psychophysical tasks involving comparison to a standard), this pattern of results is quantitatively consistent with the notion that the errors in the empty hallway correspond to the visual speed reductions measured using similar hallways by Durgin et al. [2005b]. However, contrary to the simple near-space prediction, gain matches in both types of virtual environment were quite high when walking on a treadmill. The data are summarized in Table I.

Thus, although data from walking on solid ground are consistent with the idea that speed subtraction causes gain-match errors in relatively barren environments, the treadmill data are less clear. Although there is less data from these particular treadmill conditions, the numbers seem fairly consistent with the very high gain matches reported by Banton et al. [2005]. Because speed subtraction on treadmills has been estimated to be only about 15% of walking speed, there remains a large discrepancy. Although we suspected that some of this discrepancy might be because of the heightened sense of speed on treadmills that may be related to gait, it was also possible that the level of visuomotor immersion in previous studies was partly at fault.

The treadmill studies conducted so far have simply not been equivalent to those conducted on solid ground. On each trial in a typical speed-matching task, a subject must report whether the presented visual flow was faster or slower than appropriate for their motor speed. In prior treadmill studies [Banton et al. 2005; Durgin et al. 2005a], treadmill walking was often continuous and at constant speed and the visual presentation of flow fields was intermittent. Over many trials, a participant could establish a visual speed standard and then cease to pay attention to motor speed, which is held constant (or varied among highly distinct speed categories). Moreover, the sense of motor interaction with the visual world is surely weakened by the fact that moment-to-moment variations in walking speed are not captured by visual feedback. In both of the above studies, a constant drift was added to the virtual environment and cyclical variations in treadmill belt speed resulting from foot impact were not reproduced in the virtual environment. (Indeed, frame rates in the environments used by Banton et al. [2005] were as low as 10 Hz.) In contrast, Durgin et al. [2005a] studied speed matching during normal walking by adjusting the gain between physical and visually simulated motion along the hallway axis so that people could accelerate from a standing position in a virtual environment in which the gradient of resulting visual positions (and, therefore, speeds) was simply multiplied by the gain factor; cyclical accelerations during walking were automatically incorporated into the visual feedback they received. We, therefore, set out to develop a method for producing a similarly rich visuomotor experience in treadmill VR.

1.3 Altered Gait as a Contributing Factor

Yoking the immersive VR to the actual speed of the treadmill required high-resolution, real-time measurements of treadmill speed and, using these measurements, it was possible to recover gait characteristics of the walkers in the experiment. That is, retaining a record of instantaneous treadmill belt speed and head position, made it possible to extract not only step frequency (based on periodic vertical oscillations of the head or of variations in the treadmill belt speed), but also step length (based on integrating the treadmill belt velocity signal). One signature of human gait that emerges as a useful construct in this regard is the walk ratio (WR) developed by Sekiya et al. [1996]. They found that the ratio of step length (SL) to step frequency (SF) remains invariant for most individuals over large changes in walking speed. As we will show below, WRs (SL/SF) were, indeed, invariant for most of our subjects when walking on the treadmill at different speeds, but tended to be somewhat lower than normal—reflecting relatively short and frequent steps.

The WR is presumed to reflect an energetically optimized walking rate corresponding to the height and build of the individual involved [Holt et al. 1995]. Although it is somewhat surprising that it is a fairly fixed quantity across large changes in walking speed, this constancy may have important implications for understanding motor contributions to the perception of self-motion: As mentioned above, it means that for a well-calibrated walker, SF, itself, may normally be a robust estimator of walking speed. The higher frequency step rate of individuals on treadmills might therefore represent a source of bias in the perceived speed of treadmill walking. For example, a 30% increase in speed in normal walking is attained by a 14% increase in SF combined with a 14% increase in SL ($1.14 * 1.14 = 1.30$), thus maintaining the WR. In other words, a 14% increase in SF corresponds to a 30% increase in speed. If perceptual motor-speed estimation is often based primarily on measuring SF alone, then a reduction in the walk ratio by as little as about 10%, such as treadmills produce in our studies (realized as a 5% increase in SF and a 5% decrease in SL), would be expected to produce a concomitant increase in perceived speed by the same amount as the change in the WR itself, 10%. In other words, if SF normally dominates in the estimation of motor walking speed, then subtle changes in SF caused by treadmill locomotion might produce upwardly biased motor estimates of self-motion perception. These, in turn, ought to produce higher visual speed matches.

1.4 Overview of Experiments

The goal of our first experiment was to reproduce, with a treadmill, the motor accelerations and tight visuomotor correlations available in wide-area VR. As we will show, this manipulation produces gain matches that are only 15% too high in the cluttered environment (much lower than the 35–45% of previous studies). Moreover, the WR values of our treadmill walkers were about 10% lower than typical, which is sufficient to account for the remaining discrepancy. In our second experiment, we report an analysis of previously unpublished head-tracker data from an experiment of Durgin et al. [2005a], to show that gait parameters are, indeed, different on solid ground than on treadmills, even when a head-mounted display (HMD) is used in both contexts. Together, these experiments indicate that simple gait parameters, like the WR, may provide important information concerning the way in which motor speed is perceived, and this has implications for the measurement of perceived space and self-motion in immersive VR. Finally, in Experiment 3, we examine normal walking (including the acceleration phase) using the head tracker without the HMD, in order to analyze the kinds of gait-related information normally available to perception for estimating speed of self-motion while walking. In particular, we consider the possible role of initial acceleration signals during the onset of walking as well as the possible contributions of periodic acceleration signals during continuous walking.

2. EXPERIMENT 1: HIGH FIDELITY TREADMILL VR

This experiment demonstrates that gain matches can become fairly accurate when a sufficiently immersive treadmill VR experience is used. Strong evidence is also provided that residual departures from the accuracy found with gain matching on solid ground can be attributed to gait adjustments made on treadmills that affect perceived motor speed.

Prior studies have found that, with rich environments, gain matching (intercalibration) is better on solid ground than during treadmill walking. The present experiment was designed to remove a number of differences between treadmill VR and wide-area VR in an attempt to maximize the immersion on the treadmill for a fairer comparison. In a cluttered environment (where visual speed subtraction may be minimized), this produced a reduction of gain overestimation to 15%. Moreover, within-subject variations in gait will be shown to moderate this gain value in the predicted direction: high-frequency gaits (controlling for speed) produce higher gain matches. Because gaits on treadmills are, in general, higher in frequency (lower in WR) than gaits on solid ground, it appears that the gait difference is sufficient to account for this residual differences in gain-matching between treadmill experiments (using sufficiently rich environments) and solid ground.

2.1 Methods

The participants were 40 undergraduates at Swarthmore College, aged 18–22, who were paid to participate or participated as part of a course requirement. None were aware of the purpose the experiment. All signed informed consent forms and were treated according to ethical guidelines.

2.1.1 *Apparatus and Displays.* We used head tracking and treadmill-speed monitoring sampled at 120 Hz to drive a 60-Hz frame rate stereo display in our 60° (diagonal) FOV VR that completely reflected the head position relative to the treadmill belt with millimeter accuracy and a lag estimated at less than 40 ms.

The treadmill used was a NordicTrack APEX6100xi (surface area 140 cm × 50 cm), instrumented so as to override the manual controls and allow our computer to directly set the goal speed for the treadmill's motor controller. Because the motor controller supplied accelerations that were proportional to deviations from goal speed, we could interactively set goal speeds to produce acceleration profiles appropriate to normal walking. Specifically, our goal was to provide fast and smooth acceleration to full speed, similar to normal walking. We did this by first setting the goal speed to a value 1.75 times that actually intended and then resetting it to the actual goal speed when the treadmill belt had reached 90% of the actual goal speed. This produced smooth s-shaped accelerations functions that took about 1 s to reach the goal speed, which is fairly consistent with normal walking (see Experiment 3). An initial slow movement of the treadmill belt (at about 20 cm/s) provided a warning to the subject that treadmill acceleration was imminent.

