PSYCHOLOGICAL SCIENCE

Research Article

THE ROLE OF EFFORT IN PERCEIVING DISTANCE

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Abstract—*Berkeley proposed that space is perceived in terms of effort. Consistent with his proposal, the present studies show that perceived egocentric distance increases when people are encumbered by wearing a heavy backpack or have completed 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 one's feet is the foundation for most of one's 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 the observer's physiological potential to ascend or descend an incline. In this article, 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 one's body.

Our studies of geographical-slant perception support a number of generalizations, including the following two. First, even though people's visually guided actions are relatively accurate, their 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, are encumbered by wearing a heavy backpack, have low physical fitness, are elderly, or are in declining health. In addition, hills having a slant of more than 25° appear steeper from the top than from the bottom (Proffitt et al., 1995). Because of biomechanical asymmetries, 25° to 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 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 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. If egocentric distance is viewed as an affordance (Gibson, 1979), then 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 the person's physiological potential. In other words, perceived distance should increase as distances become greater or as the effort required to walk an extent increases.

OVERVIEW OF STUDIES

We conducted three experiments. In the first, people made metric distance judgments either unencumbered or while wearing a heavy backpack. The distance judgments were greater for the latter group 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 had experienced no optic flow walked a considerable distance forward when attempting to walk in place because the visual-motor aftereffect changed their 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 than before the 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

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

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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 naive to the purpose of the experiment and had not participated in prior distance experiments.

Apparatus and 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 m 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 located at the center (Fig. 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 7 female participants were in each condition. Each participant made 24 distance estimates (12 practice trials and two blocks of 6 test trials). The six stimulus distances in each block (see Table 1) were presented in a randomized order. The radius on which the cone was presented on each trial was also randomized to minimize the use of environmental cues as a reference for distance from trial to trial.

Procedure

Participants in the backpack condition reported their approximate weight on a questionnaire and wore a backpack totaling one fifth to one sixth of their reported weight 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 six radii and held a 1-ft ruler as a scale reference. On each trial, participants faced away from the field while the cone was being placed. They 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. The session began with practice trials, to ensure that participants would begin to settle on a consistent strategy for estimating distance prior to the test trials. After 6 trials, the participants were told that practice was over, although the following 6 trials were still practice trials. Finally, 12 test trials were presented.

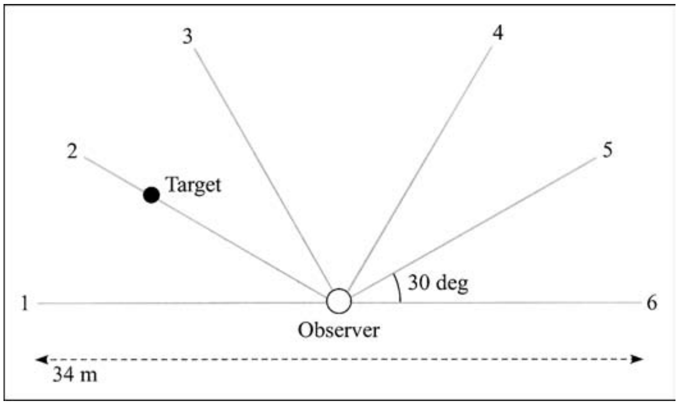

Fig. 1. Bird's-eye view of the target space in Experiment 1. Stimuli were positioned 1 to 17 m from the observer along any of the six radii (1–6).

Table 1. *Stimulus distances in each block of Experiment 1*

Practice		Test	
Block 1	Block 2	Block 3	Block 4
1 m	2 m	4 m	4 m
3 m	5 m	6 m	6 m
7 m	7 m	8 m	8 m
11 m	11 m	10 m	10 m
15 m	13 m	12 m	12 m
17 m	16 m	14 m	14 m

Note. Order of presentation was randomized within blocks. In all blocks, 9 m was both the mean and the median stimulus distance.

