Investigations on the Interactions Between Vision and Locomotion Using a Treadmill Virtual Environment

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ABSTRACT

Treadmill-based virtual environments have the potential to allow near natural locomotion through large-scale simulated spaces. To be effective, such devices need to provide users with visual and biomechanical sensations of walking that are sufficiently accurate to evoke perception-action couplings comparable to those occurring in the real world. We are exploring this problem using a custom built, computer controlled treadmill with a 6' by 10' walking surface, coupled to computer graphics presented on wide field-of-view back projection screens. The system has the added feature of being able to apply forces to the user to simulate walking on slopes and the effects of changes in walking speed. We have demonstrated the effectiveness of this system by showing that the perceptual-motor calibration of human locomotion in the real world can be altered by prior walking on the treadmill virtual environment when the visual flow associated with self-motion is mismatched relative to biomechanical walking speed. The perceptual-motor coupling that we have achieved is sufficient to allow investigation of a number of open questions, including the effect of walking on slopes on the visual estimation of slant and visual influences on gait and walking speed.

Keywords: treadmill virtual environments, locomotion, visual self-motion

1. INTRODUCTION

People naturally walk through the complex real world while maintaining spatial orientation in an effective manner. Simulated travel through virtual worlds using current computer interfaces is far less easy. Physical locomotion through an environment assists in keeping track of where you are in the environment and where other locations are with respect to your own position.[1, 2] Our ultimate goal is to exploit this effect to construct *locomotion interfaces* allowing self-propulsion through simulated spaces in a manner that helps optimize perception when people explore virtual environments (VEs). The availability of such devices could impact a broad range of applications, including education and training, design and prototyping, physical fitness, and rehabilitation. For some of these applications, natural walking provides a level of realism not obtainable if movement through the simulated world is controlled by devices such as a joystick or limited due to a small tracking space. For other applications, realistic walking is a fundamental requirement.

There are two basic options available for the construction of locomotion interfaces. One approach is to allow natural walking within a tracked space, with the visual display updated to reflect changes in eye position. The most common example of this approach is a head-mounted display (HMD), though very limited movement is possible in CAVE displays which utilize multiple, back-projected video screens partially or completely surrounding the user. Natural walking through a tracked space provides accurate biomechanical and vestibular stimuli, at least for level surfaces. Tracked spaces, however, are not practical for simulating realistic locomotion over ranges greater than a few 10s of meters. The second approach to the construction of locomotion interfaces involves devices in which a walking surface is moved in such a manner that a person can perform the biomechanical actions of walking without actually moving a substantial distance in the real world. Treadmill-based devices are the most common of these, though a number of more exotic technologies have also been demonstrated.[3–5] The biggest limitation of moving walking surface interfaces is that they cannot accurately generate vestibular stimuli or the biomechanical inertial forces associated with acceleration and turning.

Most previous research involving treadmill-based virtual environments used exercise treadmills coupled with either head-mounted displays or fixed video displays of limited extent. The results described below utilized the Sarcos Treadport at the University of Utah,[6] a system supporting both more natural walking and running and a substantially more visually

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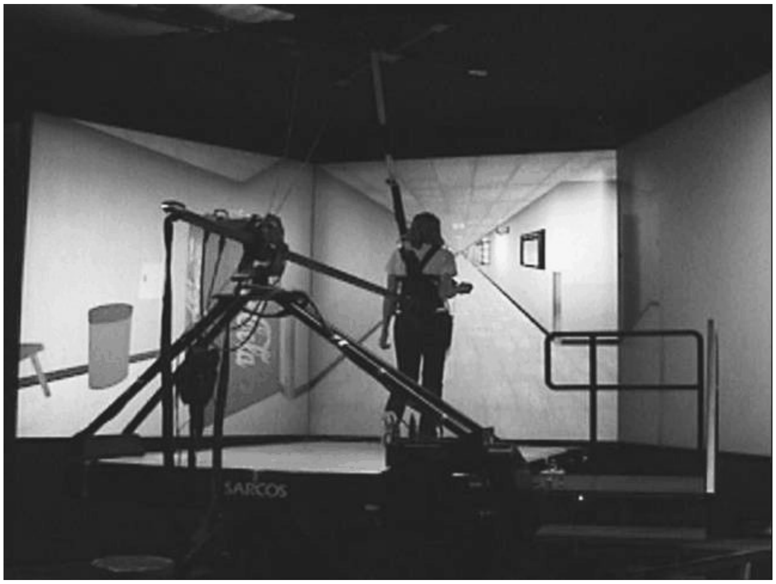

Figure 1. Sarcos Treadport virtual environment.

