ECOLOGICAL PSYCHOLOGY, 10(2), 65–91

Visual Influences on Center of Pressure Dynamics in Upright Posture

M. A. Riley, R. Balasubramaniam, S. Mitra, and M. T. Turvey

Center for the Ecological Study of Perception and Action
University of Connecticut

In 2 experiments, participants stood upright with their eyes open or closed and facing forward or to the side; the 2nd experiment also included a manipulation of optical structure. At issue were the effects of different conditions of visual exproprioperception on motions of the body's center of pressure. Also at issue was the utility of 2 characterizations of postural control under the vision manipulation: the fractional Brownian motion (over 2 time scales) and the continuous Ornstein–Uhlenbeck process models. We present a demonstration that the former is perhaps more appropriate, followed by results that suggest that visual exproprioperception reduces effective stochastic activity in the short term and decreases negatively correlated activity in the long term. Results also suggest that this visual effect may be rather general and somewhat independent of the specifics of optical structure, although 1 effect of differential optical structure was observed. We discuss the idea that the 2 time scales could reflect processes of obtaining and using information about stability.

Postural control is a complex perception–action task involving multiple perceptual systems and most of the body's major muscle groups. Control exigencies arise from a number of sources, including (but not limited to) physiological, perceptual, biomechanical, and goal-related factors. These constraints act over a range of time scales. Accordingly, Riley, Mitra, Stoffregen, and Turvey (1997) conjectured that postural control involves a temporal nesting of actions, with perceptual exploration

Requests for reprints should be sent to M. A. Riley, Center for the Ecological Study of Perception and Action, Department of Psychology, U–20, University of Connecticut, 406 Babbidge Road, Storrs, CT 06269–1020. E-mail: mar95003@uconnvm.uconn.edu

occurring over smaller time scales than the muscular actions undertaken to preserve stance, which in turn operate over shorter time scales than, for example, the achievement of certain suprapostural behavioral goals (see also Riccio, 1993; Riccio & Stoffregen, 1988). A temporal nesting of actions does not mean that they are discrete and absolutely separable or that different control processes govern each class of actions; it could be that postural behaviors operate continuously, though differentially, over various time scales (Newell, Slobounov, Slobounova, & Molenaar, 1997). Examination of the trajectories of the center of pressure (COP), which is equal and opposite to a weighted average of all downward forces due to postural muscular action acting between the feet and support surface (see Winter, Prince, Frank, Powell, & Zabjek, 1996), lends support to the idea that postural sway exhibits differential structure over different time scales. Figure 1 is a stabilogram–diffusion plot—a plot of mean squared COP displacement as a function of time scale (i.e., the mean squared distance from the COP position at time t to the COP position at time t + Δt, plotted as a function of Δt). The curve rises steeply over small time scales (small Δt) and levels off to a more gradual rise over larger time scales (large Δt). Minimally, this basic result suggests that analysis of COP trajectories over different time scales may reveal functional differences in postural dynamics over these time scales, which may reflect the temporal nesting of actions discussed previously (Riley, Mitra, et al., 1997; Riley, Wong, Mitra, & Turvey, 1997).

Here, we present two experiments that examine the effects of different types of optic flow structure (radial vs. lamellar flow) on COP dynamics of anterior–posterior (AP) and mediolateral (ML) sway at different time scales. In the first experiment,

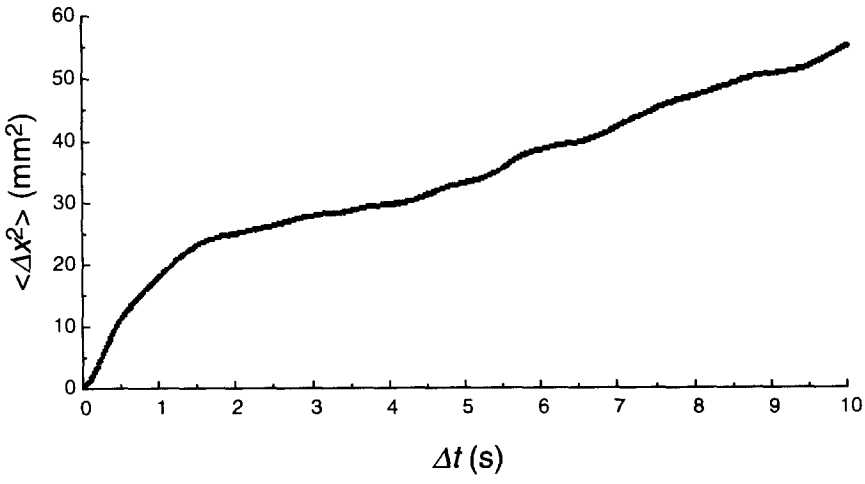

FIGURE 1 Stabilogram–diffusion plot showing clearly distinguishable steep-sloped short-term and shallow-sloped long-term scaling regions.

participants stood comfortably with their eyes open (fixating a target attached to a wall) or closed and with the head facing forward or to the side. Experimental conditions were identical in the second experiment, but participants were presented with a more structured optical environment designed to enhance radial expansions and dilations of closed optical contours in the head-forward condition and motion parallax in the head-side condition. These experiments extend previous investigations that simply involved, with respect to vision, eyes-open versus eyes-closed conditions (Collins & De Luca, 1995; Riley, Mitra, et al., 1997; Riley, Wong, et al., 1997). Following, we discuss in more detail the role of vision as it pertains to posture.

MODELS OF POSTURAL CONTROL

Stabilogram–diffusion analysis of COP trajectories was introduced by Collins and De Luca (1993). They suggested that postural control involves open-loop control over small time scales (arising from feedback-processing delays, and allowing integration of sensory information when there is no danger of falling) and closed-loop control over long time scales (providing corrective adjustments); the two observable regions of the stabilogram–diffusion plot are interpreted as corresponding to these two control regimes, respectively. This model has received criticism, however, on grounds ranging from the open- versus closed-loop interpretation (Riley, Mitra, et al., 1997; Riley, Wong, et al., 1997) to model parsimony (Newell et al., 1997). Newell et al. compared the five-parameter, dual-process correlated random walk model of Collins and De Luca (1993) to a two-parameter, single-process Ornstein–Uhlenbeck (OU) model (a linear stochastic diffusion-with-drift model; Gardiner, 1985), and found that the OU model accounted for nearly as much variance (about 92%) as the Collins and De Luca (1993) model (about 96%). Newell et al. did not test to determine if the better fit to the data by the Collins and De Luca (1993) model was simply due to it having more parameters, but this may be the case.

Newell et al. (1997) concluded that more parsimonious accounts of COP dynamics—accounts that do not involve two different control processes operating over different time scales, the respective temporal domains of which are separated by a sharp critical point—should be sought. Their argument hinges on the latter issue regarding the existence of a critical point in the stabilogram–diffusion plot and the resulting interpretation of two distinct postural control mechanisms (Collins & De Luca, 1993, 1995). Newell et al. recognized that postural control processes may differ over time scales, but emphasized that two control mechanisms (described by a more complicated model) need not be invoked to account for the differential slopes of stabilogram–diffusion plots over short and long time scales.

