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# The Perception of Walking Speed in a Virtual Environment

## Abstract

Studies of locomotion in virtual environments assume that correct geometric principles define the relationship between walking speed and environmental flow. However, we have observed that geometrically correct optic flow appears to be too slow during simulated locomotion on a treadmill. Experiment 1 documents the effect in a head-mounted display. Experiment 2 shows that the effect is eliminated when the gaze is directed downward or to the side, or when the walking speed is slow. Experiment 3 shows that the effect is unchanged by stride length. Experiment 4 verifies that the effect is not attributable to image jitter. The change in perceived speed from straight ahead to side or down gaze coincides with a shift from expanding optic flow to lamellar flow. Therefore, we hypothesize that lamellar flow is necessary for accurate speed perception, and that a limited field of view eliminates this cue during straight-ahead gaze.

## 1 Introduction

It is becoming more common to incorporate self-motion into virtual environments in order to prepare participants for real-life situations. For example, the Navy's Officer of the Deck simulation (Zeltzer & Pioch, 1996), which has been developed to train submarine officers to guide a submarine into harbor, places the user on a moving submarine. Based on the submarine's current speed, water currents, and other factors, the Officer of the Deck issues verbal commands to the crew in order to navigate the submarine. Another example is the use of driving simulations to test safety, performance, and other aspects of a car design before the car is built. In discussing the relationship between perceptual requirements and real-time graphics, Deyo, Briggs, and Doenges (1988) note that "Driving involves very low eye heights where optical flow density must change very rapidly over the field of vision available from a car. The driver must be able to judge speed and proximity to obstacles very quickly by visualizing textural cues in and around the road as well as passing 3D features" (p. 320). Clearly, providing an accurate illusion of self-motion is important in many simulations.

Despite this need, accurately simulating one's speed of motion has largely been unsuccessful. With respect to driving simulations, Suhr, Lauer, and Allgaier (1958) asked participants to report their speed during real driving and during simulated driving in an "autotrainer." Replotting their data from Tables 1 and 2 showed that real drivers estimated their own speed fairly accurately. Although simulator drivers were accurate at 30 mph, they overestimated their speed below 30 mph and underestimated above 30 mph. Simi-

Presence, *Vol. 14, No. 4, August 2005, 394–406*

lar misperceptions of speed have been found in film-based driving simulations (Hakkinen, 1963; Salvatore, 1969). More recently, Groeger, Carsten, Blana, and Jamson (1999) found that speed was overestimated in the Leeds Driving Simulator. They concluded that speed perception was simulated well enough to allow inferences to be made about real driving; however, they did not provide data from real drivers to support their claim.

Estimates of walking speed during simulation on a treadmill are often inaccurate too. Thurrell, Pelah, and Distler (1998) noted that participants looking straight ahead at projected optic flow that was matched to the speed of treadmill walking perceived optic flow to be too slow given their walking speed. A similar effect was found at faster speeds by van Veen, Distler, Braun, and Bulthoff (1998), who showed that the speed of optic flow seemed too slow for the pedaling speed during simulated bicycling.

Overall, speed of self-motion is usually misperceived in simulated environments (although see Durgin & Kearns, 2002, for an exception). This failure to accurately perceive self-motion is sometimes blamed on a lack of sensory cues, because nonvisual information, such as auditory, tactile, or vestibular cues, is also important to speed perception (Semb, 1969; Evans, 1970). In the current study, we show that optic flow can be manipulated to produce either an accurate or erroneous perceived calibration between flow and walking. We argue that misperceiving speed in a constant-velocity virtual environment is largely related to restrictions in peripheral optic flow during simulation.

## 2 Experiment 1: Optic Flow Speed Seems Slower than Walking Speed

Previous research has shown that when the simulated speed of optic flow and locomotion match, participants usually perceive the speed of optic flow to be slower than their walking speed. Experiment 1 demonstrated this effect when optic flow was presented in a head-mounted display and self-motion was simulated on a treadmill.

### 2.1 Method

**2.1.1 Participants.** Thirty undergraduates (15 female, 15 male) at the University of Virginia participated in the experiment. All had normal or corrected-to-normal vision and were shorter than 6′1″. (Taller participants brought the head-mounted sensor outside of the magnetic field of the tracker system, and thereby caused distortions in the scene). They participated to obtain credit in an introductory psychology class. Informed consent was obtained from each participant prior to testing.

**2.1.2 Apparatus.** To simulate locomotion, a motorized treadmill (Precor 9.1) was employed. The treadmill was modified by firmly attaching a crossbar to the side railings so that participants could stabilize themselves by grasping a bar directly in front of them. This improved participant stability during the experiment.