immersive experience (Figure 1). The Treadport uses a 6' by 10' walking surface, surrounded by three 8' by 8' projection screens, fixtured in borderless mounts and oriented to provide an approximately 180° horizontal field of view. The viewing distance to each of the three screens is approximately 2 meters. Extensive light shielding is used to minimize the visibility of the treadmill and other items in the laboratory, though the belt and frame of the treadmill are clearly visible to someone walking on the Treadport. Only non-stereo visual display is currently supported. A PC cluster is used to generate the visuals, with rendering frame rates ≥ 30 fps at all times. Users are able to walk or run at a speed of their choosing, with the speed of the treadmill belt automatically adjusting as needed, or the speed of the belt can be set under computer control. They wear a harness to which is attached a safety strap in case of a fall. The harness is also connected to a mechanical rod which is used to provide position sensing for establishing the correct viewpoint for the graphics and for situations in which locomotion speed is under user control. This mechanical connection to the harness can also be used to apply forces to the user to simulate the biomechanical inertial effects of acceleration and deceleration, though vestibular information is not correct. The mechanism for applying forces can also be used to simulate walking up and down slopes. In addition, the treadmill surface can be dynamically tilted under computer control to simulate slanted surfaces.

Locomotion interfaces are intended to allow natural interactions with a virtual world. As a result, it is essential that perception/action couplings in such devices operate in a manner similar to the real world. Effective locomotion interfaces can therefore also serve as a tool for better understanding the interaction between real world vision and locomotion in humans, since they can facilitate experimental manipulations that would be difficult or impossible to perform in another manner. In this paper, we start by showing that the perception/action recalibration associated with mismatches between mechanical and visual speed occurs with the Treadport. We then describe a serious of investigations aimed at better understanding the interaction between visual motion and locomotion, including differentiating between optic flow and visual information for speed in terms of their influence on calibration, the influence of visual motion on gait transitions and natural walking speed, and the influence of locomotion on visual slant perception.

Previous investigations of perception/action coupling in treadmill VE systems have been relatively limited. One of the first perceptual studies carried out in a treadmill VE studied distance perception.[7] Subjects performed actions both in the real world and in the treadmill VE and it was shown that VE distance judgments were compressed more than in the real world. It has also been shown that postural sway[8] and entrainment of the step cycle to the visual display can be induced in a treadmill VE.[9] More recently, the subjective comparison of the visual speed of graphics with walking speed has been explored in a treadmill VE.[10] In this study it was observed that the visual speed of the optic flow appeared to be too slow during simulated locomotion on a treadmill. Others have proposed that a percentage of locomotor speed is subtracted from the visual speed during treadmill locomotion.[11]

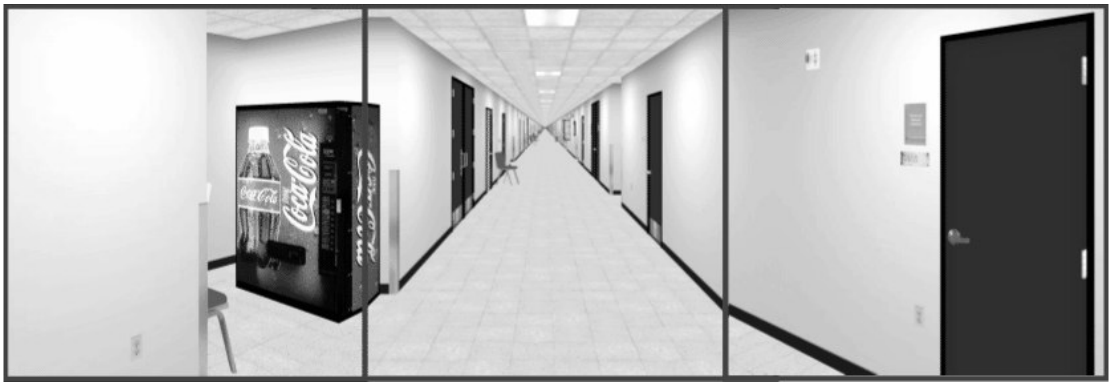

Figure 2. Endless hallway displayed on three screens.

2. PERCEPTION/ACTION CALIBRATION IN A TREADMILL-BASED VE

Perceptually guided actions require that the appropriate scaling be maintained between visual and proprioceptive information about body movements. Rieser et al. demonstrated that this scaling is adaptive and that recalibration can occur rapidly as a result of changing circumstances as a person interacts with the world.[12] The first study that we present replicates this effect on the Treadport.

2.1. Background

The methodology used by Rieser et al. involved a test of subjects walking without vision to a previously viewed target before and after an adaptation period with vision. Numerous studies have found this *blind walking* task under normal circumstances to reveal accurate distance perception from a range of 2 to 20 meters.[13, 14] The manipulation used in Rieser et al. included an adaptation phase in which subjects walked on a treadmill while experiencing visual flow consistent with either faster or slower self motion than the walking speed on the treadmill belt. The experimental apparatus consisted of an exercise treadmill towed on a trailer behind a tractor, thus allowing control of a subjects motion through the world to be independent of walking speed. Subjects who experienced visual flow that was slower than their speed of walking overshot the distance to the target in the blind walking post-test, relative to their performance on the pre-test. Those who experienced visual flow as faster than their speed of walking showed an undershoot in the post-test relative to the pretest. Rieser et al. suggested that observers maintained awareness of the previously viewed target and its surroundings and dynamically updated the representation of the target location with their own self-motion, even when walking without visual feedback. They account for the difference in blind walking performance before and after the treadmill intervention as a recalibration of this updating process.