STRUCTURE IN COP TRAJECTORIES

Perhaps the key insight from the analysis of Collins and De Luca (1993) is that COP trajectories appear to be structured in time rather than truly random. COP displace-

ments separated by a given time interval Δt are not independent, but rather are correlated with one another. COP trajectories exhibit correlated random walk (or fractional Brownian motion). In the context of COP motions, a classical random walk model with independent increments would imply that musculo-skeletal forces affecting the center of gravity are applied in a purely random fashion, which would in turn imply a lack of directed forcing of the center of gravity and the absence of a coherent control regime. This does not appear to be the case, however. Collins and De Luca (1993) first showed that COP trajectories exhibit positive correlations over small time scales (less than 1 sec) and negative correlations over larger time scales; this is reflected in the differential slopes of the two regions of the stabilogram–diffusion plot. Positive correlations point to a tendency to continue along the current direction of displacement, while negative correlations indicate the opposite tendency, that of reversing the direction of motion.

The classic example of random walk is Brownian motion (Einstein, 1905). In Brownian motion, a particle's mean squared displacement depends on the time scale over which it is measured:

$$\left\langle \Delta x^2 \right\rangle = 2D\Delta t \tag{1}$$

where the term left of the equal sign is mean squared displacement (brackets denote averaging), Δt is the time scale, and D is the diffusion coefficient, a measure of stochastic activity. Fractional Brownian motion involves the scaling law

$$\left\langle \Delta x^2 \right\rangle \approx \Delta t^{2H} \tag{2}$$

where H, the Hurst exponent, ranges from 0 to 1 (Feder, 1988; Mandelbrot & van Ness, 1968). Brownian motion corresponds to $H = .5$, in which case, Equation 2 reduces to Equation 1. If $0 \leq H \leq .5$ for a given Δt, displacements are negatively correlated. This is a behavior termed *antipersistence*. If $.5 \leq H \leq 1$, displacements are positively correlated. This is termed *persistence* (for details, see Riley, Mitra, et al., 1997). COP trajectories show persistence over short time scales and antipersistence over longer time scales. The observation that $H \neq .5$ over short time scales reflects short-term memory or serial correlation over this time scale (e.g., significant autocorrelations for short time lags), and the observation that $H \neq .5$ over long time scales indicates that COP trajectories exhibit long memory, or long-range correlations (Beran, 1994). A variety of stochastic processes (e.g., fractional autoregressive integrated moving average [ARIMA] models; Hosking, 1981) exhibit similar correlation structures.

Fractional Brownian motion is more strictly defined as a stochastic self-similar process whose increments are stationary and Gaussian (Beran, 1994). The first part of this definition regarding self-similarity is easy to demonstrate for COP signals. Such a demonstration amounts to showing that a process is equal in distribution

over several time scales of observation. That is, the qualitative properties of "stretched" or "shrunk" time series (i.e., time series obtained by effectively sampling the same series at different rates and for different trial lengths, but yielding the same number of data points) do not change as a function of the scaling (stretching or shrinking) factor. This idea is typically expressed in the literature on fractals as an object looking roughly the same no matter the distance from which it is viewed. The qualifying term *stochastic* means that the process does not have to be exactly identical over various observational scales, only qualitatively similar. Both fractional Brownian motion and ordinary Brownian motion are stochastic self-similar (or fractal) processes with self-similarity parameter H (Beran, 1994); the difference between the two processes, as stated previously, lies in the value of H.

Figure 2 demonstrates that COP time series possess the quality of stochastic self-similarity. In the figure, a COP time series is viewed at two scales. (More scales could have been depicted but were not for the sake of convenience.) The qualitative impression is that the "two processes" pictured do not differ.

The second part of the aforementioned definition may also be demonstrated for COP signals. Figure 3 depicts a time series of increments or offsets of a COP signal (created by first-order differencing of a COP time series) and its corresponding distribution. The increment time series is stationary[1] about a mean of 0, and the frequency histogram shows a roughly Gaussian distribution.

This simple two-part demonstration supports the appropriateness of the analysis of COP series as fractional Brownian motion. It does not, however, address the issue of two distinct regions in stabilogram–diffusion plots. (Stochastic self-similarity does not depend on whether fine details such as the sign of correlations between data points changes as a function of time scale of observation.) Furthermore, it is not apparent that this definition of fractional Brownian motion is exclusive (e.g., fractional ARIMA models [Hosking, 1981] may also show these characteristics). Despite this, the fractional Brownian motion approach (as an analytic technique based on the Collins & De Luca, 1993, model) appears justified as a method for extracting potentially useful information about the nature of correlations in COP series over the two time scales. Newell et al. (1997) do not discuss correlated COP motions. They emphasize, instead, obtaining a single diffusion coefficient rather than coefficients over two time scales. Diffusion coefficients index stochastic variability in COP trajectories but do not shed light on their temporal structure.

At issue is an analytic method that reveals structure in COP data, which is perhaps relevant for approaching an understanding of the underlying processes (Liebovitch & Todorov, 1996). The structure of postural sway is relevant not

[1]It should be noted that a process that has stationary increments is not necessarily stationary—a line with a nonzero slope is not stationary in the mean but has a stationary increment (its slope). Carroll and Freedman (1993) provided a demonstration of the nonstationarity of postural sway.

