The Role of Effort in Perceiving of Distance

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ABSTRACT

Berkeley (1709) proposed that space is perceived in terms of effort. Consistent with his proposal, we found that egocentric distances appear greater when people are encumbered due to their wearing a heavy backpack or following a visual-motor adaptation that reduces the anticipated optic flow coinciding with walking effort. In accord with Berkeley’s proposal and Gibson’s theory of affordances, these studies show that the perception of spatial layout is influenced by locomotor effort.
The ground beneath our feet is the foundation for most of our gross motor actions. It has two principal perceptual attributes: slant and extent. In previous work, we showed that perceived geographical slant is a function of both distal slant and an observer’s physiological potential to ascend or descend an incline. In this paper, we report studies showing that perceived extent is similarly a function of both distal extent and the effort required to walk a distance. Together these findings highlight the functional nature of perceptual awareness. Perception relates the geometry of spatial layout to the functional capabilities of our body.

Our studies of geographical slant perception support a number of generalizations including the following two. First, even though our visually guided actions are relatively accurate, our conscious awareness of a hill’s incline is grossly overestimated (Proffitt, Bhalla, Gossweiler, & Midgett, 1995). A 5° hill is typically judged to have a slant of about 20°, and the slant of a 10° hill is judged to be about 30°. Second, slant judgments are influenced by an observer’s physiological potential (Bhalla & Proffitt, 1999; Proffitt et al., 1995). Hills appear steeper when people are fatigued, encumbered due to their wearing a heavy backpack, of low physical fitness, elderly, or in declining health. In addition, hills having a slant of over 25° appear steeper from the top than from the bottom (Proffitt, et al., 1995). Due to biomechanical asymmetries, 25 - 30° is about the slant angle at which a grassy slope becomes too steep to walk down although it can still be ascended without loss of balance.

To date, the study of egocentric distance perception has consisted of psychophysical investigations delineating the perceptual response to a variety of depth cues viewed in isolation or in limited combinations (Cutting & Vishton, 1995). Optical
variables have been manipulated, but not variables associated with physiological state. The current studies assessed egocentric distance perception following manipulations of the amount of anticipated effort associated with walking an extent.

The notion that perceived distance is associated with effort is consistent with Berkeley’s (1709/1975) account of visual depth perception. After noting that the projection of a point of light into the eye conveys no information about distance, Berkeley concluded that our perception of distance must be augmented by sensations that arise from eye convergence and from touch. For egocentric distances, tangible information arises from the effort required to walk a distance, and thus, effort becomes associated through experience with visual distance cues. This account is founded upon the supposed insufficiency of visual information to support our awareness of distance.

Today, there is agreement that in complex, natural environments viewed with both eyes by moving observers, there is sufficient information in optic flow, static optical structure, ocular-motor adjustments, and binocular disparity to specify egocentric distance. Thus, a role for effort in perceiving distance seems unnecessary if the goal of perception is to achieve a geometrically accurate representation.

From a functional perspective, however, a role for effort in perceiving distance continues to be justified. Viewing egocentric distance as an affordance (Gibson, 1979), perceived distance is specified by an invariant relationship between distal extent and a person’s potential to perform gross motor actions such as walking. Thus, perceived distance should change with both the distal extent and with the person’s physiological potential. In other words, perceived distance should increase as distances become greater and/or as the effort required to walk an extent increases.
Overview to Studies

Three experiments were conducted. In the first, people made metric distance judgments either unencumbered or while wearing a heavy backpack. The distance judgments for the latter group were greater than for the former. The next two experiments manipulated anticipated walking effort in a more subtle way, with Experiment 2 setting the stage for Experiment 3. Experiment 2 demonstrated that people acquire a visual-motor aftereffect when walking on a treadmill without optic flow but not when flow is present. This aftereffect was observed when people attempted to walk in place while blindfolded. People who experienced no optic flow walked a considerable distance forward when attempting to walk in place because the visual-motor aftereffect changed the calibration between forward walking effort and anticipated optic flow. In the final experiment, people made distance judgments before and after walking on a treadmill, either with or without optic flow. Participants in the latter condition judged extents to be of greater magnitude following treadmill-walking adaptation. The visual-motor aftereffect increased the amount of anticipated effort required to produce the optic flow needed to walk to the target, and thereby, induced an increase in perceived distance.