Durgin et al. replicated this recalibration effect using a head mounted display (HMD).[15] Subjects were divided into two groups, one of which did pre- and post-testing using blind walking to targets presented using the HMD and the other using verbal reports to targets presented using the HMD. The adaptation phase consisted of walking up and down a hallway while wearing the HMD, with visual flow adjusted to be either double or half actual walking speed. Verbal distance judgments were not altered reliably by the VE adaptation, while blind walking was affected in the same directions as for Rieser et al., though by a larger magnitude.

2.2. Methodology

Our version of the Rieser et al. experiment involved simulated walking down an “endless” hallway in our engineering building (Figure 2). Belt speed, and hence biomechanical walking speed, was fixed at 1.0 m/s. The visuals were updated to simulate either 2.0x faster or 0.5x slower movement down the hallway. Since we wanted to know if recalibration due to Treadport walking was general enough to transfer to the real world, pre and post test blind walking was done in an actual hallway adjacent to the Treadport.

Twenty-four subjects (eight in each condition) participated in the experiment. All were tested to ensure that they had normal or corrected-to-normal vision, and their eye-height was measured. Each subject was given practice walking without vision in the real world for five minutes. This procedure helped to increase trust between the subject and the experimenter

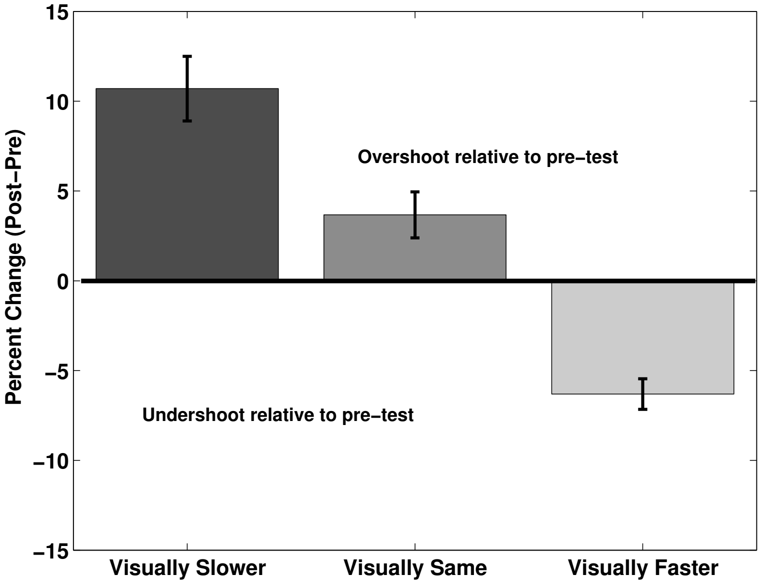

Figure 3. Recalibration Results. Error bars represent one SE.

and allowed the subject to become more familiar with the experience of walking naturally without vision. Following the training session, subjects performed in pre-test, adaptation, and post-test phases of the experiment.

The pre-test involved walking without vision to previously viewed targets on the floor in a real hallway. The targets were placed at distances of six, eight and ten meters, each presented three times for a total of nine trials. The subjects viewed a target on the floor, were instructed to create a "good image" of the target and the surrounding environment, and then walked blindfolded with eyes closed to the target location. The adaptation phase involved walking on the Treadport for ten minutes while viewing the endless hallway with one of the following conditions: visually slower (the visual speed was 0.5× the walking speed), visually same (the visual speed was matched to the walking speed) or visually faster (the visual speed was 2.0× the walking speed). The walking speed was set at 1.0 m/s. Subjects performed the post-test immediately after the adaptation phase. They were walked back to the real world hallway (without vision) and performed the same blind walking task as in the pre-test. Post-test trials were presented with the same distances in the same order as the pre-test. In all trials (pre and post) subjects did not receive feedback about their walking accuracy.

2.3. Results and Discussion

When exposed to the visually faster condition, subjects undershot the distances in the post-test trials by an average of 6% relative to the pre-test. Given the visually slower condition, they overshot the distances in the post-trials by an average of 11%. In the visually same condition, subjects overshot by an average of 3% (see Figure 3). Paired t-tests confirmed a significant difference between the percent change between the pre- and post-tests for each condition (visually slower: $t(7) = 6.57, p < .01$; visually same: $t(7) = 4.34, p < .01$; visually faster: $t(7) = -4.92, p < .01$). A univariate ANOVA comparing the effect of visual condition on the post-pretest difference showed that there was a significant effect of visual condition, $F(2,23) = 43.7, p < .01$. Planned contrasts showed that the overshoot in the visually slower condition was reliably greater than the overshoot in the visually same condition (mean difference $= 7.1, SE = 1.83, p < .01$) and that the undershoot in the visually faster condition was reliably lower than the visually same condition (mean difference $= -10.0, SE = 1.83, p < .01$).