Results

As shown in Figure 2, participants in both groups underestimated the actual distance to the target, a result 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) × 2 (backpack) × 12 (distance) repeated measures analysis of variance was performed, with target distance as the within-sub-

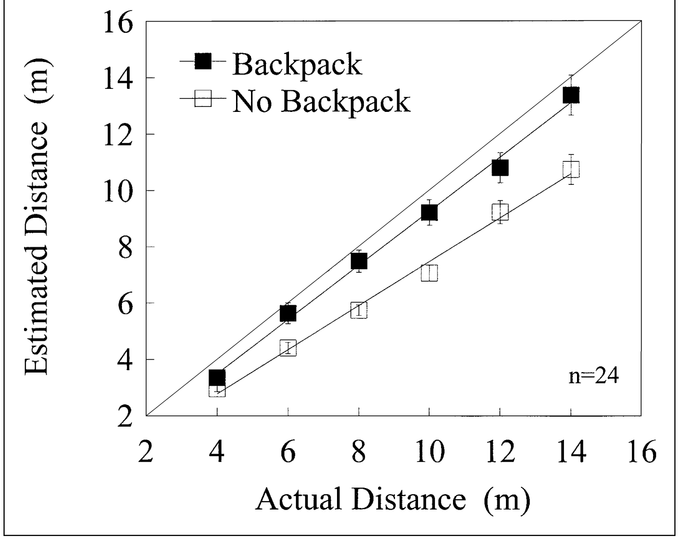

Fig. 2. Estimated distance as a function of actual distance in the backpack and no-backpack conditions of Experiment 1.

jects variable and backpack and sex as the between-subjects variables. As expected, the analysis indicated an effect of backpack, $F(1, 20) = 8.909$, $p = .007$. Thus, addition of the backpack load was accompanied by greater estimates of distance. There was no significant between-subjects effect for sex ($p = .11$), nor was there a Sex × 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 et al. (2000), who demonstrated that walking on a treadmill without optic flow induces a visual-motor aftereffect. They manipulated optic flow by having people wear a head-mounted display (HMD) that presented either a stationary or a moving virtual environment during treadmill walking. The aftereffect was assessed by having blindfolded people walk in place after their treadmill-walking experience. People who had experienced no optic flow tended to walk forward when attempting to remain stationary. Among people who had experienced optic flow, this tendency to walk forward was greatly reduced. Durgin et al. set optic flow at a higher rate than the actual walking speed. For this reason, we sought to replicate their 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. They 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 naive to the purpose of the experiment and had not participated in prior distance experiments. Participants were restricted to heights less than 6 ft 2 in. because of head-tracking limitations.

Stimuli

Both visual and motor stimulation were provided. Motor stimulation consisted of walking on a motorized treadmill set to 3 mph. Visual stimulation was a virtual reality (VR) simulation of a highway with billboards and various landmarks along the sides (Fig. 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 (Fig. 3b). Ninety degrees to the participant's right was a distant biplane also at ground level (Fig. 3c). For some observers, optic flow was present, so that the visual scene appeared to move past them 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 such peripheral targets helps them to accurately perceive the correspondence between the treadmill and optic flow speeds. 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. Requiring participants to look side-to-side increases the amount of lamellar flow they see, so their perception of their own speed is accurate (Banton, Steve, Durgin, & Proffitt, 2000).

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 three-dimensional 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 of 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) × 480 pixels (vertical) × 3 color elements. The field of view per eye was 52° 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 stereoscopic presentation. 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 the frame rate was 10 to 15 Hz, depending on scene complexity. The computer registered six 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, 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.

Design

Participants adapted to one of two visual-motor conditions for a period of 3 min. In the flow condition, participants walked on a treadmill set to 3 mph while viewing a virtual environment containing optic flow appropriate for this 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 s 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: preadaptation, adaptation, and postadaptation. 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.

Preadaptation. Before treadmill adaptation, participants were asked to march in place for 20 s while blindfolded. The beginning and end-

