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Perception of Visual Speed While Moving

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During self-motion, the world normally appears stationary. In part, this may be due to reductions in visual motion signals during self-motion. In 8 experiments, the authors used magnitude estimation to characterize changes in visual speed perception as a result of biomechanical self-motion alone (treadmill walking), physical translation alone (passive transport), and both biomechanical self-motion and physical translation together (walking). Their results show that each factor alone produces subtractive reductions in visual speed but that subtraction is greatest with both factors together, approximating the sum of the 2 separately. The similarity of results for biomechanical and passive self-motion support H. B. Barlow's (1990) inhibition theory of sensory correlation as a mechanism for implementing H. Wallach's (1987) compensation for self-motion.

It has been reported that the perceived speed of an expanding flow field is reduced if that flow field is viewed by a person walking on a treadmill (Distler, Pelah, Bell, & Thurrell, 1998; Pelah & Thurrell, 2001; Pelah, Thurrell, & Berry, 2002; Thurrell & Pelah, 2002; Thurrell, Pelah, & Distler, 1998). Such reductions are predicted by Barlow's (1990) model of contingent adaptation. According to this theory, highly correlated events, such as walking and expanding flow fields, mutually specify each other—as can be learned by perceptual experience—and therefore produce shifts in coding strategies that take advantage of the redundancy. According to Barlow, these coding shifts are produced by the strengthening of inhibitory connections between neural units that are simultaneously active. Such inhibitory strengthening can lead both to sparse coding and to contingent adaptation, such as that in the McCollough effect (McCollough, 1965). The perceived reduction of speed while walking, on this account, serves the function of de-emphasizing predictable events in favor of detecting deviations from the norm.

However, a reduction in perceived speed while walking is also consistent with motor prediction theory (Wolpert & Flanagan, 2001). According to this theory, the perceptual consequences of motor actions can be anticipated and subtracted from sensory signals. This theory articulates the role of motor prediction in terms of the need for fast, precise action when direct perceptual feedback is too slow. In conjunction with perceptual feedback, motor prediction provides error correction in motor control. An error signal is produced when control fails, and a revision of motor prediction results.

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Although the value of motor prediction in motor calibration seems clear, the value of the perceived speed reduction is less clear. In theory, motor calibration could take place with or without the perceptual reduction in predicted sensory values. In normal walking, however, if the subtraction was essentially complete, then any apparent motion of the world produced by walking could be interpreted as a control error, with prediction errors being a possible source of the error. Deviation signals are emphasized in motor prediction theory and in Barlow's (1990) correlation theory, and both theories provide a framework for understanding why the perceived speed of optic flow might be reduced while walking.

One advantage of Barlow's (1990) theory is that it is more general. For example, Barlow's interpretation, rather than motor prediction theory, would be favored if similar reductions in perceived speed were found under conditions in which other sensory signals specified self-motion without the involvement of locomotor activity. Thus, evidence that the perceived speed of optic flow is reduced under conditions of passive forward movement seems to implicate a more general theory in which inertial and other sensory signals might contribute to the sense of self-motion. Indeed, Barlow's theory might serve as a mechanism for motor prediction itself.

Wallach's (1987) Theory of Compensation

Biomechanical self-motion is normally associated with physical translation, which is the typical reason for an expanding visual flow field. Wallach (1987) has discussed the problem of apparent environmental stability in terms of compensation processes. Self-motion produces viewer-relative motions that are no different than those that would be produced if the world itself was moving; but the world, normally, is perceived as stationary during self-motion. One view of walking-induced reductions in perceived speed suggests that compensatory mechanisms that seek to stabilize the world during self-motion are activated by biomechanical activity. Wallach investigated compensation processes most extensively in head rotations (see Wallach, 1987, for a review) but also conducted several studies concerned with compensation and stabilization processes during linear self-motion (Wallach & Flaherty, 1975; Wallach, Stanton, & Becker, 1974). In particular, Wallach

and Flaherty (1975) sought to demonstrate that perceived visual motion was reduced during passive self-motion, which they attributed to compensation mechanisms. They used the indirect technique of establishing that motion aftereffects to expanding flow fields presented during (passive) forward self-motion were much weaker than those induced while stationary or during backward self-motion (similar demonstrations were later reported by Harris, Morgan, & Still, 1981). In related work, Pavard and Berthoz (1977) showed that the detection of (directionally consistent) slow visual motion was impaired during linear acceleration.

This latter finding introduces the ambiguity of interpretation between compensation mechanisms and stability mechanisms. Environmental stability, according to Wallach (1987; Wallach et al., 1974), was so powerful a goal that the detection of surreptitiously introduced environmental motions was rendered difficult during self-motion. Wallach et al. (1974) studied the "range of immobility" for the relative rotations of objects during self-motion. Normally, stationary objects rotate relative to the observer's view as he or she passes them—by an amount determined by their distance from the observer and by his or her speed. Wallach et al. (1974) found that objects had to differ in rotation by 40% from their correct relative rotation in order to be detected as other than immobile. The findings of Pavard and Berthoz (1977) seem consistent with this evident failure of motion detection during self-motion. However, failures of motion detection require only a stabilization mechanism (motion suppression) rather than a compensation mechanism (motion subtraction). The two need not be the same process.

In this context, it is important to note that although the fact of apparent world stability is clearly evident in perception during self-motion, it exists side by side with an awareness of visual motion. Just as a shadow cast across a surface allows for the appreciation that the surface is simultaneously of intrinsically uniform reflectance (lightness) and yet clearly less bright under the shadow than elsewhere, so too the perception of self-motion seems to allow a sense of world stability to exist side by side with an appreciation of apparent visual velocity. The present study was therefore concerned with understanding the extent to which reductions in perceived visual speed during passive self-motion may be attributed to a compensation process rather than to simple suppression. To the extent that compensation is involved, we expected to see subtraction in the perception of visual flow.

There is a long history of evidence concerning inhibitory interactions between visual and vestibular information in the perception of self-motion (see Dichgans & Brandt, 1978, for an excellent review), and recent evidence suggests that the inhibition is bidirectional (Brandt, Bartenstein, Janek, & Dieterich, 1998). However Brandt et al. (1998) suggested that inhibitory suppression may serve the function of reducing cue conflict between visual and vestibular signals. For example, when one is driving forward at a constant velocity, vestibular signals will be more salient concerning bumps in the road (vertical accelerations), whereas the visual signals will be primarily responsible for coding forward velocity. However, there are ways to resolve such conflicts (i.e., cue weighting) other than outright suppression of information. Moreover, the evidence for compensation processes suggests that more subtle kinds of processes are at work. Barlow's (1990) theory of inhibition is specifically subtractive (as is motor prediction theory) and therefore fits well with the functional goals of compensation discussed by Wallach (1987; Wallach et al., 1974).

Most of the studies we have reviewed have not attempted to distinguish between subtractive, multiplicative, or simply suppressive inhibition. The fact that reduced visual aftereffects are found only when the direction of physical translation is consistent with the motion (Harris et al., 1981; Wallach & Flaherty, 1975) suggests that these are not due to simple suppression, but evidence concerning the form of the reduction in perceived speed is not readily available from these studies.

The evidence concerning speed reduction during walking is similarly ambiguous, though it shares many features with the earlier work on passive translation. For example, Pelah and Boddy (1998) found that the aftereffect to an expanding flow field was also reduced when the adaptation occurred while walking on a treadmill. Apparently, either active locomotor exertion (biomechanical self-motion) or the passive experience of forward motion (physical translation) is sufficient to induce a reduction in motion signal strength.

Division or Subtraction?

Compensation theory suggests that speed reductions should be subtractive, but not all inhibitory processes are. Specifically, because Barlow (1990) used the analogy of contrast gain control, the theory is sometimes assumed to involve a divisive (i.e., multiplicative by a ratio of less than 1) mechanism. After all, gain is a multiplier, and inhibitory contrast gain adjustment is thought to be divisive, not subtractive (e.g., Heeger, 1992). Moreover, some visual aftereffects (e.g., of texture density; Durgin, 1995) are demonstrably divisive. Nonetheless, the mathematics of Barlow's (1990) model are clearly subtractive, as is evident in Equation 1, below, from Barlow (1990; see also Barlow & Földiák, 1989). In this law of repulsion, Barlow (1990) defined Ψ_A as the perceptual variable proportional to A, the input variable. Ψ_B is the corresponding perceptual variable of a correlated dimension. In the present case, A would be speed of visual motion, whereas B is the locomotor, vestibular, or some other estimate of self-motion. In Barlow's (1990) model there are reciprocal interactions (which are thought to be the case between visual and vestibular signals; e.g., Brandt et al., 1998), but the amount of inhibition need not be equal in both directions.

$$\text{Barlow's (1990) subtractive model: } \Psi_A = A - K\Psi_B \quad (1)$$

$$\text{A "divisive" model: } \Psi_A = A/K\Psi_B \quad (2)$$

If we take Barlow's (1990) model to apply to the perception of visual flow speed while walking, then we should understand that at any given perceived speed of walking (Ψ_B), a constant proportion (K) of that perceived walking speed ought to be subtracted from the actual visual speed (A). In contrast, a divisive model, as in Equation 2, would suggest that at a given walking speed, all perceived flow speeds would be reduced by a constant proportion. The subtractive model therefore seems to predict that one might perceive backward motion if walking while visually stationary (as on a treadmill), whereas a divisive formula approaches 0 more gently (by pushing low speeds below the threshold for detection). For most people, the experience of treadmill running does not involve any sensation of backward flow, which seems more con-

sistent with a divisive model. Pavard and Berthoz (1977) indicated that they never saw reversals of velocity as a result of vestibular interaction. However, a subtractive model can also handle this fact if subtraction, in this case, simply reaches a floor at 0. This makes sense if the compensation process is intended to achieve environmental stability.