To simulate optic flow, a virtual environment was viewed through a head-mounted display (n-Vision Datavisor) containing two color LCDs operating in a VGA video format. The resolution of each display screen was 640 pixels (horizontal) × 480 pixels (vertical), per color pixel. The field of view per eye was 52 degrees diagonal. The head-mounted display (HMD) presented biocular images, meaning that the left and right screens displayed identical images to the left and right eyes rather than presenting different images to each eye, as in a stereoscopic pair.[1] These images were viewed through collimating lenses that allowed the observer's eyes to focus at optical infinity. The screen refreshed at 60 Hz, and frame rate was 10–15 frames/s,

1. Stereoscopic viewing provides disparity cues in near space that could potentially improve velocity estimates in some virtual worlds. We were able to test the effect of stereoscopic viewing on speed matching in our environment, because the display software was recently modified to support stereoscopic viewing. Following the design of Experiment 1, 10 participants made speed estimates under stereoscopic and biocular viewing conditions during straight-ahead gaze. The mean matching speeds were 4.9 mph for stereoscopic and 5.2 mph for biocular viewing. A paired $t$ test showed that these means were not statistically different from each other ($p = 0.42$), suggesting that stereoscopic viewing does not make speed matching more accurate in this particular virtual environment.

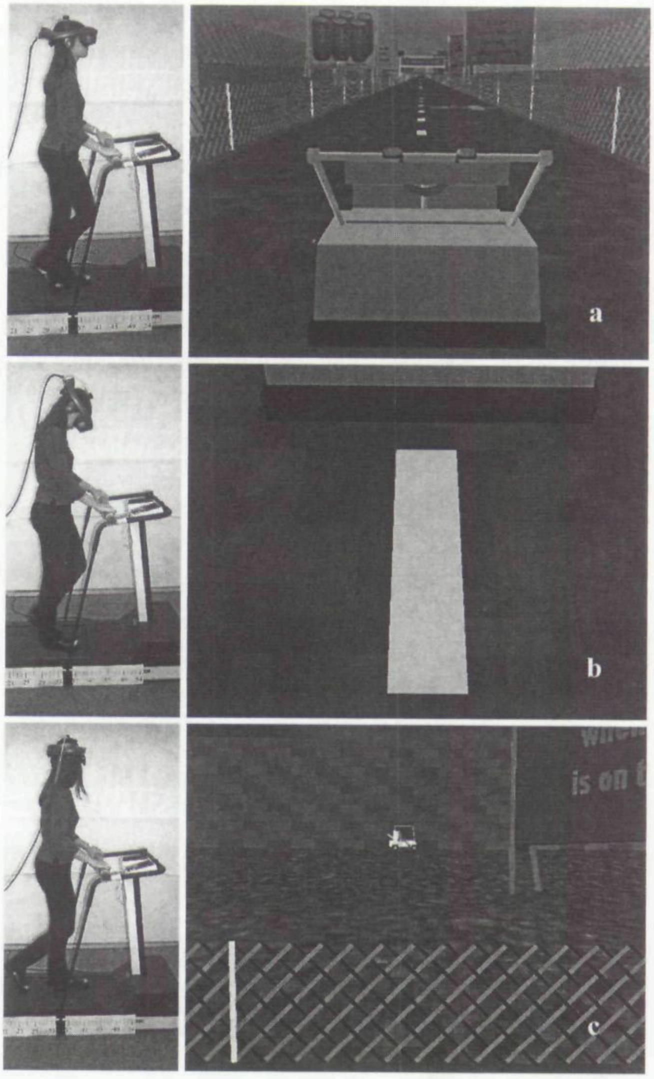


**Figure 1.** *Participants walked on a treadmill and viewed optic flow in a head-mounted display. Black and white depictions of the full-color virtual environment seen by the participant are shown for (a) straight-ahead gaze, (b) downward gaze, and (c) leftward gaze.*

depending on scene complexity. A computer registered 6 degrees of freedom of the HMD (position and orientation) through an Ascension SpacePad magnetic tracker. The computer used this position and orientation information to update the scene appropriately. The end-to-end latency of the system, which was calculated with the pendulum method described by Liang, Shaw, and Green (1991), was approximately 100 ms. End-to-end latency is the length of time it takes the tracking system to sense the HMD position and orientation changes caused by the observer's head movements and then update the scene in the HMD.

In the HMD, participants viewed a computer-graphics rendering of a highway (described in the next section). The virtual environment was designed and created using Alice98, a 3D computer-graphics authoring program (Conway et al., 2000). Program execution, rendering, and tracking were done by a PC computer with an Intel Pentium II processor, the Microsoft Windows 98 operating system, 128 MB RAM, and an ATI Rage Pro Turbo graphics card. Calibration indicated that tracker resolution was +/−1.85 mm or better in each of the $x$, $y$, and $z$ dimensions.

