Journal of Experimental Psychology:
Human Perception and Performance
1999, Vol. 25, No. 4, 1076–1096

0096-1523/99/$3.00

Visual–Motor Recalibration in Geographical Slant Perception

Mukul Bhalla
Loyola University New Orleans

Dennis R. Proffitt
University of Virginia

In 4 experiments, it was shown that hills appear steeper to people who are encumbered by wearing a heavy backpack (Experiment 1), are fatigued (Experiment 2), are of low physical fitness (Experiment 3), or are elderly and/or in declining health (Experiment 4). Visually guided actions are unaffected by these manipulations of physiological potential. Although dissociable, the awareness and action systems were also shown to be interconnected. Recalibration of the transformation relating awareness and actions was found to occur over long-term changes in physiological potential (fitness level, age, and health) but not with transitory changes (fatigue and load). Findings are discussed in terms of a time-dependent coordination between the separate systems that control explicit visual awareness and visually guided action.

In conscious awareness, the apparent slant of hills is greatly exaggerated. For example, 5° hills appear to be about 20°, and 10° ones look to be about 30° (Proffitt, Bhalla, Gossweiler, & Midgett, 1995). Be that as it may, people are not especially prone to stumble whenever the terrain over which they walk changes in slant. When ascending a 5° hill, people appropriately raise their feet to accommodate this incline, not a 20° one.

In this and our previous article (Proffitt et al., 1995), we suggest that the exaggeration of slant in conscious awareness promotes the function of relating distal inclines to one's physiological potential. Given gravity and one's physiology, a long 5° hill is actually rather difficult to ascend, and consequently it appears to be quite steep. Given this proposal, we predict that geographical slant will change with changes in physiological potential.

The first purpose of this article is to provide support for this prediction. In four experiments, we show that hills appear steeper when people are (a) encumbered by wearing a heavy backpack, (b) fatigued after a long run, (c) of low physical fitness, and (d) elderly or in poor health. None of these manipulations influenced a measure of visually guided actions directed at geographical slants.

This article's second purpose is to show that the visual systems that inform conscious awareness of slant and visually guided actions are dissociable yet are also transformationally connected. The evidence for dissociation derives from the fact that manipulations of physiological potential evoke changes in conscious awareness without any concomitant changes in visually guided actions. The evidence for transformational connectedness is seen in the finding that the guidance system can be indirectly informed by conscious representations. This is illustrated in the following example: Without looking at a hill, a person can be asked to make a motor adjustment conforming to some verbally given slant angle, say 20°. The response to such an instruction will be a motor response of 5°. Note from the earlier example that this would be the appropriate motor accommodation to a 5° hill that, in consciousness, appeared to be 20°. Conscious representations and motor adjustments are not the same, but they are internally consistent. All four of the studies reported herein investigated the time course over which this internal consistency is maintained. We found that it is not maintained over transitory changes in physiological potential lasting an hour or less; however, it is maintained over longer periods of months and years.

Conscious Slant Perception

In our previous article (Proffitt et al., 1995), we proposed that the discrepancy between conscious slant perception and visually guided actions is functionally advantageous given the different goals that these different systems subserve. Conscious slant perception informs the planning of relatively long-term molar behaviors such as selecting and modulating gait style, whereas the visual guidance system informs the execution of specific behaviors in the immediate action space. A goal of gait style selection is to maintain an acceptable rate of energy expenditure. Whenever terrain slant changes, gait must also change, or one's aerobic state will fluctuate outside of desired values. Gait selection is future oriented in that it requires the regulation of behaviors

Mukul Bhalla, Department of Psychology, Loyola University New Orleans; Dennis R. Proffitt, Department of Psychology, University of Virginia.

The experiments reported in this article were part of Mukul Bhalla's dissertation research conducted at the University of Virginia. This research was supported by National Institute of Mental Health Grant MH52640 and National Aeronautics and Space Administration Grant NCC-2-925.

We thank the students of the University of Virginia and the residents and members of The Collonades retirement community and the Charlottesville Senior Center for participating in these experiments. We would also like to thank Jill Seaks and Marie Anderson for help in running experiments. Finally, we gratefully acknowledge the helpful comments and advice of Marco Bertamini, Bennett Bertenthal, Linda Bunker, Sarah Creem, Glen Gaesser, Michael Kubovy, and Tyrone Yang.

Correspondence concerning this article should be addressed to Mukul Bhalla, Department of Psychology, Box 194, Loyola University, 6363 St. Charles Avenue, New Orleans, Louisiana 70118. Electronic mail may be sent to bhalla@nadal.loyno.edu.

over a fairly long period of time. The goal of the visual guidance system is to effectively accommodate behaviors to the immediate environment. The visual guidance system informs the placement of one's feet given a preselected gait style. In essence, the two systems are concerned with planning actions over different scales of distance and time.

The exaggeration of conscious slant perception, far from being a problem, promotes the important function of relating hill inclines to people's ability to traverse them. Overestimation is symptomatic of two constraints on the conscious psychophysical response to geographical slant. First, conscious awareness of slant exhibits response compression, as is seen in most domains of magnitude estimation such as brightness judgments (Proffitt et al., 1995). The second constraint is that slant is a cyclic variable having two especially salient values, the horizontal and the vertical. From a psychological point of view, the horizontal marks a discontinuity between ascending and descending slants. Similarly, the vertical is a special orientation. Thus, the conscious psychophysical response to slant is anchored with accurate judgments of 0° and 90°.

With respect to response compression, almost all human locomotor activities are carried out in the context of terrains ranging in inclination from a low of 0° to a high of 10°–15°. For example, the steepest public road in Virginia can be no more than 9° in inclination. Given this real constraint on the slant of terrains to which people must accommodate their actions, it is useful for people to exhibit a greater sensitivity to differences between angles within this range than within the range of larger angles. That is, it is very important to be able to notice small changes at low levels of inclination (e.g., from 5° to 7°), because they will be encountered on a regular basis and will entail significant changes in gait style. Noticing small changes between large slants (e.g., from 75° to 77°) is irrelevant to everyday actions. This heightened sensitivity to changes in small angles as opposed to larger ones results in estimates of geographical slant that can best be summarized by power functions having negative exponents. Put another way, the psychophysical response to conscious slant magnitudes exhibits response compression, in which slant needs to be increased threefold for people to perceive the slant as having doubled (Proffitt et al., 1995).

Conscious overestimation is a necessary outcome of combining response compression with the 0° and 90° anchors. People do not overestimate or underestimate vertical or horizontal slants. Given that the conscious psychophysical response is anchored at these two points and exhibits compression (the response curve is a decelerating one), it follows that people overestimate slants for angles greater than 0° and less than 90° and thereby show greater sensitivity to changes in small angles as opposed to changes of the same magnitude for larger angles.

Influence of Behavioral Potential

Conscious slant perception is malleable and can be influenced by manipulations of physiological potential. Previously, we showed that when people judged the inclination of hills after becoming fatigued, they overestimated slant much more than when they were not tired (Proffitt et al., 1995). This result was seen only for the conscious awareness of slant and not for visually guided actions directed toward the same inclines. Because conscious slant perception changes with changes in physiological state, people do not have to explicitly take their state into account when planning molar behaviors. Similar results were obtained when comparing people's judgments made from the top of hills with those made from the bottom. As a result of biomechanical constraints, people can more easily ascend steep hills of 25° to 30° than they can descend them, and, accordingly, they judge these steep hills to be steeper from the top than from the bottom (Proffitt et al., 1995).

Visually Guided Actions

The visual guidance system is concerned with the here and now, with the execution of immediate actions in the near action space as opposed to the more distant vista space (terms used by Cutting & Vishton, 1995). This function is reflected in the accuracy of visually guided actions directed toward those very slants that are verbally overestimated. Also, unlike conscious awareness, visually guided actions are unaffected by changes in physiological potential.

Despite the differences between conscious awareness and visually guided actions, there is evidence that these two systems are interconnected. In our previous studies, we asked people to provide motoric adjustments corresponding to sets of verbally given angles, called the angle judgment task (Proffitt et al., 1995). Results showed that, for example, when given an angle of 20°, people made a motoric response of 5°. As mentioned earlier, the same response (5°) was also obtained when people looked at a hill of 5°; they verbally overestimated it to be 20°. Thus, people tended to respond the same way to a verbally given angle as they did to a hill that they verbally judged to be of the same angle. Although conscious awareness and visually guided actions did not yield the same responses, they were internally consistent. The motor guidance system can be directly informed by visual information or indirectly informed by verbal instructions that are held in conscious awareness. Across these two conditions, the awareness and action systems are consistent.

Dissociation of the Two Visual Systems

These findings imply both a dissociation and an interconnection between conscious visual awareness and visually guided actions. This characterization of two visual systems is not new and has been reported by numerous other researchers in widely disparate experimental settings in which both normal and clinical populations have been assessed. The motor guidance system promotes actions directed at the environment and is generally unconscious and accurate; conversely, explicit perceptions inform conscious decision making and need not be accurate in a purely geometrical sense. This idea has its roots in a proposal made by Schneider (1969) that was later developed by Ungerleider and Mishkin (1982) and more recently modified by Milner and Goodale (1995) and others. It suggests that there are two broad streams of projections from the visual cortex. One is a ventral stream projecting to the inferotemporal cortex that is responsible for the perception of an object's identity (the "what" pathway). The other is a dorsal stream projecting to the posterior parietal cortex that is responsible for spatial localization and visually guided actions (the "how" pathway).

There is substantial electrophysiological evidence to support this distinction. For example, single cell recordings from monkeys reveal that cells in the dorsal stream are well suited to the coding of visually guided actions directed toward objects and scenes. For example, these cells do not respond to visual stimulation when the animal is placed under anesthesia, indicating that most such cells fire only when the organism is actively interacting with the environment (e.g., Hyvarinen & Poranen, 1974; Mountcastle, Lynch, Georgopoulos, Sakata, & Acuna, 1975). Cells in the ventral stream of projections to the inferotemporal region, on the other hand, remain unaffected by anesthesia, suggesting that these cells are not involved in the on-line control of the animal's behavior (Hyvarinen & Poranen, 1974; Mountcastle et al., 1975). They seem better suited for the detailed coding of object-related and environment-related attributes, being highly selective for the form, pattern, and color of objects and maintaining their responsivity over a wide range of these qualities (Gross, Desimone, Albright, & Schwartz, 1985; Gross, Rocha-Miranda, & Bender, 1972; Tanaka, Saito, Fukada, & Moriya, 1991), as well as over different viewpoints, sizes, and so forth (Perrett et al., 1984, 1991).

Neuropsychological studies of humans with damage to one or the other of these systems provide another opportunity to see this dissociation. Patients with damage to the dorsal stream show difficulties with visually guided actions while having no problems with identification of everyday objects (optic ataxia). Such patients exhibit difficulty in reaching out in the right direction and grasping in a manner appropriate to the size, shape, and orientation of the to-be-grasped object (e.g., Jacobson, Archibald, Carey, & Goodale, 1991; Perenin & Vighetto, 1983, 1988).

Perenin and Vighetto (1988) described 10 patients with unilateral damage, mainly to the parietal lobe, who performed at above-chance levels on tasks such as spatial localization of targets and perception of line orientations but experienced great difficulty in reaching toward the same targets, making errors in rotating their hands as they reached toward a large slot oriented in different directions over different trials. Similar problems with anticipatory grip scaling have also been reported (Jacobson et al., 1991; Jeannerod, 1986, 1994; Perenin & Vighetto, 1983, 1988).

Patients with visual agnosia, in contrast, have suffered damage to the ventral stream and are often unable to recognize or describe common objects, faces, or pictures, even though they are able to perform normal everyday actions. Milner et al. (1991) described the behavior of an agnosia patient, D.F., with damage to the ventrolateral region of the occipital lobe. As a consequence, she displays profound deficits in object recognition, but her visuomotor system can inform the programming and on-line control of visually guided actions based on the same object characteristics.