Because motor prediction models are also subtractive, it is not necessary to distinguish between the theories mathematically, though it is certainly possible that speed reduction due to vestibular inhibition is characteristically different from that due to biomechanical self-motion in the absence of physical translation. It is not known whether the perceived speed reductions while walking and during passive self-motion are divisive or subtractive. Although Thurrell, Pelah, and Distler (1998) showed that the reduction in perceived speed was proportional to walking speed, they did not analyze it with respect to different visual speeds. The primary goal of the experiments reported in the present study was to test whether speed reduction is in fact subtractive in various contexts of self-motion.

We also compare visual speed reductions measured when walking on solid ground to those measured with treadmill walking or with passive self-motion. As an extension of Barlow's (1990) model to the case of two predictive cues, we suggest Equation 3:

$$\text{Multicue subtractive model: } \Psi_A = A - K_1\Psi_B - K_2\Psi_C \quad (3)$$

In this multicue model, subscripts *B* and *C* might refer to motor and vestibular (or inertial) estimates of self-motion. Note that the constant *K* is now subscripted because the values of the two constants are independent. This equation suggests that (ignoring possible interactions between *B* and *C* themselves) the reduction in visual speed when two cues are present (as is the case when actually walking on solid ground) might be the sum of the subtractive components found for locomotor cues alone (as when walking on a treadmill) and inertial cues alone (as when being passively translated).

Overview of Experiments

A graphical overview of the various experimental conditions is presented in Figures 1 and 2. The first five experiments all concerned reductions in the perceived speed of visual flow while walking on a treadmill. Treadmill walking involves biomechanical self-motion in absence of physical translation. Experiments 1–3 established a novel means of measuring the effect designed to distinguish between subtractive and divisive speed reductions. Experiments 4 and 5 were concerned with walking-induced reductions in the perceived speed of visual flow while looking to the side.

In Experiments 6 and 7, we considered the visual perception of flow speed during physical translation (in the absence of biomechanical self-motion), which is the complement of treadmill walking. Motor prediction theory ought to be essentially silent concerning such a situation, because passive motion involves no obvious motor prediction, whereas Barlow's (1990) theory based on sensory–sensory inhibition is still applicable because of inertial and other signals concerning passive self-motion. On the basis of previous evidence (Harris et al., 1981; Pavard & Berthoz, 1977; Wallach & Flaherty, 1975), we expected to find reductions in perceived speed in the present study as well. Experiment 6 compared perceived speed of expanding visual flow during forward and backward passive motion with its perceived speed while stationary. Experiment 7 examined the effects of the same three movement conditions on the perceived speed of contracting visual flow. Both experiments showed evidence of subtractive reductions when the relative directions of visual and physical motion are mutually consistent.

Finally, Experiment 8 examined the perceived speed of simulated visual flow while walking on solid ground. This condition included both biomechanical self-motion and physical translation. On the basis of the multicue model (Equation 3), we predicted that this condition should show visual speed reductions that approximate the sum of those resulting from biomechanical self-motion and from physical translation alone.

General Method

Although a great deal of data are presented, the methods used to obtain them were fairly constant across many of the experiments and can be summarized in advance. Once the logic of the method is clear, its specific adaptation to the various experimental goals can be articulated quite briefly.

Magnitude Estimation

In all eight experiments, the method of magnitude estimation was used to establish correspondences between the perception of visual motion while moving and when stationary—or when moving at a different speed. Independent of an absolute scale, magnitude estimates can be used to compute the log–log slope of the judgments of perceived speed in each condition. As illustrated in Figure 3, divisive speed reduction would be predicted to produce a change in the intercept but not of the slope of the data plotted in logarithmic space. A subtractive model, however, would predict an increased slope in addition to a reduced intercept. A lowered intercept therefore represents clear evidence of speed reduction, and an increase in slope (in log–log space) represents a specifically subtractive component.

Estimating Subtraction

A higher slope in a moving condition is consistent with a subtractive speed reduction. In experiments in which log–log slopes differ reliably, a simple subtractive model can be used to estimate the size of the speed reduction in absolute terms and also to determine whether any intercept difference remains once the subtraction is taken into account. A higher slope in a moving condition is consistent with a subtractive speed reduction. Because subjective scaling of speeds is involved, the model is computed separately for each participant in order to provide individual estimates of the magnitude of the subtraction.

The subtractive model assumes that for a given walking speed, a constant amount, $K\Psi_B$, is subtracted from the underlying input. Let us call an estimator of this amount *R,* for reduction. To estimate $K\Psi_B$ for a given participant, we seek a value of *R,* which, when subtracted from the presented speeds, produces an alignment between the judgments of visual speed provided while walking and while standing still (or between whatever two conditions are being compared). In practice, for each value of actual speed presented to a given participant, a hypothesized difference, *R,* is subtracted, and the resulting slope of judged versus adjusted speed is computed in log space. The value of *R* is then selected (iteratively) so as to minimize the difference between the resulting model slope and the slope of the baseline comparison condition (e.g., speed perception while stationary) for each participant. Note that if *R* is equal to or larger than one of the presented speeds and therefore causes an adjusted speed value to go to 0 or

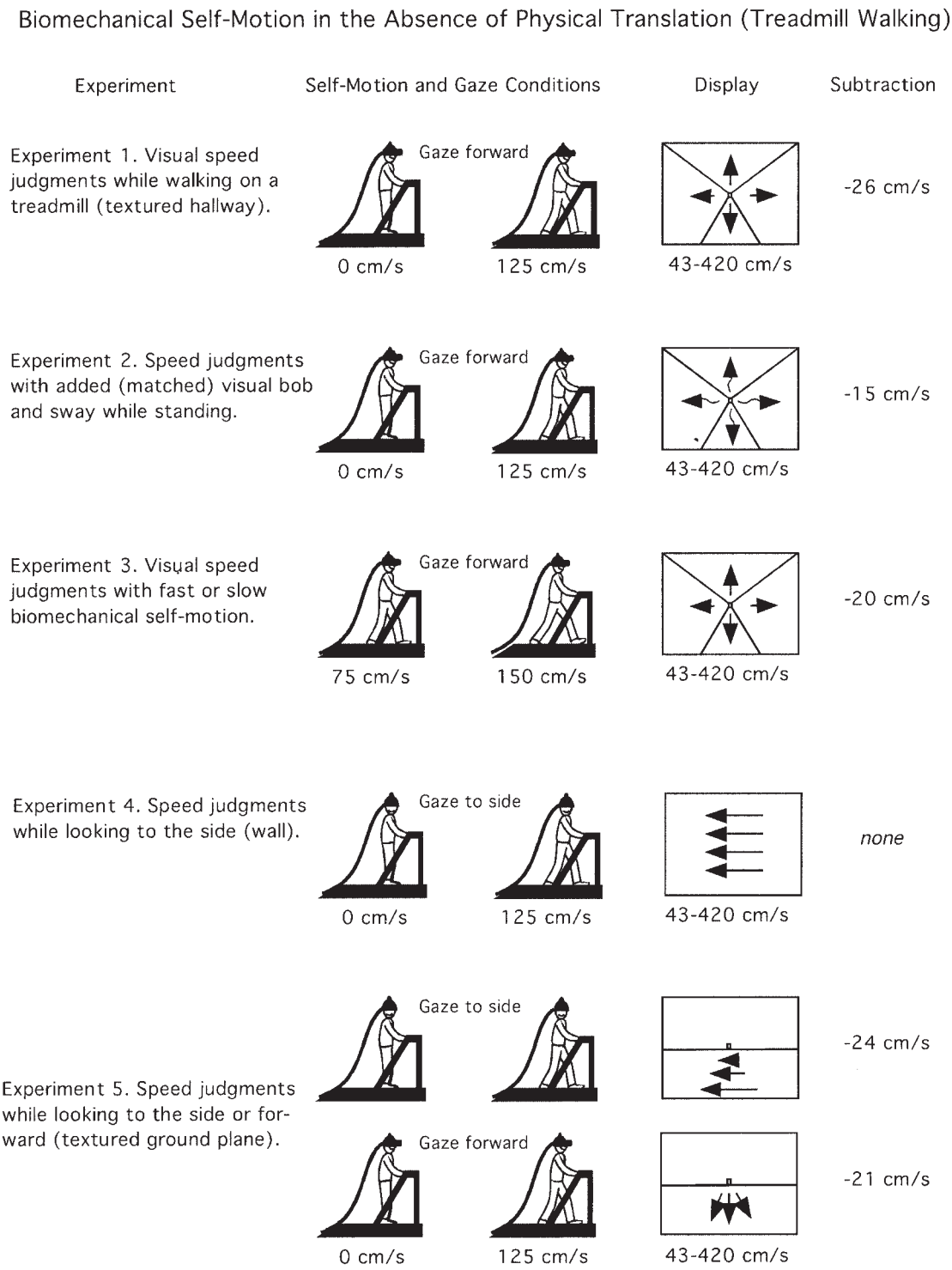

Figure 1. Schematic depictions of the various treadmill conditions tested in Experiments 1–5. Results (subtracted speeds for each condition) are shown to the right.

below, that value is not included in the computation of the model because of the apparent zeroing of low speeds.