EXPERIMENT 1

PERCEIVED DISTANCE WHILE WEARING A BACKPACK

Bhall and Proffitt (1999) found that people judged hills to be steeper while wearing a heavy backpack. This experiment was designed to see whether a similar effect would be found for distance perception. Two groups of participants made multiple
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egocentric distance judgments. One group wore a heavy backpack while the other did not. Those who wore the backpack judged distances to be of a greater magnitude.

Method

Participants

Twenty-four University of Virginia students (10 male, 14 female) participated. Participants were either paid or recruited as part of a requirement for an introductory psychology course. All had normal or corrected-to-normal vision. They were naïve to the purpose of the experiment and had not participated in prior distance experiments.

Apparatus & Stimuli

Distances were estimated in a flat, grassy field at the University of Virginia. Golf tees were used to mark distances ranging from 1 to 17 meters from the observer. The tees were placed flush with the ground so that participants could not see them. Six rows of tees were arranged in a radial pattern with the observer being located at the center (Figure 1). The tees facilitated the placement of a small construction cone used to mark each test distance.

Design

Participants were assigned to either the Backpack or the No-backpack condition in an alternating fashion. Five male and seven female participants were in each condition. Each participant made 24 distance estimates (12 practice trials and 2 blocks of 6 test trials). The stimulus distances are presented in Table 1, and their presentation order was
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randomized. The radius on which the cone was presented was also randomized to minimize the use of environmental cues as a reference to distance from trial to trial.

Procedure

Participants in the Backpack condition reported their approximate weight on a questionnaire. A backpack totaling 1/5 to 1/6 of their reported weight was worn throughout the experiment. Participants in the No-backpack condition did not wear a backpack or report their weight prior to testing.

All participants stood at the convergence point of the 6 radii and held a one-foot ruler as a scale reference. Participants faced away from the field while the cone was being placed at each distance. Participants then turned around and reported, as accurately as possible, the distance (in feet and inches) from themselves to the cone. Viewing duration was not limited. After 6 trials, the participants were told that practice was over. This was done to insure that the participants began to settle on a consistent strategy for estimating distance prior to the test trials. Unknown to the participant, six more practice trials followed. Finally, twelve test trials were presented.

Results

As shown in Figure 2, participants in both groups underestimated the actual distance to the target, consistent with previous reports of distance compression (Amorim, Loomis, & Fukusima, 1998; Loomis, Da Silva, Fujita, & Fukusima, 1992; Norman, Todd, Perotti, & Tittle, 1996). However, participants who wore a backpack made larger distance estimates than those without a backpack.
A 2(sex) x 2(backpack) x 12(distance) repeated measures ANOVA was performed with target distance as the within-subjects variable and backpack and sex as the between subjects variables. As expected, the analysis indicated an effect of backpack ($F_{(1,20)} = 8.909, p = 0.007$). Thus, addition of the backpack load was accompanied by greater estimates of distance. There was no significant between-subjects effect for sex ($p = .11$) and no sex x backpack interaction ($p = .15$).

EXPERIMENT 2

CHANGING THE CALIBRATION BETWEEN WALKING EFFORT AND OPTIC FLOW

This experiment was, in most respects, a replication of an earlier study conducted by Durgin, Banton, Walley, Proffitt, Steve, and Lewis, (2000). Durgin et al. demonstrated that walking on a treadmill without optic flow induced a visual-motor aftereffect. Optic flow was manipulated by having people wear a head-mounted display (HMD) that presented either a stationary or moving virtual environment during treadmill walking. The aftereffect was assessed by having blindfolded people walk in place after their treadmill-walking experience. It was found that without optic flow, people tended to walk forward when attempting to remain stationary. With optic flow, this tendency to walk forward was greatly reduced. Optic flow, in the Durgin et al. study, was set at a higher rate than the actual walking speed. For this reason, we sought to replicate this study with an optic flow equated to walking speed. Similar results were obtained. In both studies, the absence of optic flow induced an aftereffect that caused people to expend forward walking effort when attempting to remain stationary. This finding
established the basis for Experiment 3 in which people made distance judgments following the same experimental manipulations.

Method

Participants

Twenty-four University of Virginia students (12 male, 12 female) participated. Participants were recruited either as part of a requirement for an introductory psychology course or by offering them a beverage in exchange for participation. All had normal or corrected-to-normal vision. They were naïve to the purpose of the experiment and had not participated in prior distance experiments. Participants were restricted to heights less than 6’2” due to head-tracking limitations.