**2.1.3 Stimuli.** Walking was simulated using both visual and motor stimulation. Motor stimulation consisted of walking on the treadmill at a speed of 3 mph. Visual stimulation was displayed in the HMD using a virtual environment consisting of a highway with billboards and various landmarks along the sides (Figure 1). The participant's viewpoint was from a standing position in the middle of the road. Vertical tracking was corrected for the height of the treadmill bed (14 cm) so that the eye height of each participant was modeled correctly during simulation. The horizon was 0.2 degrees below eye height. Directly in front of the participant was a model of a golf cart (Figure 1a). The handrail on the back of the golf cart was in registration with the treadmill handrail, so that the act of gripping a handrail was modeled in the virtual environment. Familiar size cues were available from the highway, fencing, golf cart, and billboards. One object (a set of giant dice) was not in scale with the rest of the virtual environment. Although familiar size can influence the perception of object speed (Distler, Gegenfurtner, van Veen, & Hawken, 2000) and might conceivably influence the perception of one's own speed as well, the dice appeared early in the walking task and were quickly behind the participant and unavailable for reference. Shadows were not modeled in this environment.

As participants walked on the treadmill, the synthetic camera moved through the virtual environment at a speed that was independent of the walking speed. The orientation of the camera matched the participant's direction of gaze as determined by the head tracker.

**2.1.4 Design.** A method of limits was used to find the point where walking speed and optic-flow speed were perceived to be equal. Most participants accomplished this as part of an experiment in which they also walked in place for 20 s prior to treadmill walking. Due to procedural changes, 7 participants did not walk in place before treadmill walking. Because walking in place was not expected to influence speed estimation and the means of the two groups were fairly similar, the data were treated as a single set in all subsequent analyses.

**2.1.5 Procedure.** To reduce cues to the real environment, participants were led into a darkened testing room while blindfolded and wearing earplugs. Participants involved in the adaptation experiment walked in place for 20 s. All participants were then positioned on the treadmill and the blindfold was immediately replaced with the HMD so that they never saw the testing room. While holding the treadmill rail, they were encouraged to look around and familiarize themselves with the new environment. After a minute or two of familiarization, participants were asked to look forward (Figure 1a). The treadmill and flow speeds were simultaneously stepped to 3.0 mph. The participants' task was to report if the speed of optic flow should be faster or slower to match their walking speed. Optic flow was adjusted in 0.5 mph increments, and responses were obtained at each increment until two response reversals were obtained (e.g., slower to faster and faster to slower). The average of the two reversal speeds was taken as the speed of optic flow that perceptually matched participants' walking speed.

**2.1.6 Results and Discussion.** On average, participants perceived that the fixed treadmill speed (3 mph) best matched an optic flow speed of 4.6 mph (Figure 2). This is significantly faster than the geometrically correct optic flow of 3 mph ($t(29) = 6.159$, $p < .001$). Thus, straight-ahead optic flow in the HMD

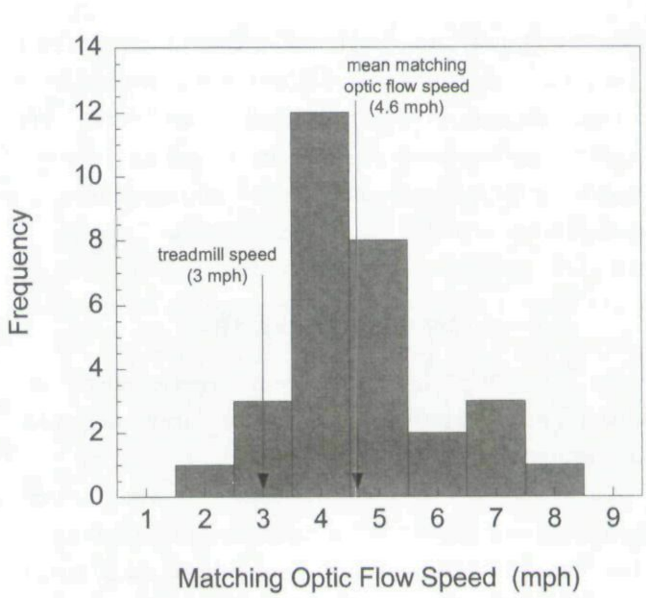


**Figure 2.** *The distribution of participants' speed matches.*

is perceived to be slower than an equivalent walking speed on the treadmill. The cause of this misperception is the subject of the next two experiments.

## 3 Experiment 2: Is the Misperception of Speed Related to the Optic-Flow Simulation?

Optic flow during forward walking with straight-ahead gaze consists of expansion from a central point yielding radial flow in central vision and lamellar flow in the periphery (Gibson, 1979). The lamellar component of the optic-flow field is known to be important in the perception of self-motion (Stoffregen, 1986). Because the HMD field of view in Experiment 1 was about one third of the natural field of vision, the restriction of lamellar flow by the HMD could conceivably alter one's perception of speed.