Once the model slope matches the baseline slope, the intercept is computed for each participant's adjusted values and used to test the fit of the model overall. According to the model, once slopes are equated, any remaining difference in intercepts between the model and the comparison condition would indicate an additional multiplicative component. This was rarely found and is probably an artifact of scale shifting.

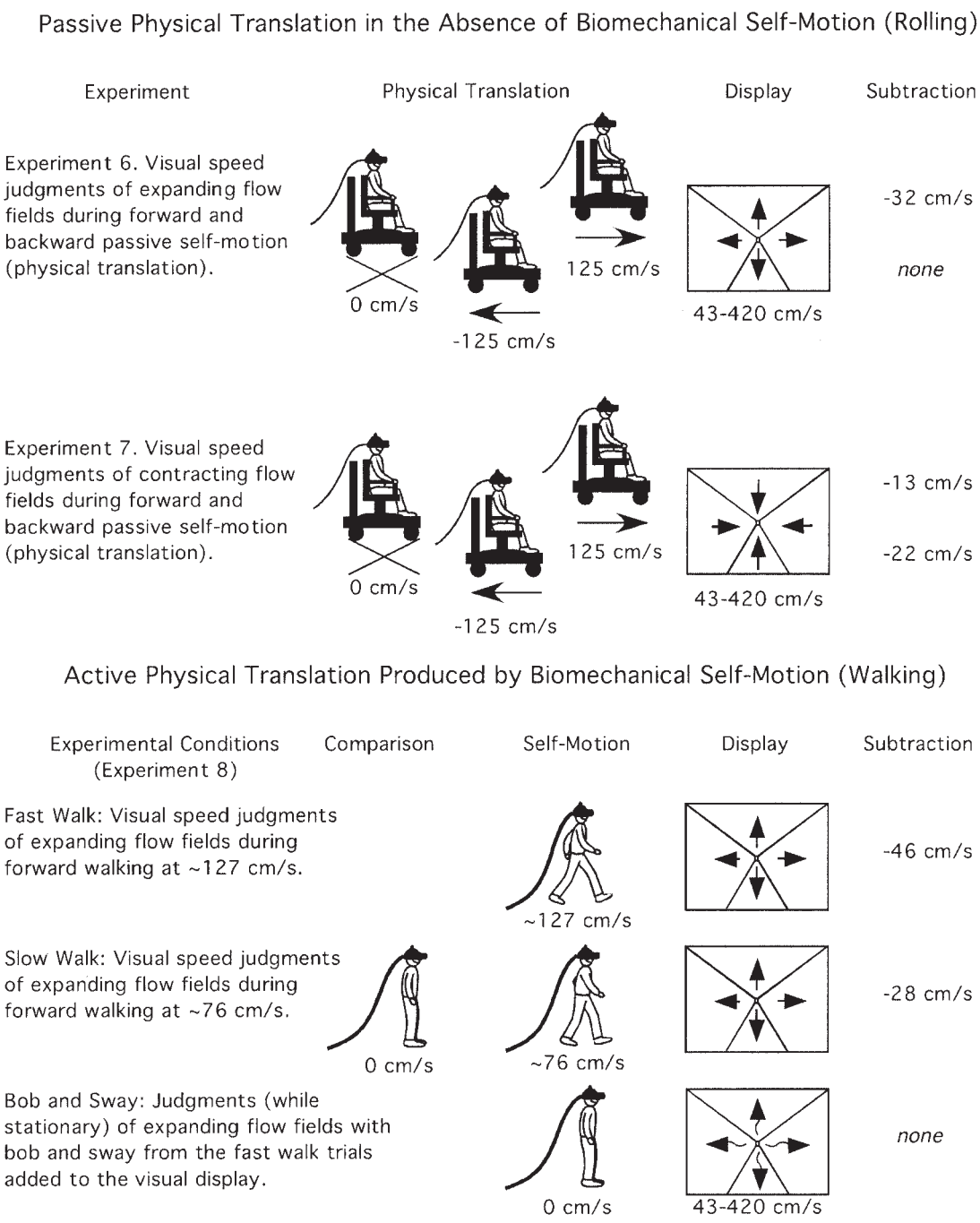

Figure 2. Schematic depictions of the physical translation conditions tested in Experiments 6–8. Results (subtracted speeds for each condition) are shown to the right.

Having estimated R for each participant, we then use the average value of R to estimate the proportion of walking speed, B, that has been subtracted from the perceived velocity. This proportion is an estimator of K, assuming that Ψ_B is approximately equal to B. Because distance perception in virtual environments may be compressed (Loomis & Knapp, 2003), it may be appropriate to similarly reduce the expected values of our simulated visual speeds by a constant factor (e.g., by 0.7), but this is not important to the theoretical interpretation of the patterns of results.

Displays

Participants made speed judgments of optic flow fields presented in a head-mounted display (HMD). The simulated world speeds presented ranged from 43 cm/s to 420 cm/s. The displays in the HMD accurately reflected changes in head angle and position, with the exception that a simulated forward or backward translational component either was added to (Experiments 1–5) or completely replaced (Experiments 6–8) any

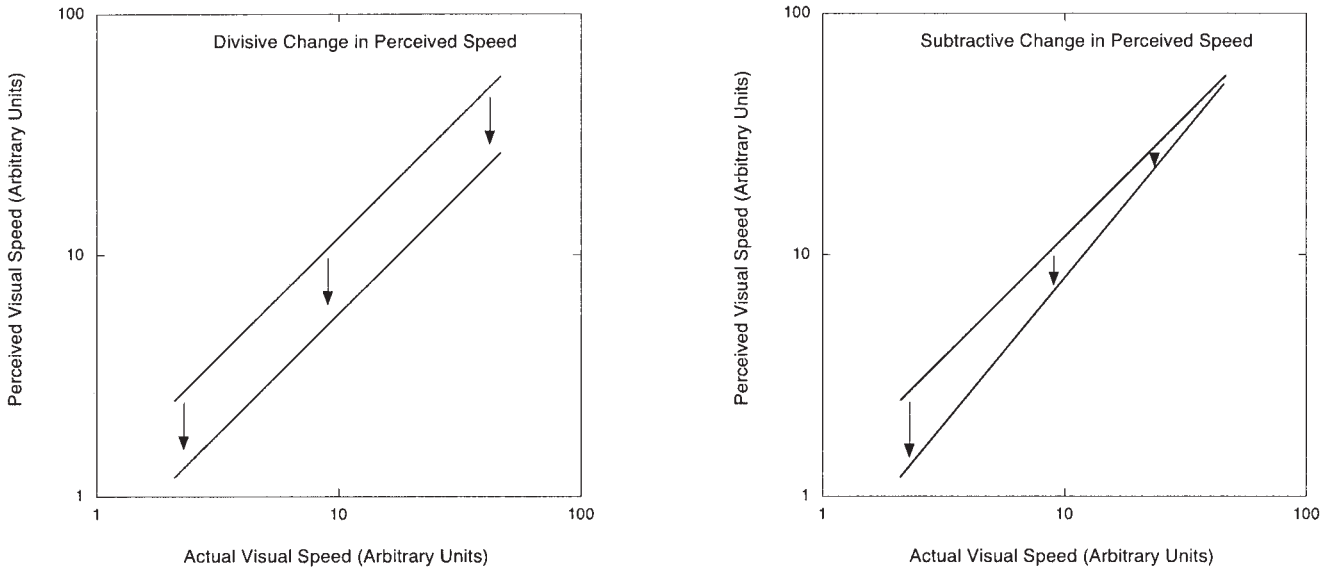

Figure 3. Theoretical log–log plots of magnitude estimation data showing divisive (left) and subtractive (right) predictions for reductions in perceived speed. A divisive model predicts a change only in intercept and no change in log–log slope (exponent of a power function). A subtractive model predicts an increased slope (exponent) in the log-transformed data.

physical head movement along the forward axis. It was the speed of this translational component that the participants were asked to judge.

For all but two of the experiments, the simulated visual environment was a richly textured hallway 2 m wide and 2.5 m high. This hallway is depicted in Figure 4 with and without texture. Except where noted, participants were required to look toward the end of the hallway when making speed judgments. For Experiment 4, the hallway was wider (6 m) so that when participants were required to look to the side, the visual distances would be more similar to those of Experiment 1–3. It was also taller (3 m), so that the ceiling was not visible in side view. For Experiment 5, a simulated grassy field was used so that perspective structure would be identical whether facing forward or looking to the side. In all cases, the same virtual scene was rendered without texture between each motion presentation to conceal translational motion information but to allow participants to orient themselves to the spatial structure of the environment.

The HMD was a Virtual Research Systems V8 with a 60° diagonal field of view and 640 × 480-pixel resolution refreshed at 60 Hz. Displays were rendered in stereo through the use of two Macintosh G4 computers with Radeon graphics cards. A pupillary distance meter was used so that geometric rendering of the stereo scenes would be correct. Each eye image was rendered at 120 Hz, and two frames at a time were blended with the OpenGL accumulation buffer in order to simulate motion blur. Head position and orientation were monitored at 120 Hz with a 3rdTech HiBall wide-area optical tracking system accurate to less than 1 mm.

Designs

For Experiments 1–5, which involved walking on a treadmill, trials were blocked by locomotor condition and presented in counterbalanced ABBA order. Each block consisted of 26 trials, in which the motion stimulus was shown for 2.5–3.5 s or until response. The 26 trials represented 19 distinct speeds distributed geometrically about 134 cm/s and ranging from 43 to 420 cm/s. Seven of the speeds in the range 66–275 cm/s were shown first in random order. These were followed by all 19 speeds in random order, though the four extreme speeds outside the range 66–275 cm/s were not analyzed. For Experiments 6–8, movement trials were interspersed with static trials, and because more than two conditions were compared in each of these experiments, only 26 trials were presented per condition. Responses were given verbally in all cases.