A similar dissociation between conscious perception and action is seen in normal (brain-intact) participants. For example, Bridgeman, Lewis, Heit, and Nagle (1979) found that saccadic suppression could mask target displacement during the saccade; however, accurate reaching for the target still occurred after the saccade. Similar results have been reported by researchers even under two-alternative forced-choice reporting of target displacement (Bridgeman & Stark, 1979; Goodale, Pelisson, & Prablanc, 1986; Pelisson, Prablanc, Goodale, & Jeannerod, 1986). In another study using the Titchner illusion, Goodale, Aglioti, and DeSouza (1994) showed that whereas the explicit perception of objects is subject to the illusion, actions directed toward them are not. Similarly, Loomis, Da Silva, Fujita, and Fukusima (1992) found that participants displayed remarkable accuracy in blind walking to targets even though they misperceived the distance between various targets, as measured by visual matching tasks.

Interconnection of the Two Visual Systems

Despite the large body of evidence indicating dissociation between the conscious perception and visual guidance systems, there is also considerable evidence indicating their interconnectedness. Obvious support for interconnections between the dorsal and ventral streams comes from the harmonious and well-coordinated functioning of awareness and action in day-to-day activities. Some communication between the two systems would be necessary to convey top-down knowledge about the object to supplement the bottom-up sensory information used in visually guided tasks. For example, information that is essential to the visual guidance system for not just grasping a rose stem but also holding it in a pincer grasp so as to avoid the thorns would have to be made available by the perceptual system that identifies the object as a rose. In addition to the growing electrophysiological evidence showing actual anatomical connections between structures belonging to the two streams, evidence is also available from studies conducted with both normal and clinical samples. For instance, it has been proposed that a higher level praxic system with access to the output of the ventral stream's processing instructs the relevant visuomotor systems (Jackendoff & Landau, 1994; Jeannerod, 1994; Milner & Goodale, 1995). Sirigu et al. (1995) described a patient whose behavior suggested damage to this praxic system. She suffers from neither visual agnosia nor optic ataxia, in that she can recognize familiar objects and reach for them efficiently. But, when shown a familiar object and asked to pick it up and use it, she will often do so using a grasp that is efficient but inappropriate for the use of the object. Thus, although the two systems are functioning adequately in isolation for this patient, they appear to be disconnected from each other. D.F. (Milner & Goodale, 1995) has also shown similar behavior with everyday objects. If she fails to identify an object, she behaves like Sirigu et al.'s patient: She grasps it efficiently but inappropriately. On the basis of these results, one can assume that information about an object's identity cannot be transferred to D.F.'s praxic and visuomotor systems.

Jeannerod, Decety, and Michel (1994) reported another case of a patient with bilateral posterior parietal lesions who has no problems in identifying and reaching toward an object's location but shows marked deficits in grasping. This deficit is remarkably reduced when the participant reaches for more familiar objects (e.g., lipstick or a reel of thread) instead of neutral objects (e.g., plastic cylinders). It appears that the problem with grasping the neutral objects arises because the semantic system is unable to inform the pragmatic system about the identity of the to-be-grasped object, which is essential for proper grasping, and with more familiar objects this information is filled in by cognitive cues based on prior experience.

Instances have also been reported in which interconnections between the conscious perception and visual guidance systems have been manifested in the form of interference between the two. Studies with both normal (Rossetti & Regnier, 1995) and clinical (Rossetti, Rode, & Boisson, 1995) patients have shown that either simultaneous activation of verbal and motor responses (naming a target location and pointing directly at it) or introduction of a delay in responding results in considerable deterioration of the motoric response: Accuracy for tasks such as pointing drops, sometimes even to random levels. These results indicate that when the "pragmatic" representation normally used to drive the motor response cannot be used, both the verbal and motor responses are subserved by the "semantic" representation. This apparent "switch" from the pragmatic to the semantic representation provides further support for the functional interconnectedness of the two streams.

Creem and Proffitt (1998) demonstrated similar effects in studies of memory for geographical slant. They found that when people view a hill, close their eyes, and then are asked to estimate the hill's slant, their verbal estimates are greater than when viewing the hill. However, their estimates made via motor adjustments are unaffected. If there is a sufficient delay in responding, or if the individual is moved to another location, then the motor adjustment increases with the verbal estimate, indicating that both are being informed by the same explicit conscious representation.

Calibrating the Connection Between the Two Visual Systems

As described earlier, evidence for interconnection between the visual awareness and guidance systems is also seen in the internal consistency that is observed between conscious and motoric slant judgments (Proffitt et al., 1995). This consistency between apparent slant and actions is suggestive of implicit learning. Feedback about one's performance navigating through the environment could lead to motor responses consistent with a 5° hill whenever one encounters a hill that appeared to be about 20°. As the correspondence between the motor and verbal responses changes—for example, as a result of fatigue in Proffitt et al.'s (1995) study—the transformations relating visually guided actions to visual awareness could also be modified to yield a new mapping.

The time course for recalibrating the transformation relating perceived slant and corresponding actions can be fast or slow. With respect to the former alternative, it is possible that visually guided actions compensate for increased overestimation in visual awareness by rapidly recalibrating the transformation relating the awareness and guidance systems. For example, in the Proffitt et al. (1995) study, fatigue was introduced by having people run for about an hour. This caused verbal reports, but not motoric adjustments, to increase. It is possible that the transformation mapping conscious visual experience into motoric adjustments was constantly being modified during the runs, thereby counteracting the increased overestimation in conscious perception.

On the other hand, it is just as likely that the recalibration of the transformation relating conscious perception and action is not immediate, but rather, occurs only after long-term changes in the organism's physiological potential. The reason why fatigue affected the verbal but not the motoric responses of the tired joggers could be that these two responses are informed by systems that are independent over the short term. This account is represented in Figure 1.

It is known that the two systems are transformationally related because the guidance system can be informed by explicit verbal instructions, and in such cases motoric adjustments are consistent with those made when viewing hills. There is a test for whether the fatigue induced by running results in a recalibration of the transformation relating the awareness and guidance systems. For example, the tired joggers could have been asked to make motoric adjustments in response to verbal instructions. If these adjustments changed so as to maintain internal consistency with their increased hill judgments, then recalibration would be in evidence. For example, if before the run they made adjustments of 5° either when viewing a 5° hill that appeared to be 20° or when told to make a 20° adjustment, then after the run they should make an adjustment of 5° when told to make a 25° adjustment because, with fatigue, a 5° hill now appears to be 25°. On the other hand, if the system is relatively slow to modify the mapping between awareness and actions, then temporary fatigue would not bring about a recalibration; tired joggers would make a 5° adjustment to a 20° instruction just as they had before becoming fatigued. It did not occur to us to make this test when we conducted the

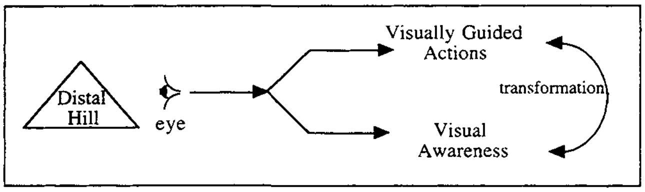

Figure 1. Nearly decomposable systems: Visual awareness and visually guided actions are segregated in the short term but coordinated in the long term. Haptic responses are transformationally related to and can be driven by verbal–visual responses.

initial fatigue study; we did not assess the joggers for changes in internal consistency. For this reason, the study had to be conducted again, along with three others.

Overview of Experiments

The four experiments described here were designed with two goals in mind. The first was to demonstrate that changes in physiological potential in a variety of contexts affect the conscious awareness of slant. The current experiments showed that conscious slant overestimation is increased by the reduction in physiological potential brought about by carrying a heavy load (Experiment 1), becoming fatigued by running (Experiment 2), being less physically fit (Experiment 3), or being elderly or in poor health (Experiment 4). By contrast, visually guided actions were unaffected by these conditions.

The second goal was to assess the time course for the recalibration of the transformation relating conscious awareness and the visual guidance of actions as these two systems relate to geographical slant. This was addressed by testing groups of participants who had been at their particular level of behavioral potential for varying periods of time. Experiments 1 and 2 showed that, after temporary or short-term changes in physiological potential, recalibration was not evident. However, with the long-term changes assessed in Experiments 3 and 4, recalibration was observed.

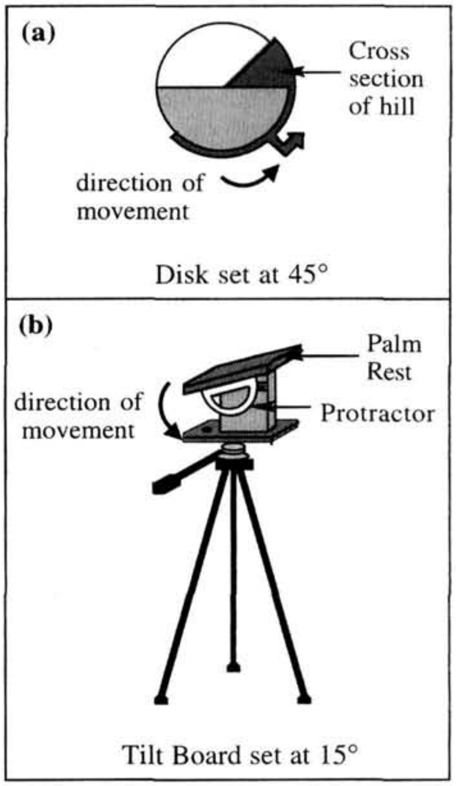

Figure 2. a: Visual measure. b: Haptic measure.

General Method

In the following sections, first the stimuli, apparatus, and procedure common to all four experiments are described, and then each experiment is discussed.

Stimuli

Experiments 1–3 used hills on the grounds of the University of Virginia. These hills were a subset of the hills used in experiments reported by Proffitt et al. (1995). Experiment 4 used hills on the premises of two retirement communities in the Charlottesville area. Each hill was selected on the basis of three criteria. First, it had to be a reasonably long hill so that the top was well above the horizon. Second, it was required to have a fairly uniform and even surface, with no major changes in its inclination or bumps along its surface. Finally, it had to be a sidewalk, walkway, or grassy slope easily and safely accessible by all participants.

Apparatus

In all of the experiments, participants reported their judgments in three ways: verbally, visually, and haptically. The verbal report was simply an estimate of how much the hill was inclined from the horizontal (in degrees).[1] The visual judgment was made with a disk (see Figure 2a) that consisted of an adjustable angle representing a cross section of the inclination of a hill, with a protractor mounted at the back that allowed the experimenter to determine the angle to which the participant had set the cross section. Haptic judgments were made by using a tilt board with a flat palm rest (see Figure 2b) the tilt of which could be adjusted upward or downward to match the inclination of the hill. The tilt board also had a protractor on its side, concealed from the observer, which allowed the experimenter to determine the angle to which it was set. The tilt board itself was mounted on a tripod whose height could be adjusted to just above waist level for each individual participant, to provide a comfortable position for participants to make their judgments. The tilt board was placed by the participants' side, and they adjusted it with their dominant hand without looking at it.

Procedure

All participants first performed the *hill judgment* task, in which they viewed the hills binocularly, in daylight, while standing at the base of the hills. They looked directly ahead at the hill and were not allowed to obtain a side view. For each hill, participants judged the angle of inclination of the hill with respect to the horizontal, reporting their judgments on the three measures (verbal, visual, and haptic) in a counterbalanced order assigned randomly to them. All participants also performed the *angle judgment* task, which tested for internal consistency in their verbal, visual, and haptic judgments. For this task, participants adjusted the visual or the haptic

[1] The decision to use degrees rather than percentage grade as the unit of measurement resulted from feedback from participants who revealed that they were more comfortable with the concept of degrees than of grade, even though Americans in general might be expected to be more familiar with the latter unit of measurement in that highway signs tend to specify slopes (if at all) in percentage grade. Furthermore, participants' ease with angles is seen in the accuracy of the settings of the visual measure during the angle judgment task.