Stimuli

Both visual and motor stimulation was provided. Motor stimulation consisted of walking on a motorized treadmill set to 3mph. Visual stimulation was a virtual reality (VR) simulation of a highway with billboards and various landmarks along the sides (Figure 3a). The participant’s viewpoint was from a standing position in the middle of the road. Ninety degrees to the participant’s left was a distant helicopter at ground level (Figure 3b). Ninety degrees to the participant’s right was a distant biplane also at ground level (Figure 3c). For some observers, optic flow was present so that the visual scene appeared to move past the observer in synchrony with their walking rate on the treadmill. During optic flow, the airplanes appeared to fly in the same direction and at the same rate as the observer walked. Having participants look alternately at these peripheral targets
helps them to accurately perceive the correspondence between the treadmill and optic flow speeds (Banton, Steve, Durgin, & Proffitt, 2000). Because of the restricted field of view in the HMD, participants do not see as much lamellar flow as they would normally and this causes them to perceive their own velocity as slower than simulated. By requiring participants to look side-to-side, more lamellar flow is seen, and their perception of their own speed is accurate.

**Apparatus**

A motorized treadmill (Precor 9.1) was employed. While walking, participants viewed the computer graphics rendering of a highway through an HMD. The virtual environment was designed and created using Alice98, a 3D computer-graphics authoring program. 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.

Observers viewed the virtual environment through an n-Vision Datavisor with two color LCDs operating in a VGA video format. The resolution of each display screen was 640 pixels (horizontal) x 480 pixels (vertical), per color pixel. The field-of-view per eye was 52 degrees diagonal. The HMD presented images biocularly, 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. 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 Hz, depending on scene complexity. The 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 VR system, which was calculated with the pendulum method described by Liang, Shaw, & Green (1991), was approximately 100 msec. 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.

**Design**

Participants adapted to one of two visual-motor conditions for a period of 3 minutes. In the Flow condition, participants walked on a treadmill set to 3 mph while viewing a virtual environment containing optic flow appropriate for the 3 mph walking speed. In the No-flow condition, participants walked on the treadmill at 3 mph while viewing a stationary virtual environment. All observers walked in place for 20 seconds before and immediately after treadmill walking. The order of the conditions was alternated between subjects. An equal number of males and females were in each condition.

**Procedure**

The experiment consisted of three phases: a pre-adaptation measure, adaptation, and a post-adaptation measure. Each participant wore foam earplugs (Aearo EAR classic) throughout the study and a blindfold when outside of the HMD to reduce cues to the physical environment.
**Pre-adaptation.** Before treadmill adaptation, participants were asked to march in place for 20 seconds while blindfolded. The beginning and ending position of the leading foot was marked. The distance inadvertently walked during marching in place provided a pre-adaptation measure of motor activity.

**Adaptation.** With the blindfold still in place, participants were led onto the treadmill. They gripped a safety bar in front of them and wore a safety clip for emergency stopping. Participants closed their eyes, removed the blindfold, and the headmount was placed on their heads. After opening their eyes, they were encouraged to look around the virtual environment and locate the airplane and helicopter. The treadmill was accelerated to 3 mph in 0.1 mph increments. For the duration of the 3-min. adaptation period, participants alternated their gaze between the plane and helicopter, fixating each for 30 s. at a time. At the end of adaptation, the treadmill was stopped and the headmount was replaced with the blindfold.

**Post-adaptation.** Participants were led off of the treadmill, and immediately asked to march in place for 20 s. The beginning and ending position of the leading foot was marked. The distance inadvertently walked provided a post-adaptation measure of motor activity.

**RESULTS**

Ratios of post-adaptation drift / pre-adaptation drift (R) were calculated for each participant. An R = 1 meant that there was no effect of treadmill adaptation while an R > 1 indicated that drift increased after treadmill adaptation. Ratios for 0 mph optic flow were larger than for 3 mph optic flow (Figure 4). This difference was statistically
significant \[t_{22} = 3.231, p=0.004\], indicating that the absence of optic flow during adaptation induced participants to drift farther than when the optic flow was appropriate for the treadmill walking speed. Interestingly, ratios were greater than 1 for both optic flow conditions, suggesting that there was a slight increase in drift just from being on the treadmill. To provide a sense of the absolute magnitude of the visual-motor aftereffect, note that the mean difference between post- and pre-adaptation walking in place was 0.60 m. for the No-flow condition, and 0.34 m. for the Flow condition.