In addition, high-resolution speed information was obtained from the treadmill by attaching 10 magnets to the flywheel and using a Reed switch to trigger a timing signal that allowed us to measure with great precision, treadmill speed at 60 Hz, in the range of speeds between 25 and 175 cm/s. Our three goal speeds were 100, 115, and 132 cm/s, and typical speeds fell with a 10% range below each goal speed (because of footfalls). This treadmill model uses a foam belt for which we found no slippage under normal conditions of walking. That is, calibration tests showed that the integrated distance signal computed on the fly differed by less than 0.5% from the directly measured motion of the belt (measured by counting belt rotations and multiplying by the length of the belt) and the error was no different during walking than it was during constant belt motion in the absence of any load. The treadmill speed reading and writing were accomplished by a computer that also received head-tracker signals from a HiBall (a 6DOF optical tracking device with submillimeter accuracy) at 120 Hz, and broadcast the combined head position and integrated treadmill belt position information to the graphics machines with a delay of less than 1 ms. The raw head-position signals, treadmill speed, and the derived virtual head position signals were also recorded to a data file at 120 Hz for gait analysis.

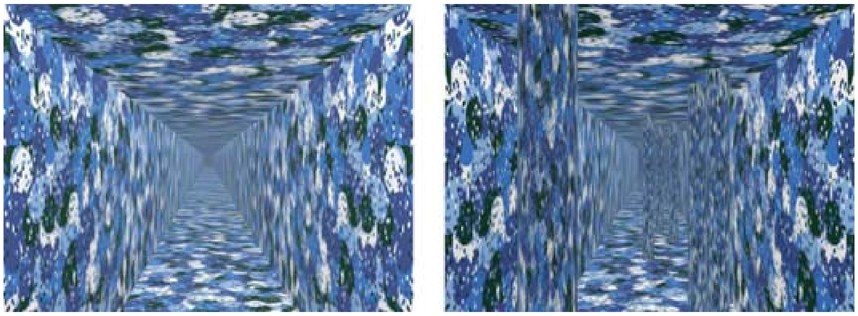

Fig. 1. Images of the empty hall (left) and columned hall (right). Originals were stereo and immersive.

Graphics were supplied using two Macintosh G4 computers with Radeon 9500 graphics cards, one for each eye. The HiBall signal, communicated on a private Ethernet network, served to synchronize the graphics on the two machines. A gain function was applied to the position coordinate along the main axis of motion (essentially multiplying the z coordinate of the head position by the gain for the present trial) and a geometrically accurate hallway scene was rendered at 120 Hz using OpenGL and displayed at 60 Hz.

Two different head-mounted displays (HMD) were compared. Both had 60° FOV and 60-Hz refresh rates. The V8 model had VGA screen resolution of 640 × 480 and was identical to that used in the studies reported by Durgin et al. [2005]. The nVis Cybermind HMD had XVGA resolution of 1280 × 1024. Equal numbers of subjects were run in each condition with each headset so that any differences could be noted. Gain matches were, numerically, slightly better (lower) with the nVis, but the difference was not statistically reliable and all data reported here are, therefore, pooled.

The virtual hallway in which judgments were made was 2 m wide and 2.5 m high, with the floor positioned to coincide in height with the surface of the treadmill belt. The hallway was rendered to the graphic clipping plane (100 m). Between trials, the hallway was made a uniform gray with a single narrow yellow stripe down the center of the floor so that it provided no speed information concerning self-motion, though it remained responsive to movements of the head (was immersive) because of differential shading of the floor, ceiling, and walls. Motion stimuli were presented by texturing the hall using high-contrast large and small elements so as to maximize motion information at many distances. The OpenGL mip-map texture setting was used, which provides high-resolution texture mapping in near space and somewhat lower resolution in far space. In addition to wall, floor, and ceiling texture, those in the cluttered-environment condition had approximately 60 virtual columns scattered randomly in the 50-m space ahead of them. These columns were textured similarly to the hallway and provided near-space structure in the environment. The columns were 20 cm in diameter and stretched from floor to ceiling. They were constrained not to intersect with the walls or with each other, but were otherwise randomly scattered in the hallway, including in the path of walking. They disappeared at point of contact (near clipping plane of 10 cm), and were not visible from within (external texture only). Sample displays are shown in Figure 1.

2.1.2 *Design.* Subjects were assigned in alternation to either the empty or the cluttered hall condition. In each condition, there were 108 trials, with 36 trials at each of 3 different treadmill speeds. Visual gain (ratio of visually simulated motion provided for each unit of actual head and treadmill belt motion) was controlled by a staircase method using gain units that were powers of 1.05. One staircase started at −10 units (a gain of 0.61), one at +10 units (gain of 1.63), and one at 0 (a gain of 1.0). A staircase moved by three units after each trial: Up, if the visual gain was described as too high, and down, if the visual gain was described as too slow. A logistic function was used to compute PSEs based on the resulting probability of describing a given gain as too high. In prior work, we have found that 36 trials is sufficient to estimate a stable PSE. Because gain values turned out to be independent of actual speed, an overall PSE was also computed across all speeds using the full 108 trials.

The three motor speed goals were nominally 1.00, 1.15, and 1.32 m/s, so that they increased by ratios of 1.15. Because of footfalls and friction, the average speeds achieved during the experiment were 0.96, 1.09, and 1.25 m/s. In all cases, visual speed was proportional to the measured instantaneous speed. The purpose of varying speed in this experiment was twofold. First, we thought it would force participants to continuously evaluate the relationship between motor and visual information rather than establishing a visual standard and making a response with respect to that. Second, it allowed us to examine whether small changes in treadmill speed affected the walk ratio adopted by people on the treadmill. For this reason, we chose a range of speeds that varied sufficiently (32%) to be salient, but also varied by amounts (15%) that were not expected to be either distracting or easily categorized.

2.1.3 *Procedure.* Participants were instructed in the task and provided informed consent in accord with ethical standards. Interpupillary distances (IPD) were measured with a digital PD meter, so that stereo simulations in the VR reflected true IPD. Participants were positioned on the treadmill and fitted with the HMD. They were instructed to hold onto the handrails of the treadmill at all times, to walk on the belt, and to make verbal judgments concerning whether the visual speed on each trial was “slow” or “fast” compared to the treadmill motion.

A single trial would start with a person standing on the stationary treadmill looking at a textureless virtual hallway with a yellow line down the middle of the floor. Participants were instructed to gaze toward the end of the hallway. The experimenter would press a button that replaced the gray hallway with the proper experimental hallway (either the empty, but well-textured hallway, or the same hallway with scattered columns) and started the treadmill belt moving. The visual movement of the virtual hallway was linked to the motion of the treadmill belt, combined with any head motion. The treadmill belt would reach full speed within about 1 s of trial initiation and the trial would continue for an additional 4 s, at which point the graphics would go blank and the treadmill would decelerate back to rest. Participants were allowed to respond before the conclusion of the motion and did so when the visual motion was obviously discrepant. Once the subject responded by indicating whether the visual speed had been “fast” or “slow” compared to the treadmill speed, their answer was entered by the experimenter and the graphics returned to the gray hallway.

Trials from all three speeds (six of each) were randomly ordered in each of 6 blocks of 18 trials each. At the conclusion of the experiment, participants were informed about the purpose of the study and paid.

2.2 Results and Discussion

We consider the gain-matching data and the gait data separately and then in combination. The goal of the section is to provide a thorough enough analysis of the relationship between gait and the gain matching data to justify the following six claims.

1. Gain matches on our high-fidelity treadmill VR are more accurate and more similar to those on solid ground than those of previous treadmill studies.
2. Gait on our treadmill differs systematically from normal gait.
3. The direction of overall gait change (increased SF, reduced SL) is consistent with the domination of SF, rather than SL if the (increased) perception of locomotor speed is because of this altered gait.