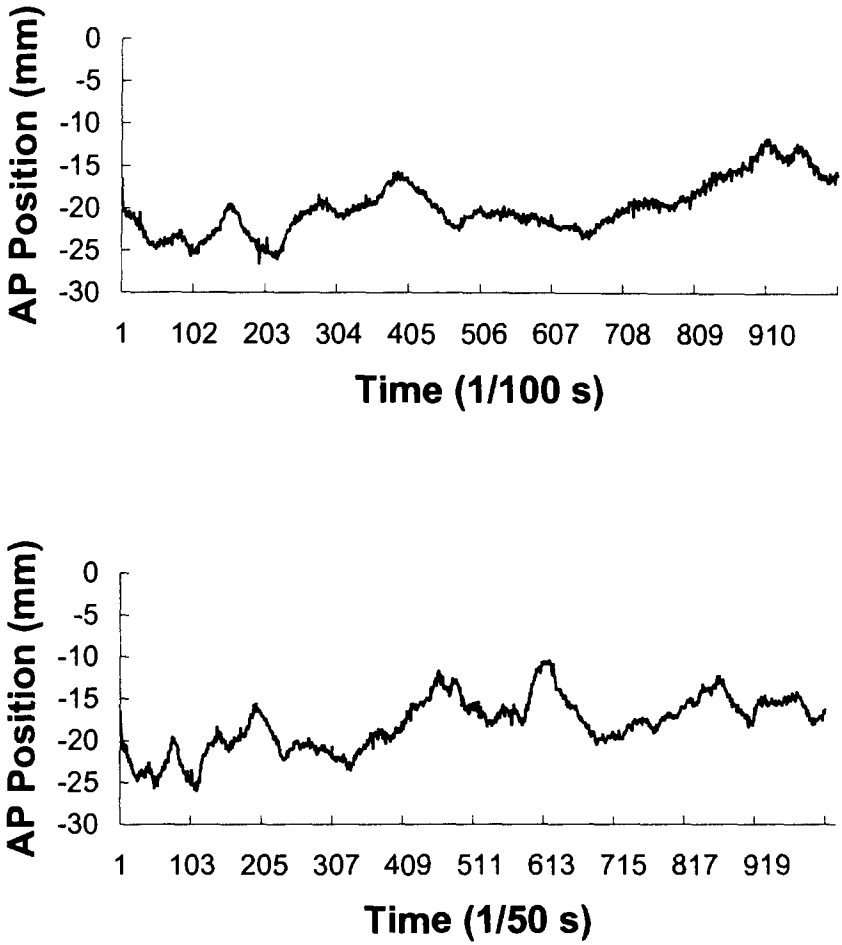

FIGURE 2 Typical time series of the AP position of COP viewed at two different scales of observation. Top panel: Effective sampling rate = 100 Hz, 10 sec of data (1,000 data points). Bottom panel: Effective sampling rate = 50 Hz, 20 sec of data (1,000 data points). The "processes" pictured at the two scales of observation are qualitatively similar, suggesting stochastic self-similarity.

only to the scientist seeking an understanding of such processes but it is also potentially important for the organism attempting online postural control (Riccio, 1993). Accordingly, methods that examine this structure would seem to be a major priority. Also, although a wide class of systems, including low-dimensional systems of coupled differential equations (e.g., the visual perturbation model of Schöner, 1991), could produce stabilogram–diffusion plots in agreement with

those observed, determination of such models for unperturbed stance, which is usually stochastic in nature, has been elusive. As such, and given the demonstration (which is independent of the Collins and De Luca, 1993, model) that COP signals do show characteristics of fractional Brownian motion, we focus on the stabilogram–diffusion analysis.

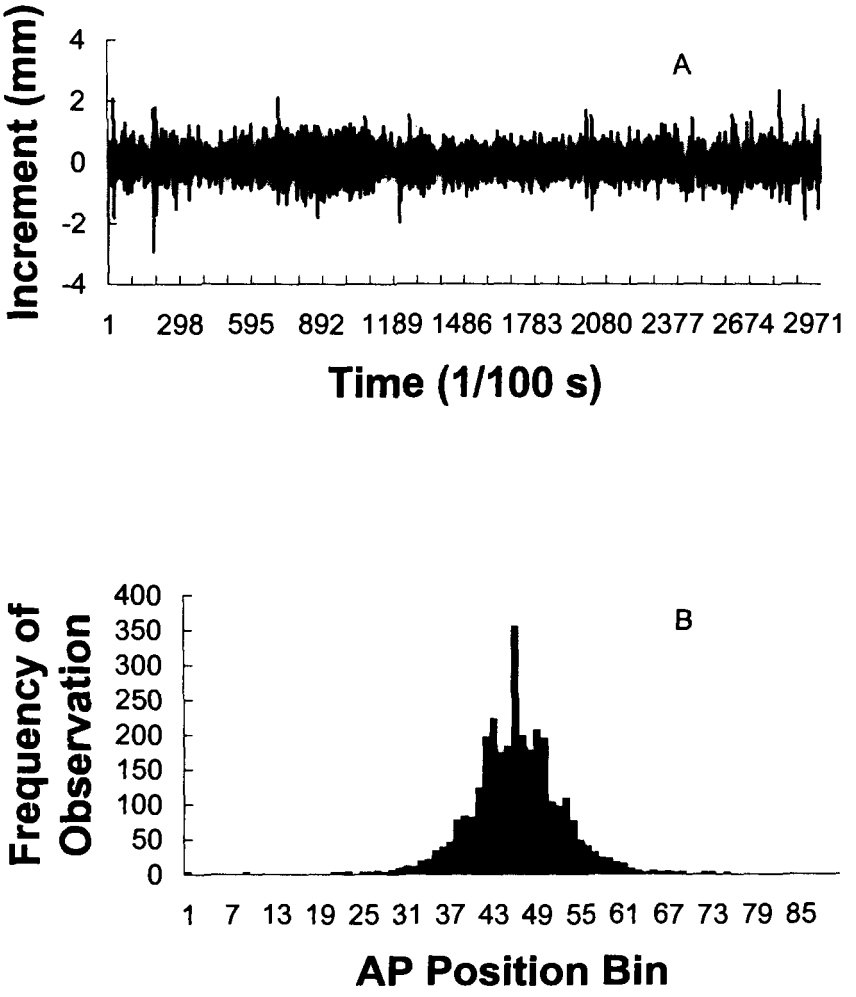

FIGURE 3 (a) Time series of the increments of 30 sec of data for the same time series pictured in Figure 2. The increment series is stationary about a mean of 0. (b) Frequency histogram (distribution) for the increment series.

VISION AND POSTURAL CONTROL

Unperturbed stance is affected by vision. The body sways more, in both the AP and ML directions, when the eyes are closed (e.g., Edwards, 1946; Paulus, Straube, & Brandt, 1984; Travis, 1945; but see Black, Wall, Rockette, & Kitch, 1982). Postural sway in the absence of vision is magnified by circumstances that impede the control ordinarily provided by the haptic perceptual system through contact with the support surface, as in standing on a surface that gives or tilts (e.g., Berthoz, Lacouer, Soechting, & Vidal, 1979; Woollacott, Shumway-Cook, & Nashner, 1986). Recent experiments on unperturbed stance examined the effect of vision on short and long time scales (Collins & De Luca, 1995; Riley, Mitra, et al., 1997; Riley, Wong, et al., 1997). Whereas Collins and De Luca (1995) limited their study to upright stance with hands by the sides, Riley, Mitra, et al. included standing with a forward lean, and Riley, Wong, et al. included gentle fingertip contact with a nearby surface. With respect to vision, these studies involved only a manipulation of eyes open versus eyes closed. The outcomes of these different experiments are alike in suggesting that both persistence and antipersistence are decreased when participants can see their surroundings. With eyes open, H deviates less from .5 for short and long time scales. A decrease in correlated COP activity over both time scales suggests that postural control is, in a sense, more online when vision is available then when it is not; decreased correlations may mean that the current postural state is less dependent upon previous postural states.