To test this idea, we increased exposure to lamellar flow by asking participants wearing the HMD to gaze downward or 90 degrees to the left while matching optic flow to walking speed. Under these conditions, participants were maximally exposed to lamellar flow. We predicted that speed matches should become more accurate if the lamellar flow lost during forward viewing in the HMD was critical for making speed estimates. We found that optic flow was accurately matched to walking speed when lamellar flow was restored through downward gaze (Experiment 2a) or leftward gaze (Experiment 2b).

### 3.1 Experiment 2a: Method

**3.1.1 Participants.** Nine undergraduates (4 female, 5 male) at the University of Virginia participated in the experiment. All had normal or corrected-to-normal vision and were shorter than 6′1″. They participated to obtain credit in an introductory psychology class. Informed consent was obtained from each participant prior to testing.

**3.1.2 Apparatus.** The apparatus was the same as in Experiment 1.

**3.1.3 Stimuli.** The stimuli were the same as in Experiment 1. In one condition however, the golf cart was removed from the virtual environment.

**3.1.4 Design.** Each participant used the method of limits to match optic-flow speed to three treadmill speeds (1, 2, 3 mph). They did this for two gaze directions (straight ahead, downward), and two visual worlds (golf cart present, golf cart absent). Presentation of the conditions was counterbalanced. The initial flow speed was randomly chosen from the set of 0.5, 1, 2, 3, and 4 mph.

Two visual worlds were tested because when participants looked downward, the golf cart might occlude enough of the lamellar flow information to have an impact on perceived speed. The condition without the golf cart maximized lamellar flow during downward gaze.

**3.1.5 Procedure.** To reduce cues to the real environment, participants were led into a darkened testing room while blindfolded and wearing earplugs. They were then positioned on the treadmill, and the blindfold was immediately replaced with an HMD so that they never saw the testing room. While holding the treadmill rail, participants were encouraged to look around and familiarize themselves with the new environment. After a minute or two of familiarization, participants were asked to look forward as the treadmill and flow speeds were simultaneously stepped to the initial speed (1, 2, or 3 mph; randomly selected). They were then asked to look downward or to continue to look straight ahead. To help them maintain proper gaze during downward looking, participants were asked to watch the highway texture as it emerged from beneath the golf cart in front of them (Figure 1b). This provided a consistent gaze location slightly in front of their feet and prevented the participant from noticing that their legs were not modeled in the environment. The task was to report if the speed of optic flow should be faster or slower to match their walking speed. Optic flow was adjusted in 0.5 mph increments, and responses were obtained at each increment until two response reversals were obtained (e.g., slower to faster and faster to slower). The average of the two reversal speeds was taken as the speed of optic flow that perceptually matched participants' walking speed.

### 3.2 Experiment 2a: Results and Discussion

The manipulation of the visual world (golf cart vs no golf cart) had no effect on optic-flow matches ($p = 0.10$), so the data were collapsed across the "cart" and "no cart" conditions in subsequent analyses.

In a 2 (gaze) × 3 (speed) repeated measures analysis of variance (ANOVA), the direction of gaze influenced the perceived matching speed. Matches made during straight-ahead gaze were different from those made during down gaze ($F(1,8) = 15.056$, $p = .005$). As seen in Figure 3, the speed of participants' optic-flow matches did not differ from their walking speed when they looked down, but did differ when they looked straight ahead. This is consistent with the prediction that speed perception should be more accurate when lamellar flow is available.

Finally, there was a significant interaction between the direction of gaze and the treadmill speed ($F(1,8) = 3.985$, $p = .005$). This indicates that one's own speed is

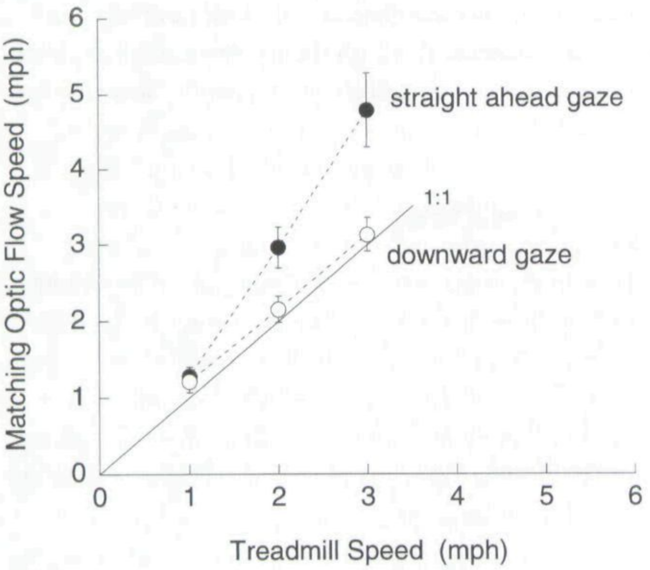


**Figure 3.** *The speed of optic flow in the HMD believed to match the treadmill walking speed during straight-ahead gaze and downward gaze. The matches are accurate during downward gaze.*

most likely to be misperceived as one walks faster (Figure 3).