Table 1
Criterion Used to Determine Weight of Backpack Given to Each Participant

Participant weight		Backpack weight	
lb	kg	lb	kg
100–120	45.36–54.43	20	9.07
121–150	54.89–68.04	25	11.34
151–180	68.49–81.65	30	13.61
181–210	82.10–95.26	35	15.88

measure, or both, to the following set of verbally given angles: 5°, 10°, 15°, 20°, 30°, 45°, 60°, and 75°. The angles were presented in a random order, one at a time, and the participant adjusted the measure to the given angle from 0°. After the participant's response had been recorded from the concealed protractor, the measure was reset to 0°, and the next angle was presented.

Experiment 1: Backpack Study

In this study, participants wore a heavy backpack while judging the slant of hills. The main purposes of this experiment were (a) to demonstrate the effect of physiological potential on explicit geographical slant perception and (b) to test what participants' responses would be like were they not given an opportunity to recalibrate the mapping between visual awareness and visually guided actions.

Method

Participants. One hundred thirty students from the University of Virginia, naive to the purpose of the experiment, participated. Forty participants (20 men and 20 women) wore a heavy backpack for the duration of the experiment and were given course credit toward an introductory psychology course. The remaining 90 participants (45 men and 45 women) were students who were stopped as they passed by one of the two hills on their way to classes and asked whether they would like to participate in an experiment. (The latter participants were part of the normative data sample tested by Proffitt et al. [1995] in their Experiment 1.)

Stimuli. Two hills (5° and 31° in inclination) on the grounds of the University of Virginia were used.

Apparatus. Participants reported their judgments on the verbal, visual, and haptic measures described earlier. Exercise free weights in 2.3-kg (5-lb) and 4.6-kg (10-lb) increments were used to load an ordinary school backpack.

Procedure. All participants first performed the hill judgment task and reported the inclination of one of the two hills on the verbal, visual, and haptic measures either without a backpack or while wearing a heavy backpack loaded to between one sixth and one fifth of their body weight. Participants in the backpack condition were first taken to the base of the hill, and self-reports of their weight were used to determine the weight of the backpack (see Table 1). Once the backpack was loaded, the participants were asked to put it on. All participants arrived at the hill without the backpack and were given no opportunity to walk while wearing it. They were then asked a set of questions related to estimating the weight of their backpack and the length of the hill, along with the crucial question about the inclination of the hill. The distractor questions were introduced to prevent participant bias; the goal was for participants to believe the study was about estimating weights, distances, and angles in general and not specifically about the relationship between the backpack and their inclination judgments. The participants who judged the inclination of the hill without a backpack were simply asked to judge the inclination of the hill on the three measures.

After judging the inclination of the hill, all of the participants also performed the angle judgment task, which tested for internal consistency in their verbal, visual, and haptic judgments. For this task, participants adjusted either the visual or the haptic measure to a set of verbally given angles. All participants with backpacks adjusted one of the two measures to the following angles: 5°, 10°, 15°, 20°, 30°, 45°, 60°, and 75°. The normative (nonbackpack) participants judging the 5° hill set the two measures to 5°, 10°, 15°, and 20°, and those judging the 31° hill set the measures to 15°, 30°, 45°, 60°, and 75°. The order in which the participants were given the angles was random.

Results and Discussion

Figure 3 and Table 2 present the judgments of the normative participants and the backpackers for the two hills (5° and 31°) on the verbal, visual, and haptic measures. As predicted, the participants wearing the heavy backpack overestimated the inclination of both of the hills on the verbal and visual measures more than did the normative participants. The haptic reports were no different. A 2 × 2 analysis of variance (ANOVA) for the 5° hill assessed the effect of backpack (present vs. absent) and sex (male vs. female) on slant judgments for the verbal, visual, and haptic measures. (Our previous study showed that there were significant differences between male and female participants on the hill judgment task for the visual and verbal reports, and hence this experiment and others looked for the effects of sex and the interaction of sex with other variables of interest.) Results revealed that there was a significant interaction between measure (verbal, visual, or haptic) and backpack (present or absent), $F(2, 196) = 7.25$, $p < .01$. Further analysis revealed that this interaction arose from the fact that the verbal, $F(1, 98) = 4.65$, $p < .05$, and visual, $F(1, 98) = 9.79$, $p < .01$, measures showed a significant effect of backpack, but the haptic measure did not, $F(1, 98) = 1.06$, $p = .31$. The effect of sex was significant for the verbal, $F(1, 98) = 4.65$, $p < .05$, and visual, $F(1, 98) = 8.9$, $p < .01$, reports for the 5° hill, but not for the haptic report. Female participants tended to overestimate the inclination of

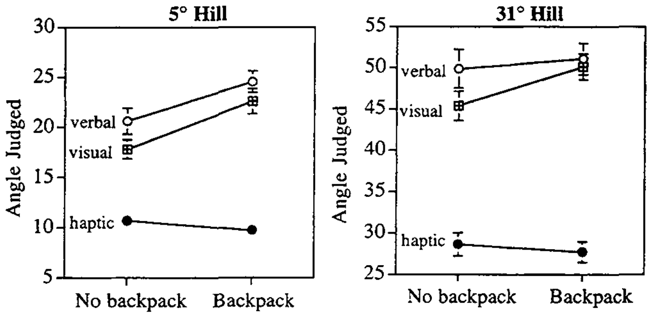

Figure 3. Judgments of geographical slant for the 5° and 31° hills by participants with and without a backpack on the verbal, visual, and haptic measures: Experiment 1.

Table 2
Mean Hill Judgments: Experiments 1–4 and Experiment 1 of Proffitt et al. (1995)

Group	Hill	Verbal judgment		Visual judgment		Haptic judgment	
		M	*SE*	*M*	*SE*	*M*	*SE*
Backpackers	5°	24.52	1.09	22.57	1.26	08.79	0.62
	31°	53.70	2.77	51.50	2.64	28.35	1.71
Joggers (before run)	5°	21.20	1.88	19.20	1.68	07.90	0.74
	31°	48.55	2.34	46.00	2.15	28.40	2.01
Joggers (after run)	5°	27.70	1.64	27.75	1.96	09.45	1.01
	31°	59.40	2.72	54.90	1.71	28.85	1.40
Fitness	5°	20.41	1.25	19.87	0.87	10.26	0.58
	6°	19.44	1.32	17.00	0.85	09.44	0.49
	21°	39.24	1.30	36.31	1.17	21.21	0.82
	31°	59.46	1.54	53.12	1.18	31.41	1.03
Elderly	2°	10.35	1.06	08.90	0.69	05.85	0.48
	3°	13.59	1.39	12.03	1.09	07.59	0.68
	4°	14.95	1.81	12.50	1.49	08.35	1.11
	5°	15.42	3.43	13.58	2.25	07.75	1.02
	10°	24.58	3.61	20.50	1.51	11.25	1.37
	25°	52.65	4.01	52.65	3.95	24.35	1.30
	29°	58.75	4.81	56.25	3.99	25.33	2.17
Normative (Proffitt et al., 1995)	2°	09.67	1.34	10.30	1.90	04.50	0.51
	4°	20.93	2.26	14.10	0.89	07.70	0.69
	5°	20.63	1.30	17.80	0.95	10.70	0.65
	6°	22.00	1.89	17.10	1.29	10.27	1.12
	10°	31.13	1.95	26.07	1.23	15.90	1.09
	21°	40.17	1.66	35.07	2.08	21.67	1.30
	31°	49.83	2.34	45.37	1.79	28.63	1.39
	33°	54.40	1.60	51.60	1.65	29.17	1.31
	34°	57.93	2.32	53.27	1.70	29.90	1.48

hills more than the male participants. The interaction between sex and backpack was not significant.

The results for the 31° hill showed similar trends, although the effects were not significant for all of the measures. A 2 × 2 (Backpack × Sex) ANOVA revealed a significant difference in the visual reports of the backpackers and the normative participants, $F(1, 68) = 3.96, p < .05$, and, although the means for the verbal reports were in the predicted direction, the difference was not significant, $F(1, 68) = 0.40, p = .56$. As with the 5° hill, the difference in the haptic reports was not significant, $F(1, 68) = 0.20, p = .64$. The effect of sex was not significant, nor was the interaction between sex and backpack.

The increases in overestimation for the 5° hill were 3.89° (19%) for the verbal reports, 4.77° (27%) for the visual reports, and −0.96° (9%) for the haptic reports. For the 31° hill, they were 1.21° (2%) for the verbal reports, 4.73° (10%) for the visual reports, and −0.92° (3%) for the haptic reports. The results obtained with the backpackers were very similar to the results obtained in Experiment 5 of Proffitt et al. (1995), which manipulated fatigue, although the magnitude of the increase was not as great for the load manipulation.

The angle judgments of the backpackers were also compared with those of the nonbackpack participants, of whom some had set the visual or haptic measure to one subset of angles (5°, 10°, 15°, and 20°) and others had set the measures to another subset (15°, 30°, 45°, 60°, and 75°). The backpackers, on the other hand, set the visual and haptic measures to the entire set of angles (5°, 10°, 15°, 20°, 30°, 45°, 60°, and 75°). As a result, the angle judgments of the backpackers and the normative participants were compared in two separate analyses, with one regression comparing judgments for shallow angles and another comparing judgments for steep angles.

Angle judgments were unaffected by the load manipulation (see Figure 4 and Tables 3 and 4). A regression analysis looked at the effect of backpack and angle on the angle judgments of participants for both the visual and haptic measures. Results revealed that the backpack manipulation did not affect participants' angle judgments on the visual measure for the shallow angles (5°, 10°, 15°, and 20°), *F*(1,

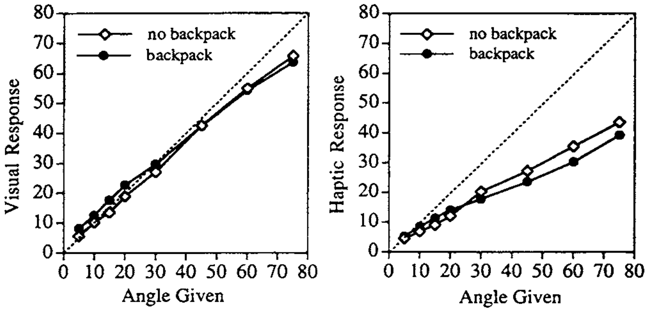

Figure 4. Angle judgments on the visual and haptic measures by participants with and without backpacks in response to verbally given angles: Experiment 1.

Table 3
Mean Visual Angle Judgments: Experiments 1–4 and Experiment 1 of Proffitt et al. (1995)

Group	5°	10°	15°	20°	30°	45°	60°	75°
Backpackers								
M	8.07	12.59	17.66	22.66	29.66	42.32	54.20	63.69
SE	0.59	0.69	0.85	0.99	0.78	1.04	1.45	1.23
Joggers (before run)								
M	8.00	12.25	17.19	20.56	28.19	44.44	57.56	68.6
SE	0.69	0.91	0.87	1.29	0.79	0.63	1.06	1.20
Joggers (after run)								
M	8.44	12.94	18.19	22.13	29.00	44.50	56.13	68.94
SE	0.65	0.78	1.30	0.82	1.08	0.90	1.53	1.19
Fitness								
M	7.01	12.19	15.37	20.63	28.43	44.00	55.62	65.50
SE	0.28	0.45	0.42	0.52	0.50	0.53	0.70	0.69
Elderly								
M	6.09	9.91	13.50	17.22	28.78	43.16	56.75	66.44
SE	0.44	0.68	0.62	1.00	1.12	1.30	1.47	1.21
Normative (Proffitt et al., 1995)								
M	5.55	10.12	13.50	18.90	27.04	42.56	54.87	65.71
SE	0.19	0.31	0.42	0.52	0.70	1.11	1.28	1.39

580) = 2.16, $p = .14$, or the steep angles (15°, 30°, 45°, 60°, and 75°), $F(1, 426) = 0.15$, $p = .70$. Similarly, the difference between the angle judgments of the backpackers and the normative participants on the haptic measure was not significant for the shallow angles, $F(1, 588) = 0.45$, $p = .50$, or the steep angles, $F(1, 436) = 0.01$, $p = .94$.