Our results show that a mismatch between visual flow of a VE and walking on a treadmill will recalibrate visually directed locomotion in the real world. The effects are similar to those found using real-world visual flow and treadmill walking. These results are consistent with the explanation that subjects spatially update their representation of the environment as a function of the learned relationship between visual flow and locomotor activity. There was a larger effect for the visually slower condition compared to the visually faster condition. This asymmetry is consistent with the small but significant overshoot found in the visually-same condition. There are several possible explanations for the visually-same

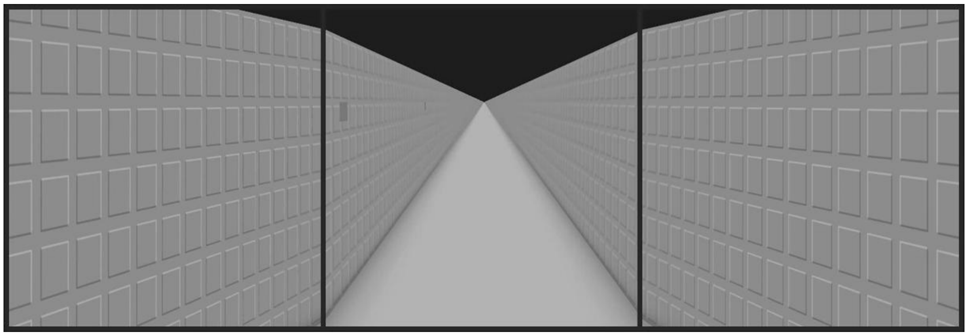

Figure 4. Smaller hallway, providing cues for faster self-motion. (In this and the subsequent figure, the perspective is set so that the hallway walls appear straight when viewed in the three wrap-around screens.)

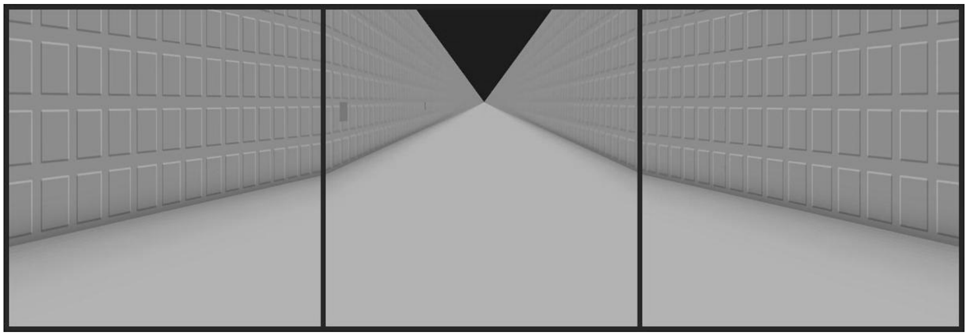

Figure 5. Larger hallway, providing cues for slower self-motion.

effect. It is possible that subjects perceptually compressed distances while viewing the endless hallway in the VE. A systematic underestimation in distance judgments has been found in numerous VE studies using head-mounted displays.[16, 17] Although we have not directly tested distance estimations in the treadmill VE, a compression of distance would be predicted to lead to an overshoot in blind walking, similar to the visually slower condition. A second possible explanation is the distinction between walking on a treadmill belt and walking on the real ground. On the treadmill, while the subject has information from their motor and visual systems that they are moving, they have conflicting vestibular and cognitive cues that they are staying in the same place.[18] If subjects were to calibrate to the perception of reduced self-motion, then we would also expect to find error in blind walking in the direction of the visually slower condition.

3. CALIBRATION OF LOCOMOTION: PERCEPTION OF SELF-MOTION OR MAGNITUDE OF OPTIC FLOW?

We have determined that the perceptual-motor calibration of human locomotion can be manipulated by exposure to a treadmill-based VE in which the visual flow associated with self-motion is altered relative to biomechanical walking speed. An open question remains as to whether this recalibration is based on perception of the speed of movement through the world or on the magnitude of optic flow itself. We are able to address this issue with our treadmill-based VE.

3.1. Methodology

As before, this experiment independently varied actual walking speed and the simulated visual experience of moving down a hallway. For this experiment, the hallway consisted of textured walls and textureless floor and ceiling, so that the visual flow information was only available from the walls. Subjects were exposed to one of two conditions. Actual walking speed was 1.2 m/s in both cases. In one condition, visual information corresponded to movement down a long hallway at a speed one third less than the biomechanical rate of walking (see Figure 4). In the second condition, the visual information corresponded to motion three times faster than the first condition down a hallway that was three times larger (see Figure 5). Because the scale of the space was increased by the same amount as the increase in velocity through