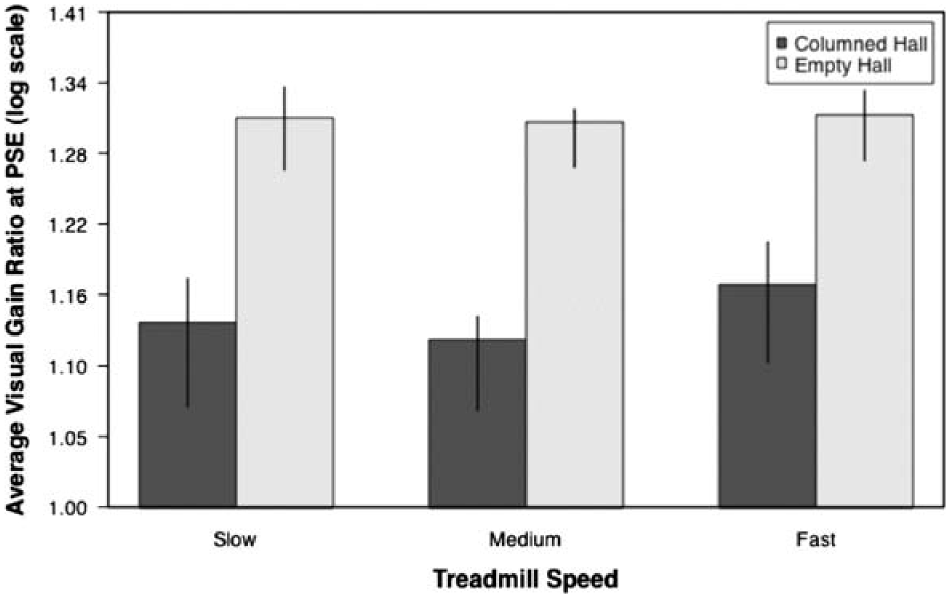

Fig. 2. Mean PSE gain ratios as a function of treadmill speed and visual environment in Experiment 1. Both between-subject (descending) and within-subject (rising) standard errors bars are shown.

4. Detailed within-subject analysis supports the idea that trial-to-trial variations in gait (SF) predict (are correlated with) trial-to-trial variations in perceived locomotor speed as assessed by the gain matching task.
5. Efforts to explain these gain-gait correlations as effects of visual gain on gait rather than of gait on perceived locomotor speed are not supported by the data.
6. Subtractive visual speed reduction may account for remaining gain match error.

2.2.1 *Gain Analysis.* Our primary analysis was of the psychophysical judgments regarding the relative gain between visual and motor speed. As is shown in Figure 2, participants' gain matches were constant across all treadmill speeds. This suggests that people were consistent in judging the motor speeds. Failure to differentiate motor speeds would have resulted in lower gain matches for high speeds.

A 2 (headset) × 2 (virtual environment) × 3 (treadmill speed) mixed-design ANOVA revealed a reliable effect of the virtual environment, $F[1, 36] = 5.80$, $p < 0.05$, but no effect of headset, $F[1, 36] < 1$, nor of treadmill speed, $F[1, 72] < 1$. Recomputing the overall PSE across the three speed conditions provides an overall estimate of the gain ratio that made visual stimulation seem to match motor stimulation. These numbers were averaged in log space and then converted to ratios for clarity. With the columns present, this overall match ratio averaged 1.15, with a standard error of 0.06. With the columns absent, the ratio averaged 1.32, with a standard error of 0.04. Thus, with straight-ahead gaze in a richly textured virtual environment, the presence of columns was sufficient to produce gain matches that departed from accuracy by only 15%. Indeed, this value was only marginally different from 1, $t[19] = 1.80$, $p = 0.087$. Thus, as found by Durgin et al. [2005a], for walking on solid ground, the addition of near-space objects in the virtual environment provided for much more accurate gain-matching judgments than found in their absence.

2.2.2 *Gait Analysis.* The periodic stepping of the feet on the treadmill belt produced a clear step profile after the acceleration phase was complete. For each of the 108 trials for each subject, treadmill

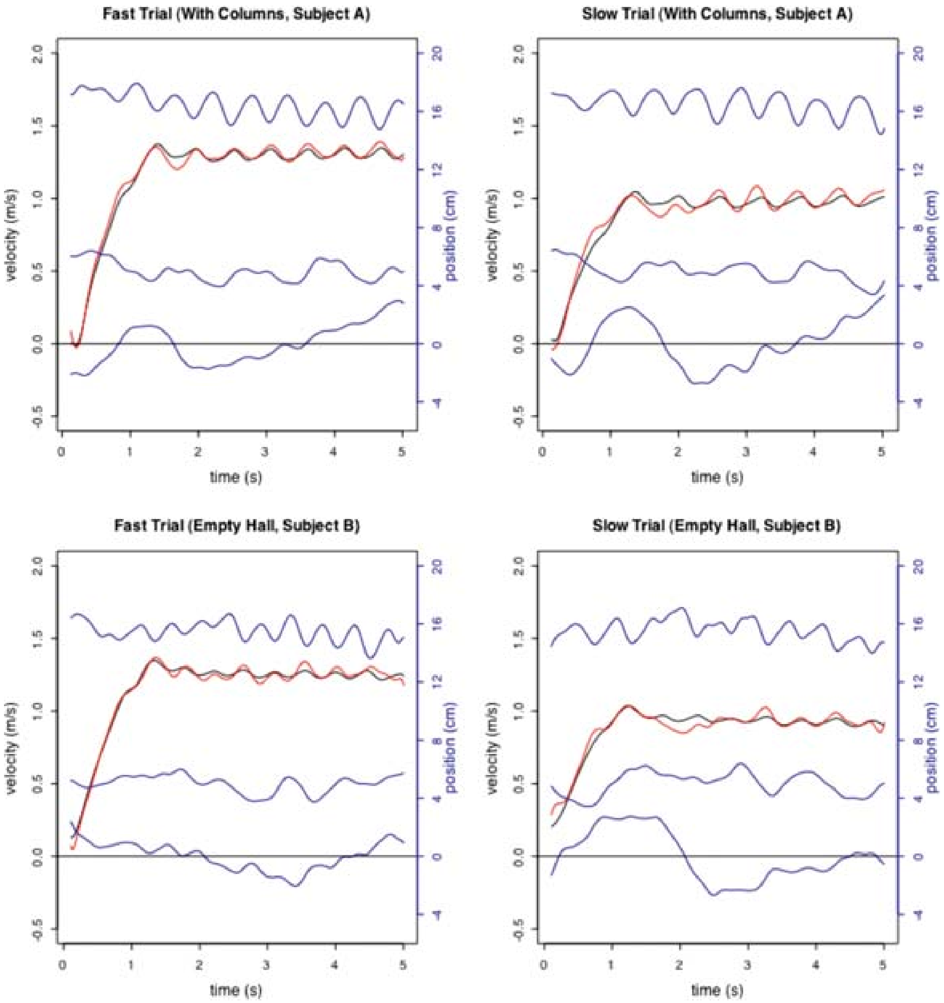

Fig. 3. Sample smoothed speed and position data from four trials of Experiment 1. Instantaneous head velocity (red) relative to the treadmill belt is superimposed on treadmill belt velocity (black), with the signs of both signals made positive. Visual velocity corresponded to the head velocity signal times a gain factor. The blue traces (offset vertically from one another for clarity) are position signals representing the vertical (top), lateral (middle), and forward (bottom) displacement of the head (in cm) over time. The separations between the red and black traces are the result of forward movements of the head relative to the treadmill apparatus (i.e., the derivative of the lowest blue trace).

belt velocity signals were smoothed using the KernSmooth algorithms in R [R Development Core Team, 2005; S original by Matt Wand. R port by Brian Ripley, 2005; Wand and Jones, 1995], and local minima during the plateau portion of the walking were used to denote footfalls. The reciprocal of the average temporal interval between these footfalls was used to estimate step frequency (SF), while the average step length (SL) was computed from the integrated treadmill speed signal combined with head position. Some gait data was lost due to an equipment malfunction during the experiment, but nearly all of the gait data from 38 of the 40 subjects was available for analysis. Sample data are shown in Figure 3.