### 3.3 Experiment 2b: Method

**3.3.1 Participants.** Nine undergraduates (4 female, 5 male) at the University of Virginia participated in the experiment. All had normal or corrected-to-normal vision and were shorter than 6′1″. They participated to obtain credit in an introductory psychology class. Informed consent was obtained from each participant prior to testing.

**3.3.2 Apparatus.** The apparatus was the same as in Experiment 1.

**3.3.3 Stimuli.** The stimuli were the same as in Experiment 1, except a second golf cart was added in the distance, 90 degrees to the left of the observer (Figure 1c). The additional cart traveled in the same direction and at the same speed as the golf cart directly in front of the participant.

**3.3.4 Design.** Participants used the method of limits to match optic-flow speed to three treadmill speeds (1, 2, 3 mph) during two gaze directions (straight ahead, 90 degrees left). The conditions were counterbalanced.

**3.3.5 Procedure.** To reduce cues to the real environment, participants were led into a darkened testing room while blindfolded and wearing earplugs. They were then positioned on the treadmill, and the blindfold was immediately replaced with an HMD so that they never saw the testing room. While holding the treadmill rail, participants were encouraged to look around and familiarize themselves with the new environment. After a minute or two of familiarization, participants were asked to look forward as the treadmill and flow field were simultaneously stepped to the initial speed. They were then asked to look 90 degrees to the left or to continue to look straight ahead. To help them maintain proper gaze direction during leftward looking, participants were instructed to always watch the golf cart to their left (Figure 1c). The task was to report if the speed of optic flow should be faster or slower to match their walking speed. Optic flow was adjusted in 0.5 mph increments, and responses were obtained at each increment until two response reversals were obtained (e.g., slower to faster and faster to slower). The average of the two reversal speeds was taken as the speed of optic flow that perceptually matched participants' walking speed.

### 3.4 Experiment 2b: Results and Discussion

In a 2 (gaze) × 3 (speed) repeated measures ANOVA, the direction of gaze again influenced the perceived matching speed (Figure 4). Matches made during straight-ahead gaze were different from those made during leftward gaze ($F(1,8) = 7.245$, $p = .027$). Participants' optic-flow matches did not differ from their walking speed when they looked leftward ($p = .503$), but did differ when they looked straight ahead ($F(1,8) = 10.786$, $p = 0.011$). Accurate speed matching on side gaze was unlikely to stem from the motion of the distant golf cart because, in Experiment 2a, removal of the cart

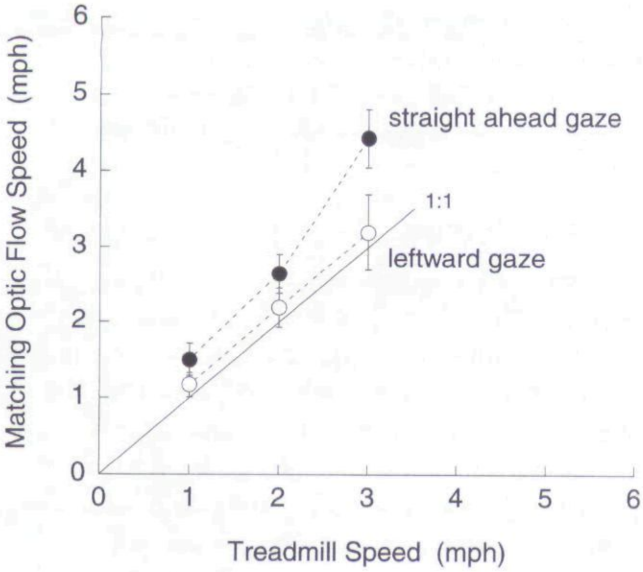


**Figure 4.** *The speed of optic flow in the HMD believed to match the treadmill walking speed during straight-ahead gaze and leftward gaze. The matches are accurate during leftward gaze.*

had no effect on perceived speed. Because lamellar flow was greater on side gaze, the result is consistent with the prediction that speed perception should be more accurate when lamellar flow consistent with self-motion is available.

Again, there was a significant interaction of gaze × speed ($F(1,8) = 4.563$, $p = 0.027$). This indicates that one's own speed is most likely to be misperceived as one walks faster (Figure 4).

## 4 Experiment 3: Is the Misperception of Speed Caused by the Walking Simulation?

In Experiment 2, we argued that our findings were not particular to treadmill walking, because the treadmill characteristics did not change with gaze position. Nevertheless, it might be possible that when participants changed their head position to look down or to the side, their stride changed in a way that induced a misperception of speed. Experiment 3 investigated this possibility by measuring the magnitude of the illusion for small step sizes. We predicted that stride length would not affect the illusion, and would provide converging evidence with Experiment 2 that the miscalibration was not due to changes in treadmill walking characteristics.