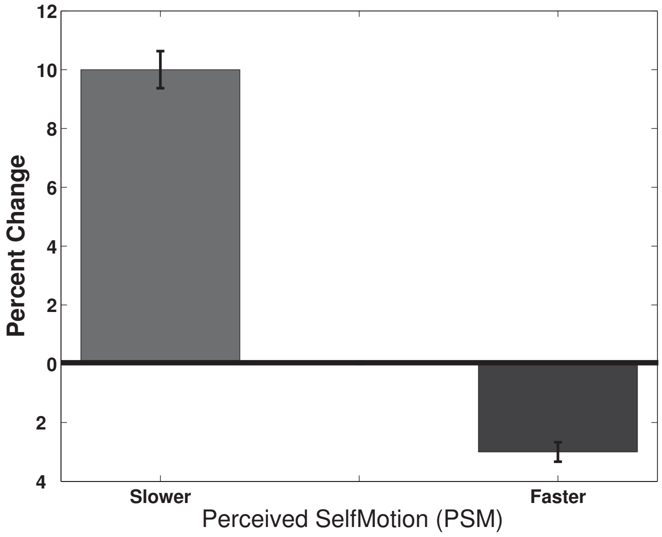

Figure 6. Perception of Self-Motion Results. Error bars represent one SE.

the space, the magnitude of optic flow remained essentially constant, though flow due to the walls moved upward in the visual field. In order to be sure that subjects were looking at the left and right screens we had subjects call out a number that appeared on small posters when in the center of the left and right screen. These posters were randomly ordered in colors of red, green, blue and had random numbers placed on them. The series of posters were the same for each subject. Perceptual-motor calibration was evaluated by having subjects walk blindfolded to previously viewed targets at 6, 8, 10m before and after 10 minutes of walking on the treadmill.

3.2. Results and Discussion

For the visually slower condition, subjects increased the distance they walked by an average of 10.1% between the pre and post tests. For the visually faster condition, subjects decreased the distance they walked by an average of 3.2% (see Figure 6). Paired t-tests confirmed a significant difference between the percent change between the pre- and post-tests for the two conditions(slower perceived self-motion: $t(7) = 7.32, p < .01$; faster perceived self-motion: $t(7) = 5.04, p < .01$). A univariate ANOVA comparing the effect of perceived self-motion on the post-pretest difference showed that there was a significant effect of perceived self-motion, $F(1,15) = 54.8, p < .01$. The overshoot in the slower perceived self-motion condition was reliably greater than the undershoot in the faster perceived self-motion condition (mean difference $= 13.3, SE = 1.48$). These differences demonstrate that the recalibration depended at least in part on visual perception of the speed of self-movement, not just on the magnitude of optic flow.

4. VISION AND THE HUMAN GAIT TRANSITION

The human gait transition from walking to running (Walk-Run) is made at approximately 2.1 m/s and from running to walking (Run-Walk) at approximately 1.85 m/s. Scientists from different disciplines have investigated why the transitions occur at these speeds. A common explanation is an energetic trigger, that a gait transition occurs when running/walking (in kcal/m) becomes more metabolically efficient than walking/running.[19] Diedrich & Warren proposed a related dynamical account, in which gait transitions reflect critical points in the competition between preferred stable gaits, which are determined by the mechanics of driving the legs at different frequencies and stride lengths.[20,21] While energetics and dynamics may largely determine the gait transition speed, cognitive effects may also be a factor. The speed at which the gait transition occurs is affected both by the length of time a person expects to be running[22] and by non-motor cognitive load.[23]

Our goal was to examine an unexplored question regarding the role of visual information on the human gait transition. We asked whether the speed of visual flow would alter the speed at which the Run-Walk and Walk-Run transitions occurred.

Preliminary results suggested a small but reliable effect.[24] Although difficult to study in the real world, our treadmill-VE easily allowed for the manipulation of visual flow during locomotion.

4.1. Methodology

Ten subjects participated in the experiment. They were trained on the Treadport to ensure that they were comfortable with the given walking and running pace and to make sure that they were comfortable with the safety harness. The training consisted of a minute of walking at 1.0 m/s, a minute of running at 2.75 m/s and a five minute ramp session in which the speed of the belt was ramped linearly from 1.0 m/s to 2.75 m/s and back down to 1.0 m/s, with an acceleration of 0.1 m/s^2 (each ramp lasted 35 s). After training, each subject had three five minute ramp sessions on the Treadport while viewing the endless hallway separated by five minutes of walking around in real world hallways in our engineering building. Each ramp session required the subject to perform 16 gait transitions (8 Walk-Run and 8 Run-Walk). The conditions (randomly ordered) for the three sessions were visually slower ($0.5\times$), visually same, and visually faster ($2.0\times$), as in the recalibration experiment described in section 2 above. In each of the sessions the subjects performed a visual attention task. They were asked to call out "left" or "right" when double doors in the hallway fully entered the left or right screen in order to increase immersion in the hallway setting. This visual attention task also served as a distractor from the ramping speed of the belt and possible associated effects such as the pulling of the harness. The experimenter recorded the speed at which the transitions occurred and each session was video-recorded as a means of verifying the collected data.