The average measured walking speeds for the three goal speeds were 0.95, 1.09, and 1.25 m/s, which successfully represent speed ratios differing by 1.15 from one another. If our participants held their walk ratios (WR) constant, they would need to increase both SF and SL by 7% for each 15% of additional speed. Indeed, this is precisely what they did. The mean step durations (SDur) were 0.618, 0.577, and 0.537 s, while average SL were 0.586, 0.628, and 0.673 m. Expressing these as WR (SL/SF = SL * SDur) using meters and seconds as units, these are: 0.362, 0.362, and 0.361. If WR is instead computed separately for each participant, the overall average is 0.363 ± 0.007 (SE). Prior studies of WR in adult humans walking on solid ground report values averaging 0.40 or more [Terrier and Schutz, 2003], which is about 10% higher than the WR measured here. As we suggested above, a 10% reduction in WR could account for a 10% increase in perceived motor speed if SF is used preferentially to estimate motor speed during walking. Indeed, based on the findings of Mittelstaedt and Miteelstaedt [2001], deviations from normal locomotor speed are probably perceptually exaggerated. Although the gain matches were much more accurate in the cluttered environment, WRs were actually 4% lower for these participants (0.356), than for those in the empty hallway condition (0.372), though this difference was not reliable, $t[37] = 1.07$, $p > 0.10$. That is, gait does not account for the differences between these environments, but it may help to account for differences between gain matches for treadmill walking and those for normal walking in cluttered environment.

There were some individual departures from constant walk ratios. Hirasaki et al. [1999] have reported that during treadmill walking, changes in SL are used preferentially to changes in SF, whereas Terrier and Schutz [2003] have reported the opposite for slow walking on solid ground. For each of our subjects, we computed Hirasaki's stride length index: $\mathrm{SLI} = \log(\mathrm{SL}_0/\mathrm{SL}_1)/\log(\mathrm{speed}_0/\mathrm{speed}_1)$. An SLI of 1 means that all change was because of an alteration in SL, whereas a score of 0 represents exclusively a change in SF. The average score for our participants was 0.49 ± 0.02 (SE), which is consistent with a constant WR. However, we did have four participants for whom this score exceeded 0.70, and 1 for whom it was less than 0.30. That is, about 13% of our participants seemed to depart substantially from a constant WR across the small range of speeds we used, and 80% of those did so by adjusting SL preferentially. Of course, our participants were required to rapidly attain one of three speeds and to maintain it for only a few seconds, so the gaits we are measuring may reflect less adaptation to the treadmill than those measured by Hirasaki et al. [1999]. In addition, our participants were wearing a weight on their head (the HMD) and holding onto the handrails (for safety), and this could have affected the both the kinematics and the energetics of the situation.

2.2.3 *Gain Matching as a Function of Gait.* Because there was trial-to-trial variability in the gaits people chose (presumably the variability was increased because they were not in control of setting the walking speed), we tested the altered gait hypothesis by a within-subject analysis and found that changes in SF did, in fact, predict changes in matched gain for those in the cluttered hallway conditions. Specifically, for each participant we split the (36) trials at each speed into those that had step frequencies either above or below the median SF for that speed for that subject. We then separately computed gain matches for low and high frequency gait for each participant, based on 54 trials each, pooled across all three speeds (this was justified by the absence of any speed effect on matched gain). For the 19 subjects in the cluttered hall condition for whom gait data was retained, gain matches were indeed higher for high-frequency (1.19) than for low-frequency gaits (1.11), $t[18] = 2.12$, $p < 0.05$. The corresponding average walk ratios were 0.334 and 0.378. In other words, an average increase in WR by 13% (and, hence, a decrease in step frequency by 6.4%) predicted an average decrease in gain matches by 6.7%. (Note that because SL and SF negatively covary at each treadmill speed, our analysis could be understood as indicating that smaller SL produced higher perceived locomotor speed. However, during normal walking, a smaller SL predicts a lower locomotor speed, not a higher one. This is why we are interpreting our results in terms of SF rather than SL.)

Somewhat surprisingly, this pattern was not evident for the group that evaluated the speeds of empty hallways. For these subjects, average gain matches in trials with high-frequency steps (1.30) did not differ from those with low-frequency steps (1.31), despite corresponding walk ratios of 0.353 and 0.392, $t[18] = 0.33$, $p > 0.10$. However, there is reason to believe that temporal trends could have masked a positive relationship (see section 2.2.4, below).

Because visual motion was present during treadmill acceleration, the selection of a particular gait might, in addition, be controlled by visual factors indicating speed of self-motion [Mohler et al. 2004; Prokop et al. 1997]. We, therefore, considered whether gait parameters (SF, SL, WR) were, in fact, affected by the visual gain presented on a given trial. For each participant, we computed correlations between gait parameters and gain at each treadmill speed. The average correlation between gait and gain never rose above 0.07, which was the average correlation between visual gain and SL at the lowest goal speed. As an alternative approach, we tested whether performing a median split on visual gain would produce groups of trials with different walk ratios.

For those in the clutter condition, the average WR for high-gain trials (0.355) did not differ reliably from the average WR for low-gain trials (0.357), though the average gains in the two sets of trials (1.33 and 0.91) differed by a factor of 1.46. On the other hand, for those in the empty-hall condition, the average WR for high-gain trials (0.374) was marginally higher than that for low-gain trials (0.371), $t[18] = 1.81$, $p = 0.086$. However, this was a difference of less than 1%, whereas the average gains for the two sets of trials (1.44 and 1.01) differed by a factor of 1.42.

In summary, we found a strong and reliable effect of gait (SF) on matched gain when the virtual environment included near objects. We have found some evidence that visual speed also weakly affected gait.

2.2.4 *Adaptation of Gait.* Over the course of 108 walking trials, participants did adapt their gait somewhat. WRs in the final third of trials were higher in both the empty (0.376) and cluttered hallway environments (0.363) than they were in the initial third (0.368; 0.349); they were intermediate in the middle third. The overall change in WR from the first to final third of trials was reliable, $t[37] = 2.65$, $p < 0.05$. Since it reflects a departure toward a more normal WR (e.g., 0.40), it may reflect growing comfort and familiarity with the treadmill apparatus.

As WR increased over time (and therefore SF decreased), it might be expected that PSEs would decrease. In contrast to this expectation, PSE matches computed for the first one-third of the trials (1.10 for columns; 1.26 for the empty hall) were actually lower than those computed for the final third of trials (1.18; 1.34), $t[37] = 2.84$, $p < 0.01$. However, these apparent PSE drifts may reflect measurement bias introduced in the first one-third of trials by the balanced starting points of the staircases. In any case, they make clear that the strong association between gait and PSE found for the columns world was not mediated by common temporal drift in the two measures, because the temporal drifts are in opposed directions. If anything, then, the overall trial-to-trial association between gait (SF) and PSE is probably stronger than we have estimated, because that association is diluted by the opposed temporal drifts of the two measures.

2.2.5 *The Speed-Subtraction Account.* With near-space objects, matches on the treadmill are higher than those on solid ground. We attribute this to an error in perceived motor speed on the treadmill caused by altered gait. In support of this, we have documented that gait is altered, and found evidence that trial-to-trial variations in step frequency affected perceived speed as measured by visual matches.