As mentioned earlier, because the backpackers and the nonbackpackers (normative participants) had set the haptic and visual measures to different sets of angles, the results obtained for the angle judgment task were verified by comparing the angle judgments of the backpackers with the judgments of another group of participants who were more comparable to them. These were the joggers of Experiment 2 (described in detail in a later section) *before* the experimental manipulation (the run) was introduced. They judged the same hills following the same procedure and, more important, performed the angle judgment task in an identical manner, setting the visual or haptic measures to the same set of angles as the backpackers (5°, 10°, 15°, 20°, 30°, 45°, 60°, and 75°). They could thus be considered an appropriate control group for the backpackers. Results revealed no significant differences between the angle judgments provided by the backpackers and the before-the-run participants on either the visual, $F(1, 516) = 1.3$, $p = .27$, or haptic, $F(1, 516) = 1.2$, $p = .37$, measure. Together with the findings discussed earlier, these results indicate that, as expected, there was no recalibration of the mapping between visual awareness and visually guided actions because the partici-

Table 4
Mean Haptic Angle Judgments: Experiments 1–4 and Experiment 1 of Proffitt et al. (1995)

Group	5°	10°	15°	20°	30°	45°	60°	75°
Backpackers								
M	5.26	8.42	11.35	13.98	17.72	23.56	30.23	39.19
SE	0.36	0.76	0.75	1.12	1.19	1.43	1.83	1.92
Joggers (before run)								
M	6.64	10.50	12.95	15.73	19.09	25.55	30.77	37.50
SE	0.72	0.94	1.10	1.26	1.57	1.59	1.84	2.01
Joggers (after run)								
M	6.31	10.09	11.82	14.64	18.55	24.82	30.59	35.32
SE	0.59	0.92	1.18	1.19	1.89	1.53	1.59	1.78
Fitness								
M	6.78	10.18	12.46	14.93	18.62	26.13	32.11	40.32
SE	0.38	0.53	0.66	0.62	0.84	0.98	1.15	1.36
Elderly								
M	7.34	9.81	11.72	15.34	17.38	23.44	27.53	32.06
SE	0.77	1.05	1.19	1.30	1.39	1.36	1.39	1.07
Normative (Proffitt et al., 1995)								
M	4.46	6.81	9.02	12.05	20.22	27.22	35.44	43.53
SE	0.25	0.30	0.44	0.53	1.12	1.42	1.81	2.02

pants' hill judgments changed in response to load, whereas their angle judgments did not.

These angle judgments were then used to test for internal consistency in the slant judgments of the backpackers and the normative participants. The performance of both groups of participants (those with backpacks and those without) on the angle judgment task was used to obtain a prediction of what a participant should have reported visually or haptically for a particular hill given what he or she judged the hill to be verbally (for details, see Appendix A). Regression analyses testing how well these derived scores (for the visual and haptic measures) predicted actual hill judgments revealed little evidence for a reduction in internal consistency in the judgments made by the backpackers. This was to be expected given that the increase in verbal estimates of slant due to the backpack was small.

Thus, it appears from these results that a model proposing constant recalibration of the mapping between visually guided actions and visual awareness cannot adequately account for the data obtained for the backpackers. The verbal and visual overestimation of slant did increase with a decline in behavioral potential due to load, but, as expected, the haptic reports remained accurate, despite a lack of opportunity for recalibration. Therefore, explicit awareness of slant and visual guidance of action seem to function independently over the short term. Had this not been so, and the haptic response was driven by the same representation that informed the verbal response, we would have seen the haptic response increase along with the verbal response, because there was no opportunity for recalibration. However, the presence of internal consistency in the normative participants in previous experiments precludes complete independence, suggesting that the two systems must maintain calibration over some duration. The next experiment was conducted to test whether the mapping between awareness of slant and visually guided actions is recalibrated over a short length of time of about an hour.

Experiment 2: Fatigue Study

Experiment 2 (similar to Experiment 5 of Proffitt et al., 1995) tested for the effect of fatigue on slant perception by having the participants go on an exhausting run. It also tested the participants for internal consistency to see whether the time spent during the runs was sufficient to recalibrate the mapping between the visual awareness of slant and visually guided actions directed at inclines.

Method

Participants. The participants were 40 students from the University of Virginia (20 men and 20 women) who habitually ran three times a week at approximately 4.8 km (3 miles) per run. Participants were either paid \$5 or given course credit toward an introductory psychology course.

Stimuli. Two hills (5° and 31° in inclination) on the grounds of the University of Virginia (the same hills used in Experiment 1) were used.

Apparatus. The same apparatus was used to record the verbal, visual, and haptic responses of the participants.

Procedure. Participants performed the hill and angle judgments both before and after their runs. As part of the hill judgment task, participants judged the inclination of two hills, one before and one after an exhausting run that lasted anywhere between 45 and 75 min. Participants were given the starting and finishing points for their run, which were the 5° and 31° hills, respectively, for half of the participants and the 31° hill and the 5° hill for the other half; however, participants were not told that their starting and finishing points would be hills. They then went on a run of their own choosing (i.e., there were no constraints on the length, route, duration, or terrain of the runs other than that participants be exhausted when they reached the finishing point).

Participants were taken to the base of the starting hill and asked to judge the inclination of the hill on the three measures, along with a set of distractor questions pertaining to length of runs, the terrain people chose to run over, and so forth. Participants were then asked to adjust either the visual or the haptic measure to a set of verbally given angles. As in Experiment 1, the following angles were used: 5°, 10°, 15°, 20°, 30°, 45°, 60°, and 75°. Next, participants started off on their runs. On completing the run, they were met at the finishing hill and were first asked to provide a self-report on their fatigue levels. These reports were verified by the experimenter by a visual inspection of the state of the runner as well as by asking whether he or she would like to continue running. When participants responded no, they were asked to judge the inclination of that hill, along with some more distractor questions. They also performed the angle judgment task on either the visual or the haptic measure, the same measure as the one they had used before the run.

Results and Discussion

Hill judgments were compared from before the run and after in a 2 × 2 ANOVA testing the effects of sex and the order in which each hill was seen (before the run vs. after) on the verbal, visual, and haptic measures for the 5° and 31° hills. As predicted, the exhausting run reduced the participants' physiological potential and, consequently, increased their verbal and visual overestimations of these inclinations. This increase in overestimation was evidenced for both the verbal and visual reports but not for the haptic report. For the 5° hill, the interaction between order (before run vs. after run) and measure was significant, $F(2, 72) = 3.66, p < .05$; further analyses revealed that the reason was that, as predicted, the effect of order was significant for the verbal, $F(1, 36) = 6.72, p < .05$, and visual, $F(1, 68) = 10.76, p < .01$ measures, but not for the haptic measure, $F(1, 36) = 1.89, p = .18$.

Similarly, for the 31° hill, the interaction between measure and order was significant, $F(2, 72) = 4.84, p < .05$, again because the effect of order was significant for the verbal, $F(2, 36) = 8.87, p < .01$, and visual, $F(2, 36) = 10.14, p < .01$, measures but not for the haptic measure, $F(2, 36) = 0.03, p < .85$. The effect of sex and the interaction between sex and order were not significant for either of the two hills tested. Figure 5 and Table 2 present the judgments of the joggers both before and after their runs for the two hills on the three measures.

The increases in overestimation for the 5° hill were 6.5° (31%) for the verbal reports, 8.55° (45%) for the visual reports, and 1.55° (20%) for the haptic reports. For the 31° hill, the corresponding increases were 10.85° (22%), 8.9° (19%), and 0.45° (2%). These findings replicate the results

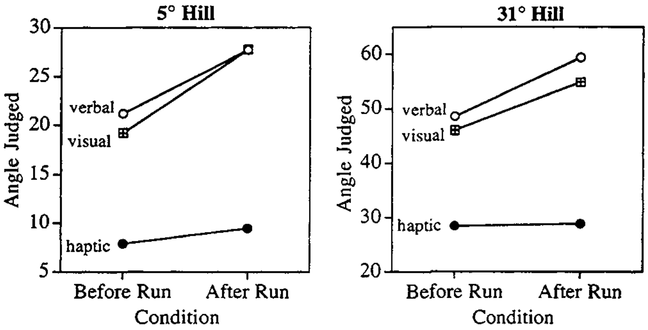

Figure 5. Judgments of geographical slant for the 5° and 31° hills by participants before and after a tiring run on the verbal, visual, and haptic measures: Experiment 2.

obtained in Proffitt et al.'s (1995) Experiment 5. Analyses revealed no significant differences between the results of this study and Experiment 5 of that article. The results are also very similar to the findings for the backpackers, although the magnitude of change was greater for the joggers than for the backpackers. Figure 6 presents a comparison of the results obtained for the normative participants, the backpackers, and the joggers after their runs.

Angle judgments on the visual and haptic measures for the angles given verbally before the run were compared with those given after the run. They were found to be unaffected by the fatigue manipulation. Although hill judgments increased in response to fatigue, angle judgments were unchanged, indicating that recalibration had not occurred during the period of the runs. This was seen by looking at the angle judgments on both the visual and haptic measures for the effect of order (before run vs. after run) and angle. Results revealed that there was no difference in the angle judgments of the participants from before the run to after for either measure: visual, $F(1, 252) = 0.03$, $p = .87$, and haptic, $F(1, 348) = 0.01$, $p = .92$ (see Figure 7 and Tables 3 and 4).

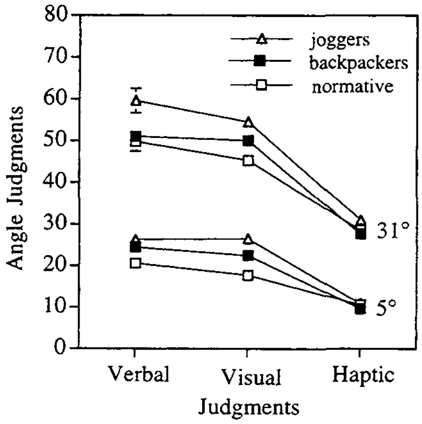

Figure 6. Judgments of geographical slant for the 5° and 31° hills by the normative participants, backpackers, and fatigued joggers on the verbal, visual, and haptic measures: Experiment 2.

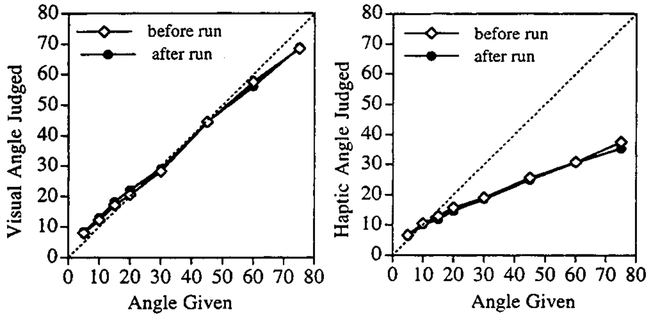

Figure 7. Angle judgments by the joggers before and after runs, made in response to verbally given angles on the visual and haptic measures: Experiment 2.

Because verbal judgments of slant made after the run showed an increase but angle judgments remained unchanged, a loss of internal consistency was evident. Derived scores for the before- and after-run judgments were obtained on the basis of the angle judgments, and regression analyses tested how well the derived scores for the visual and haptic measures could predict actual participant performance on the hills (see Figure 8). Results revealed that the R^2 value for the haptic measure declined for the after-run judgments relative to the before-run judgments (dropping from .67 to .51). For the visual measure, the R^2 value remained essentially unchanged (.77 before the run vs. .75 after the run).

The results of the fatigue manipulation were similar to the backpack data: Participants overestimated the inclinations of hills on the verbal and visual measures more when they were tired, whereas their haptic reports remained unaffected. This again shows a dissociation between visually guided actions and visual awareness. In addition, despite the opportunity to recalibrate the mapping between the two systems (during the run), we found that the angle judgments of the participants remained unchanged, indicating that the time permitted by the run was not enough to bring about a recalibration. Experiments 3 and 4 were conducted to test groups with more long-term changes in physiological potential.