4.2. Results and Discussion

Though it has been thought that proprioceptive information primarily drives the change from walking to running, we have discovered that visual information can alter this transition point. In the visually same conditions, in which the visual flow was matched to speed of walking, the Walk-Run transition occurred at 2.11 m/s and the Run-Walk transition occurred at 1.86 m/s. These results replicate the hysteresis effect reported by Diedrich and Warren,[20] in which the Walk-Run transition tends to occur at a higher speed than the Run-Walk transition. More notably, we found that the speed of transition was modulated by the visual flow rate presented in the treadmill VE. For Walk-Run, the transition occurred at 2.18 m/s for the visually slower condition and at 2.04 m/s for the visually faster condition. Likewise, for Run-Walk, the transition occurred at 1.97 m/s for the visually slower condition and 1.78 m/s for the visually faster condition (see Figure 7). A repeated measures ANOVA compared the visually slower, same, and faster conditions for the Run-Walk and Walk-Run gait transition speeds. For both gait transitions, there was a significant effect of visual condition on speed of the transition, (Walk-Run: $F(2,18) = 49.03, p < .01$; Run-Walk: $F(2,18) = 36.15, p < .01$). For both the Walk-Run and the Run-Walk transitions, planned contrasts showed the transition point in the visually faster condition was significantly slower than the visually same condition, and in the visually slower condition it was significantly faster ($p < .01$ for all contrasts).

In previous work it has frequently been found that the gait transition is initiated slightly before the energetic cross-over point,[19] although humans switch to a gait that is more efficient at the post-transition speed.[25] Thus, it is likely that there is sensory information that specifies when the person is approaching the crossover point. We suggest that the visual system has calibrated the optic flow rate that corresponds to the energetic crossover point (along with other proprioceptive information), and is using it to anticipate that point and initiate a transition.

5. VISION AND NATURAL WALKING SPEED

The gait transition results demonstrated that visual information can affect the way that a person responds to changes in biomechanical locomotion forced by changes in the speed of the treadmill belt. The next study investigated the possible influence of visual motion when a person has control over walking speed and that speed is held approximately constant. In walking (unlke running), there is a preferred walking speed of 1.3 m/s which minimimizes both energy expenditure and mechanical effort.[20]

5.1. Methodology

For this experiment, the Treadport was configured to adjust belt speed as the user's walking speed rather than forcing a particular belt speed. Ten subjects participated. Each subject had three minutes to gain familiarity walking on the Treadport with no visuals projected on the screens. Following this, each subject was directed to walk comfortably for three different conditions, visually slower (0.5X), visually same (1.0X) and visually faster (2.0X) than their walking speed. We intentionally provided no elaboration on what was meant by walking "comfortably". They were also given a distractor

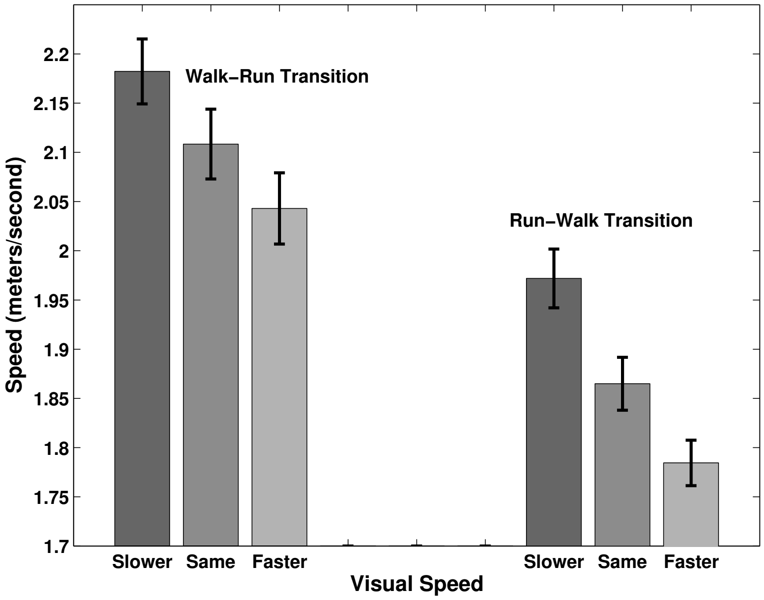

Figure 7. Gait Transition Results. Error bars represent one SE.

task. They were asked to point out double doors in the hallway by calling out "left" or "right" depending on where the double doors appeared. The practice and each of the three conditions were separated by five minutes of walking around in the actual hallway. The conditions were randomly ordered for each subject.

5.2. Results and Discussion

Subjects on average chose a walking speed of 1.41 m/s for the visually slower condition, a walking speed of 1.21 m/s for the visually faster condition and a walking speed of 1.29 m/s for the visually same condition (see Figure 8). A repeated measures ANOVA compared the visually slower, same, and faster conditions. There was a significant effect of visual condition on the comfortable walking speed($F(2,18) = 44.804, p < .01$). Planned contrasts showed the comfortable walking speed in the visually faster condition was significantly slower than the visually same condition, and in the visually slower condition it was significantly faster ($p < .01$ for all contrasts). This indicates that subjects use the speed of the visual flow when deciding their own comfortable walking speed. When a person is instructed to walk at a comfortable speed, their actual walking speed is influenced by the velocity of visual flow that they experience. This is a surprising result, given that ”walking comfortably” would seem to depend on purely biomechanical factors.