EXPERIMENT 3

CHANGING THE CALIBRATION BETWEEN WALKING EFFORT AND OPTIC FLOW CHANGES PERCEIVED DISTANCE

The previous experiment showed that pairing forward walking effort with zero optic flow caused an aftereffect in which blindfolded people walk forward when attempting to walk in place. The visual-motor system has been recalibrated to anticipate that some forward walking effort is required to produce zero optic flow. It follows that the aftereffect should also cause the system to anticipate an increase in the forward walking effort required to walk to a target. If perceived distance to the target is influenced by anticipated effort, then the aftereffect should cause an increase in the magnitude of perceived egocentric distance. This was found.
METHOD

Participants

Twenty-four University of Virginia students (12 male, 12 female) participated. Participants were recruited either as part of a requirement for an introductory psychology course or by offering them a beverage in exchange for participation. All had normal or corrected-to-normal vision. They were naïve to the purpose of the experiment and had not participated in prior distance experiments. The height restrictions were the same as those in Experiment 2.

Apparatus

The apparatus was the same as that used in Experiment 1. In addition, an orange construction cone and a one-foot ruler were used during distance estimation.

Stimuli

The stimuli used during treadmill adaptation were identical to those in Experiment 2. The distance estimates were made in a long corridor adjacent to the adaptation room. An orange construction cone measuring 9 inches high with a 6-inch base was used as a target for distance estimation.

Design

Each participant made egocentric distance estimates before and after treadmill adaptation. The experiment consisted of four phases: practice distance estimation, pre-
adaptation distance estimation, treadmill adaptation (3 min.), and a post-adaptation distance estimate.

Half the participants adapted to the Flow condition and half adapted to the No-flow condition. An equal number of male and female participants were in each condition. Assignment to the conditions was alternated between participants.

Procedure

Practice distance estimation. Practice was provided for participants to develop consistent strategies for estimating distance. Participants wore the foam earplugs to attenuate ambient noise. They were led into a hallway, given a 1-foot ruler to use as a reference, and blindfolded. Participants were then positioned at one of 4 pre-determined starting positions (each 1m apart) to minimize the use of hallway landmarks. Each starting point was used twice during practice. The experimenter placed a construction cone at one of eight distances (3, 4, 5, 7, 9, 11, 12, 13m) specified by one of twelve pre-determined random orders. Cone placement was identical between conditions (i.e. – participant 1 in the Flow and No-flow conditions received the same practice order). Participants removed the blindfold and estimated (in feet and inches) the distance between themselves and the cone. No feedback was given. The blindfold was replaced and the process was repeated for the 7 remaining practice trials.

Pre-adaptation distance estimation. Following practice, participants were brought to a different part of the hallway to make 3 pre-adaptation distance estimates. The same procedure was followed as in practice, but this time the cone was placed at 6, 8, and 10m in a counterbalanced order. The distances were produced from one of 3 starting points.
(each 2m apart). The starting points were randomized, and each starting point was used once during the 3 pre-adaptation trials.

**Adaptation.** With the blindfold in place, participants were led into a dark room and onto the treadmill. Three minutes of adaptation were conducted as in Experiment 2. At the end of adaptation, the treadmill was stopped and the HMD was replaced with the blindfold.

**Post-adaptation distance estimation.** Participants were led back into the hallway. They were given the reference ruler and the blindfold was removed. A single post-adaptation distance of 8m was presented. It was shown from one of the starting points used in the pre-adaptation trials, but in the opposite direction (180 degrees) from the pre-adaptation direction. The direction of pre- and post-adaptation testing was counterbalanced within conditions.

**Results**

Ratios of post-adaptation distance / pre-adaptation distance (R) were again calculated for each participant. The group means and standard errors are plotted in Figure 5. Ratios were significantly larger for 0 mph optic flow than for 3 mph optic flow \([t_{22} = 2.323, p=0.03]\), indicating that participants made larger distance estimates in the absence of optic flow during adaptation than when the optic flow was consistent with the treadmill walking speed. The mean difference between post- and pre-adaptation distance judgments for the 8 m. target distance was 0.37 m for the No-flow condition, and -0.76 m for the Flow condition. Note that the aftereffect caused the predicted increase in perceived distance; however, the decrease in perceived distance found for the Flow group
was unanticipated. Although we cannot provide a definitive explanation for this decrease, one possibility is that it was brought about by the aerobic potentiation induced by the 3-min walk on the treadmill.

GENERAL DISCUSSION

The following subtitle of a chapter by Mace (1977) aptly captures the essence of Gibson’s approach to perception: “Ask not what’s inside your head, but what your head’s inside of.” To this admonition, we would add the proviso that the head is not only inside of an environment; it is also part of a body. Both contribute to what is perceived. We believe this to be in accord with Gibson’s (1979, Ch. 8) theory of affordances, which states that perception reveals how surfaces and entities in the environment relate to an organism’s behavioral potential.