### 4.1 Method

**4.1.1 Participants.** Ten undergraduates (5 female, 5 male) at the University of Virginia participated in the experiment. All had normal or corrected-to-normal vision and were shorter than 6′1″. They participated to obtain credit in an introductory psychology class. Informed consent was obtained from each participant prior to testing.

**4.1.2 Apparatus and Stimuli.** These are identical to those in Experiment 1.

**4.1.3 Design.** We used a within-subjects design consisting of three randomized treadmill speeds (1, 2, and 3 mph) by two counterbalanced step sizes (normal walking and *baby steps*). In each condition, a method of limits was used to find the point where treadmill speed and optic-flow speed were perceived to be equal.

**4.1.4 Procedure.** The procedure was the same as in Experiment 1, with the exception that participants' feet were filmed so that stride length could be measured relative to the ruler on the side of the treadmill. For each participant, 10 normal steps and 10 baby steps were measured at a treadmill speed of 3 mph, the most difficult condition in which to take baby steps.

### 4.2 Results and Discussion

Participants' baby steps were smaller than normal strides. Mean step lengths and standard errors were 55.4 +/− 0.42 cm for baby steps and 63.4 +/− 0.47 cm for normal walking. Moreover, individual *t* tests confirmed that each participant's baby steps were significantly smaller than their normal stride length.

Step size did not affect perceived speed. In a 2 (step size) × 3 (speed) repeated measures ANOVA, there was no main effect of step type ($p = 0.073$), and there was no

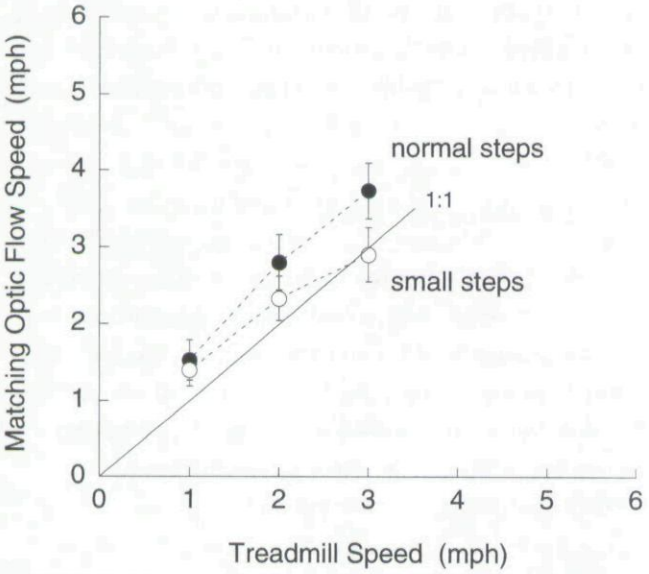


**Figure 5.** *The speed of optic flow in the HMD believed to match the speed of treadmill walking for a normal stride length and a smaller stride length.*

interaction between step type and treadmill speed ($p$ = 0.176). Although small steps slightly reduced perceived speed at 3 mph (Figure 5), the nonsignificant change is in the wrong direction. In theory, small strides should increase the deviation from a perfect visual-motor match, but in practice, small strides improved the matches slightly. Thus, deviations from a natural stride, induced by treadmill walking or head turning, are unlikely to account for the misperception of speed in our simulation.

## 5 Experiment 4: Is the Misperception of Speed Caused by Image Jitter?

Image jitter increases with walking speed, due to HMD instability with increased movement on the treadmill. Jitter could contribute to the misperception of speed by elevating motion-detection thresholds and increasing latencies (Probst, Brandt, & Degner, 1986). This would be most problematic during straight-ahead gaze, where optic flow is slowly expanding and difficult to detect. On side or down gaze, where lamellar flow speeds are well above motion-detection thresholds, speed perception may be relatively unaffected by image jitter. Because the results of Experiments 1–3 are consistent with this hypothesis, HMD jitter was manipulated in Experiment 4 to determine if jitter had an effect on perceived speed.

### 5.1 Method

**5.1.1 Participants.** Eight students (4 female, 4 male) at the University of Virginia participated in the experiment. All had normal or corrected-to-normal vision and were shorter than 6′1″. They participated as volunteers or to obtain credit in an introductory psychology class. Informed consent was obtained from each participant prior to testing. Some of the participants had previous experience estimating speed in virtual environments, but none was aware of the purpose of the experiment.

**5.1.2 Apparatus and Stimuli.** The apparatus and stimuli were identical to those used in Experiment 1, but only the 3-mph treadmill speed was used. To eliminate HMD jitter, the head-tracking sensor was turned off.

**5.1.3 Design.** A within-subjects design consisting of two counterbalanced jitter levels (head tracking and no head tracking) was used. In each condition, a method of limits was used to find the point where treadmill speed and optic-flow speed were perceived to be equal during forward gaze.