General Procedure

A standard speed (440 cm/s) called *100* was presented to participants at the beginning of the experiment, and they were allowed to view it as many times as they wanted (typically three or four times). They were instructed that higher speeds might be shown (though none were)—so estimates higher than 100 were acceptable—but that they should use a scale in which 0 represented no motion and 100 represented a speed like the standard. Thereafter, participants were given 10 practice trials in which to begin to stabilize their use of the scale, and they were encouraged to try to be self-consistent after that point once the experimental trials began. Because all comparisons would be made within participants, no effort was made to require participants to maintain the precise standard provided, and they were not given any further feedback concerning the standard. All responses were given orally and entered into a computer by an assistant. The assistant did not know what actual speed the participant was seeing. The entire experimental session typically took between 25 and 30 min per participant.

Variations in procedures are briefly described for each experiment. A full table of results for the various experiments is provided in Table 1.

Experiment 1: Subtractive Reduction in Perceived Speed While Walking on a Treadmill

Method

In Experiment 1, 12 Swarthmore College students participated as part of a class project. Students were instructed to look toward the end of the hall throughout. Moving treadmill speed was 125 cm/s for all but 1 participant, for whom it was 112 cm/s.

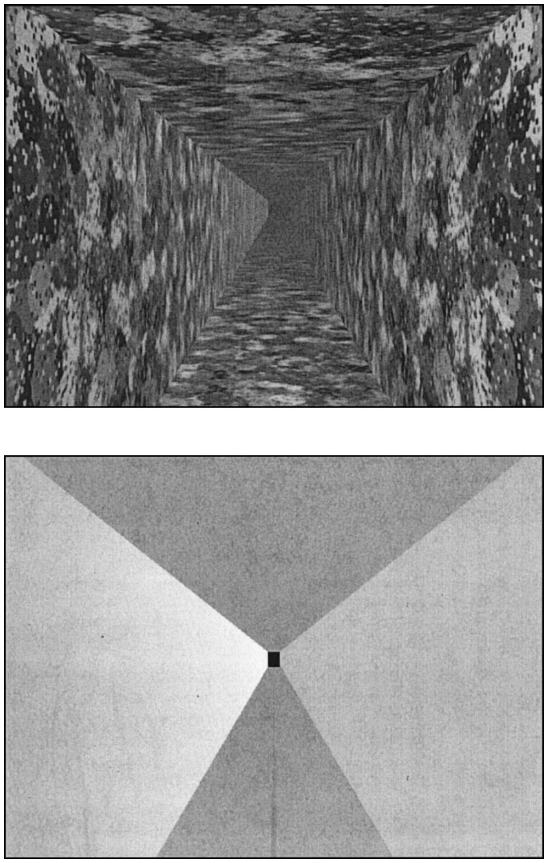

Figure 4. Forward view of the textured (top) and untextured (bottom) corridor used in most of the experiments reported in the present study. Horizontal field of view is ~45°. The scenes are rendered from an eyeheight of 1.7 m. Apparent end of hallway represents the clipping plane of the renderer, 100 m away. The end of the hallway was used as a fixation point.

Results and Discussion

Representative log–log plots are shown in Figure 5. The shape of the plots clearly supports the subtractive prediction. The mean slope in the walking condition (1.70) was indeed higher than that in the static condition (1.33), $t(11) = 4.93$, $p < .01$. The walking intercept (−5.52) was lower than the static intercept (−3.57), $t(11) = 4.37$, $p < .01$. These two facts are consistent with subtractive speed reduction. The use of the simple subtractive model to minimize slope differences provided an estimated subtraction of 26 cm/s, or 21% of the treadmill speed. As predicted for a purely subtractive model, there was no reliable difference between the average static intercept and the average intercept computed on the basis of the model of the moving condition (−3.35), $t(11) = 2.18$, $p > .05$. The data from this experiment provide support for a subtractive model. However, we wished to next establish that this was not due to added head motions during walking.

Experiment 2: Replication With Control for Head Motions

Head motions while walking (even on a treadmill) often include *bob* (head drops several centimeters during each step), *sway* (head translates left and right a few centimeters as body shifts from one foot to the other), and *lunge* (moments of forward acceleration sometimes associated with the forward thrust of taking each step). In this experiment, head motions recorded during walking were played back during half the static trials to test whether these added motion signals were responsible for the apparent reduction in perceived speed.

Method

Sixteen students were paid to participate. Whereas Experiment 1 was conducted as a class project, in Experiment 2, the participants were unaware of the experimental hypotheses. The design of this experiment always included an initial block of treadmill walking trials (125 cm/s) and then two stationary blocks, of which one showed pure translational motion and the other showed playbacks of the translational motion as well as the bob, sway, and lunge from the trials of the initial block. A fourth block of trials was done on a moving treadmill again, resulting in an ABCA or ACBA order.

Results and Discussion

The log–log slope of speed judgments in the moving condition (1.39) differed reliably from that of the static playback condition (1.19), $t(15) = 3.82$, $p < .01$, and from the static translation condition (1.18), $t(15) = 2.28$, $p < .05$. The playback and simple translation conditions did not differ reliably from each other, $t(15) = 0.49$, $p > .10$. The estimated difference based on the subtractive model was 15 cm/s (it was the same when computed with respect to either baseline), which was 12% of walking speed.

Thurrell et al. (1998) used a bite bar and a fixed display screen to ensure that the perceived speed reduction they measured was not due to image jitter. Our results comparing speed perception with and without added bob and sway suggest that these added motions are in no way responsible for the speed reductions observed during treadmill locomotion.

Experiment 3: Comparison of Two Different Walking Speeds

If visual speed perception at a given walking speed is subject to a subtractive reduction proportional to perceived walking speed, then our subtractive model ought to apply between two different walking speeds.

Method

In this experiment, the ABBA design was used to compare speed perception at two different treadmill speeds, 0.75 and 1.5 m/s. No static condition was included. Twelve students were paid to participate.

Results and Discussion

The average slope in the fast walk condition (1.94) was reliably greater than that in the slow walk condition (1.59), $t(11) = 4.09$, $p < .01$. A subtractive model was applied to the fast walk condition to equate the individual slopes with those in the slow walk condition. The average estimate of the subtractive difference was 20 cm/s, or 26% of the difference in walking speed. The average model intercept (−4.66) did not differ reliably from the average slow walk intercept (−4.89), $t(11) = 1.90$, $p > .05$, though the

Table 1
Results and Model Parameters for All Experiments

	Data parameters		Model parameters[a]		
Condition	Slope	Intercept	Intercept	R[b] (cm/s)	% moving speed
Experiment 1					
Walk	1.70 ± 0.11	−5.52 ± 0.74	−3.35 ± 0.60	26 ± 4	21
Static	1.33 ± 0.13	−3.57 ± 0.58			
Experiment 2					
Walk	1.39 ± 0.10	−3.79 ± 0.54	−2.76 ± 0.56	15 ± 8	12
Playback	1.19 ± 0.10	−2.89 ± 0.55		none	
Static	1.18 ± 0.07	−2.77 ± 0.39			
Experiment 3					
Fast walk	1.94 ± 0.16	−6.68 ± 0.85	−4.66 ± 0.59	20 ± 4	26
Slow walk	1.59 ± 0.12	−4.89 ± 0.62			
Experiment 4					
Walk side gaze	1.48 ± 0.16	−3.97 ± 0.91		none	
Static side gaze	1.43 ± 0.15	−3.40 ± 0.83			
Experiment 5[c]					
Walk side gaze	1.36 ± 0.17	−3.45 ± 0.90	−1.85 ± 0.77	24 ± 3	19
Static side gaze	1.09 ± 0.15	−1.88 ± 0.82			
Walk front gaze	1.49 ± 0.07	−5.08 ± 0.45	−3.53 ± 0.40	21 ± 4	17
Static front gaze	1.22 ± 0.07	−3.49 ± 0.40			
Experiment 6					
Forward roll	1.85 ± 0.18	−5.98 ± 0.98	−2.92 ± 0.86	32 ± 7	25
Backward roll	1.37 ± 0.13	−3.54 ± 0.72		none	
Static	1.31 ± 0.16	−2.97 ± 0.81			
Experiment 7[d]					
Forward roll	1.53 ± 0.11	−4.38 ± 0.57	−3.52 ± 0.76	13 ± 6	10
Backward roll	1.71 ± 0.13	−5.49 ± 0.64	−3.61 ± 0.74	22 ± 6	17
Static	1.38 ± 0.14	−2.97 ± 0.71			
Experiment 8[e]					
Fast walk	2.07 ± 0.26	−7.60 ± 1.46	−2.75 ± 0.76	46 ± 6	36
Slow walk	1.64 ± 0.20	−5.09 ± 1.07	−2.68 ± 0.74	28 ± 6	37
Playback	1.21 ± 0.12	−2.98 ± 0.70		none	
Static	1.22 ± 0.14	−2.94 ± 0.78			

Note. Reported values are means (± *SE*s) except those in last column.
[a] Model slope is not shown because it was set equal to comparison slope (usually static). [b] R is the average subtractive reduction used in fitting the data. [c] Participants in Experiment 5 were shown a grassy field rather than a hallway. [d] Participants in Experiment 7 were shown a contracting, rather than expanding, flow field. [e] Participants in Experiment 8 walked on solid ground rather than on a treadmill.

intercept in the fast walk condition (−6.68) did, $t(11) = 4.39$, $p < .01$.