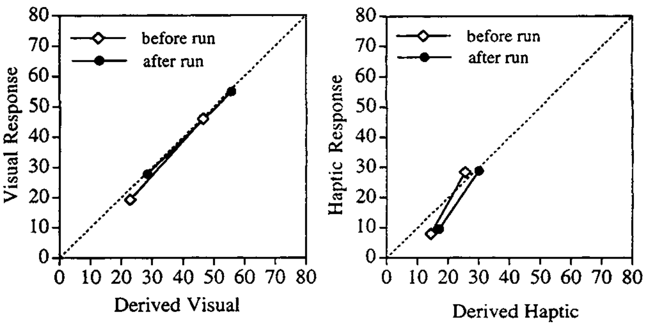

Figure 8. Internal consistency measures for the joggers (before and after runs) on the visual and haptic measures: correspondence between derived scores and actual performance, Experiment 2.

Experiment 3: Fitness Study

This experiment was designed to directly explore the role of level of physical fitness in slant overestimations. Participants included athletes as well as nonathletes, both of whom varied along a continuum of physical fitness. It was expected that slant overestimations would be inversely related to fitness level. Moreover, because these individuals had been at a particular level of physical fitness for a fairly long time, they should have adjusted to it. Hence, the mapping between their actions and conscious awareness was expected to be internally consistent.

Method

Participants. Seventy-four students from the University of Virginia participated, of whom 24 (16 men and 8 women) were members of the cross-country or track team and 50 (23 men and 27 women) were not members of any athletic team. Most participants volunteered in exchange for course credit. Some participants were specially recruited to obtain a better representation of a wide range of fitness than would be possible from testing the normal average population. Toward this end, varsity athletes were recruited to represent above-average fitness. As a means of obtaining below-average fitness participants, sign-up sheets were posted eliciting volunteers to participate in the study who did not work out on a regular basis. These participants made up 4 of the 50 nonathletic participants included in the study. Data from 7 participants (3 men and 4 women) were not included in the analyses because these individuals did not complete the fitness assessment.

Stimuli. Four hills on the grounds of the University of Virginia (5°, 6°, 21°, and 31°) were used.

Apparatus. Participants reported their verbal, visual, and haptic judgments on the same apparatus as the other participants. A Monark stationary bicycle was used for the fitness assessment.

Procedure. Participants performed the hill and angle judgment tasks in one session and underwent the fitness assessment in another session. Some participants took part in the hill judgment session first and then the fitness assessment; others first took part in the fitness assessment. No more than a week was allowed to elapse between the two sessions to ensure that the fitness of the participant did not change significantly over the course of the experiment. For the hill judgment task, participants viewed four hills in a random order and, while standing at the base of each hill, answered some questions about their ability to walk up and down the slope. They were then asked to judge the inclination of the hill on the verbal, visual, and haptic measures. For the last hill, they were also asked to perform the angle judgment task on both the visual and haptic measures for the same eight angles (5°, 10°, 15°, 20°, 30°, 45°, 60°, and 75°) used in the previous two experiments.

On another visit, participants completed the physical fitness assessment test, which was a cycle ergometer test (using the YMCA protocol) designed to determine their cardiorespiratory endurance. They were met at a university gymnasium where their height and weight were measured and their resting heart rate (HR) was assessed by taking their carotid pulse. After a brief warm-up period, assessment began. Participants were instructed to monitor the bike odometer to maintain a steady pedaling rate of 60 revolutions per minute for the 12-min testing period. Pedal resistance was increased in small increments every 4 min (three stages; see Appendix B for details regarding the assessment). HR was recorded in the last 15–30 s of the 3rd and 4th minutes of each of the three stages. Participants were continuously monitored for signs of excessive discomfort or fatigue. The test was terminated at the end of the 12-min testing period or if the participant reached 85% of age-predicted maximal HR or showed signs of excessive discomfort. At the end of the testing session, the participants were allowed an appropriate cool-down period.

Analysis. Four measures of fitness were obtained from all participants. The first three were based on HR. HR difference was the difference between HR at 4 min of exercise (first stage) and HR at 12 min of exercise (last stage). The smaller the change in HR from the first stage to the last, the more fit the individual. The second measure, end HR, was the HR of participants at the end of the testing session. This is also a good indicator of fitness: The lower the HR at the end of the exercise period, the higher an individual's fitness level. The third measure was cardiorespiratory endurance, defined as the ability to perform large-muscle, dynamic, fairly high-intensity exercise for long periods of time. It is considered to be highly correlated with habitual physical activity, with high levels of fitness being associated with higher levels of physical activity. It was measured by estimating maximal oxygen uptake, calculated from the HR response of participants during the incremental exercise. Detailed information about this measure is given in Appendix B. The fourth measure, body mass index (BMI, or the Quetelet index),[2] was calculated for each participant to assess weight relative to height. The BMI scores of the participants were not used in any analyses because, contrary to expectations, we did not obtain enough variability in the BMI scores of participants: The mean for these fitness participants fell in the normal range (values ranged from only 20.95 to 22.04 kg/m^2).

Some preliminary analyses were first performed on the data. A principal-components analysis was performed on the three fitness measures retained (end HR, HR difference, and maximal oxygen uptake) to derive a single, composite "fitness" component that could account for most of the variability between participants on the three fitness measures. Although principal-components analysis yields a few components or dimensions, only the first component derived from the three fitness variables was used in the analyses for the sake of simplicity. It accounted for 79% of the total variability in the data. This yielded a fitness score for each participant, the value of which could range from -2 to 4 (from low fitness to high fitness). A summary of the results for this analysis is given in Appendix C.

Results and Discussion

The slant judgments provided by the participants are presented in Figure 9 on linear (Figure 9a) and log–log (Figure 9b) coordinates for the verbal, visual, and haptic measures (see also Table 2). As can be seen from Figure 9 and as the R^2 values also indicated, both linear and power functions provided a good fit for the data. As with participants in previous studies, these individuals tended to overestimate the inclination of hills, more so on the verbal and visual measures than on the haptic measure. This fact is borne out by looking at the intercept values for the three measures on the linear scale (verbal: 11.09; visual: 10.79; and haptic: 5.10). Analyses (t tests) revealed that judgments of incline made by the fitness participants were significantly different from the actual inclines of the hills for the verbal,

[2] BMI (calculated by dividing body weight in kilograms by height in meters squared) is a relatively good indicator of total body composition and is related to a person's overall health and fitness. Normal BMI scores range from 20 to 25 kg/m^2, and obesity-related health risks begin in the range of 25 to 30 kg/m^2.

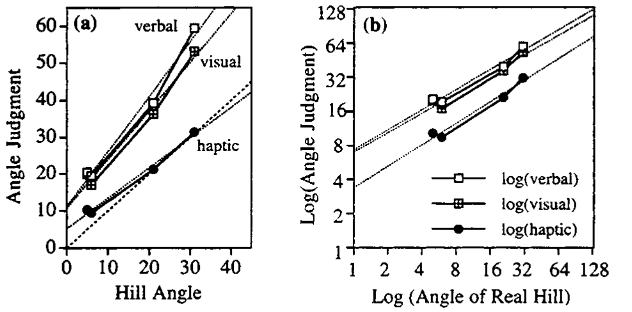

Figure 9. Mean judgments of geographical slant by fitness participants in Experiment 3 for the verbal, visual, and haptic reports. a: Linear coordinates: verbal, $1.495x + 11.092$ ($R^2 = .98$); visual, $1.320x + 10.785$ ($R^2 = .98$); haptic, $0.824x + 5.101$ ($R^2 = .99$). b: Log–log coordinates: verbal, $7.312x^{0.585}$ ($R^2 = .97$); visual, $6.964x^{0.569}$ ($R^2 = .95$); haptic, $3.356x^{0.631}$ ($R^2 = .97$).

$t(271) = 24.86, p < .01$; visual, $t(271) = 27.84, p < .01$, and haptic, $t(271) = 5.83, p < .01$, measures. A log–log transform of the data showed a linear trend (Figure 9b), indicating that a power function also provides a good fit for the curves obtained for the three measures. The exponents obtained were less than 1 for all three measures (verbal: 0.585; visual: 0.569; and haptic: 0.631), indicating response compression.

Regression analyses then examined the relationship between the fitness component and the hill judgments of the participants. As can be seen in Figure 10, a negative correlation between fitness and overestimation of slant on the verbal and visual measures was obtained: As the participants' scores on the fitness component increased (or the more physically fit the individual), verbal and visual overestimation of slant decreased. The haptic responses were unaffected by fitness level. A repeated measures regression analysis of the fitness component for the three measures resulted in a significant interaction between measure (verbal, visual, or haptic) and the fitness component, $F(2, 536) = 4.15, p < .02$. Further analyses revealed that the effect of fitness was significant for the verbal, $F(1, 268) = 9.57, p < .01$, and visual, $F(1, 268) = 5.69, p < .02$, reports but not for the haptic report. For all of the hills, participants judged slant to be steeper on the verbal and visual measures (but not the haptic) when they were less fit than when they were more fit. This is in keeping with the results of Experiments 1 and 2: The lower the behavioral potential to traverse a hill, the greater will be the verbal and visual overestimation of an incline.

Like the hill judgments, the angle judgments were also tested to determine whether they were affected by the physical fitness of the participants. A regression analysis revealed that, for the visual measure, there was no effect of fitness on performance, $F(2, 65) = 0.38, p = .69$. For the haptic measure, although the effect of fitness was not significant overall, the interaction between fitness and angle was significant, $F(7, 462) = 3.26, p < .01$, and further analyses revealed that the effect of fitness was significant for the two steepest hills: 60°, $F(1, 66) = 2.57, p < .05$, and 75°, $F(1, 66) = 3.94, p < .05$. As can be seen in Figure 11, there was a positive correlation between fitness and haptic angle judgments for the 60° and 75° angles.

As before, derived scores were obtained on the basis of the participants' performance on the angle judgment task. As predicted, these derived scores for the visual and haptic measures proved to be good predictors of the participants' performance on the hill judgment task (Figure 12). R^2 values were .84 for the visual measure and .66 for the haptic measure.

The findings of this experiment revealed that physical fitness did influence the hill judgments of participants, in that the more fit an individual, the less she or he overestimated the inclinations of hills on the verbal and visual measures. As before, the haptic measure was the most accurate and remained unaffected by the fitness manipulation.

The findings with the angle judgments were consistent with the recalibration account outlined earlier: Because fitness level represents a long-term influence on participants' perceptions of hills, it should also cause a recalibration in the mapping between visually guided actions and visual awareness. Consequently, hill judgments should be negatively correlated with fitness, whereas angle judgments should be positively correlated with physical fitness. This was found for the two steepest hills. For example, when participants at a low level of fitness looked at a 30° hill, they verbally estimated it to be 60° but set the palm board accurately to

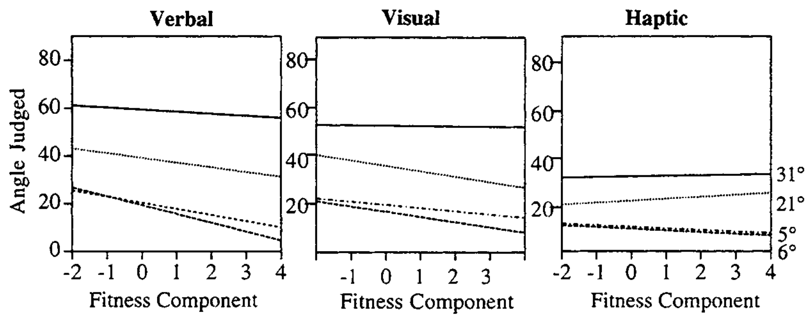

Figure 10. Effect of fitness on mean judgments of geographical slant for four hills by fitness participants on the verbal, visual, and haptic measures: Experiment 3.