**5.1.4 Procedure.** The procedure was the same as in Experiment 1.

### 5.2 Results and Discussion

HMD jitter was not responsible for the misperception of walking speed, because speed was similarly misperceived in the presence and absence of jitter. Mean matching speeds were 4.31 mph with head tracking and 4.69 mph without, and a paired $t$ test showed that the conditions were not statistically different from each other ($p$ = 0.496). The lack of a jitter effect is consistent with the results of walking simulations using rearprojection displays, where HMD-induced jitter is absent yet speed is similarly misperceived (Distler, Pelah, Bell, & Thurrell, 1998; Thurrell et al., 1998; Pelah & Thurrell, 2001; Pelah, Thurrell, & Berry, 2002; Thurrell & Pelah, 2002). Perhaps the misperception of speed is not tied to the HMD, stemming instead from jitter due to treadmill walking. However, Pelah et. al. (2002) reduced head jitter with a bite-bar and found no change in the perception of walking speed. Thus, there is no evidence to suggest that image jitter from any source can account for the misperception of speed during walking simulation. Jitter can detract from an immersive experience however, since many (but not all) participants felt that the nontracked condition was more natural than the head-tracked condition.

## 6 General Discussion

In these experiments, the speed of simulated self-motion was misperceived at fast walking speeds during straight-ahead gaze. Under these conditions, participants perceived their visually specified speed of motion to be too slow for their walking speed. What caused the misperception of speed in our geometrically correct walking simulation? We believe that a lack of lamellar optic flow was primarily responsible.

### 6.1 Lamellar Optic Flow

We believe that speed was misperceived during straight-ahead gaze partly because lamellar optic flow, characteristic of the periphery, was restricted by the HMD. Van Veen et al. (1998) demonstrated in a bicycling simulation that perceived cycling speed depended on the peripheral field of view. Cycling speed was underestimated with a field of view smaller than 73 degrees, was accurate at 73 degrees, and was slightly overestimated with fields of 103 degrees and larger. Osaka (1988) showed that perceived driving speed decreased as field of view decreased from 55 degrees to 3 degrees. Similarly, Segawa, Ujike, Okajima, and Saida (2003) reported that the perceived speed of motion in a simulated tunnel gradually declines as the stimulus area is reduced from 100% to 5%.

Simulated-walking studies appear to be consistent with these findings. Our field of view was 54 degrees, and a 3-mph walking speed was perceived to be about 50% slower than normal during straight-ahead gaze. Thurrell and colleagues (Thurrell et al., 1998; Thurrell & Pelah, 2002) projected optic flow subtending 90 degrees horizontally onto a screen in front of the observer, thus increasing lamellar flow. In their studies, a 3-mph walking speed was perceived to be only 20% slower than normal. Returning to the present study, when lamellar flow was maximized by using downward or sideways gaze (Experiment 2), a 3-mph walking speed was accurately perceived. Thus, perception of walking speed improves as lamellar flow increases. Other functions such as estimates of time to contact (Cavallo, Laya, & Laurent, 1986; Groeger & Brown, 1988), and simulated-flight accuracy (Irish, Grunzke, Gray, & Waters, 1977) also improve as the field of view (and thus the amount of lamellar flow) increases.

On the other hand, it might be argued that our results stemmed from a decrease in peripheral retinal stimulation, rather than a decrease in lamellar flow. Two pieces of evidence suggest that the misperception of speed during simulated walking is not simply related to reduced peripheral retinal stimulation: (1) the shift from straight-ahead to downward or sideways gaze during simulation maintained the field of view yet altered speed perception (Experiment 2); and (2) Wolpert (1990) experimentally disambiguated retinal locus from type of optic flow in a flight simulation, and found that the type of optic flow best predicted performance accuracy.

The key to perceiving speed accurately in the presence of lamellar flow may be the flow-field velocity: During forward locomotion, the angular velocity of optic flow in the periphery is much greater than in the frontal field (Gordon & Michaels, 1965). Faster speeds should be easier to sense, thus making it easier to estimate speed of self-motion when optic flow is available to the side (Salvatore, 1967). Consistent with this idea, Durgin and Kearns (2002) showed that as the walls of a virtual corridor were moved closer to the participant, their perceived walking speed increased and thus became more accurate. In the present studies, the use of a more open virtual environment and a slightly smaller field of view reduced the fast peripheral lamellar flow and made speed matching less accurate.

### 6.2 Distance Compression

During self-motion, the angular retinal velocities of objects in the optic-flow field are inversely related to their distance from the perceiver. Therefore, misperception of simulated distance might result in misperception of simulated speed.

Previous work shows that distance is often underestimated in both natural (Baird & Biersdorf, 1967; DaSilva, 1985) and virtual (Witmer & Kline, 1998; Witmer & Sadowski, 1998; Loomis & Knapp, 2003; Thompson et al., 2004) environments. In these studies, perceived distance is a linear or slightly compressive function of physical distance. A compressed function is one in which apparent distance is related to a power of actual distance with the exponent being less than 1.