The amount of subtraction found in the present experiment is similar to that found in Experiment 1. Consistent with the reports of Thurrell et al. (1998), it appears that subtraction may be roughly proportional to walking speed. Although it is not necessary in Barlow's (1990) model that Ψ_B (perceived walking speed) be directly proportional to B (walking speed), the assumption that they are roughly proportional is supported to the extent that the proportional amount subtracted in this experiment between different walking speeds is similar to that found in Experiment 1, which compared walking with standing. To the extent that this value is somewhat higher than those of Experiments 1 and 2, it may reflect the fact that, subjectively, a walking speed of 1.5 m/s is more than twice as fast as 0.75 m/s. The terms in Barlow's equations are perceived walking speed, not actual, though our use of his model treats the two as roughly proportional.

Experiment 4: Looking to the Side (at a Wall 3 m Away)

If subtraction is a consequence of visual experience, then somewhat less subtraction might be anticipated when looking directly to the side instead of ahead, insofar as gaze may be more typically directed forward during walking. Moreover, Banton, Stefanucci, Durgin, Fass, and Proffitt (in press) have reported that when attempting to match world speed to treadmill speed in virtual reality (VR), participants who look to the side do not show the oversetting of VR speed that those who look forward do. If speed oversetting was the result of subtractive effects on visual speed, then we should expect a similar result in our experiment when gaze is directed to one side.

Method

Twelve students were paid to participate. The design was the same as that for Experiment 1, but the geometry of the hallway was altered so that the virtual walls were 3 m away to prevent wall speed from being excessive. The ceiling of the simulated hallway was also raised to 3 m so that the side view of the hall did not normally include it. As a result, the visual stimulus presented to participants when they looked to the side was a textured frontoparallel plane that depicted linear motion. In both the walking and stationary conditions, participants were required to keep their lower body oriented to the major axis of the virtual hallway and to turn their head to one side.

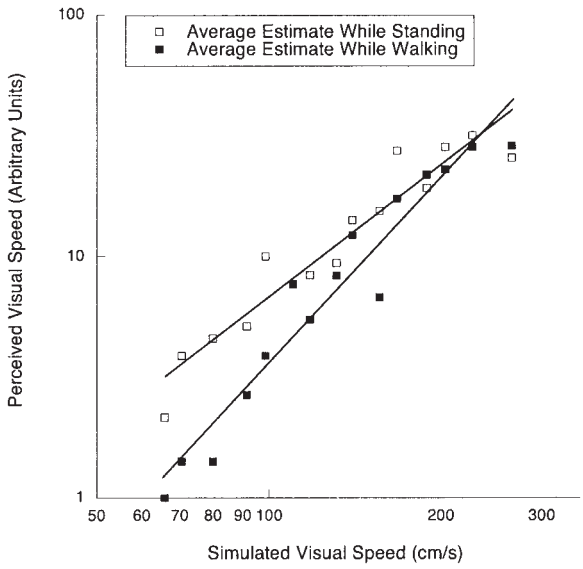

Figure 5. Representative magnitude estimation data from an individual participant in Experiment 1, showing lines fitted in log–log space. The slope difference is consistent with a subtractive theory of visual speed reduction. Plot points are averages of multiple judgments by a single participant.

Results and Discussion

No evidence of visual speed subtraction was found. Slopes in log–log space were approximately the same whether walking on the treadmill (1.48) or standing stationary (1.43), $t(11) = 0.53$, $p > .05$. Average intercepts (−3.97 for walking, −3.40 for standing) did not differ reliably either, $t(11) = 0.93$, $p > .05$. Evidently, neither a subtractive effect nor a divisive effect was found. However, because the structure of the visual scene when looking to the side differed dramatically from that viewed when looking straight ahead in the hallway, a further experiment was conducted to determine whether the important variable was the direction of gaze or the resulting environmental structure.

This initial result is consistent with the idea that mismatched speed settings in treadmill virtual reality (Banton et al., in press) may be due to the misperception of visual speed during biomechanical self-motion, inasmuch as both effects seem to be eliminated by looking to the side. However, it is important to evaluate whether environmental structure, rather than gaze direction, is responsible. Environmental structure has been implicated previously for the speed matching task (Durgin & Kearns, 2002).

Experiment 5: Looking Forward or to the Side in a Grassy Field

Because the part of the visual environment that participants observed in Experiment 4 consisted of a vertical planar surface, there were several important differences between the resulting environmental structure and the resulting retinal speeds that were available to the visual system. There was very little perspective structure and no ground plane to help scale distance. Retinal speeds were quite high relative to previous experiments, and there was no natural fixation target for gaze equivalent to the receding end of the hallway; thus, eye movements could quite likely have affected speed perception as well (Diener, Wist, Dichgans, & Brandt, 1976). We therefore decided to perform a direct comparison of visual speed perception to the front and side while walking on a treadmill in a visual environment consisting only of a ground plane.

This manipulation has many advantages. In addition to providing more similar retinal speeds, a textured ground plane provides excellent distance scaling information. If speed subtraction is in world coordinates, rather than retinal coordinates, it is possible that subtractive speed mechanisms would not be able to operate on an image lacking clear egocentric distance information (but see McKee & Smallman, 1998). One powerful source of visual information about egocentric distance is angle of regard along a ground plane (Ooi, Wu, & He, 2001). A textured ground plane has the additional virtue of providing the same perspective structure in all viewing directions.

Method

A grassy field was simulated by using a texture composed of two visual noise patterns filtered at different spatial scales and blended to provide large-scale and small-scale texture features. The texture was rendered in shades of green. Red poles were placed at the horizon both straight ahead and off to one side as fixation targets for the two viewing conditions. A grayscale version of the view is shown in Figure 6.

Twenty-four students were paid to participate. Half viewed the environment while gazing 90° to the side. The other 12 looked straight ahead during the experiment. The design was otherwise the same as that in Experiments 1 and 4. Treadmill speed was 125 cm/s during the moving trials.

Results and Discussion

In contrast to Experiment 4, the results of this experiment showed speed subtraction in both the side and forward gaze conditions. For the side gaze condition, the average log–log slope in the moving condition (1.36) was reliably larger than that in the static condition (1.09), $t(11) = 4.21$, $p < .01$. The model estimate was a subtraction of 24 cm/s, or 19% of the walking speed. For the

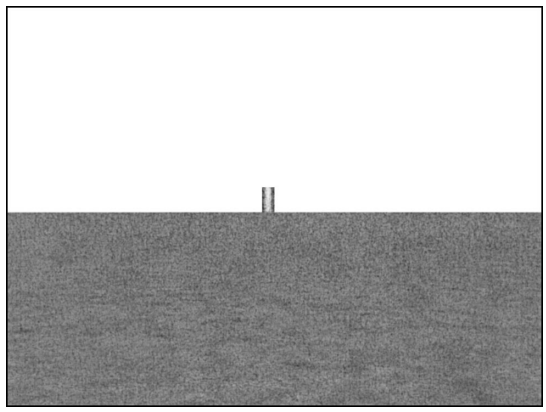

Figure 6. View of the grassy field display used in Experiment 5. The distant pole was used as a fixation point for participants, whether presented straight ahead or off to one side. The sky was light blue, the pole was red, and the ground texture was green in the original.

front gaze condition, the average log–log slope in the moving condition (1.49) was reliably larger than that in the static condition (1.22), $t(11) = 5.22$, $p < .01$. The model estimate was a subtraction of 21 cm/s, or 17% of the walking speed. There were no reliable differences between the two gaze direction conditions.

We conclude that subtractive effects are independent of the direction of gaze when the environmental structure is a textured ground plane. The results of Experiment 4 (no reduction in perceived speed when looking to the side) were likely due to the specific visual stimulus presented. Durgin and Kearns (2002) have reported that the structure of the environment affects the perception of visual speed in virtual environments, and this may have also played a role in the findings of Banton et al. (in press). Although they simulated a ground plane, they included a chain-link fence in the foreground of their side view that probably produced high retinal speeds that were not subject to substantial subtraction.

The use of a textured ground plane, alone, in the present experiment produced effects that were similar to those in our hallway when looking forward. Similar reduction effects were also found in the ground-plane environment when looking to the side.

Overall, the five experiments we conducted on treadmills suggest that perceived world speed is subtractively reduced by biomechanical self-motion on a treadmill. The average reduction across these five experiments was about 19% of biomechanical speed. We turn now to experiments in which participants made speed judgments while being physically translated.

Experiment 6: Subtractive Reduction of Visual Speed During Passive Movement

As reviewed in the introduction, the reduction in perceived speed during treadmill locomotion (biomechanical self-motion in the absence of physical translation) is consistent with motor prediction theory as well as contingent theories of perceptual learning. Under Barlow's (1990) theory, for example, visual speed is reduced when it can be predicted by concomitant signals, whether they are motor, proprioceptive, or exteroceptive. But Barlow's theory additionally predicts that passive self-motion, with its concomitant sensory signals, should also produce reductions in perceived visual speed. Wallach and Flaherty (1975; see also Harris et al., 1981) found evidence that motion aftereffects to expanding flow fields were reduced when the expanding flow fields were coupled with passive forward motion. They found no effect for contracting flow fields, however. Pavard and Berthoz (1977) have reported that the detection of visual speed is delayed during linear acceleration.