6. THE EFFECT OF WALKING ON SLOPES ON SLANT PERCEPTION

All of the results presented above involved various effects associated with the relationship between visually indicated movement and biomechanical walking/running speed. The last experiment we describe involves the perception of environmental shape using the Treadport.

6.1. Background

The phenomenon that what humans perceive is not always consistent with how they act suggests that visual space may be represented differently by separable visual systems for specific goals. In circumstances when conscious perception may be biased, actions directed toward a stimulus often remain accurate. For example, to the everyday observer, hills appear to be steeper than their physical slant. However, this bias in visual awareness is not revealed through a visually guided action directed at the hill.[26–29]

Furthermore, manipulations of behavioral potential (e.g., wearing a heavy backpack or going on a long run) have been shown to increase conscious overestimations of slant[26,28] but not visually guided actions. In these studies, visual awareness of slant was assessed by verbal report, as well as visual matching of a pie-shaped segment on a disk. The visually guided

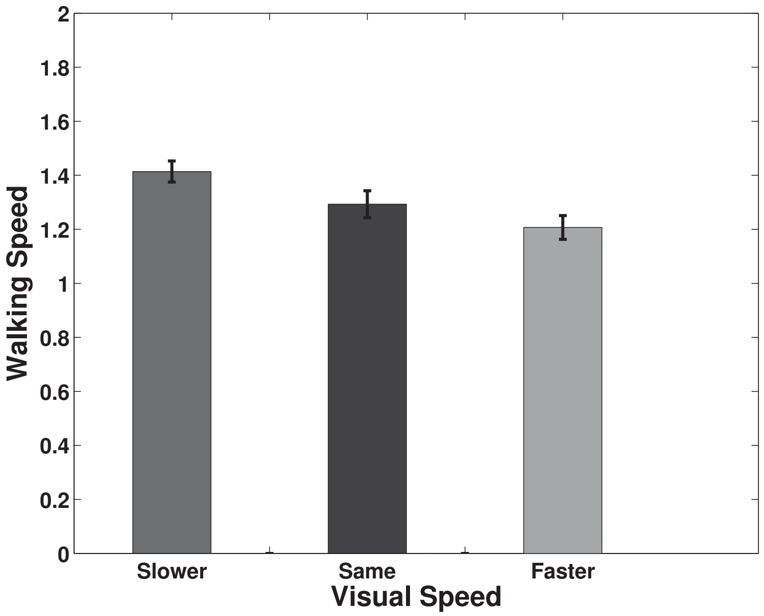

Figure 8. Natural Walking Results.

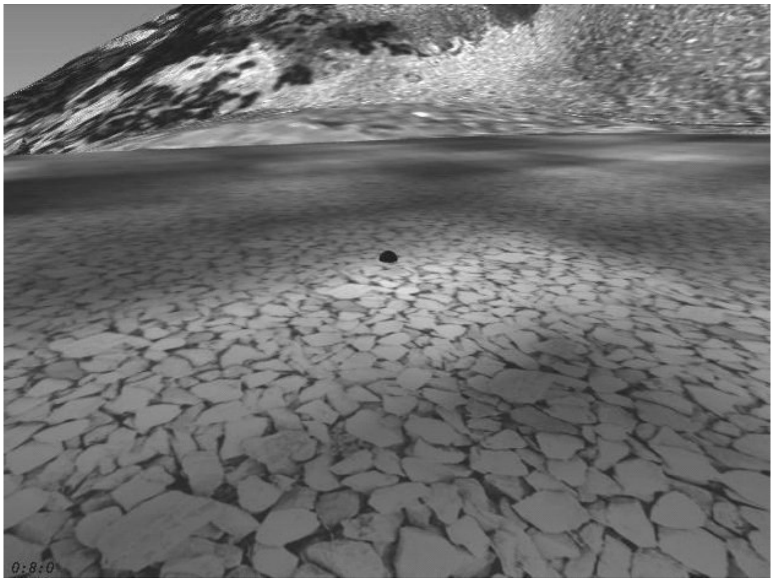

Figure 9. Center screen of mountainous terrain with a marker.

action was the adjustment of a palm board (without vision of the hand) to correspond to the slant of the hill. These results involving slant perception, along with recent evidence of the influence of perceived effort on distance perception[30] suggest that the potential to act in an environment influences phenomenal perception of space. Our experiments on slant perception using the treadmill-based VE addressed the relationship between action and perception by examining the contribution of biomechanical information from walking on hills to judgments of hill slant within a simulated mountainous environment.