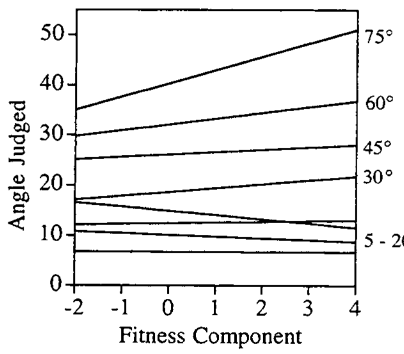

Figure 11. Effect of fitness on angle judgments for eight angles made by fitness participants on the haptic measure: Experiment 3.

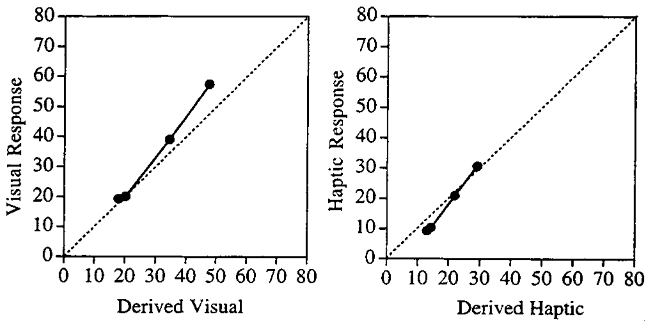

Figure 12. Internal consistency measures for the fitness participants on the visual and haptic measures: correspondence between derived scores and actual performance, Experiment 3.

30°. Accordingly, for the angle judgment task, when participants were asked to set the palm board to 60°, they set it to 30°. Participants at high fitness levels, on the other hand, estimated a 30° hill as 50° and set the palm board to 30°. In the angle judgment task, when participants were verbally given an angle of 50°, they set the palm board to 30°; when given a 35° angle, they set it to 60°.

Experiment 4: Elderly Study

The participants for this study, like the joggers, backpackers, and individuals who were minimally fit, also represented a group that had a reduced physiological potential. However, in this study the reduction arose from old age (participants were 60 years of age and older) and, thus, was probably the most gradual of all. These participants were expected to show greater overestimation of slant with increasing age and declining health and fitness. In addition, like the fitness participants, they were expected to be internally consistent in their responses.

Method

Participants. Participants were 32 volunteers from the community of Charlottesville and surrounding Albemarle County ranging in age from 60 to 87 years ($M = 73$). All had normal or corrected-to-normal vision, with no other major visual problems. Participants also had to be ambulatory and able to walk unaided (except with the use of a cane for some participants). They were recruited from two locations. One was a senior living community that was also the location of four of the hills used in the study. The other was a community center for older adults. This was close to another elderly living community and was the location of the remaining four hills used in the study. Flyers were posted at both locations, and volunteers called in to sign up for the study. They were then scheduled to complete the experiment at the testing location most convenient to them.

Stimuli. Eight slopes at two elderly living communities were used in this study. Four (2°, 3°, 4°, and 25°) hills were at one location, and the remaining four (3°, 5°, 10°, and 29°) were at the other. The criteria for selecting the hills were the same as those used in the previous studies, with the additional safety consideration that participants did not need to leave paved walkways to stand at the base of the hill to judge the inclinations. The six shallow hills were quite familiar to most participants, because most lived near them and had to walk up and down them on a daily basis. The two steep hills were grassy slopes by the sides of roads.

Apparatus. Participants reported their judgments on the same verbal, visual, and haptic measures as the other participants. These participants also filled out a brief self-report questionnaire about their health and general physical fitness (see Appendix D). It has been shown that self-reports of health by the elderly are highly correlated with assessed fitness and physical well-being (e.g., see Friedsam & Martin, 1963; Suchman, Phillips, & Streib, 1958). Participants rated their health and fitness (via 10 questions) on a 5-point rating scale ranging from *poor health–physical fitness* (1) to *excellent health–physical fitness* (5). Totals on the health measure could thus range from 10 to 50.

Procedure. Participants judged four of the eight hills used in the study, depending on the location where they were tested. Participants were first given the self-report questionnaire about their health and general physical fitness to fill out. They were then taken to each of the four hills, where they were asked questions related to the walkability of the hills for a person their age. They were then asked to judge the inclination of the hills, reporting their judgments on all three measures (verbal, visual, and haptic) in one of six counterbalanced orders. After judging the inclination of the four hills, participants adjusted both the visual and haptic measures to a set of verbally given angles (5°, 10°, 15°, 20°, 30°, 45°, 60°, and 75°).

Results and Discussion

The data obtained for the elderly participants were first analyzed to determine whether age and health had any impact on the hill and angle judgments. The elderly participants were then also compared, as a group, with the entire group of young, normative participants tested in an earlier study (Proffitt et al., 1995). This normative group consisted of 300 (150 male and 150 female) student-aged participants tested earlier who provided their judgments on one of nine hills (2°, 4°, 5°, 6°, 10°, 21°, 31°, 33°, and 34°).

Figure 13 presents the results from the elderly participants. Figure 13a displays the results on linear coordinates, and Figure 13b displays the results on log–log coordinates. These participants, like the participants in all previous experiments, tended to overestimate the inclinations of hills on the verbal and visual measures. The haptic reports, as usual, were the most accurate (see also Table 2).

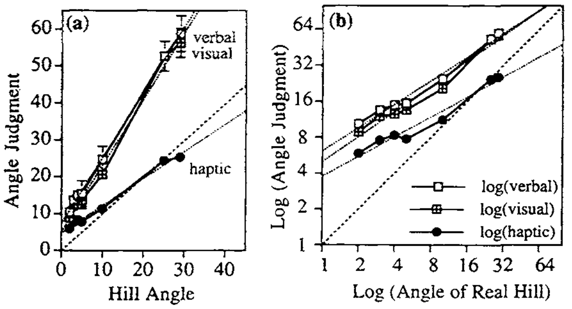

Figure 13. Mean judgments of geographical slant by elderly participants in Experiment 4 for the verbal, visual, and haptic reports. a: Linear coordinates: verbal, $1.790x + 7.242$ ($R^2 = .99$); visual, $1.809x + 5.040$ ($R^2 = .99$); haptic, $0.738x + 4.698$ ($R^2 = .99$). b: Log–log coordinates: verbal, $6.127x^{0.653}$ ($R^2 = .98$); visual, $4.967x^{0.702}$ ($R^2 = .97$); haptic, $3.748x^{0.553}$ ($R^2 = .96$).-

In addition to a linear function, a power function also provided a good fit for the data, seen in the linear trend in the log–log transformation of the data. The exponents obtained were all less than one; moreover, the exponents for the verbal and visual measures were greater than those obtained in Experiment 3 (Fitness Study) as well as those obtained by Proffitt et al. (1995) for their normative data in Experiment 1. The exponents for the elderly data were verbal, 0.65; visual, 0.70; and haptic, 0.55. Those for the fitness data were verbal, 0.59; visual, 0.57; and haptic, 0.63. Finally, those for the normative data in Proffitt et al. (1995) were verbal, 0.59; visual, 0.64, and haptic, 0.76. These larger exponents obtained for the elderly data indicate a greater sensitivity to larger slopes on the part of the elderly participants than on the part of the younger student population tested in the other two experiments. In the case of the elderly, an increased sensitivity to changes in steeper angles is behaviorally quite important in helping them gauge which slopes are traversable and which are too dangerous to attempt for a person their age.

Analyses (t tests) revealed that, as expected, slope judgments made by the elderly were significantly different from the actual inclines of the hills: verbal, $t(127) = 12.65, p < .01$; visual, $t(127) = 12.17, p < .01$; and haptic, $t(127) = 13.83, p < .01$. Unlike results from previous studies, the effect of sex on slant judgments was not significant for the elderly participants. Because the participants were tested in two different locations, analyses were conducted to determine whether location of the hill had any significant effect on the participants' reports. The difference was not significant.

A repeated measures regression analysis tested how well the age and health ratings of the elderly participants predicted their performance on the hill judgment task. On the verbal measure, it was found that, overall, the effects of health and age were not significant; however, the interaction between hill incline and age was significant, $F(1, 123) = 68.57, p < .01$, as was the interaction between hill incline and health ratings, $F(1, 123) = 6.71, p < .05$. Similarly, for the visual measure, the overall effects of age and health were not significant, but the interactions between hill angle and age, $F(1, 123) = 51.64, p < .01$, and between hill angle and health, $F(1, 123) = 5.90, p < .01$, were significant. Neither age nor health nor any of the interactions were significant for the haptic reports.

Next, the hills were grouped into shallow (2°, 3°, 4°, 5°, and 10°) and steep (25° and 29°) categories, and separate regression analyses were conducted for each set of hills for age. Results revealed that there was no effect of age on slope judgments for shallow hills. The regression analysis for the steeper hills yielded an interaction between measure and age, $F(2, 60) = 5.43, p < .01$, and this was borne out by the fact that the effects of age were significant for the verbal measure, $F(1, 30) = 8.81, p < .01$, but not for the visual, $F(1, 30) = 2.98, p = .09$, and haptic, $F(1, 30) = 0.05, p = .82$, measures (see Figure 14a). Thus, age was positively correlated with verbal hill judgments for steep hills: As age increased, so did verbal overestimations of slant.

Similarly, the regression analysis for the shallow hills did not yield a significant relationship between health ratings and slope judgments. However, as can be seen in Figure 14b, and as was revealed by the regression analyses for the steeper hills, there was a significant interaction between health and measure, $F(2, 60) = 4.481, p < .05$, again shown in the significant effect of health on the verbal, $F(1, 30) = 7.22, p < .05$, and visual, $F(1, 30) = 4.48, p < .05$ measures, but not the haptic measure, $F(1, 30) = 0.21, p = .65$. Thus, health was negatively correlated with verbal and visual hill judgments for steep hills: As health improved, verbal and visual overestimations of slant tended to decrease. The results regarding the effect of age and health on hill judgments indicate that the older and less healthy elderly participants tended to overestimate (verbally and visually, not haptically) the slopes of hills more than did other elderly participants who were younger and healthier than them. But this effect was seen only for the two steepest hills used in the study, namely the 25° and 29° slopes.

Hill judgments made by the elderly were also compared with the hill judgments obtained from the young, normative participants by Proffitt et al. (1995) in their Experiment 1 (see Figure 15). A 2 × 2 ANOVA examining the effect of age group (young vs. old) and sex (male vs. female) on judgments of slant revealed that, overall, there was no significant difference between the elderly and young participants on the verbal, visual, and haptic measures; however, there was a significant interaction between hill and age group for the verbal, $F(1, 336) = 9.75, p < .01$, and visual, $F(1, 336) = 6.43, p < .05$, measures but not for the haptic measure. The hills were segregated into steep and shallow categories in the same way as for the previous analyses, and the effect of age group was then tested. The shallow hills did not show an effect of age group for any of the measures. The effect of age group for the steep hills was significant for the verbal, $F(1, 148) = 5.37, p < .05$, and visual, $F(1, 148) = 7.60, p < .01$, measures but not for the haptic measure. These results are consistent with the findings obtained by comparing the elderly participants within their group: Just as those elderly participants who were older (and less healthy) verbally and visually overestimated the slants of steep hills more than their younger (and more healthy) counterparts,

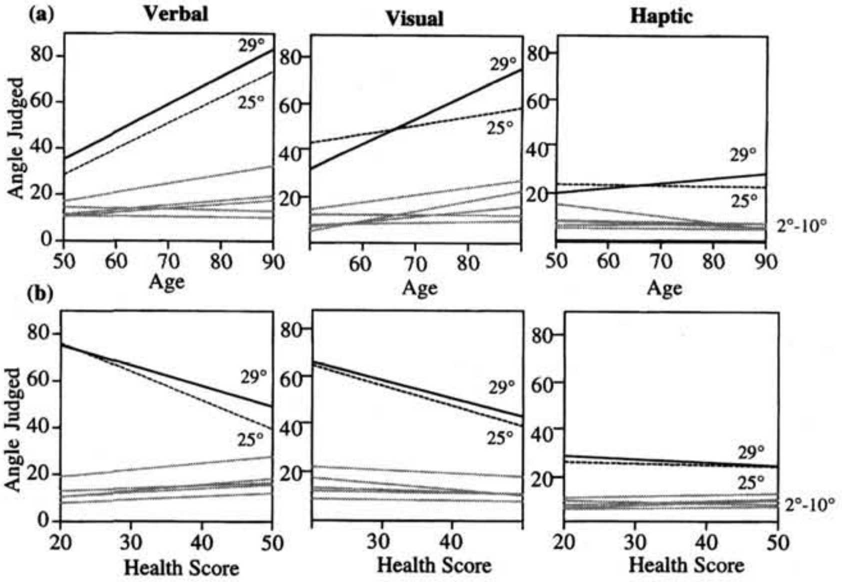

Figure 14. Effect of age (a) and health ratings (b) on mean judgments of geographical slant by elderly participants on the verbal, visual, and haptic measures for steep hills and shallow hills: Experiment 4.

overall the elderly overestimated (verbally and visually) the slants of steep hills more than did a younger, student-aged sample. Their haptic judgments, on the other hand, were no different.