Although the detection of inertial self-motion probably depends in part on accelerations sensed by means of vestibular signals, there are many other sources of self-motion information that are neither visual nor vestibular that may combine to form the perception of passive self-motion. These include inertial cues of changes in skin pressure but also cues to velocity, such as auditory localization cues and cooling effects of passing through air, and cues indicating the continuation of movement, such as vehicle vibrations. Although vestibular systems are commonly regarded as sensing only accelerations, the full interplay of nonvisual sensory signals is not well understood. The vestibular coding of rotary movements, for example, actually ends up being linear with angular velocity over the normal range (see Howard, 1982). We note that being pushed on a rolling chair down a hallway (without vision) results in a continuous sensation of self-motion for the times and distances used in the present experiment.

In Experiment 6, we sought to directly measure a reduction in visual speed during forward and backward motion (physical translation). Speed judgments were therefore made during forward passive motion, during backward passive motion, and while stationary.

On the basis of the results of Wallach and Flaherty (1975) and Harris et al. (1981), we expected that passive forward motion would reduce the perceived speed of a virtual hallway coming toward the participant but that backward motion might have no effect. Alternatively, it was possible that perceived speed might be supplemented when physical motion was in the same direction as hallway motion (e.g., motion toward the participant while moving backward) and decremented when, as is normally the case, it was in the opposite direction (e.g., motion toward the participant when moving forward).

Method

Ten students were paid to participate. Visual displays in the HMD compensated for all head movements of the participant except translation along the hall axis. Motion along this axis was visually undetectable when in the untextured hallway and was replaced by a constant speed during presentation of the textured moving hallway. Participants wore the HMD while they were seated in a chair mounted on a cart. Their simulated eye level was similar to that when standing. The cart was moved smoothly through a physical space 10 m in length that was tracked by the HiBall head tracker. The cart was rolled by an experimenter, who controlled the speed with the help of a computer monitor that showed a plot of the cart's speed and also signaled when the motion stimulus was being presented. A minimum speed of 120 cm/s was required to trigger the onset of the motion stimulus, which lasted 2.5–3.0 s. The target physical speed was approximately 125 cm/s. For static trials, the experimenter triggered the motion stimulus manually.

Trials from the static, forward-motion, and backward-motion conditions were interleaved. Whether static trials preceded or followed forward-motion trials was alternated between participants. After an initial 9 trials of practice at the task, there were 26 trials in each motion condition as the participant was rolled either backward or forward, or kept stationary, in turn.

Results and Discussion

Analyses of log–log slopes and intercepts in the three conditions supported the conclusion that forward physical motion produced subtraction but that backward motion had no effect. Log–log slopes in the forward-motion condition (1.85) were larger than those in the static condition (1.31), $t(9) = 4.31$, $p < .01$, but log–log slopes in the backward-motion condition (1.37) were no different than those in the static condition, $t(9) = 0.78$, $p > .10$. The same pattern was evident for the intercepts. Thus, a subtractive model was applied only to the forward condition, which produced a subtraction estimate of 32 cm/s, or approximately 25% of the rolling speed. As in previous experiments, the model intercept did not differ reliably from the static intercept, $t(9) = 0.61$, $p > .10$.

These results show that passive forward self-motion (physical translation in the absence of biomechanical self-motion) produces subtractive visual speed reductions similar to those produced by

treadmill walking (biomechanical self-motion in the absence of physical translation). No decrement (or increment) was found, however, in the anomalous situation in which physical motion was backward but the visual motion was toward the participant. Consistent with our predictions, physical translation is sufficient to produce subtractive reductions in (directionally consistent) perceived speed. The directional selectivity of the reduction is consistent with that reported in the studies of reduced motion aftereffects (Harris et al., 1981; Wallach & Flaherty, 1975). These results seem to confirm that speed reduction during passive physical translation, like that for biomechanical self-motion in the absence of physical translation, is subtractive, which is consistent with the idea of a compensation mechanism and Barlow's (1990) model.

Experiment 7: Subtractive Reduction of Visual Speed During Passive Movement When the Visual World Moves Away From the Observer

We found no change in speed perception during backward self-motion in Experiment 6, but that might have been either because forward physical motion is more typical or because backward movement was inconsistent with the visual motion information. We therefore repeated the experiment using visual motions that represented motion away from the participant (consistent with backward motion). If consistency is important, then this should have been sufficient to produce subtraction during backward movement.

Method

The methods were identical to those of Experiment 6, except that visual speeds were judged of flow fields that moved away from the participants. Fourteen students were paid to participate.

Results and Discussion

As predicted by the consistency hypothesis, the analysis of log–log slopes showed evidence of subtractive visual speed reduction in the backward-motion condition. The slope of the backward condition (1.71) was reliably higher than the slope of the static condition (1.38), $t(13) = 3.44$, $p < .01$. Application of the subtractive model provided an estimate of apparent speed reduction by 22 cm/s, or 17% of the physical motion speed. This magnitude of reduction is not reliably different from that found for forward motion in Experiment 6, $t(22) = 1.13$, $p > .10$. There was, again, no reliable difference between the model intercept and the static intercept.

On the other hand, even with visual motion away from the participant, the forward translation condition showed some evidence of subtraction. The forward-motion slope (1.53) was marginally higher than the static slope, $t(13) = 1.80$, $p = .09$. The estimate of speed reduction provided by the subtractive model for this case was 13 cm/s, or 10% of the physical speed, which was reliably greater than 0, $t(13) = 2.21$, $p < .05$, and marginally less than the subtraction found in the backward case, $t(13) = 1.89$, $p = .08$. The estimated subtraction that resulted from forward physical motion in this experiment was reliably less than that in Experiment 6, in which visual motion was toward the participant, $t(22) = 2.18$, $p < .05$. Model intercepts did not differ from the static intercept for either backward physical translation, $t(13) = 0.65$, $p > .10$, or forward physical translation, $t(13) = 0.60$, $p > .10$.

The pattern of results of Experiments 6 and 7 generally supports the consistency hypothesis: Physical motion is partly subtracted from visual motion when that visual motion is consistent with the physical motion. Contrary to a simple adjustment model, physical motion does not seem to generally add to visual motion when it is in the opposite direction, for example (although 3 of the 14 participants had data consistent with increased visual speed in the forward-motion condition). In general, however, forward motion appears to produce some subtraction even for motion away from the participant. This might be because forward motion is so frequent that consistency is not entirely necessary, or because passive forward motion is more easily mistaken for backward motion in the presence of inconsistent visual flow. In any case, subtractive speed reduction is less strong in the inconsistent direction. Although not strictly consistent with a perfect compensation process, the subtraction in inconsistent cases may be considered as evidence that the mechanisms underlying the compensation process are heuristic, like the Barlow (1990) model.

By taking the average of the consistent conditions of Experiments 6 and 7, we estimate the proportional subtraction due to physical translation (sensed by whatever means) is roughly 21% of the speed of translation. This is quite similar to the average amount found for biomechanical self-motion in the absence of physical translation.

For our final experiment, we sought to measure visual speed reductions when both biomechanical self-motion and physical translation were present. In this experiment, our modified model predicts that speed reduction should be the sum of that found separately for passive physical translation and for biomechanical self-motion in the absence of physical translation.

Experiment 8: Subtractive Reduction of Visual Speed While Walking

In the first seven experiments, participants were asked to provide visual speed estimates with regard to 3D scenes presented to them in an HMD. The participants were either walking on a treadmill or being rolled in a chair or were stationary when making these judgments. In all these cases it is relatively easy to (partly) dissociate viewed motion from self-motion. Indeed, some of our participants were surprised to learn afterward that the displays had actually compensated for head movements. They had not noticed that they were not simply looking at an independent computer display. In this experiment we had our participants walk on solid ground in our wide-area VR while they viewed the motion displays. The participants began walking in a gray, textureless hallway, and the speed display (a textured hallway) was presented after they had reached a critical speed. As in the rolling experiments, the display reflected head movements except those along the axis of the hallway, which were replaced by a constant motion.

A natural ambiguity in this procedure is introduced if the immersion in the virtual environment leads the participant to understand the speed estimate to be of the world as perceived (e.g., as stable and unmoving) or of the display itself. In fact, our participants readily appreciated what we wanted them to judge, but the subtraction of visual speed in this case was so profound that the

task seemed to pose different demands than those in the previous experiments.

Method

Twelve students were paid to participate. One of these was eliminated from analysis because of a strikingly reduced ability to discriminate most of the speeds while walking.

Each participant made speed judgments in four different conditions. Two of the conditions involved walking but differed in the walking speed required to trigger the display. The fast walk condition required an average walking speed between 125 and 150 cm/s to trigger the visual motion (many participants slowed down somewhat as they walked, so that the average speed overall in the fast condition was 127 cm/s), whereas the slow walk condition required an average walking speed between 60 and 85 cm/s (empirical overall average was 76 cm/s). For the other two conditions, the participant was stationary. One stationary condition added the bob and sway recorded in a previous fast walk trial to the motion stimuli; the other did not. Note that this experiment thereby combined all of the manipulations used in Experiments 1–3 on the treadmill.

The four trial types proceeded in sequence as the participant walked in one direction in the hallway, stopped, walked back, and stopped again. The order of the trial types was randomized between participants. The speeds shown were the same as those in the previous experiments. Prior to the experiment, participants practiced walking at the required speeds with continual feedback. Once the experiment began, participants were shown the standard speed, and there were 12 practice trials (3 of each type) and then 104 experimental trials.