The preceding observation may be consistent with the proposal that fluctuations provide information about the moment-to-moment postural condition of the body—information used to guide the patterning and magnitude of muscular contractions that preserve upright posture (Riccio, 1993; Riccio, Martin, & Stoffregen, 1992; Riccio & Stoffregen, 1988, 1991; Riley, Mitra, et al., 1997; Riley, Wong, et al., 1997).[2] The kind of information needed is expropriospecific information, that is, information about the position, orientation and movement of the body, or body segments, relative to the environment (Lee, 1978). With eyes open, exploratory motions required to obtain expropriospecific information are likely to be reduced; thus, if persistence is a measure of exploratory motions, H with eyes closed should be larger in the short term than with eyes open (Riley, Mitra, et al.;

[2]Riccio (1993) suggested that low-frequency modulation (e.g., variation in amplitude, frequency, or symmetry) of high-frequency variability may be a means of obtaining information about low-frequency postural dynamics. In support of this possibility, he noted the research of Watanabe, Yokoyama, Takata, and Takeuchi (1987), showing that high frequency and low frequency variability of COP are negatively correlated. Furthermore, there is evidence that visual egocentric distance information is defined only in the presence of head movements (Bingham & Stassen, 1994). In the latter case, movements of the body serve an exploratory (information-generating) function. Related findings regarding head movements under monocular reaching-to-grasp conditions also highlight an exploratory (information-generating) function of movement variability (Marotta, Kruyer, & Goodale, 1998).

Riley, Wong, et al.). Correspondingly, greater exploration qua persistence may lead to increased corrective adjustments qua antipersistence (i.e., incrcreased correlations in the long term with eyes closed). The upshot is the interaction of time scale and vision observed in Collins and De Luca (1995), Riley, Mitra, et al., and Riley, Wong, et al.

In our two experiments, the interaction between vision (eyes open vs. closed) and scaling region (short vs. long term) was generalized to different viewing conditions induced by different surface layouts and orientations of the head to the body. In Experiment 1, participants focused on a closed contour flush with a wall approximately 3.5 m away. In Experiment 2, participants looked at a layout of objects arranged in depth at a distance of approximately 1 m—a layout designed to enhance motion perspective and parallax. In both experiments, participants' bodies were aligned perpendicular or parallel to the environmental arrangement. They either directly faced the arrangement or viewed it with the head turned sideways. (Although turning the head to the side is a biomechanical manipulation as well as an optical manipulation, it does not threaten biomechanical stability in any obvious way.) This head-forward versus head-sideways manipulation (and the effects of optic flow on the different sway components) has also been examined by Stoffregen, Smart, and Bardy (1998) in the context of a suprapostural looking task. At issue here was whether vision's interaction with time scale depended on the particulars of optical structure induced by the two head orientations. A popular hypothesis about the visual control of stance is that AP sway minimizes radial transformations (expansions, dilations) of closed optical contours corresponding to frontal surfaces (Lee & Lishman, 1975; Paulus, Straube, Krafczyk, & Brandt, 1989). This makes sense only if the eyes are looking straight ahead, and not to the side. For the latter case, it has been suggested that motion parallax may be more relevant (e.g., Warren, Kay, & Yilmaz, 1996). Accordingly, if the type of optical structure is of significance to AP sway, vision's influence should depend on head position. Given that ML sway is associated with motion parallax with the head forward and radial expansion–dilation with the head to the side, the eyes-open condition should be sensitive, and the eyes-closed condition insensitive (obviously), to head position and sway direction.

If the interaction of vision with time scale depends on details of optical structure, we should see effects of the particular environment that is seen and the person's orientation to it. Certain data suggest, however, that optical specifics may be irrelevant; that is, the interaction is very general, and the difference between eyes open and eyes closed depends only on the availability of expropriospecific information, whatever its form. Andersen and Dyre (1989) found that both radial and lamellar flow patterns in the central visual field induced postural sway and, more dramatically, Jeka and Lackner (1994, 1995) and Riley, Wong, et al. (1997) found that expropriospecific information in the form of nonforceful fingertip contact with a nearby surface had the same effect on sway as did vision.

EXPERIMENT 1

Experiment 1 extended previous investigations of vision's influence on unperturbed standing by combining the conditions of eyes open and eyes closed with the head facing straight ahead and the head facing to the side. The goal of the experiment was to establish the effects of different optic flow structure associated with a given head orientation for each component direction (AP and ML) of sway.

Method

Participants. Six undergraduates and six graduate students at the University of Connecticut served as participants. The undergraduates received partial course credit for their participation. The graduate students participated voluntarily. Of the 12, 8 participants were men and 4 were women. Their ages ranged between 18 and 37 years (M = 22.83 years). Body weights ranged from 45.45 kg to 76.36 kg (M = 65.18 kg), and heights ranged from 155 cm to 175 cm (M = 164 cm). None of the participants had any history of any skeletal or neuromuscular disorders. None reported any recent injuries at the time of the experiment. All 12 participants had normal or corrected-to-normal vision in both eyes.

Apparatus and data collection. COP data were obtained using a Kistler multicomponent force platform Type 9281B with a Kistler charge amplifier Type 9865 (Kistler Manufacturing Corporation, Amherst, NY) set to 10,000 pC on both principal axes of the platform. For each trial, the participant stood barefoot on the force platform, arms relaxed at the sides, feet abducted 10°, and heels 3 cm apart mediolaterally. Each participant was instructed to stand as still as possible and to focus the eyes within a specified region of a nearby wall (see following). Data collection was started after participants took position on the platform and signaled the experimenter that their stance was stable and their breathing was normal.

The noise characteristics of the force platform were measured by placing a 45.5-kg weight on the platform for 30 sec. In the absence of any movement, the platform produced a signal with an average displacement of 0.7 mm in the platform's x axis and 1.55 mm in the platform's y axis. Because the experiment included a manipulation of head orientation (head facing forward and head facing sideways), and differential AP and/or ML sway characteristics were considered possible as a function of this manipulation, the difference in the baseline noise on the two axes of the platform were controlled for in each experimental condition. Each participant received 10 trials in each of four conditions (i.e., eyes open and head straight, eyes closed and head straight, eyes open and head sideways, and eyes closed and head sideways) in randomized order. In 5 of the 10 trials in each condition, the participants' AP axis was aligned with the platform's x axis; and in the

other 5, their AP axis was aligned with the platform's y axis. Because all analyses were carried out on averages over all 10 trials for each condition (see following), all systematic variation in AP sway relative to ML sway that could be attributed solely to asymmetric baseline noise on the two axes of the platform were eliminated by the counterbalancing. Furthermore, baseline-force platform noise was subtracted from each averaged stabilogram–diffusion series (see following). In all eyes-open trials, participants were instructed to focus on a U.S. letter-sized (21.6 cm × 27.9 cm) sheet of white paper pinned at eye level on a wall approximately 3.65 m away. The sheet subtended a visual angle of 3.39° horizontally and 4.38° vertically. There were no other objects between the participant and the wall. Figure 4 depicts the viewing and head position conditions.