The first experiment demonstrated that perceived egocentric distance is expanded when wearing a heavy backpack. This is consistent with our earlier demonstration that hills appear steeper when people are similarly encumbered (Bhalla & Proffitt, 1999). It could be argued that participants in this study were influenced to make greater distance judgments by the demand characteristics inherent in the backpack manipulation. By this account, participants might have inferred that wearing a backpack was related to our expectation that it would influence their distance judgments. Being concerned about this possibility, we conducted the aftereffect experiments believing that participants could not infer from the procedures that they encountered what the influence of these procedures on distance perception might be.
As was found previously by Durgin et al. (2000), Experiment 2 showed that manipulating the presence or absence of optic flow, while people walked on a treadmill, influenced the calibration between forward walking effort and anticipated optic flow. It was found that after walking on a treadmill without optic flow, blindfolded participants walked forward when attempting to walk in place. This finding is consistent with the results of a number of similar studies. Anstis (1995) had participants jog either forwards or backwards on a treadmill. They then attempted to jog in place with their eyes closed. Those who were adapted to forwards jogging drifted forwards, and conversely, those who were adapted to backwards jogging drifted backwards. Durgin and Pelah (1999) showed that the aftereffect could be modulated by optic flow during outdoor running. Participants ran over open ground either with full vision or while wearing a blindfold. In both conditions, they held onto and ran behind a moving golf cart. Following this adaptation, the aftereffect was assessed by having participants attempt to run in place while wearing a blindfold, and those who had adapted to running without optic flow showed a much larger aftereffect. In a set of ingenious studies conducted by Rieser, Pick, Ashmead, and Garing (1995), participants walked on treadmills placed on trailers being pulled across a field by a tractor, and thereby, they decoupled the rate of optic flow from the rate that the participants were walking. Following this adaptation, participants were shown targets, and after being blindfolded, they attempted to walk to the target locations. Participants whose treadmill-walking rate was greater than the tractor’s speed walked too far, and conversely, those who walked at a slower speed than the tractor walked too short a distance. Together, these studies clearly show that forward walking effort and optic flow are dynamically calibrated within the visual-motor system. This calibration adapts so as
to maintain an accurate anticipation of the rate of optic flow associated with forward walking effort.

As in Experiment 2, Experiment 3 adapted participants to either a stationary or a moving virtual world as they walked on a treadmill, and following this adaptation, those who experienced zero optic flow estimated distances to be farther than those who had experienced flow consistent with their walking speed. The aftereffect induced in the zero optic flow condition caused a recalibration in the amount of anticipated forward walking effort required to produce the amount of optic flow needed to walk to the target, and thus, increased its perceived distance. Recent research supports the notion that optic flow influences perceived distances even when the observer is standing still (Beusman, 1998).

The current studies clearly show that anticipated walking effort can influence apparent distance; however, there remain many questions to be answered. We do not know whether our manipulations would evoke changes in distance perception in all cases or whether effort’s effects are situation or task specific. In this vein, Rieser et al. (1995) found that producing a mismatch between optic flow and treadmill speed influenced blind walking but not blind throwing. Moreover, we know nothing about the mechanisms by which effort exerts its influence on apparent distance. Potential mechanisms range from those that influence the pickup of optical information to those that entail an internal modulation of visual information by physiological factors.

CONCLUSION

Distance is perceived as a function of both distal extent and the anticipated effort required to walk the extent. Perceived distance specifies an invariant relationship
between extent and effort, and thus, it is a function of both. Similar effects have been
found for perceiving geographical slant. In perceiving spatial layout, the distinction
between perception and action becomes blurred. Perception informs action; however, the
potential for action is formative in perception, itself. Prior to perception’s influence on
action is action’s influence on perception.
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References


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Table 1: Stimulus distances in each block of Experiment 1. Order of presentation was randomized within blocks.
Figure 1: A birds-eye view of the target space. Stimuli were positioned 1 to 17 meters from the observer along any of the six radii (1-6).
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Figure 2: The effect of backpack adaptation on distance estimates.
Figure 3: (a) Forward view of the virtual environment from the observer's perspective.
(b) Leftward view of the virtual environment showing a close-up of the airplane used for
leftward fixation. (c) Rightward view of the virtual environment showing a close-up of
the airplane used for rightward fixation.
Figure 4: The effect of treadmill adaptation with and without optic flow on walking-in-place.
Figure 5: The effect of treadmill adaptation with and without optic flow on distance estimation.