Results and Discussion

As in Experiment 2, there was no difference between the average slopes in the stationary playback (1.21) and normal stationary (1.22) conditions, $t(10) = 0.10$, $p > .10$, nor in the intercepts (-2.98 and -2.94, respectively), $t(10) = 0.11$, $p > .10$. The slope in the fast walk condition (2.07) was reliably greater than that in the slow walk condition (1.64), $t(10) = 3.83$, $p < .01$. Both of these were reliably greater than those in the other two conditions ($p < .01$). Model estimates of speed subtraction in the fast and slow walk conditions were 46 and 28 cm/s, respectively. Compared with the average walking speeds of 127 and 76 cm/s, these represent speed reductions by 36% and 37%, respectively.

Post hoc comparisons showed that speed reduction in the fast walk condition was greater than that found in the consistent physical translation conditions of Experiments 6 and 7, $t(33) = 2.70$, $p < .02$, and greater than that found in the biomechanical-only data of Experiment 1, $t(21) = 2.80$, $p < .02$. Average self-motion speeds (biomechanical, physical, or both) in these experiments were essentially identical.

In this experiment alone, model intercepts did differ reliably from their static counterparts. Specifically, the intercepts in the model of the fast walk condition were reliably higher than those in the static condition, $t(10) = 3.38$, $p < .01$, as also were those in the slow walk condition, $t(10) = 4.84$, $p < .01$. Although such a discrepancy may indicate a true multiplicative component, it is likely that these intercept differences reflect scale shifting in response to the extreme differences in the range of speeds perceived while walking compared with while stationary. In recent experiments using a method of two-alternative forced choice to measure speed reduction during walking, clear evidence was found of subtractive differences in perceived speed corresponding to 43% of walking speed (Durgin, Gigone & Schaffer, 2004). No evidence of a multiplicative component was found in those studies.

Expressed as a percentage of moving speed, the amount of subtraction found in the present experiment is nearly equal to the sum of the amounts computed for biomechanical self-motion (19%) and for physical translation alone (21%). Indeed, insofar as self-motion estimates from various sources are mutually inhibitory, Barlow's (1990) model might suggest that the effects of combining different sources would be subadditive. On the other hand, the simple additive model is a reasonably good fit to the present data.

General Discussion

The experiments reported in the present study have not only replicated and extended previous findings concerning visual speed reduction during treadmill locomotion and passive translation but have also shown that even larger reductions occurred during active locomotion on solid ground. A summary of the data is shown in Table 1. In all cases, a subtractive model was sufficient to account for the magnitude estimation data. Overall, a modified, multicue model seems to fit the data fairly well. In general, the data support a model like Barlow's (1990) as a means of accomplishing compensation, as described by Wallach (1987; Wallach & Flaherty, 1975).

Experiments 1–3 replicated the speed reduction findings previously reported on treadmills (biomechanical self-motion in the absence of physical translation) through the use of our magnitude estimation method to demonstrate that the effects are subtractive. Our experiments used an immersive environment, and speed reductions were expressed in terms of the speed of the 3D environment. In Experiments 4 and 5 subtractive effects were found when gaze was to the side in a simple ground-plane environment, but no evidence of subtraction was found when a textured frontoparallel plane (a wall) was viewed to the side. Future work is needed to determine the factors governing speed subtraction, but it is at least clear that the structure of the environment may matter. The ground plane is likely a special case.

In Experiments 6 and 7, we found similar speed subtraction during passive self-motion (physical translation in the absence of biomechanical activity) when the direction of environmental motion was consistent with self-motion (either forward or backward). Although these findings occurred during periods of constant physical speed, it is likely that vestibular signals contributed to the perception of self-motion. Future studies could elucidate the basis of the nonvisual perception of self-motion in these conditions, but the point is that nonvisual and nonmotor factors affected perceived visual speed in a manner consistent with subtractive speed reduction. The fact that there was greater directional selectivity in the case of expanding flow fields is consistent with the frequency of such experiences.

Finally, in Experiment 8, we found that speed subtraction during normal walking was greater than that found during passive physical translation or biomechanical self-motion in the absence of translation. It approximated the sum of the two.

One aspect of our data that we have not discussed is the fact that our exponents in the static conditions were consistently larger than 1. Although this aspect of the data is incidental to our main concern and not clearly relevant to the logic of our experimental

conclusions, it is somewhat surprising because previous studies of velocity scaling have tended to find exponents quite near to 1 (e.g., Diener et al., 1976). In those studies, displays were of simple linear motion rather than 3D scenes. One speculation we can offer is that our motion displays themselves produced speed subtraction by serving as visual cues to self-motion. Had we presented similar displays on monitors that were surrounded by stationary visual information, it is possible that our exponents would have dropped to 1. There is no contradiction in including an additional subtractive term in our multicue equations, assuming that full-field visual motion itself produces a subtractive inhibition. However, that term would be expected to include a multiplicative component because higher visual speeds ought to signal higher speeds of self-motion and therefore greater subtraction.

Another possibility is that an overall subtractive reduction in perceived speed resulted from motion adaptation during the course of the experiment (Carlson, 1962; Gibson, 1937; Goldstein, 1957). Insofar as such adaptation would have affected all conditions equally, it would not bear on the logic or conclusions of the experiments, and it is acceptable to ignore. Some support for this idea includes the point that exponents in the stationary condition of Experiment 4 were numerically higher than those in any other stationary condition, and it was in Experiment 4 that retinal speeds were highest overall. Because the possibility of additional motion adaptation is probably not relevant to our main concerns, we leave it to future investigations to determine whether the high exponents may indeed be due to experimentally induced motion adaptation.

A Model of Compensation

Whereas motor prediction theory can offer an account of the speed reduction in active contexts, such as walking on a treadmill or on solid ground, the fact that passive self-motion produces similar reductions suggests that Barlow's (1990) more general theory of subtractive sensory inhibition might be preferable in all cases and may provide a mechanism for motor prediction itself. The present results also seem to argue against theories of motion suppression in favor of theories of compensation such as Wallach's (1987). Barlow's model represents a very general case of compensation that seeks to stabilize not only the spatial environment but also the sensory environment as a whole, so that signals predicted by prior correlations tend to blend into the background of perception.

Of the results we have observed, one of the most problematic for sensory inhibition theory, however, is the failure to find any speed reduction in Experiment 4 when looking directly to the side at a wall. Although looking to the side is less typical while walking (and therefore perhaps less well learned), full speed reduction was found when a ground plane was used in Experiment 5. The fact that higher retinal speeds were involved in Experiment 4 may be important. It may have rendered the amount of subtraction too small to measure with this method.

In general, sensory inhibition seems too crude a mechanism to fully account for subtractions involving world speed rather than retinal speed (see McKee & Smallman, 1998, for models of recovering world speed). However, there are three kinds of answers that might be offered for this concern. First, it remains possible that the ground plane represents a special case in which walking speed calibration can function best. After all, only ground-plane flow provides a consistent mapping of speed to angle of inclination across a variety of environments, and subtraction might be applied in a manner most appropriate for the ground plane. Because a stipulated function of subtraction in the theories we are considering is to reduce the salience of completely predictable signals, the predicted movement of the ground plane seems like a good candidate for a neutral point during self-motion, which could serve to emphasize the faster retinal flows due to the motion parallax of objects that protrude into motor space.

Second, there are known interactions between perceived speed and spatial frequency that might mean that spatial frequency can also serve, like angular declination, as a proxy for distance (Diener et al., 1976). This would allow fairly low-level mechanisms to also tune the amount of retinal speed inhibition as a function of size and therefore distance.

Finally, an alternative view of the failure to detect any subtraction in Experiment 4 is that retinal speeds were much higher in the case of the wall, and this rendered the subtraction unmeasurable by the present method. Pavard and Berthoz (1977) suggested that speed reductions due to physical accelerations occurred only for low visual speeds. The results of Durgin et al. (2004) suggest that subtraction continues well past walking speed but becomes less noticeable as the amount of subtracted speed becomes a smaller and smaller fraction of the pedestal speed.

We note that although a retinal-speed subtraction, if applied point by point, could theoretically produce geometric distortions in most visual scenes, it is imaginable that inhibiting early motion signals would have an effect similar to lowering contrast—a global slowing (Stone & Thompson, 1992) but not an obvious geometric consequence. On this account, the content of perception represents the spatial structure of the environment, whereas local speed information, like color and texture, acts like a surface feature applied to the perceived world (e.g., Durgin, 2002).

In general, our extension of Barlow's (1990) sensory inhibition theory seems to fare well in accounting for reductions in perceived speed. The fact that motion aftereffects to expanding flow fields are also reduced both by active locomotion (Pelah & Boddy, 1998), and by passive movement (Harris et al., 1981; Wallach & Flaherty, 1975), supports the notion that speed reduction occurs fairly early in the visual pathway. We consider our interpretations to be compatible with Wallach's (1987) theory of compensation but regard Barlow's model as an explicit description of a mechanism for achieving world stability.

An apparent discrepancy between our passive motion results and those of reduced motion aftereffects (Harris et al., 1981; Wallach & Flaherty, 1975), however, is that we found evidence of speed reduction in three of the four passive conditions we tested (though the effects were strongest when directionally consistent), whereas Wallach and Flaherty (1975) and Harris et al. (1981) found reduced motion aftereffects only with forward physical motion and expanding flow fields. However, the methodologies they used (simple report of motion aftereffect or the cancellation of motion aftereffect by method of adjustment) may have been less sensitive than our magnitude estimation method. Moreover, the physical speeds attained in our experiments were certainly higher than those attained in the very short distances used by Harris et al. ($\sim$1 m) and by Wallach and Flaherty (40 cm). Although it is possible that the speed reductions found by our methods occurred at a different neural site than those that reduced the motion

aftereffect, the two phenomena seem likely to be more closely related.