In the empty corridor, gain matches are numerically quite similar on the treadmill to those found on solid ground. This actually corresponds to a quantitative prediction of the inhibitory subtraction account of gain-match errors in open environments combined with the misperception of motor speed on treadmills. Durgin et al. [2005b] showed that visual speed subtractions were greater on solid ground than on treadmills. In the solid-ground data, the difference in gain matches between cluttered and empty hallways corresponds to the value estimated by Durgin et al.: 30% of walking speed. Similarly, on the treadmill, the difference in gain matches between cluttered and empty hallways corresponds to the subtraction of 15% of walking speed estimated by Durgin et al. for treadmill walking. This means that the similarity between gain matches on the treadmill and on solid ground in an empty virtual environment could be an accident of the speed-subtraction for solid-ground walking (30%), being quantitatively similar to the product (27%) of the speed subtraction for treadmill walking (15%) and the overestimation of walking speed on treadmills (10%).

2.2.6 *Alternative Accounts.* The overall improved performance with our treadmill apparatus might be attributed to the insertion of low speeds during acceleration rather than to improved immersion, in general. Banton et al. [2005] reported that gain matches were more accurate at low treadmill speeds. However, there is evidence that very slow motor speeds are themselves underestimated [Mittelstaedt and Mittelstaedt 2001], which would predict lower gain matches when walking at slow speeds. Such biases are not reported to occur as a result of accelerating through low speed on the way to normal speeds, however. Moreover, the gain matches obtained by Banton et al. [2005] at slow speeds may have been biased, because the speed increments used in their method of limits for all speed were 50% of the 45 cm/s walking speed at their lowest speed. This may have actually precluded detecting deviations in the range expected.

Similarly, although, Banton et al. [2005] reported that gain matches did not differ from 1.0 when looking was toward the ground or to the side (and this seems inconsistent with the claim that the same motor speed is probably perceived as 10% faster on a treadmill), the same measurement concerns apply. Because their method of limits was not designed to detect a 10% deviation from accuracy, their failure to detect motor speed errors should not be regarded as discrepant with the detection of motor speed errors here.

In our experiment, gaze was forward, and trial-to-trial variations in gait were found to affect gain matches in a manner consistent with the idea that step frequency dominated the perception of motor speed. We believe that overall gait changes (higher step frequency) on treadmills may account for the small errors in gain setting relative to normal walking when the near environment was spatially rich. In normal walking, stride frequency is a fairly stable and accessible estimator of motor speed. Although Banton et al. [2005] directly manipulated gait in one of their experiments (requiring subjects to shorten their stride), they do not report controlling gaze direction in that experiment. Moreover, although WRs would have been (by definition) decreased by their manipulation, the manipulation was overtly of stride length and may have called attention to SL, rather than SF. For example, the evaluation of motor speed in an overt manipulation of SL while looking at the ground in VR might be rather different because one could treat the task as one of reaching with the (felt but unseen) foot toward a moving surface and evaluate whether the intended contact point was hit or whether it slid past prior to felt contact. We believe that the present data, in which naturally occurring trial-to-trial gait differences predict differences in gain matches, is powerful evidence of an effect of gait.

2.3 Conclusions

We have found that participants' gain matches in a virtual environment with near clutter are more accurate than their gain matches in an empty hallway. This reproduces a phenomenon previously found using the same VR worlds on solid ground [Durgin et al. 2005a], and differs from earlier treadmill studies [Banton et al. 2005; Durgin et al. 2005a]. Our treadmill apparatus allowed us to closely yoke perception and action and to provide relatively normal acceleration phases for both. All the data are consistent with the idea that residual gain-match errors are the result of speed-subtraction processes in empty environments combined with a misperception of motor speed on treadmills.

3. EXPERIMENT 2: GAIT WHILE GAIN-MATCHING ON SOLID GROUND

Although the walk ratios reported above seem low relative to published means, we sought to compare them to solid-ground walking with an HMD in order to determine whether they were low because of the treadmill or because of the HMD. To do this, we analyzed the unpublished gait data from Experiment 2 of Durgin et al. [2005a]. The principal finding of our analysis is that, even when wearing an HMD, the average WR is, indeed, much higher on solid ground than on the treadmill.

3.1 Method

Durgin et al. [2005a] had 13 participants perform a gain-matching task in VR while walking on solid ground at normal walking speeds over distances of 6 to 10 m. The experiment was performed in the middle of a long hallway of which 15 m was instrumented for position tracking, and participants simply rotated between trials so as to alternate walking direction in the hall. The virtual hallway environments were identical to those used in Experiment 1 here and were slightly narrower than the physical hallway in which the experiment was conducted. Each participant did 36 trials in one type of environment followed by 36 in the other (order counterbalanced), while wearing the V8 HMD. As reported by Durgin et al. [2005a] the overall gain matches were 1.04 for the cluttered hallway and 1.29 for the empty hall (including both blocks of data). There was no effect of order. Since speed was self-controlled in that experiment (apart from a requirement to walk somewhat quickly), we considered speed variations in addition to other gait parameters.

The head-tracker data for each trial in the study of Durgin et al. [2005a] had been stored at only 30 Hz and we used the smoothed head-bob data to isolate series of consecutive steps from which to extract gait parameters. The initial two steps of walking were automatically excluded as atypical (see Experiment 3). We required that each remaining step in the series have an average speed within 10% of the fastest step and typically this yielded about eight steps from each trial ($M = 8.33$). The total distance traveled and total duration of an integral number of steps thus extracted were used to estimate average step length and duration, which were then multiplied together to compute the WR, and divided to compute average speed.

3.2 Results and Discussion

The overall average WR was 0.393 ± 0.02 (SE), and the average walking speed was 1.50 ± 0.05 m/s; neither of these differed by the type of virtual environment. As anticipated, this WR was higher than the average WR (0.363) of Experiment 1, $t[49] = 1.89$, $p < 0.05$, one-tailed. This provides additional evidence that treadmill gaits are unusual, even controlling for the presence of an HMD. The average WR, while wearing an HMD on solid ground, did not differ reliably from the values of 0.40 or 0.41 that have been reported in the literature for normal walking.

Although people adopted a more normal walk ratio, there were still intertrial differences in the WR, (though, as expected, they were smaller than on the treadmill). Therefore, as in Experiment 1, we split the data according to whether the WR on a given trial was higher or lower than the median. Although this kind of analysis had shown that changes in step frequency had affected speed judgments in the cluttered environment on the treadmill, no reliable differences were found for the cluttered environment when walking on solid ground. Nonetheless, changes were in the expected direction (i.e., the direction predicted by the idea that step frequency often serves as an estimator for motor speed). For example, the walk ratio differed by 7% between the upper and lower halves of the data (representing an average increase in frequency by about 3% for the lower WR trials), and the corresponding difference in match ratio for the two halves of the data was by 4%, though it was not a statistically reliable difference.

In contrast to this small effect in the cluttered hall, a median split by WR for trials for each subject in the empty hall environment showed that the gain matches were marginally higher (1.42 versus 1.26) when the WR was only 4% lower, $t[12] = 2.00$, $p = 0.069$. Such a large change (13%) could not be easily explained by the 2% change in step frequency. However, it might indicate, instead, a complex effect of visual gain on gait. Specifically, when dividing the trials according to whether the visual gain was above or below the median for each subject, no reliable difference in WR was found, but there was a reliable difference in walking speed. Specifically, participants walked faster on low-gain trials (1.51 m/s) than they did on high-gain trials (1.47 m/s), $t[12] = 3.37$, $p < 0.01$. A similar, but nonreliable effect was found when walking in the cluttered virtual environment. Such adjustments are consistent with visual information altering perceived motor speed.

Particularly in the empty virtual hallway, there appeared to be evidence of a less direct process of evaluating the appropriate visual speed. By splitting the data according to the motor speed on a trial-by-trial basis, we found that on the faster one-half of the trials for each subject, walking speed averaged 1.57 m/s as against 1.44 m/s for the slower one-half. This large speed difference (9%) had no reliable impact on the gain matches in the cluttered hallway (1.04, 1.06 respectively, a 2% difference), as is appropriate but produced reliably different gain matches in the empty hallway, (1.25, 1.32; a 6% difference), $t[12] = 2.64$, $p < 0.05$. This pattern of results is consistent with the idea that the participants were less aware of variations in their own motor speed in the empty hallway and tended to compare the trials based on absolute visual speed. Note that this pattern of nonuse of motor speed information is similar to the non-effect of WR on gain matches in the empty hallway of Experiment 1.