6.2. Methodology

In each of four experiments, participants were acquainted with the Treadport and instructed on how to adjust the harness and how to turn while standing in place. Participants stood on each hill, facing a marker (see Figure 9), and gave three

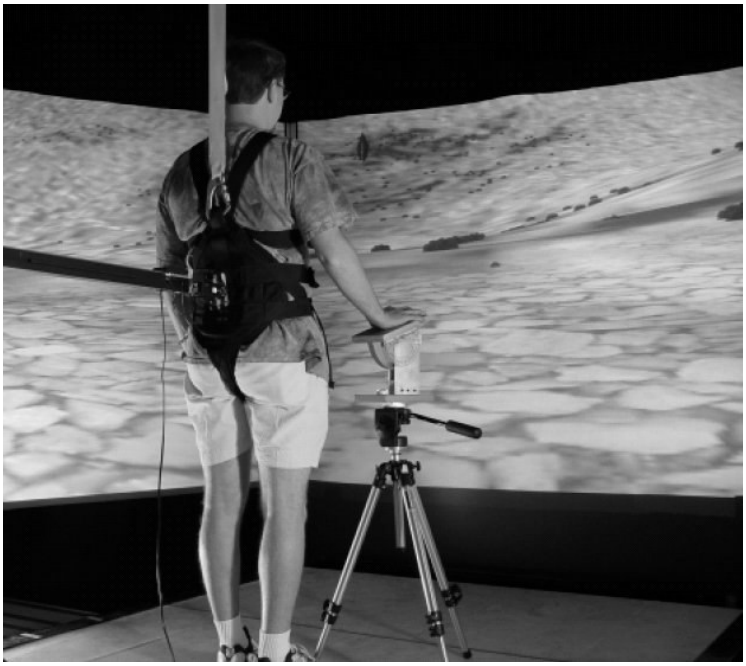

Figure 10. Palm Board used to indicate slant perception.

types of judgments of the slope of the hill at the marker: verbal, visual, and haptic, with the order counterbalanced across participants. For the verbal estimate, participants were instructed to report a number in degrees that reflected the slope of the hill. A description of 0° as flat ground and 90° as a vertical wall was provided by the experimenter to each participant so that it could assumed that all observers began with a similar basic knowledge of angles. For the visual measure, they adjusted a pie-slice on a hand-held disk to make the perceived cross-section of the hill while holding it in the frontal plane. For the haptic estimate, participants placed the palm of their dominant hand on a tilting board which was sitting on top of a tripod placed about waist high (see Figure 10). They were instructed to tilt the board backward to match the slope of the hill without looking at the palm board or their hand, as if they were placing their hand on the hill. We have previously defined the haptic adjustment as one that recruits the visuomotor system because it involves an egocentric adjustment of one's hand to become parallel to the slant of the hill. In contrast, the verbal and visual measures require knowledge of the environmental horizontal to represent geographical slant.[27]

We examined slant estimation in four different conditions, which manipulated the amount and nature of interaction with the environment as simulated on the Treadport which the visual information that was presented being the same across all of the conditions. The first condition involved viewing slopes without any movement. In the second condition, subjects stood on the stationary Treadport belt while viewing a display simulating movement from the initial observation point to the point of interest on the slope. Slope judgments were made after the visuals were reset to the correspond to the initial point. The third and fourth conditions took advantage of the Treadport's unique ability to allow active walking while at the same time manipulating horizontal forces applied to the observer. The third condition was identical to the second, except that subjects actively walked on the Treadport belt towards the target, with walking speed under subject control and the visually indicated speed of self motion coupled to the biomechanical walking speed. The only external forces applied in the third condition simulated inertial effects associated with acceleration and deceleration while walking over level ground. The final condition differed from the third condition in that additional horizontal force was applied to simulate the added effort associated with walking up a real hill.[31]

Each hill site was repeated twice, with hill presented in a different random order for each subject. The entire experiment was completed in about 1 hour. In all conditions, participants were encouraged to rotate their viewpoint so that they could examine the regions surrounding the hill that they were looking at. The rotational viewing allowed the observer to see the entire space surrounding the hill, including the regions behind them. Our intent was that the context would provide a better sense of presence in the virtual environment.

6.3. Results and Discussion

Haptic indications of slant were accurate in all cases, consistent with results from the real world showing accurate haptic indications of slant while standing at the base of a hill.[28] Verbal and visual (pie segment) indications of slant were overestimated in all cases, also consistent with previous results obtained on real hills. Passive visual translation over the hill did not change slant estimation for any of the measures in a statistically significant manner. To our surprise, actual walking over the slope also did not change slant estimation for any of the measures, as long as the forces involved were consistent with walking on level ground. When forces corresponding to the additional effort of walking up the hills were added, both the verbal and visual indications of slant increased. The difference between verbal responses in the walking conditions with and without slope forces was statistically significant. Visual indications of slant did not increases as much as verbal reports when slope forces were added and did not reach significance.[32]

7. SUMMARY

To serve either as interfaces to large-scale virtual worlds or as devices for better understanding human perception, treadmill VEs should provide users with an accurate and integrated visual and proprioceptive sensation of walking. We have demonstrated that it is possible to construct a treadmill VE in which manipulations of perception/action couplings in VE transfer to behaviors in the real world, providing evidence that perception/action couplings involving locomotion are similar in the two environments. We have discovered that altering the perception of self-movement causes calibration of locomotion. We have also used our treadmill-based VE to investigate how walking on slopes effects the visual estimation of slopes. We have further demonstrated the utility of treadmill VE to support controlled experimentation involving the perception of self-motion and locomotion by showing that visual information affects the speed of the human gait transition and natural walking. These results would be very difficult if not impossible to find without our treadmill-based VE.

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