Design and analysis procedure. COP data were analyzed using the stabilogram–diffusion method introduced by Collins and De Luca (1993) and developed further by Riley, Mitra, et al. (1997). In the first step of this method, a displacement analysis is performed on the COP trajectory for each trial, in which the squared displacements between all pairs of data points separated by a given time interval Δt are calculated. These squared displacements are then averaged over the number of intervals of size Δt in the trial. This analysis is repeated for several different values of Δt. In general, for a given Δt that spans m data intervals

$$\left\langle \Delta r^2 \right\rangle_{\Delta t} = \frac{\sum_{i=1}^{N-m} (\Delta r_i)^2}{N-m} \tag{4}$$

where r is the displacement in question (e.g., anteroposterior or mediolateral displacement), and N is the total number of data points in the trial.

In this study, AP and ML COP time series were obtained over 30 sec at a sampling rate of 100 Hz, yielding 3,000 data points per trial. Thus, the shortest available Δt was 10 msec, and there were 2,999 such intervals in every trial. For each trial, mean squared displacements were calculated for time intervals (Δt) ranging from 10 msec to 10 sec (in steps of 10 msec, the experimental resolution), yielding 1,000 mean squared displacement measures for each trial. Figure 5 shows the stabilogram–diffusion plots of each of the 10 trials that were averaged to produce Figure 1. Inspection of Figure 5 reveals that intertrial variability was greater for the longer-term time intervals. As noted previously, in any given trial, the number of available time intervals of longer duration is much smaller than the number of such intervals of shorter duration. In consequence, the stabilogram–diffusion plot of any particular trial provides a better estimate of the mean squared displacement over the shorter as opposed to the longer time intervals. Averaging stabilogram–diffusion series over a number of trials is thus a method of obtaining more reliable estimates of mean squared displacement over time intervals of all sizes that are

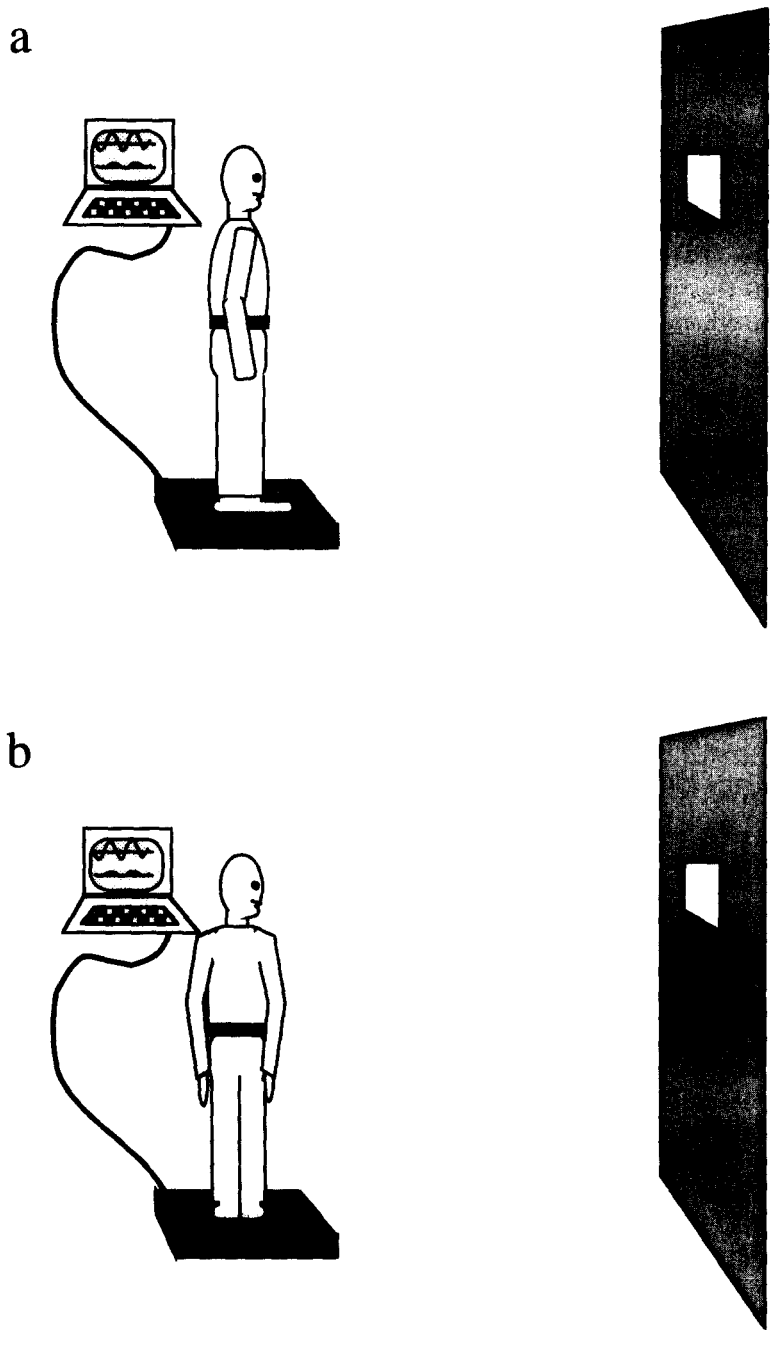

FIGURE 4 Visual target surface and head position in Experiment 1.

required for the subsequent analyses. Also, it should be noted that in the individual trial data (Figure 5) there is evidence of periodicity in the COP signal (e.g., "waves" in the long-term region). This periodicity could not be quantified using standard Fourier-based techniques due to the nonstationary properties of postural sway