Splitting the trials according to walking speed also produced a highly reliable difference in WR, with faster trials showing a higher WR (0.397) than slower trials (0.389), $t[12] = 4.10$, $p < 0.01$. This shift in WR (which corresponds to taking relatively longer steps to increase speed) was present for the cluttered trials alone, as well as overall, but did not, in itself, produce changes in gain matching. The implication is that step frequency may dominate locomotor perception on treadmills more than on solid ground—at least in the present context.

In general, when walking on solid ground, gait factors, including speed and WR, had little impact on performance of the gain-matching task in the cluttered environment where performance is generally quite good. However, gait factors, especially speed, played a measurable role in influencing the gain-matching task with the empty, textured hallway. This pattern of results is consistent with the idea that visuomotor interaction with near-space objects provides a kind of feedback that helps to anchor perceived speed of self-motion. Durgin et al. [2005a] suggested that cluttered environments engage obstacle-avoidance systems that are probably better tuned to objects in near space.

Although, the data in the cluttered environment are not inconsistent with the domination of SF signals in the evaluation of walking speed, we suspect that individual step speeds may, in addition, be calibrated by acceleration signals when walking on solid ground. However, the temporal resolution of our solid ground data was insufficient to estimate acceleration parameters. We, therefore, conducted a further experiment to try to characterize inertial signals that might be available during normal walking and serve as feedback for the evaluation of step length.

4. EXPERIMENT 3: NORMAL GAIT MEASURED BY HEAD TRACKER

The foregoing experiments have suggested that SF is a powerful source of information about speed of self-motion on a treadmill and may be particularly useful for estimating self-motion speed over a series of several steps. However, in near space, on-line estimates of self-motion may give more weight to periodic inertial signals associated with individual steps. Such measures might be particularly relevant to obstacle avoidance where unintended variations in instantaneous velocity may require rapid correction to avoid collision. Inertial signals would probably not play as much of a role on the treadmill where some of the periodic forces associated with walking are apparently absorbed by the treadmill belt and where haptic contact with the treadmill hand grips may help to stabilize the head more than in normal walking. To assess the extent to which inertial signals could serve as cues to instantaneous velocity during walking, we used a head tracker to measure head velocity during walking and used the derivative of the smoothed velocity signal to estimate the inertial signals associated with each step.

The goals of this study are twofold. First, it is difficult to characterize the potential role of inertial signals in walking without knowing how they covary with walking speed. The integration of multiple sources of information in assessing self-motion ought to take greatest advantage of whatever sources of information are most precise for a given purpose, but some sources of information may also covary in useful ways. The present study, therefore, sets out to characterize the general relationships between gait parameters and the rate of forward movement of the head during walking. Second, because the results of Experiments 1 and 2 suggest that treadmills (in which periodic inertial signals are reduced by haptic contact with the handrails) tend to produce greater reliance on SF rather than SL, we sought to measure, on a stride-by-stride basis, the relationship between these gait parameters and local acceleration signals. For researchers interested in understanding the role of inertial signals in the perception of self-motion during locomotion, these data may provide a source for generating further hypotheses to test.

In order to manipulate people's walking speed, we chose two different kinds of manipulation. One was explicit. Mittelstaedt and Mittelstaedt [2001] have reported that when people are asked to deviate from their preferred speed, their estimates of self-motion become biased. They had people walk to a previewed target without visual feedback and found that when people followed instructions to walk "somewhat fast" or "very fast" they would undershoot the target, but when they followed instructions to walk "somewhat slow" or "very slow," they would overshoot the target. Such errors are consistent with overestimating the achieved deviation from normal speed. Although our subjects walked with eyes open, we used the same set of speed instructions (including "normal").

The other method we used to manipulate walking speed was implicit, in an effort to avoid artificial gait changes that might be produced by explicit instructions: We varied the distances people were required to walk from trial to trial. This was done in an attempt to get a more naturalistic sampling of different walking speeds for comparison with the explicit manipulation. We assumed that people might accelerate differently for a very short distance that required only a few steps (e.g., 3 m), than for longer ones that required many steps (e.g., 6 or 9 m). This manipulation was performed first for each participant so as to reduce the participants' overt attention to their speed. Because this method yielded few steps for the short distance, however, it was mostly useful for evaluating initial acceleration patterns.

4.1 Method

Participants were 18 undergraduate students who were paid to participate. None were aware of the purpose of the experiment. All signed informed consent forms and were treated according to ethical guidelines.

4.1.1 *Apparatus.*

The HiBall head-tracking device was worn on the top of the head using a lightweight, adjustable plastic mount. The HiBall, which samples position information at over 1000 Hz, estimated position and velocity at 120 Hz, using a sampling window of 20 ms. Onset and offset of trials were signaled by a remote keyboard, which triggered the collection of data. All walking was done with full vision.

4.1.2 *Design.*

Twenty-four walking trials were measured for each participant. The first nine trials required the subject to walk each of three distances (3, 6, and 9 m) three times. No speed instructions were given except to walk normally. For the final 15 trials, there were three blocks of five randomly ordered trials in which participants were asked to walk a 6-m distance at one of five speeds described as "very slow," "somewhat slow," "normal," "somewhat fast," and "very fast."

4.1.3 *Analysis.* We wished to extract gait parameters that we have already considered (speed, SL, SF or step duration, and WR), but also to extract peak acceleration on each step. The tracker data were analyzed using the KernSmooth library's "locpoly" function in R, with a bandwidth of 100 ms and fourth-order polynomial to generate smoothed acceleration, velocity, and position profiles at the same temporal resolution as the raw data. We did not independently calibrate our estimates of peak acceleration, but for purposes of our present analysis, the relative (rather than absolute) magnitudes were of most interest. Steps edges were defined by local maxima in the smoothed vertical position data, which fell in between periods of peak acceleration for each step. Step lengths were reconstructed from the smoothed position data, while peak linear acceleration was derived from the smoothed velocity data. The onset of walking was determined from the velocity data in conjunction with vertical head position.

Steady-state gait was analyzed using consecutive steps (after the second step) that were all within 10% of the peak speed. Gait initiation was analyzed by looking at the very first step. Because there is evidence that peak accelerations play a dominant role in the perception of the speed of passive self-motion [Schaffer and Durgin 2004], we were particularly interested in including peak accelerations in our analysis of initial steps.

4.2 Results and Discussion

Although the primary concern of this paper is steady-state gait parameters, we also report step parameters associated with gait initiation, because these may also be relevant to understanding the perception of self-motion.

4.2.1 *Gait Parameters During Steady-State Walking* (*Steps at Speed Plateau*). The implicit manipulation of walking speed was partly successful, but the shortest distance (3 m) only occasionally provided more than one full step within 10% of peak velocity, and the average peak velocity only reached 1.09 m/s. It appeared that the acceleration and decelerations phases of walking often overlapped for these short distances, because the first steps were fairly similar across distances, but peak speeds were much lower for the short distance. Therefore, the analysis of steady-state gait was restricted to data from the medium and long distances.

The medium distance provided an average of 4.4 steps (at plateau) for analysis for each trial and the long distance provided an average of 7.6 steps for analysis. The average speed for the long distance (1.34 m/s) was reliably greater than that for the medium distance (1.30 m/s), $t[17] = 3.73$, $p < 0.01$. This speed difference was accomplished by a statistically reliable decrease in average step duration from 0.555 to 0.548 s, $t[17] = 3.66$, $p < 0.01$, and a reliable increase in SL from 0.719 to 0.729 m, $t[17] = 2.60$, $p < 0.05$. The average WR for each distance was 0.399 ± 0.009. Thus, the manipulation of walking distance did provoke small, measurable changes in speed, but not in WR.