As with the hill judgments, angle judgments made by the elderly were tested to determine whether they were affected by the age and health of the participants. A regression analysis revealed that angle judgments by the elderly for the visual measure were not affected by health or age. Although, for the haptic measure, there were no significant effects overall, the interactions between age and angle, $F(1, 251) = 16.45$, $p < .01$, and between health and angle, $F(1, 251) = 14.11$, $p < .05$, were significant. Further analyses revealed that the effect of age on angle judgments was significant only for two angles: 60°, $F(1, 30) = 6.98$, $p < .05$, and 75° $F(1, 30) = 7.37$, $p < .05$. Similarly, the effect of health on angle judgments was significant only for the two steeper angles: 60°, $F(1, 30) = 6.84$, $p < .05$, and 75°, $F(1, 30) = 7.96$, $p < .05$. As can be seen in Figure 16, there was a negative correlation between age and haptic angle judgments, and there was a positive correlation between health and haptic angle judgments for the two steeper angles.

This indicates recalibration as well as good internal consistency in the judgments of the elderly participants, because the change in angle judgments was consistent with the increase in their verbal estimates of slope. Whereas the older and less healthy elderly participants showed greater verbal *over*estimation of hill inclines than the younger and more healthy elderly participants on the verbal and visual measures for steep hills in the hill judgment task (Figure 14a and Figure 14b), they showed a larger *under*estimation of angles in the angle judgment task than their younger and more fit counterparts on the haptic measure for the steep angles (Figure 16). This indicates that the elderly participants were internally consistent in their judgments. For example, if younger (and healthier) participants looked at a

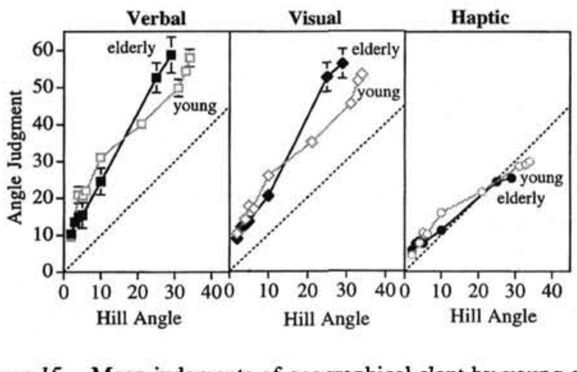

Figure 15. Mean judgments of geographical slant by young and elderly participants compared on the verbal, visual, and haptic measures: Experiment 4.

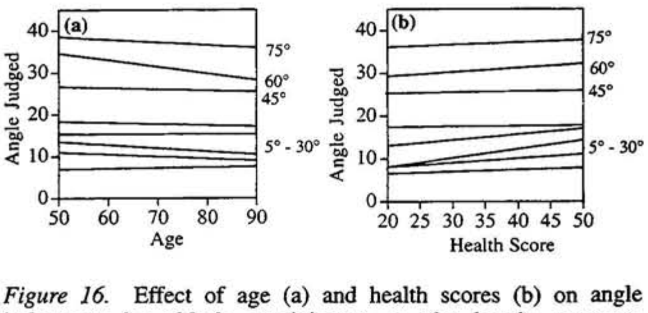

Figure 16. Effect of age (a) and health scores (b) on angle judgments by elderly participants on the haptic measure: Experiment 4.

30° hill, they verbally judged it to be 50° and set the palm board accurately to 30°. Accordingly, for the angle judgment task, they set the palm board to 30° for a verbally given angle of 50°. In contrast, the older (and less healthy) participants verbally judged a 30° hill to be 60° and set the palm board to 30°. In keeping with their judgments for hill inclines, these participants set the palm board to 30° when verbally asked to set it to 60° and to 25° when asked to set it to 50°.

The angle judgments of the elderly participants were also compared with those of the young normative participants (Proffitt et al., 1995). Because some of the young normative participants had set the visual or haptic measure to one subset of angles (5°, 10°, 15°, and 20°) and others had set the measures to another subset (15°, 30°, 45°, 60°, and 75°), two regression analyses were run, one comparing the slopes of the functions for the shallow angles for the two age groups and another examining the steep angles. A regression analysis for the steep angles revealed that the angle judgments for the haptic measure made by the elderly participants were significantly lower than those made by the young participants, $F(1, 381) = 12.81, p < .01$ (see Figure 17). No significant differences were obtained on the visual measure for the steep angles. Also, no significant differences were found for the shallow angles for either the haptic or the visual measure (see Tables 3 and 4 for means and standard errors).

These results point to a recalibration within the elderly age group and show that not only were their hill judgments affected by age and health, but so were their angle judgments, and in a manner that indicates that they were just as internally consistent as the younger participants. This is borne out by the derived scores for the elderly participants. As expected, these derived scores for the visual and haptic measures proved to be good predictors of elderly participants' performance on the hill judgment task, as can be seen in Figure 18 (the R^2 value for the visual measure was .76, and the R^2 value for the haptic measure was .62). These values were similar to those seen for the young participants in Experiment 1 (Proffitt et al., 1995), in which the R^2 values were .76 for the visual measure and .62 for the haptic measure.

The fact that the only significant difference in angle judgments involved the steep hills corresponds to the finding that the less healthy and older participants tended to differ from the healthier and younger participants on hill judgments only on the steep hills. There was no difference among the elderly participants on the shallow hills, so there was no reason to expect a difference in their angle judgments for the shallow angles.

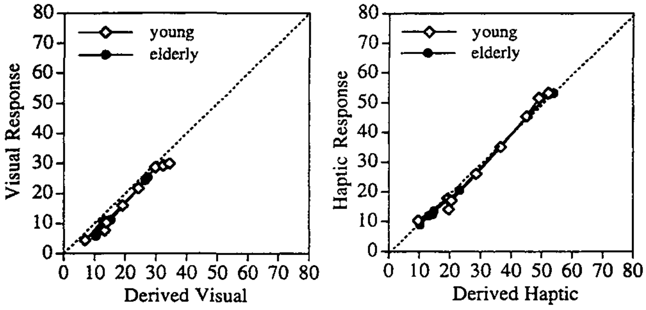

Figure 17. Angle judgments for the elderly and young participants on the visual and haptic measures: Experiment 4.

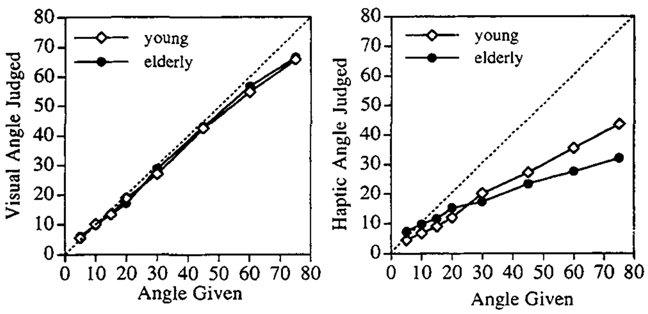

Figure 18. Internal consistency measures for the elderly and young participants on the visual and haptic measures: correspondence between derived scores and actual performance, Experiment 4.

Thus, the results for the elderly participants show that judgments of inclination are indeed affected by a reduction in physiological potential brought on by a decline in health and levels of physical activity associated with old age. The older and less healthy participants tended to overestimate the slant of steep hills on the verbal and visual measures more than the participants who were younger or more healthy. Moreover, similar results were seen when all of the elderly participants were compared with a younger, student-aged sample tested previously. In addition, the elderly participants exhibited a recalibration of the mapping between visually guided actions and visual awareness, as well as good internal consistency in their judgments, because the change in angle judgments was consistent with the increase in their verbal estimates of slope.

General Discussion

The results of the four experiments support three important generalizations. First, they show that perceived geographical slant is not only exaggerated in conscious awareness but can also be influenced by a person's physiological potential. Neither of these findings hold true for visually guided actions. Second, despite this dissociation between conscious awareness and visually guided actions, it is clear that these two systems are interconnected, in that actions can be guided by conscious representations. Finally, these studies also show that the interconnection between the awareness and guidance systems recalibrates slowly with long-term changes in physiological potential. These findings have important implications for an understanding of geographical slant perception in particular and the visual system in general.

Exaggeration of Geographical Slant

These experiments reveal that conscious awareness of geographical slant is highly exaggerated, whereas a motoric response provides far more accurate estimates. Furthermore, the data show that the participants' explicit slant judgments exhibited response compression. Such ratio-scaled magnitude estimations have functional utility in that they allow for higher sensitivity to slant changes at small values relative to larger ones. This is especially significant, because the slopes that people can traverse and normally encounter in their daily lives are, even by generous estimates, no more than 30°. Hence, noticing very small changes in this range has important implications for decisions regarding locomotion. On the other hand, changes in angles that lie beyond one's ability to act on them do not need the same degree of sensitivity.

Influence of Physiological Potential

Not only is conscious awareness of slant exaggerated, but it is also malleable in that it is affected by people's physiological potential: Hills look steeper to people who are encumbered, tired, of low fitness, elderly, or in declining health. Thus, changes in physiological potential influence apparent slant regardless of whether the changes are short term and temporary, such as those seen for the backpackers and the joggers, or more long term or permanent, such as those seen for the fitness and elderly participants. Any change in the capacity to traverse hills will also bring about a change in the conscious awareness of their slant. In contrast, visually guided actions are accurate and remain unaffected by changes in physiological potential.

Interrelation of Awareness and Action

Despite the differences between visual awareness and the visual guidance of actions, there is also a mapping between them that promotes internal consistency. Clear evidence for an interconnection is seen in the consciously mediated haptic responses made by the normative participants in our earlier studies (Proffitt et al., 1995). In particular, it was found that the haptic response to a hill of a given incline is the same as the haptic response to a verbally given angle that is evoked when viewing that incline, implying that haptic judgments are calibrated to the apparent slant overestimations that inform verbal reports.

Recalibration of Mapping Between Awareness and Action

Physiological potential is important not just for conscious awareness of slant but also in the relationship between visual awareness and visually guided actions. Our results show that if a change in physiological potential is long term, then it also brings about a change in the transformation relating conscious awareness and visually guided actions. This was most clearly seen in the elderly participants. Not only did they report that steep hills appeared steeper than did young participants, but also they set the palm board to verbally given angles in a manner that was consistent with their more exaggerated hill judgments. Similar results were seen for the participants who had been at their levels of fitness for an extended period of time. When the change in physiological potential was of a temporary nature (wearing a backpack) or lasted for a short duration (fatigue), no recalibration of the mapping between conscious awareness and motoric actions was observed. These changes can be considered temporary and reversible in nature.