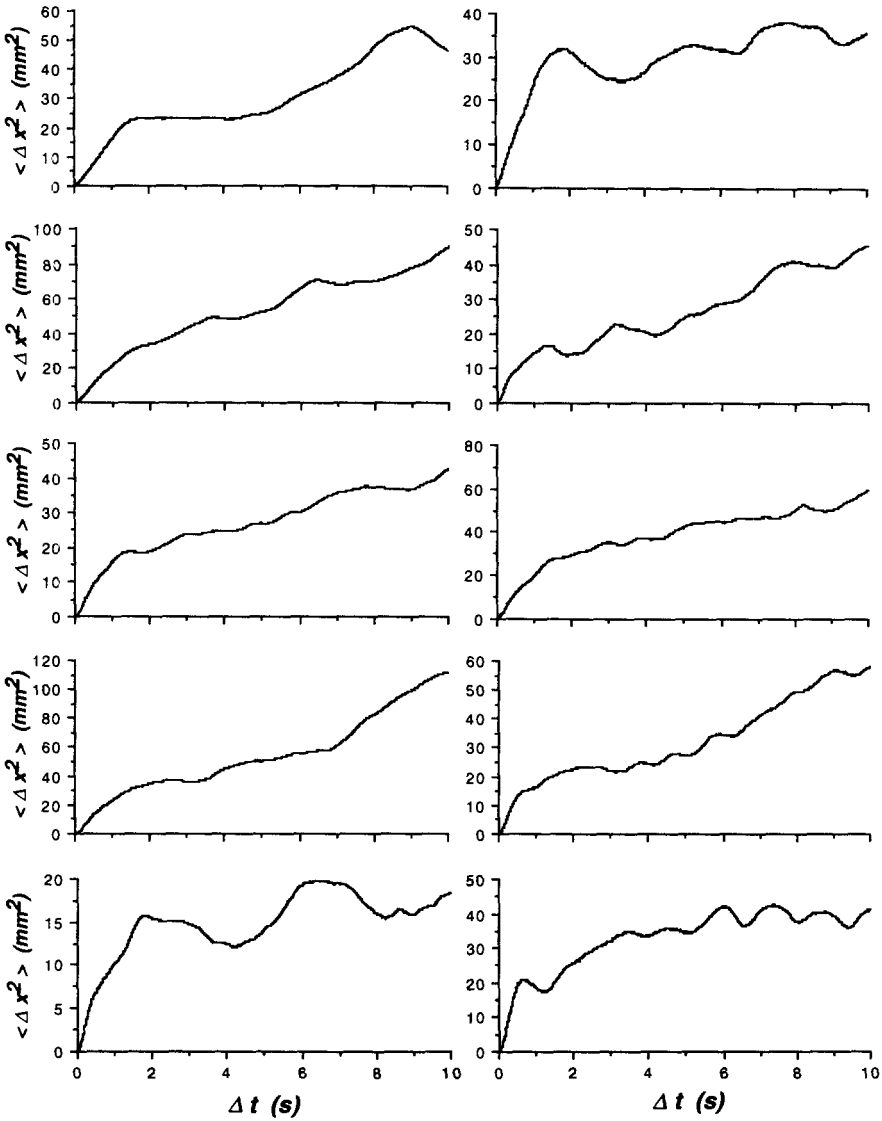

FIGURE 5 Plots of the 10 stabilogram–diffusion series (of 10 individual trials) that were averaged to yield the series plotted in Figure 1.

(Carroll & Freedman, 1993). While the presence of periodicity in individual plots would seem to confirm the aforementioned suggestion that a variety of processes could generate similar stabilogram–diffusion plots to those obtained here, the demonstration that COP signals are fractional Brownian motion (by virtue of being stochastic self-similar processes with stationary, Gaussian increments) was seemingly unaffected by this apparently periodic structure. Clearly, future research must address this feature of COP time series.

The four experimental conditions in the experiment were: (a) eyes open and head straight, (b) eyes closed and head straight, (c) eyes open and head sideways, and (d) eyes closed and head sideways. Since, as described previously, 10 trials of COP data were obtained from each participant for each of the four conditions, the mean stabilogram–diffusion figures for each condition (for a given individual) were obtained by averaging over the 10 trials in that condition.[3] This gave one stabilogram–diffusion series per condition for each participant. The extraction of the short- and long-term diffusion coefficients and Hurst exponents were performed on these resultant stabilograms.

For this study, the stabilogram–diffusion series were divided into short- and long-term regions using predetermined criteria (Riley, Mitra, et al., 1997) that were applied uniformly to the stabilogram data in all four experimental conditions. To obtain the diffusion coefficients and Hurst exponents, the stabilogram data were first fitted to the linear model

$$\left\langle \Delta r^2 \right\rangle = \beta_0 + \beta_1 \Delta t \tag{5}$$

where $\beta_1 = 2D$, and then (using the Levenberg–Marquardt technique) to the exponential model

$$\left\langle \Delta r^2 \right\rangle = e^{\alpha} \cdot \Delta t^{2H} \tag{6}$$

where r is displacement. The brackets in both equations denote the averaging discussed previously. The fit to the linear model (Equation 5) is equivalent to extracting the slope of the linear–linear stabilogram–diffusion plot (with β_0 providing the y intercept and β_1 providing the slope). The nonlinear fit to (Equation 6) is equivalent to extracting the slope of the natural log–natural log stabilogram–diffusion

[3]Following Collins and De Luca (1993, 1995), we underscore that in the stabilogram–diffusion analysis, the parameters are determined from the plots derived from 10 trials of data. Individual 30-sec trials are not parameterized. The stochastic nature of stabilograms makes the individual short trial a poor basis for obtaining repeatable parameters (see text for the discussion of this point). Further, pragmatic reasons (e.g., fatigue of patients) argue against lengthy trials when many conditions must be examined. It should also be noted that the time averaging in stabilogram–diffusion analysis is consistent with studies on diffusion processes in physical and chemical systems in which data are often collected in the form of a large number of small time series.

plot, with α providing the y-intercept and $2H$ providing the slope (see Collins & De Luca, 1993). These fits were performed on the first 150 data points of the stabilogram–diffusion series (a Δt range of 10 msec through 1,500 msec) and parameter values were noted. The final data point (i.e., the 150th) in the series was dropped, and the fits repeated. This was continued until the R^2 obtained on the linear fit dropped below .985. The last point at which $R^2 \geq .985$ was the point that defined Δt_c. The process works backward through the stabilogram–diffusion series (starting at a longer time scale, where the function is fairly linear) and is repeated until the linear fit becomes unsatisfactory. As data are dropped (i.e., data for larger time scales are eliminated), the examined region of the plot becomes less linear (hence the decrease in linear R^2 values). The $R^2 = .985$ criterion was adopted because it was the midpoint of R^2 ranges reported by Collins and De Luca (1993). It should be emphasized that this division into short- and long-term regions provides a consistent means for obtaining parameter estimates over the two time scales using a predetermined criterion. However, it is often the case that the change in slope in the stabilogram–diffusion plots is not sharp and discontinuous, but more gradual. (This may be due to averaging across trials.) This suggests that stochastic COP dynamics differ but may be continuous over short- and long-term regions (Newell et al., 1997). It is also often the case that calculated cutoff points are lower than what visual inspection of the stabilogram–diffusion plot might suggest (see Riley, Wong, et al., 1997).