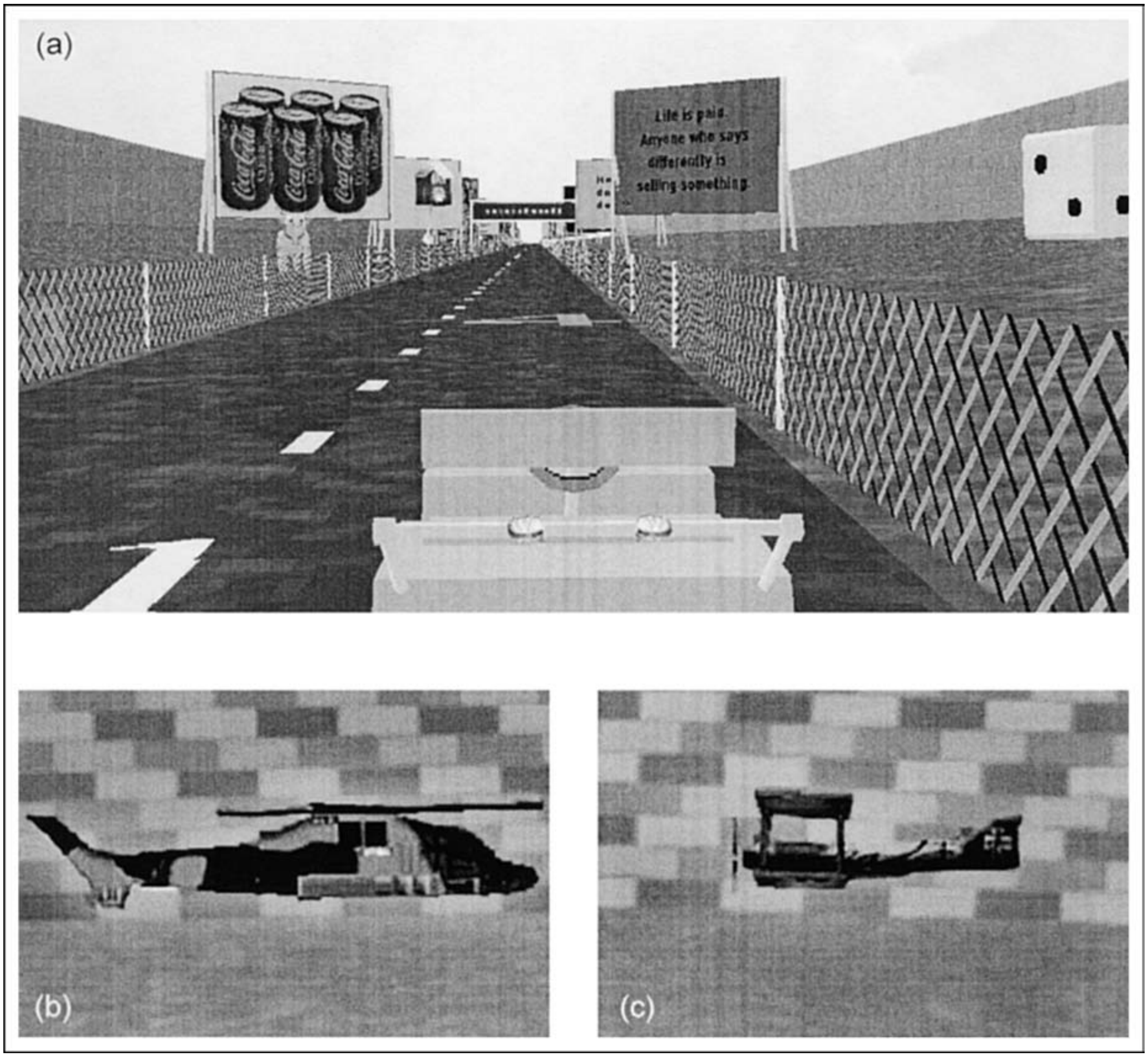

Fig. 3. The virtual environment in Experiments 2 and 3. The scene in (a) is the forward view from the observer's perspective. The leftward (b) and rightward (c) views show close-ups of the helicopter and airplane used for leftward and rightward fixation, respectively.

ing position of the leading foot was marked. The distance inadvertently walked during marching in place provided a preadaptation 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 and 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 HMD was replaced with the blindfold.

Postadaptation. Participants were led off 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 postadaptation measure of motor activity.

Results

The ratio of postadaptation drift to preadaptation drift was calculated for each participant. A ratio equal to 1 meant that there was no effect of treadmill adaptation; a ratio greater than 1 indicated that drift increased after treadmill adaptation. Ratios were larger for 0-mph optic flow than for 3-mph optic flow (Fig. 4). This difference was statistically significant, $t(22) = 3.231$, $p = .004$, indicating that the absence of optic flow during adaptation induced participants to drift farther than was the case with optic flow 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. The mean difference between the post- and preadaptation dis-