Average peak accelerations (0.55 m/s^2 along the axis of travel) for each step did not differ reliably between the long and medium distance. However, by computing within-subject correlations between peak acceleration and average speed for each step from the pool of steps used in the long- and medium-distance analyses (separately for each participant—based on about 35 steps, typically), we found that the average correlation between peak acceleration and step velocity (0.10) was reliably different from zero, $t[17] = 2.21$, $p < 0.05$. As expected, it was SL that was marginally correlated with peak acceleration (0.08), $t[17] = 1.99$, $p = 0.063$, whereas there was no reliable correlation between peak acceleration and step duration (−0.02), $t[17] = 0.35$, $p > 0.10$. In other words, variations in peak acceleration during normal walking do seem to reflect speed variations related to changes in SL. The neglect of SL information on treadmills might, therefore, be related to the attenuation of acceleration signals (e.g., when haptic contact is maintained with the handholds).

Table II. Average Steady-State Step Parameters as a Function of Verbal Speed Instruction

Verbal Speed	Duration[a] (s)	Length (m)	Acceleration (m/s^2)	Speed (m/s)	Walk Ratio (ms)
Very slow	0.686 ± .016	0.581 ± .013	0.55 ± .04	0.86 ± .03	0.397 ± .009
Somewhat slow	0.602 ± .010	0.663 ± .014	0.54 ± .05	1.11 ± .04	0.398 ± .008
Normal	0.549 ± .008	0.731 ± .015	0.51 ± .05	1.34 ± .04	0.401 ± .009
Somewhat fast	0.505 ± .008	0.796 ± .017	0.55 ± .06	1.59 ± .05	0.401 ± .009
Very fast	0.461 ± .008	0.875 ± .020	0.65 ± .06	1.91 ± .06	0.403 ± .011

[a] Values given are means and between-subject standard errors of the means.

The explicit manipulation of walking speed was extremely effective. The average walking speeds attained under the five different instructions ranged from 0.86 to 1.91 m/s. The average “normal” walking speed was 1.34 m/s. Although there was a trend for WR to increase slightly with increasing speed, the trend was not reliable. The overall WR (0.400) was no different than in the first part of the experiment. A summary of the average step parameters is shown in Table II.

Peak acceleration on each step differed widely between individuals and was somewhat differently related to speed for different individuals. Some individuals showed a positive linear relationship between walking speed and average peak acceleration (for 5 of 18 the R^2 between average step speed and average peak acceleration was greater than 0.50, mean $R^2 = 0.31 \pm 0.07$), but a V-shaped relationship was more common (for 9 of 18, the R^2 using a V-shaped speed contrast was greater than 0.50, mean $R^2 = 0.59 \pm 0.07$), and had a reliably higher R^2, $t[17] = 3.08$, $p < 0.01$. Since it is probably more energy efficient to minimize periodic accelerations and decelerations of the body mass, the better minimization of periodic peak acceleration at “normal” speed is sensible. Averaging across the direction of speed change (i.e., averaging peak step acceleration estimates for “very slow” with those of “very fast” and averaging those of “somewhat slow” with those of “somewhat fast”) revealed reliable differences between average peak accelerations for “normal” (0.51 m/s^2) and for the small deviations in speed (0.54 m/s^2), $t[17] = 2.13$, $p < 0.05$, as well as between those for the small and for the more extreme deviations in speed (0.60 m/s^2), $t[17] = 2.20$, $p < 0.05$.

The correlations between peak acceleration and three gait parameters (SL, SDur, and speed) were also computed among steps from the same speed category within each individual. No reliable effects were found, though the trends were in the same direction as found with the implicit speed manipulation: The average correlation between step velocity and peak acceleration was 0.125, and that between step length and peak acceleration was 0.089, while that between step duration and peak acceleration was only 0.043.

4.2.2 *Gait Initiation.* When initiating gait, walkers usually take an initial step with high acceleration that is followed by a second, short step that basically completes the transition to steady-state walking. Neither the first nor the second step reflects the normal walk ratio. In our data, the average WR for the second step did not differ by verbal speed and was 0.359 ± 0.010. This step is typically similar in duration to the later steps, but spatially shorter by about 10%. By the third step, neither the walk ratio (0.389) nor the average speeds were reliably different from their ultimate values (for ”normal” speed walking, the WR on the third step was 0.396).

When asked to walk different distances (at normal speed), initial steps for all three distance conditions had similar peak accelerations, with a mean of about 1.88 m/s^2 and similar durations (1.14 s). Although initial step lengths for the shortest distance (0.67 m) were reliably shorter than for the intermediate distance (0.71 m), $t[17] = 2.58$, $p < 0.05$, they were similar to those of the longest distance (0.68 m). In other words, the initial step in all three of the distance conditions was fairly similar and this may reflect the fact that gait initiation (for normal walking) is probably highly routine.

For the explicit speed task, first steps differed along all three primary step parameters. These are summarized in Table III. Notably, peak accelerations on the first step varied in a manner that was

Table III. Average First Step Parameters[a] as a Function of Verbal Speed

Verbal Speed	Duration (s)	Length (m)	Peak Acceleration (m/s^2)
Very slow	1.30 ± .04	0.515 ± 0.027	1.15 ± .06
Somewhat slow	1.26 ± .04	0.658 ± 0.026	1.55 ± .08
Normal	1.15 ± .03	0.726 ± 0.010	1.97 ± .13
Somewhat fast	1.08 ± .03	0.757 ± 0.025	2.57 ± .15
Very fast	1.06 ± .03	0.865 ± 0.026	3.42 ± .14

[a] Values given are means and between-subject standard errors of the means.

nearly linear with ultimate speed. Linear fits between average speed at plateau and average first-step peak acceleration for each participant had an average slope of 2.20 ± 0.15, and an average R^2 of 0.92 ± 0.03. The average exponent of power functions fit the same way was 1.39, but the average R^2 (0.92) was no better than for the linear fit.

What is notable about the initial step data is that the duration of the first step varies much less than the length—and that both the step lengths and the peak accelerations clearly reflect the goal speeds adopted by the walkers. Indeed, the step lengths chosen for the first step are quite similar to the sizes that will be taken on subsequent steps. Thus, it would appear that a particular walking speed is initiated, in some sense, by defining a stride length and that the temporal frequency necessary to support that step length falls into place on subsequent steps.

4.2.3 *Perceptual Implications of Walking Data.* Although the present data are based on a small number of steps taken following gait initiation, they suggest that deviations from normal step lengths will tend to produce less efficient walking (greater peak accelerations on each step). Because of this, they do not indicate the extent to which the periodic accelerations associated with each step might serve as a cue to either walking speed or to deviations from current speed. There was a trend for a linear relationship in about one-third of our walkers, so the amplitude of cyclical accelerations may be a stronger cue to walking speed for these individuals than for the others.

Clearly the peak acceleration during gait initiation is strongly correlated with initial step size and with ultimate speed. This kind of inertial information (either sensed vestibularly, or via proprioceptively sensed forces) could be a very valuable cue in assessing the result of a first step that fails to be as long as intended because of a loss of friction with the ground surface, for example. In such cases, inertial signals might help to select the appropriate driving frequency for the step size achieved.

Finally, we note some caveats. The present analysis is based on dividing steps according to peaks in vertical head position. For the analysis of steady-state walking, it is not especially crucial that this be perfectly in phase with the stepping motions, because two aspects of the data to be recovered involve the average duration and average distance of a series of steps and for this purpose phase is not important. (Lateral sway, for example, its slightly ahead in phase of vertical bob, because of the need for the swinging leg to more easily clear the ground surface.) Moreover, the peak accelerations for each step clearly occur between these vertical peaks, so no artifacts are added there as a result of our method of delineating steps. However, the analysis of the length of the first step is more problematic because it must assume that the head peaks at the moment it passes over the stationary foot, which we think is a reasonable approximation. This may require some correction to account for vertical accelerations accompanying the initiation of forward acceleration on each step. Our analysis is appropriate to the characterization of the movement of the head through space, which is presumed to be chiefly relevant to the multimodal perception of self-motion.