Parameter values recorded at Δt_c were used as the short-term values in subsequent analyses. The long-term region was defined as the region of the series from $\Delta t_c + 2$ sec (the point at which long-term parameter values are recorded) through $\Delta t = 10$ sec. For example, if for a given stabilogram–diffusion series $\Delta t_c = 0.5$ sec,

TABLE 1
Means and Standard Deviations of AP and ML Short-Term Scaling Region Cutoff Intervals as a Function of Vision and Head Orientation

	AP Sway		*ML Sway*	
Condition	M	SD	M	SD
Experiment 1				
Head straight, eyes open	0.383	0.077	0.433	0.103
Head straight, eyes closed	0.365	0.086	0.446	0.143
Head sideways, eyes open	0.388	0.114	0.416	0.112
Head sideways, eyes closed	0.349	0.123	0.393	0.108
Experiment 2				
Head straight, eyes open	0.431	0.194	0.471	0.134
Head straight, eyes closed	0.446	0.173	0.485	0.199
Head sideways, eyes open	0.474	0.186	0.570	0.298
Head sideways, eyes closed	0.490	0.326	0.503	0.164

Note. AP = anterior–posterior; ML = mediolateral. Times are in seconds.

the long-term region for that series would consist of the series spanning $\Delta t = 2.5$ sec through $\Delta t = 10$ sec. (For further details of the procedure, see Riley, Mitra, et al., 1997.) Table 1 provides the means and standard deviations of the cutoff intervals obtained for all four experimental conditions.

Results

The short- and long-term values of D and H were computed for each participant in each condition in the manner described previously. Within the summary of the H analysis, there were three instances of $H > .5$ in the long-term scaling region. These anomalous exponents were included in all analyses. Similar anomalous values were reported by Collins and De Luca (1993; see their Table 2), suggesting that the occurrence of these values in this analysis is not necessarily due to methodological idiosyncrasies.

Two $2 \times 2 \times 2 \times 2$ analyses of variance (ANOVAs) were conducted on the factors of Vision (eyes open vs. eyes closed), Head (forward vs. side), Region (short term vs. long term), and Sway (AP vs. ML). One ANOVA was directed at D and one at H.

Short-term and long-term diffusion coefficients. Short-term D ($M = 6.9$) was greater than long-term D ($M = 1.5$), $F(1, 11) = 55.87, p < .0001$. D with eyes closed ($M = 5.1$) exceeded D with eyes open ($M = 3.3$), $F(1, 11) = 36.91, p < .0001$. D in AP sway ($M = 5.0$) exceeded D in ML sway ($M = 3.4$), $F(1, 11) = 56.88, p < .0001$. D for head to the side ($M = 4.45$) exceeded D for head forward ($M = 3.95$), $F(1, 11) = 11.85, p < .05$. The relative increase in D with eyes closed was greater in the short term than in the long term, $F(1, 11) = 19.68, p < .001$ (as shown in Figure 6a); and the difference in D favoring AP sway was greater in the short term than in the long term, $F(1, 11) = 4.98, p < .05$. An ANOVA conducted on the data of Table 1 in Collins and De Luca (1993), found the same interaction, $F(1, 9) = 6.58, p < .05$. Closing the eyes magnified the difference in stochastic activity between AP sway and ML sway, $F(1, 11) = 33.34, p < .0001$. There was one three-way interaction reflecting the greater influence of vision on the difference between AP and ML sway in the short term than in the long term, $F(1, 11) = 4.91, p < .05$.

Short-term and long-term scaling exponents. Short-term H ($M = .67$) was greater than long-term H ($M = .25$), $F(1, 11) = 200.53, p < .0001$. The two factors of vision and region interacted as shown in Figure 6b, with eyes open reducing short-term H, and increasing long-term H, relative to eyes closed, $F(1, 11) = 19.79, p < .001$. Planned comparisons revealed that short-term H with eyes open was not significantly less than short-term H with eyes closed, $F(1, 11) = 4.00, p =$

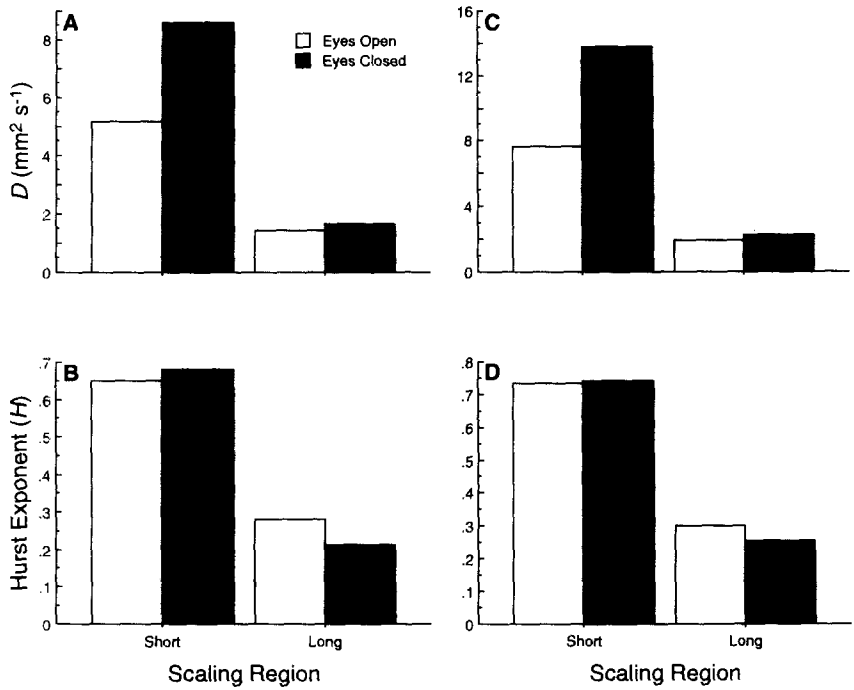

FIGURE 6 *D* and *H* as a function of scaling region and vision. Panels (a) and (b) are the results of Experiment 1, and (c) and (d) are the results of Experiment 2.

.07, and that long-term *H* with eyes open was significantly greater than long-term *H* with eyes closed, $F(1, 11) = 18.42$, $p < .001$. None of the main effects of vision, head position, and sway were reliable, and none of the remaining interactions were reliable ($p > .05$, in all cases).

Returning to the nearly significant effect of vision in the short-term region, subsidiary ANOVAs on the AP short-term data found significant differences favoring eyes closed in the head-forward condition, $F(1, 11) = 9.88$, $p < .01$, and in the head-to-the-side condition, $F(1, 11) = 7.05$, $p < .02$. With respect to the ML short-term data, the corresponding ANOVAs were: $F(1, 11) = 4.77$, $p = .05$, and in the head-to-the-side condition, $F(1, 11) = 4.22$, $p = .07$.

Discussion

These results reinforce the understanding that postural sway shows different correlation structure over different time scales. Other aspects of the observations of Col-

lins and De Luca (1993), Riley, Mitra, et al. (1997), and Riley, Wong, et al. (1997) are also corroborated, namely, a higher magnitude of effective diffusion in the short term and a higher magnitude of effective diffusion for AP sway than ML sway. This latter outcome is attributable to the fact that the ankle joint permits rotation in the sagittal plane and not in the frontal plane.