This process can be illustrated by the following example. Suppose that a typical young adult is standing at the base of a 5° hill. The hill will appear to be 20° to her, whereas her motor adjustment to the hill will be 5°. When later asked to provide motor adjustments to a range of verbally given angles, she will make a 5° adjustment when instructed to make one of 20°. Now suppose that this individual becomes fatigued. She now perceives the 5° hill to be steeper, say 25°; however, her motor behavior remains unaffected. When given a verbal instruction to provide a motor adjustment of 20°, she will provide a 5° response, as was the case before fatigue set in. A 25° instruction will evoke a motor adjustment of 7°, indicating a slight loss of internal consistency. Now consider another observer at a low level of physical fitness. When viewing the 5° hill, he reports that it is 25° but makes an accurate 5° motor adjustment. When asked to make a motor adjustment of 25°, he provides a 5° response. This individual exhibits an internal consistency between conscious representations and motoric actions.

Visual Awareness and Guidance: Nearly Decomposable Systems?

The differences between awareness and guidance arise from the different functions that these systems subserve. Explicitly perceived steepness provides information about the affordances of hills, including the possibility of and effort entailed in traversing them. An important function of conscious awareness of slant is to inform the planning and modulation of gait so as to expend energy at a desired rate. Slant overestimation serves this purpose by exaggerating the apparent steepness of hills and thereby increasing sensitivity to small inclines within the range of people's physiological potential. The increase in apparent slant that occurs with a decrease in physiological potential further facilitates the planning of actions. People do not have to assess their physiological state before planning a hill's ascent. Their physiological state has already influenced their perception of the hill's steepness. This also relates to why the effect of physiological potential in the elderly participants was seen only for the steeper slopes: With increasing age or declining health, not only does the ability to traverse steep hills decline, but it would be dangerous to attempt to traverse these hills. Hence, such slopes appear steeper and more difficult, thereby promoting a tendency toward cautiousness that is often seen in other contexts as well (e.g., see Salthouse, 1979).

In contrast, the task of visually guiding one's feet over inclines is accurate and unchanging, and it requires the veridical evaluation of surface layout for effective interaction with the immediate environment. Regardless of one's physiological potential to traverse a slope, one needs an accurate judgment of the motoric demands of the task, and hence visually guided actions are not participant to any of the biases observed in the conscious awareness of hills. This account is consistent with the distinction between the "what" and "how" systems proposed by Milner and Goodale (1995), in which the distinction between the two systems is rooted in a functional rather than an informational dissociation. The information supporting the explicit perception of slants and the actions directed at them is very similar, but the use to which this information is put varies considerably.

Nevertheless, one cannot ignore the evidence for cross talk between the two systems. This is seen in the internal consistency between motor adjustments made in viewing hills and those made in response to verbal instructions. As reviewed in the introduction, the finding that the visual awareness and guidance systems are dissociable in terms of function but also are interconnected is not new. Mounting electrophysiological and neuropsychological evidence suggests that the seamless, harmonious functioning between awareness and guidance is the result of connections between the "what" and "how" systems. In many situations, the "what" system may need to identify an object before an appropriate action can be initiated.

Not only do the visual awareness and guidance systems communicate in planning and initiating actions, but there exists a mapping between the two systems that is recalibrated over the long term as a result of fairly permanent changes affecting the individual. Short-term changes, on the other hand, are not adequate to revise the mapping between visually guided actions and conscious awareness. Thus, changes in physiological potential commensurate with old age not only cause a change in the conscious awareness of slant but also result in a reworking of the mapping that relates explicit representations of slant to actions driven by them.

This description of dissociable systems that recalibrate to each other gradually is consistent with Simon's (1990) discussion of near decomposability. Simon pointed out that, within hierarchical systems, the interactions between subsystems are usually "weak but not negligible" (p. 210). A system can be considered to be completely decomposable if the behavior of its subsystems is mutually independent over all time scales. Organisms in general, and the visual system in particular, cannot be considered to be completely decomposable but only to be nearly so, because, in the long run, their subsystems are influenced by the aggregate behavior of the larger system to which they belong (Proffitt, 1993).

The data described here suggest that there are important interconnections between the visual awareness and guidance systems that are modified over long-term changes affecting the individual. The visual system is "decomposable" because the behavior and functioning of its subsystems are independent of one another over the short run. Conscious awareness of slant is subject to short-term influences, such as fatigue, that affect one's physiological potential, whereas visually guided actions are accurate and unchanged by such factors. But it is a *nearly* decomposable system because in the long run, these subsystems maintain an internal consistency with each other, and, despite dissociation, the mapping between them is modified as a result of long-term or irreversible changes in the individual, such as a change in physiological potential due to declining health and fitness in old age.

Conclusions

These studies support three main conclusions. One is that conscious awareness of a hill's incline is influenced by people's physiological potential to climb it. Conscious slant perception is malleable and changes as the physiological potential of the observer changes, regardless of whether these changes are long or short term. Hills appear steeper to someone who is wearing a heavy load, tired, of low fitness, elderly, or in poor health. Visually guided actions are accurate and unaffected by changes in physiological potential. The second conclusion is that, despite their seemingly independent functioning, there exists an interconnection between conscious awareness and visually guided actions. People exhibit an internal consistency between their visually guided actions and actions made in response to verbal instructions. The third conclusion is that this interconnection between the two systems recalibrates slowly. Evidence for recalibration was observed in response to relatively permanent determinants of physiological potential (fitness, age, and health) but not transitory ones (load and fatigue).

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Appendix A

Calculation of Internal Consistency Measure

Angle judgments obtained from the participants were used to test for internal consistency in their judgments. Regression equations were used to derive, from the participants' angle judgments, a prediction of what a participant should have reported visually or haptically for a particular hill, given what he or she judged the hill to be verbally. This was done in the following manner (the example discusses the procedure in terms of the haptic reports, denoted by H_i; the same procedure was used for the visual measure).

1. The equation describing the line used to fit the data obtained for participants' performance on the angle judgment task was derived.

2. In this equation—$y = (x) + C$—the value of Ve_i was substituted for x to yield the derived haptic score, $H^*_i = (Ve_i) + C$, where Ve_i is verbal judgment to hill of slant i and H^*_i is derived haptic adjustment to Ve_i. A simple regression analysis was then conducted to test how well these derived (H^*_i [haptic] and Vi^*_1 [visual]) scores predicted the actual (H_i [haptic] and Vi_1 [visual]) reports that participants gave for each of the hills.

Appendix B

Fitness Assessment and Calculation of Maximal Oxygen Uptake

Traditionally, the criterion measure of cardiorespiratory endurance, maximal oxygen uptake (VO_{2max}), is measured directly and is expressed relative to body weight (i.e., $ml \cdot kg^{-1} \cdot min^{-1}$). It involves the analysis of expired air samples collected while an individual performs exercise of progressive intensity. Because direct measurement of VO_{2max} was not feasible in our study, it was calculated from heart rate (HR) at a specified power output, recorded when the participants were performing submaximal exercise of increasing intensity.

To accurately determine the relationship between a participant's HR and his or her VO_2 during progressive exercise, we measured HR at three submaximal exercise intensities (or work rates) represented by three resistance settings. These resistance settings were used in the three stages of the fitness assessment and were appropriate for the cycle ergometer used in the study, which had a 6 meters per revolution flywheel. The first stage began with a resistance of 1.0 kg (at 60 km/hr), yielding a work rate of 360 kg · m/min (6 m/rev × 60 rev/min × 1.0 kg). In the second stage the resistance was increased to 1.5 kg, and in the third stage it was increased to 2.0 kg. HR measured during the last minute of each stage was then plotted against work rate and used to extrapolate the age-predicted maximal HR for each participant. A corresponding maximal work rate and VO_{2max} were then estimated. (A detailed account of the steps is provided subsequently.)

Submaximal exercise tests make several assumptions. The first is that a steady-state HR is obtained for each exercise work rate. This was ensured by measuring participants' HR in the 3rd and 4th minutes at each work rate; if there was a difference of more than 5 beats per minute from the 3rd to the 4th minute, exercise at that level was continued for another minute, and HR was measured again. The second assumption is that a linear relationship exists between HR and oxygen uptake. This was checked for all participants by plotting HR against work rate (which was representative of oxygen uptake), and for the majority of the participants the relationship was a linear one. The third assumption is that a maximal HR for a given age is uniform. Finally, the fourth assumption is that mechanical efficiency (i.e., VO_2 at a given work rate) is the same for everyone. All of these assumptions are not always met, however, and this contributes to errors in predicting VO_{2max}. It is nevertheless a reasonably accurate reflection of an individual's fitness level.

Before VO_{2max} for a leg cycle ergometry protocol was calculated, the data were converted to appropriate units. Weight in pounds was converted to kilograms; speed in miles per hour was converted to meters per minute. Because the activity was a non-weight-bearing activity (cycling), VO_2 was transformed to milliliters per minute.

Every metabolic equation considers three components of energy expenditure: a resting component (R), a horizontal component (H), and a vertical component (V). The sum of the three ($R + H + V$) equals the entire energy cost of the activity (VO_2 in milliliters per minute). The following steps were followed to obtain the three components:

1. $R = 3.5\ ml \cdot kg^{-1} \cdot min^{-1} \times$ body weight in kg (multiplication by body weight converts $ml \cdot kg^{-1} \cdot min^{-1}$ into ml/min).
2. $H = 0$ (because there is no horizontal component for this activity).
3. $V = 2.0 \times$ power output (in kgm/min), where 2.0 is the regression constant for converting kgm/min to ml/min and power output (in kgm/min) is resistance or tension setting on the ergometer multiplied by meters per pedal revolution (6 m/rev for the Monark ergometer used in this study) and pedal rate (held constant at 60 rev/min for all participants).
4. The relationship between a participant's HR response and his or her VO_2 was then used to predict his or her VO_{2max}.

(Appendixes continue)

Appendix C

Principal-Components Analysis Results

Eigenvalues	Value		Variance proportion
e1	2.371		79.0
e2	0.494		16.5
e3	0.135		4.5
Eigenvectors	**1**	**2**	**3**
HR difference	0.584	0.534	0.611
VO_{2max}	0.528	0.822	0.214
End HR	0.617	0.198	0.762
Unrotated factor matrix	**1**	**2**	**3**
HR difference	−0.899	−0.375	−0.225
VO_{2max}	−0.812	0.578	−0.709
End HR	0.950	0.135	−0.280

Note. "Fitness" component = −0.01537732 × End HR − 0.03238466 × HR Difference + 0.00033828 × VO_{2max} + 2.3089897. (A linear combination of the original three fitness measures—end HR, HR difference, and VO_{2max}—along with a constant term to adjust for the means of the measures and to take into account the contribution of each variable to the new component, provided an estimate of the score the participant would have received on the fitness component had it been measured directly.) HR = heart rate; VO_{2max} = maximal oxygen uptake.

Appendix D

Health Questionnaire

1. I would rate my health at the present time as being (much better/better/average/worse/much worse) compared with other people my age.
2. Relative to other people my own age, I am a (very strong/strong/average/weak/very weak) walker in terms of ease and endurance.
3. I (very often/often/sometimes/rarely/never) worry about my health.
4. Relative to other people my age, I think I am (much more/more/average/less/much less) physically fit. ("Fit" here implies the ability to participate in physical exercise, etc.)
5. In terms of my attitudes and thinking I see myself as being (much older/older/my age/younger/much younger) than my actual age.
6. Relative to other people my age, I engage in (much more/more/average/less/much less) physical exercise.
7. During the past year I have (very often/often/sometimes/rarely/never) had to change or cut down on my daily activities such as driving, gardening, taking walks and the like, because of my health or physical condition.
8. Do you have any particular physical or health problems at present? If yes, how severely debilitating is this problem for you? (very severe/severe/average/minor/very minor)
9. Have you been seen by a doctor during the past year for any of the following? If yes, please indicate the number of times.
   For illness (yes or no)
   For first aid/accident (yes or no)
   For regular exam (yes or no)
10. Have you been admitted to the hospital for any reason during the past year? (yes or no)

Received September 11, 1997
Revision received March 13, 1998
Accepted July 13, 1998 ■