5. GENERAL DISCUSSION

We have shown using gain-matching data that stride frequency dominates step length in the perception of locomotor speed on treadmills. Naturally occuring variation in SF from trial to trial during Experiment 1 predicted variations in judgments of appropriate visual speed. Based on the lowered WR found on treadmills (which means a relatively high SF) we have estimated that walking speed may be overperceived by about 10% on treadmills. This accords well with the fact that gain matching in a cluttered visual environment in our high-fidelity treadmill virtual reality is about 10% higher than we have reported in the past for the same environment, while walking on solid ground [Durgin et al. 2005a].

To support the idea that SF could reasonably play a role in misperceiving locomotor speed, we have shown in Experiment 3 that people do indeed maintain a constant WR across a very wide range of locomotor speeds. A constant WR means that estimates of SF and SL are redundant. Evidence of the domination of SF on treadmills does not require that SF also dominates on solid ground, but SF has somewhat lower variability than SL in natural walking at preferred speed [Terrier and Schutz 2003]. We have also shown in Experiment 2 that the lowered WR of subjects in Experiment 1 cannot be attributed to the HMD, but must be attributed to the treadmill.

Finally, we have used gait parameters from normal gait initiation and walking at various speeds to suggest some additional kinds of perceptual information that may play a role in evaluating locomotor speed in the absence of visual feedback.

5.1 The Role of Near-Space Objects

We have speculated that gain matches are improved in the context of near space objects because we are calibrated to detect these kinds of speeds in normal locomotion. Durgin et al. [2005b] have shown that visual speeds seem slower during self-motion, but they reported that the introduction of a close vertical surface (3 m away) eliminated this visual speed subtraction when gaze was to the side on treadmills. In contrast they found that the amount of speed subtraction (about 15% of locomotor speed on treadmills) was identical with either forward or side gaze when the visual scene consisted of a textured ground plane. The findings of Banton et al. [2005], that lateral gaze improves gain matches, may be interpreted as consistent with the view that visual speed perception is more accurate during walking in the presence of near visual objects. Because the ground plane is omnipresent, its ”subtraction” from visual flow may be useful for the detection of nonground flow, but may also result in gain-matching errors in relatively sparse virtual environments (like empty hallways or ground planes).

Because of the smaller amount of expected reduction in perceived visual speed on treadmills, there is less relative cost to gain matching on treadmills when near-space objects are absent. In Experiment 1, we measured a difference of about 15%, which is consistent with the amount predicted by Durgin et al. [2005b] for treadmill locomotion using similar empty hallways. Durgin et al. [2005a] found that the result of using an empty hallway was a 30% increase in gain matches (relative to a cluttered virtual hallway) when walking on solid ground. This number also corresponds to the amount of visual speed subtraction measured by Durgin et al. in the context of walking on solid ground. Our present results, therefore, suggest that the difference between near-space objects and sparse environments results from speed subtraction differences. There are two other possible interpretations of the difference between near- and far-space objects, but, at present, neither of them fits the results as well.

One interpretation that remains open is that errors in gain matching are related to errors in distance perception in VR [Loomis and Knapp 2003]. Such errors have been shown to be quite persistent [Messing and Durgin 2005; Thompson et al. 2004]. However, they are thought to be less problematic in near space. It could be that near objects improve speed perception, because flow speed is scaled by perceived distance—and the distances to near objects are more accurately perceived. This explanation may have some merit, but, given the evidence that locomotor speed is overestimated on treadmills, it cannot explain why gain matches for empty scenes are about the same when walking on a treadmill as when walking on solid ground.

A second kind of alternative interpretation of the solid-ground near space advantage might emphasize that obstacle avoidance systems are engaged for near-space objects and these systems can may take advantage of, for example, periodic accelerations that are more likely to be well-calibrated on solid ground than are treadmills. Given the strong direct evidence that SF produces shifts in matches on the treadmill with near-space objects, however, it would seem that the difference between solid-ground and treadmill walking have much more to do with errors in the perception of motor speed than with the degradation of the obstacle avoidance system on treadmills. It remains possible that the greater relevance of near-space objects is related to why they may be immune to speed subtraction. For example, there is evidence that locomotor speed of self-motion is used in the evaluation of time to contact [Thibodeau et al. 2005] and this implies that estimates of locomotor speed are probably used for obstacle avoidance (rather than purely optical estimates of time to contact, for example).

5.2 Interactivity

The goal of our treadmill VR apparatus was to recreate the level of interactivity available when walking on solid ground. One way we did this was by tying the visual display to the instantaneous speed of the treadmill belt, in addition to tying it to the head motions of the participants. In addition, we varied the treadmill speed slightly from trial to trial. Finally, we included the acceleration phase of walking in order to equate the interactivity of our treadmill VR with real walking. We also ensured that our graphics were both of high spatial and temporal resolution. The major remaining discrepancies were that speeds were not self-selected nor were initial steps similar to normal walking. Nonetheless, even with the empty hallway, gain matches were 10–15% lower than in previous studies. Our gait analysis indicated that in the cluttered hallway, in particular, participants judgments were sensitive to trial-to-trial variations in gait when on the treadmill. This advantage for the richer environment corresponds to the finding in Experiment 2 that trial-to-trial variations in walking speed when on solid ground were also better reflected in judgments made in the cluttered hallway. This is consistent with the idea that by providing a high level of interactivity, and a rich near-space environment, we engaged better-calibrated systems for detecting discrepancies between vision and action.

5.3 A Note on HMDs

Although our analysis in Experiment 2 showed that WR was normal for walking while wearing an HMD, it may be important that there was visual feedback (even if of the wrong gain) provided during the walking. Willemsen et al. [2004] have suggested that the evaluation of distances walked while wearing mechanical weights like those of an HMD may be overestimated (that is, people undershoot a previewed target when walking to it without vision wearing a dummy headset). This would be consistent with an altered gait. Because distance estimation by walking is normally done with closed eyes, the data presented in Experiment 2 simply do not address the important issue of whether gait is altered by added head weight when there is no visual feedback provided during walking. It is hoped that future experiments involving walking tasks with HMDs will try to measure the WR of their subjects. Because the vertical head position can be used to count steps and the WR may be estimated by multiplying together the average step length and the average step duration for a series of steps, a head tracker can easily be used to capture this aspect of gait.

5.4 Conclusions

On treadmills, gait parameters differ from normal walking. Step frequency is relatively high for a given locomotor speed, which leads to an overestimation of motor speed. In a well-structured visual environment, gain matches between visual speed and motor speed are higher on treadmills than they are on solid ground—as if locomotor speed is overestimated on the treadmill. Indeed, trial-to-trial variations in step frequency predicted large and reliable differences in the matched gain visual speed. All of these findings are consistent with the dominance of step frequency in the evaluation of motor speed. This dominance is normally appropriate, because of the long-documented coupling of locomotor speed with step frequency [Grieve and Gear 1966].

Large gain-matching errors have been reported in the past when the tight yoking of perception and action was not maintained in treadmill VR. We have found that when high-fidelity treadmill VR was used to assess gain matches, the remaining discrepancies between gain matches on treadmills and on solid ground could be explained in terms of the misperception of locomotor speed on treadmills when there was near-space structure to the environment. For environments without near-space structure, additional differences could be accounted for by differences in subtractive visual speed reduction as a function of whether walking was on a treadmill or on solid ground [Durgin et al. 2005]. The role of near-space structure in self-motion perception deserves further study.

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