Although we have focused our discussion on Barlow's (1990) model, alternative theoretical perspectives have previously been applied to perceived world stability in the context of head movement. For example, Gogel (1977) studied the perception of object motion during head movement as a way of estimating perceived egocentric distance. Although his investigations are limited to impoverished visual environments in which optic flow is eliminated and concern lateral rather a forward motion, Gogel's work also raises issues involving the perceived stability of the world (see also Shebilske, 1977). In normal human locomotion, detecting world stability is rarely a direct concern. It is goals, obstacles, pitfalls, and other moving things that are generally of interest. However, important questions remain about whether visual speed subtraction during self-motion is sophisticated enough to make real object motion more salient or just helps to reduce the salience of retinal motion signals with a direction predicted by the motion of the participant (see Wallach et al., 1974). This, in itself, would be a useful function.

The fact that visual speed subtraction appears quantitatively insufficient to account for full world stability suggests that compensatory processes are only part of the story in the case of linear self-motion and that assumptions of world stability (such as those illustrated by Wallach et al., 1974) play an additional role in suppressing the perception of world movement. Wallach's (1987) work on eye rotations was primarily concerned with the limits of perceived world stability in cases involving manipulations of the gain between eye movements and resulting perceptions, and in these cases, the compensation appears to be more complete. Of course, compensation for visual rotary motion seems less complicated than that for linear motion because all points move by the same retinal angle.

Enhanced Speed Discrimination

Finally, there are questions concerning whether visual discriminations are aided by speed subtraction. The primary effect of speed subtraction we have observed is to increase the exponent of the power function relating actual to reported speed. If visual speed is ultimately encoded logarithmically (as psychophysical power functions suggest), the result of an initial linear subtraction would be to increase the discriminability of those speeds that are above the subtracted value while making speeds below that value essentially indiscriminable from no motion at all. This is actually the heart of Barlow's (1990) theoretical contribution: Subtractive inhibition ought to serve the functional goals not merely of compensation, but also of enhanced speed discrimination (Clifford & Wenderoth, 1999).

Durgin et al. (2004) have recently reported evidence consistent with the idea that discrimination for visual speeds near walking speed is enhanced by the act of walking. Thus, although stability mechanisms may render the motions of embedded objects less discriminable (Probst, Krafczyk, Brandt, & Wist, 1984; Wallach et al., 1974), the coding of the speed of the visual flow field as a whole is likely enhanced by processes of subtractive inhibition. In addition to the merits of compensation theory in accounting for environmental stability (Wallach, 1987), we suggest that theories of enhanced speed discrimination (Barlow, 1990; Clifford & Wenderoth, 1999) provide further motivation for subtractive inhibition during self-motion. This inhibition can serve not only to stabilize the environment. It may also render the visual system more sensitive in the range of visual motion information that it can typically expect during self-motion.

References

Banton, T., Stefanucci, J., Durgin, F. H., Fass, A., & Proffitt, D. R. (in press). The perception of walking speed in a virtual environment. *Presence: Teleoperators and Virtual Environments*.

Barlow, H. B. (1990). A theory about the functional role and synaptic mechanism of visual aftereffects. In C. Blakemore (Ed.), *Vision: Coding and efficiency* (pp. 363–375). Cambridge, England: Cambridge University Press.

Barlow, H. B., & Földiák, P. (1989). Adaptation and decorrelation in the cortex. In R. M. Durbin, C. Miall, & G. J. Mitchison (Eds.), *The computing neuron* (pp. 54–72). Wokingham, England: Addison-Wesley.

Brandt, T., Bartenstein, P., Janek, A., & Dieterich, M. (1998). Reciprocal inhibitory visual–vestibular interaction: Visual motion stimulation deactivates the parieto-insular vestibular cortex. *Brain, 121,* 1749–1758.

Carlson, V. R. (1962). Adaptation in the perception of visual velocity. *Journal of Experimental Psychology, 64,* 192–197.

Clifford, C. W. G., & Wenderoth, P. (1999). Adaptation to temporal modulation can enhance differential speed sensitivity. *Vision Research, 39,* 4324–4332.

Dichgans, J., & Brandt, T. (1978). Visual–vestibular interaction: Effects on self-motion perception and postural control. In R. Held, H. W. Leibowitz, & H.-L. Teuber (Eds.), *Handbook of sensory physiology, Vol. 8: Perception* (pp. 755–804). Berlin, Germany: Springer-Verlag.

Diener, H. C., Wist, E. R., Dichgans, J., & Brandt, T. (1976). The spatial frequency effect on perceived velocity. *Vision Research, 16,* 169–176.

Distler, H. K., Pelah, A., Bell, A. G., & Thurrell, A. E. I. (1998, August). *The perception of absolute speed during self-motion.* Poster session presented at the annual meeting of the European Conference on Visual Perception, Oxford, England.

Durgin, F. H. (1995). Texture density adaptation and the perceived numerosity and distribution of texture. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 149–169.

Durgin, F. H. (2002). The Tinkerbell effect: Motion perception and illusion. *Journal of Consciousness Studies, 9,* 88–101.

Durgin, F. H., Gigone, K., & Schaffer, E. (2004). Improved visual speed discrimination while walking. *Journal of Vision, 4,* 802a. Abstract retrieved February 13, 2005, from http://journalofvision.org/4/8/802/

Durgin, F. H., & Kearns, M. J. (2002). The calibration of optic flow produced by walking: The environment matters. *Journal of Vision,* 2, 429a, Abstract retrieved July 2, 2004, from http://journalofvision.org/2/7/429/

Gibson, J. (1937). Adaptation with negative aftereffect. *Psychological Review, 44,* 222–244.

Gogel, W. C. (1977). The metric of visual space. In W. Epstein (Ed.), *Stability and constancy in visual perception: Mechanisms and processes* (pp. 129–181). New York: Wiley.

Goldstein, A. G. (1957). Judgments of visual velocity as a function of length of observation time. *Journal of Experimental Psychology, 54,* 457–461.

Harris, L. R., Morgan, M. J., & Still, A. W. (1981, September 10). Moving and the motion after-effect. *Nature, 293,* 139–141.

Heeger, D. J. (1992). Normalization of cell responses in cat striate cortex. *Visual Neuroscience, 9,* 181–197.

Howard, I. P. (1982). *Human visual orientation.* Toronto, Canada: Wiley.

Loomis, J. M., & Knapp, J. M. (2003). Visual perception of egocentric distance in real and virtual environments. In L. J. Hettinger & M. W.

Haas (Eds.), *Virtual and adaptive environments* (pp. 21–46). Hillsdale, NJ: Erlbaum.

McCollough, C. (1965, September, 3). Color adaptation of edge-detectors in the human visual system. *Science, 149,* 1115–1116.

McKee, S. P., & Smallman, H. S. (1998). Size and speed constancy. In V. Walsh & J. Kulikkowski (Eds.), *Perceptual constancy: Why things look as they do* (pp. 373–408). Cambridge, England: Cambridge University Press.

Ooi, T. L., Wu, B., & He, Z. J. (2001, November 8). Distance determined by the angular declination below the horizon. *Nature, 414,* 197–200.

Pavard, B., & Berthoz, A. (1977). Linear acceleration modifies the perceived velocity of a moving visual scene. *Perception, 6,* 529–540.

Pelah, A., & Boddy, A. (1998). Adaptive modulation of the motion after-effect by walking [Abstract]. *Journal of Physiology (London), 506P,* 111P–112P.

Pelah, A., & Thurrell, A. E. I. (2001). Reduction of perceived visual speed during locomotion: Evidence for quadrupedal perceptual pathways in human?. *Journal of Vision, 1,* 307a. Abstract retrieved August 22, 2002, from http://journalofvision.org/1/3/307

Pelah, A., Thurrell, A. E. I., & Berry, M. (2002). Reduction of perceived visual speed during walking: Evidence against the involvement of attentional or vestibular mechanisms. *Journal of Vision, 2,* 630a. Abstract retrieved March 23, 2003, from http://journalofvision.org/2/7/630/

Probst, T., Krafczyk, S., Brandt, T., & Wist, E. R. (1984, August 3). Interaction between perceived self-motion and object-motion impairs vehicle guidance. *Science, 225,* 536–538.

Shebilske, W. L. (1977). Visuomotor coordination in visual direction and position constancies. In W. Epstein (Ed.), *Stability and constancy in visual perception: Mechanisms and processes* (pp. 23–69). New York: Wiley.

Stone, L. S., & Thompson, P. (1992). Human speed perception is contrast dependent. *Vision Research, 32,* 1535–1549.

Thurrell, A. E. I., & Pelah, A. (2002). Reduction of perceived visual speed during walking: Effect dependent upon stimulus similarity to the visual consequences of locomotion. *Journal of Vision, 2,* 628a. Abstract retrieved June 27, 2003, from http://journalofvision.org/2/7/628/

Thurrell, A. E. I., Pelah, A., & Distler, H. K. (1998). The influence of non-visual signals of walking on the perceived speed of optic flow [Abstract]. *Perception, 27,* 147–148.

Wallach, H. (1987). Perceiving a stable environment when one moves. *Annual Review of Psychology, 38,* 1–27.

Wallach, H., & Flaherty, E. W. (1975). A compensation for field expansion caused by moving forward. *Perception & Psychophysics, 17,* 445–449.

Wallach, H., Stanton, L., & Becker, D. (1974). The compensation for movement-produced changes in object orientation. *Perception & Psychophysics, 15,* 339–343.

Wolpert, D. M., & Flanagan, J. R. (2001). Motor prediction. *Current Biology, 11,* R729–R732.

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