At face value, our speed data are not underestimated in this way. For short viewing distances, such as those occurring during downward gaze (Experiment 2a), speed estimates were relatively accurate. However, at long viewing distances, the data were mixed: Straight-ahead gaze toward the horizon (Experiment 1) resulted in speed compression on the order of 64% (3 mph/4.7 mph), while side gaze toward a distant target (Experiment 2b) yielded accurate speed matches.

Our results could follow a compressive function of distance if, on side gaze, the optic flow from foreground objects inadvertently dominated participants' speed estimates. For instance, one might argue that optic flow from the virtual fence in the foreground drove the speed estimate rather than motion from distant objects where attention was directed. If so, our experiments would suggest that perceived speed is accurate at near distances but is underestimated at longer distances. This is consistent with the work of Durgin and Kearns (2002), which showed that speed estimates made during simulated walking become more accurate as the width of a virtual corridor is narrowed. It is also qualitatively consistent with the distance-compression hypothesis.

Despite the qualitative agreement between distance and speed compression, it is speculative to assume that the two are related. Recall that to take the putative relationship this far, we assumed that perceived speed is derived from perceived distance, that the relationship between the two is geometrically consistent, and that foreground motion dominates speed perception on side gaze. Even if these prove to be true, there are still incongruities between perceived speed and perceived distance in virtual environments. For example, at short distances, perceived speed in our study was accurate but perceived distance in previous studies was significantly underestimated by verbal report (Witmer & Kline, 1998; Witmer & Sadowski, 1998). In addition, it is difficult to make comparisons between perceived speed and distance across existing studies because of potential effects due to the specifics of the modeled environments, the available field of view of the HMDs, or the methodologies. Note that Loomis and Knapp (2003) report accurate distance perception at short range when participants are asked to walk the perceived distance rather than report it verbally. Finally, it is possible that apparent distance and apparent speed are not causally related, but both are influenced by a common compressive factor evoked in virtual reality. Clearly, additional studies that map both perceived distance and perceived speed in a virtual environment are needed in order to assess the feasibility of the distance-compression hypothesis.

### 6.3 Spatial Image Characteristics

Perceived speed is known to be reduced under conditions of low contrast and low spatial frequency (Stone & Thompson, 1992; Distler & Bulthoff, 1996; Snowden, Stimpson, & Ruddle, 1998). If the straight-ahead view in our experiment were of lower contrast and spatial frequency than the downward and sideways views, then spatial frequency and contrast could account for the reduction in perceived speed with straight-ahead gaze. This seemed unlikely from visual inspection of the images in Figure 1, because the down-gaze image appeared to have the lowest contrast and spatial-frequency content. Nevertheless, we analyzed spatial-frequency content by calculating 2D fast fourier transforms (FFTs) of the images in Figure 1. The FFTs confirmed that the down-gaze image was richest in low-frequency content. Furthermore, the luminance ranges of these images indicated that the straight-ahead image could support higher luminance contrasts than the other images. These results are inconsistent with the hypothesis that lower image contrast and spatial frequency account for a reduction of perceived speed during straight-ahead gaze.

### 6.4 Incomplete Self-Motion Simulation

Several sources of information help to specify self-motion, including optic flow (Gibson, 1979), acoustic flow (Rosenblum, Carello, & Pastore, 1987), proprioception (Harris et al., 2002), and vestibular input (Harris, Jenkin, & Zitovitz, 2000). However, the full complement of cues is rarely modeled in a virtual environment, even though incompletely specifying the set of self-motion cues can lead to erroneous perception in both natural and simulated environments (Evans, 1970; Groeger and Brown, 1988; Harris et al., 2002). Nevertheless, we have shown that accurate estimates of constant speed can be obtained using only vision and proprioception if the direction of gaze is appropriate. Therefore, a complete set of sensory information is not always necessary for accurate speed perception during treadmill walking, although the additional cues may improve other aspects of self-motion perception.

## 7 Conclusions

In simulations where accurate speed of self-motion is critical, the present experiments suggest that it is important to ensure that lamellar optical flow is available. The best way to do this is to provide a wide field of view, thus preserving the flow gradient from central expansion to peripheral lamellar flow.

Since hardware constraints can preclude the use of wide fields, narrow-field solutions are sometimes necessary. Based on our findings, participants could look to the side to make lamellar flow available during speed-critical activities. However, participants are sometimes reluctant to turn their heads in an HMD (Pausch, Snoddy, Taylor, Watson, & Haseltine, 1996). Furthermore, some simulations, such as driving, are not conducive to having users look to the side. An alternative approach is to offset the misperception by adjusting the speed of optic flow during simulation. This approach has the advantage that the speed of simulated optic flow could be dynamically linked to head position, allowing perceived speed matches in all gaze positions in the virtual environment.

## Acknowledgments

This research was supported by NSF ITR/Carnegie Mellon Grant 0121629, and ONR Grant N000140110060, to Dennis Proffitt.

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