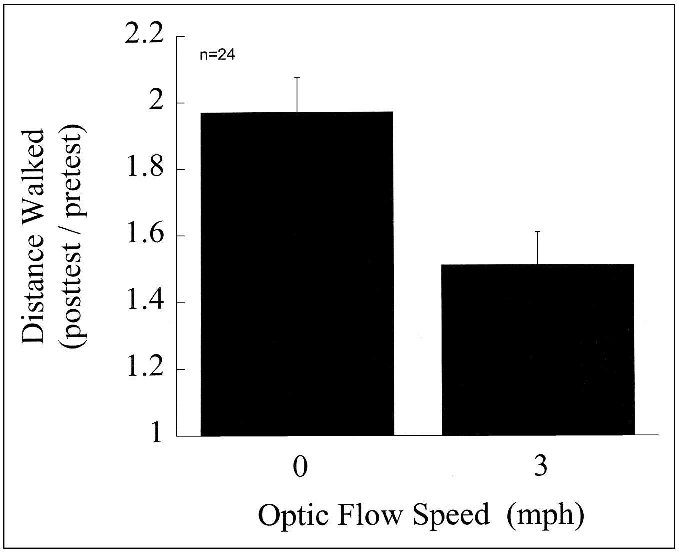

Fig. 4. Ratio of posttest to pretest distance walked while attempting to walk in place in the two optic-flow conditions of Experiment 2. Error bars show standard errors of the mean.

tances traversed while attempting to walk in place provides a sense of the absolute magnitude of the visual-motor aftereffect. This difference 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

Experiment 2 showed that pairing forward walking effort with zero optic flow causes 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 is what we found.

Method

Participants

Twenty-four University of Virginia students (12 male, 12 female) participated. They 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 naive 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 2. In addition, an orange construction cone and a 1-ft 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 in. high with a 6-in. 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, preadaptation distance estimation, treadmill adaptation (3 min), and postadaptation distance estimation.

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-ft ruler to use as a reference, and blindfolded. Participants were then positioned at one of four predetermined starting positions (spaced 1 m apart) to minimize the use of hallway landmarks. Each starting point was used twice for each participant during practice. On each trial, the experimenter placed a construction cone at one of eight distances from the starting point (3, 4, 5, 7, 9, 11, 12, and 13 m), as specified by 1 of 12 predetermined random orders. The participant removed the blindfold and estimated (in feet and inches) the distance between him- or herself and the cone. No feedback was given. The blindfold was replaced, and the process was repeated for the seven remaining practice trials. Cone placement was identical between conditions (i.e., the first participant in the flow condition and the first participant in the no-flow condition received the same practice order).

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

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

Results

A ratio of postadaptation distance to preadaptation distance was 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, $t(22) = 2.323$, $p = .03$, indicating that participants made larger distance estimates when they had experienced no optic flow during adaptation than when the optic flow was consistent with the treadmill walking speed. The mean difference between post- and preadaptation 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, chap. 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 an observer is 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 the demand characteristics inherent in the backpack manipulation influenced participants in this study to make greater distance judgments. By this account, participants might have inferred that wearing a backpack was related to our expectation that it would influence their distance judgments. Because we were 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.

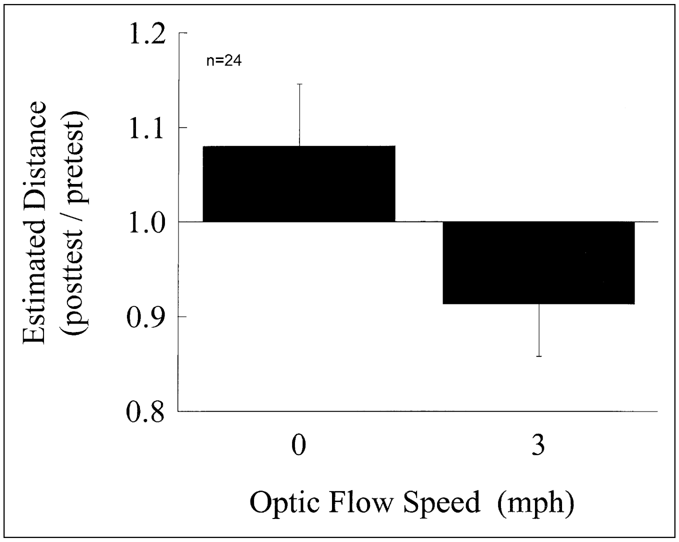

Fig. 5. Ratio of posttest to pretest estimated distance in the two optic-flow conditions of Experiment 3. Error bars show standard errors of the mean.

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 their calibration between forward walking effort and anticipated optic flow. 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 forward or backward on a treadmill and then attempt to jog in place with their eyes closed. Those who were adapted to forward jogging drifted forward, and conversely, those who were adapted to backward jogging drifted backward. 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, they attempted 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. This procedure 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, in Experiment 3 participants adapted to either a stationary or a moving virtual world as they walked on a treadmill. Following this adaptation, those who had 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 (Beusmans, 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. Evidence relevant to this issue comes from Rieser et al. (1995), who 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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