The main goal of the experiment was to clarify how effective diffusion, persistence ($H > .5$) and antipersistence ($H < .5$) relate to vision in the sense of the relative values of D and H under conditions of differential optical structure effected by having participants stand with the head facing straight ahead or to the side and with the eyes open or closed. Figure 6a shows that eyes closed resulted in more effective diffusion[4] than eyes open in the short term but not in the long term. Figure 6b shows that eyes closed resulted in both greater persistence (H values closer to 1) and greater antipersistence (H values closer to 0). Planned comparisons revealed that vision's effect on H was significant in the short term (for AP sway) and in the long term. The reduced D in the short term with eyes open means that the rate of change of average mean square displacement of the COP as a function of Δt was less than with eyes closed. The reduced H in the short term with eyes open means that for any given ratio of two time intervals, the ratio of the corresponding changes in average mean square displacements was less than for eyes closed. The reduced H with eyes open means that the COP step increments were less positively correlated than with eyes closed. An additional noteworthy effect of vision on D was that the greater effective stochastic activity associated with AP sway relative to ML sway was magnified when the eyes were closed. Absence of vision amplified stability differences between the standing body's major planes of motion.

The manipulation of head position affected only D, with D slightly larger for head facing the side than head facing forward. The lack of interaction with vision indicates that the effect of head position was most likely due to biomechanical factors (less stability with head turned) or, perhaps, to asymmetrical adjustments of the postural musculature by the tonic neck reflexes. The hypothesis that looking ahead and looking to the side entail the registration of different optical transformations with different consequences for the postural control mechanisms was not upheld. In the H analysis, head position did not interact with vision or sway, suggesting an indifference of vision's effect to the type of optical structure present. Alternatively, the absence of these latter interactions might have been due to an optical manipulation that was simply too weak or inexact.

---

[4]It is worth repeating that because the nonlinear data analysis in double logarithmic coordinates leads to H values distinct from .5 (confirmed by the main effect of scaling region in the ANOVA), the COP diffusion coefficients from the linear data analysis can only be viewed as rough approximations or "effective" diffusion coefficients. Only if $H = .5$ can the obtained D values measure actual diffusion (see Collins & De Luca, 1995). The persistence in increments ($H > .5$) is synonymous with diffusion that is faster than ordinary Brownian motion, and antipersistence ($H < .5$) means diffusion that is slower than Brownian motion (Mandelbrot, 1983).

Along with the results of Riley, Mitra, et al. (1997) and Riley, Wong, et al. (1997), the results of Experiment 1 yield a reasonably compact interpretation of the role of vision. In comparison, the conclusions of Collins and De Luca (1995) were much less straightforward. In large part, complications arose in the Collins and De Luca (1995) study because the results for D suggested the possibility that participants divided into two groups reflecting two distinct strategies for visual regulation of posture. The basis for the division was that D for the long-term scaling region was increased by eyes open relative to eyes closed for some participants, whereas for other participants, the opposite was true. Inspection of the data of Collins and De Luca (1995), in particular their Figure 7, does not, however, provide compelling support for the notion of two groups using two strategies. The short-term D values behaved similarly as a function of vision (eyes open vs. eyes closed) for the two ad hoc groups, as did the short- and long-term values of H. Thus, for example, the long-term scaling exponent for both groups was numerically larger for eyes open for each of the measures of AP, ML, and planar (incorporating both AP and ML) sway. The implication is that there may have been no truly significant interactions (ANOVAs were not computed) between groups and vision, or between groups and scaling region. The data obtained here allow for an evaluation of this hypothesis. The additional condition of looking to the side meant that for each participant, there were four long-term, eyes-open values of D to be compared with four long-term, eyes-closed values. D was uniformly larger for eyes closed in only one participant (Participant 4) and uniformly larger for eyes open in only one participant (Participant 12). For the remaining 10 participants, the number of times (out of 4) that D for eyes open exceeded D for eyes closed were: 2, 3, 1, 2, 1, 1, 2, 2, 1, and 2. In short, there is no indication of a division into two groups. Also, the preceding numbers underscore the importance of determining effects through ANOVA.

EXPERIMENT 2

The results of Experiment 1 provided further evidence as to how postural sway over the two time scales is influenced by vision. With eyes open, less stochastic activity (effective diffusion) and decreased persistence were observed over the short-term region (possibly reflecting a reduction of the activation level of postural muscles). Over the long-term region, eyes open produced decreased levels of antipersistence but with the same level of effective stochastic activity evident when vision was absent (see Figures 6a and 6b). These features of vision's contribution to postural control are consistent with the hypothesis that fluctuations at short-term time intervals are exploratory actions designed to obtain information about the postural dynamics (Riccio, 1993) and are promoted through changes in the level of postural muscle activation (or, for Collins & De Luca, 1995, muscle stiffness). Without vision, an increased level of fluctuations, and more "directed" fluctuations (e.g., increased cor-

relations), are needed. That this strategy can compensate for lack of vision is suggested by the identical levels of stochastic activity at the long-term time intervals for the eyes-open and eyes-closed conditions (see Figure 6a).

Experiment 2 was conducted to substantiate the preceding interpretation of the influence of vision on COP trajectories. Additionally, it was directed at a further feature of Experiment 1, namely, that the effects of vision were independent of the orientation of the eye–head system and the type of sway. The difference between Experiment 2 and Experiment 1 was with respect to the structure of the visible surroundings. In Experiment 1, participants focused on a white sheet of paper flush to a wall, as shown in Figure 1. In Experiment 2, they focused on an arrangement of vertical wooden dowels arrayed in depth, as shown in Figure 7. The purpose of the depth grading was to enhance radial expansion and contraction (or motion perspective; Gibson, 1979/1986) in AP sway when looking forward and ML sway when looking to the side, and to enhance motion parallax in AP sway when looking to the side and ML sway when looking forward. Under these particular optical conditions of Experiment 2, we asked: Would vision's effect on D and H interact with scaling region in the manner shown in Figures 6a and 6b, and would vision's effect depend on the conjunction of eye–head orientation and sway direction?

Method

Participants. A total of 10 participants, 4 graduate students and 6 undergraduates at the University of Connecticut, participated in this experiment. The graduate students participated voluntarily, and undergraduates received partial course credit. Of the 10, 5 participants were men and 5 were women. All had normal or corrected-to-normal vision, and none reported a history of skeleto-muscular disorder or injury at the time of the experiment. Participants' ages ranged from 17 to 31 years, heights ranged from 149 cm to 176 cm (M = 158 cm), and body weights ranged from 43.12 kg to 82.65 kg (M = 59.93 kg).

Apparatus and data collection. The experimental arrangement and equipment were identical to those of Experiment 1 except that in eyes-open conditions, participants were asked to look at the depth-grading apparatus shown in Figure 7. There were three rows of nine wooden dowels, with each dowel 0.8 cm in diameter. The dowels in a given row were 10 cm apart, and the distance between successive rows was 18 cm. Participants were positioned 122 cm from the nearest row. The whole apparatus was 92 cm wide (subtending a horizontal visual angle of 41.32° at the nearest row) and 105.6 cm high (subtending a vertical visual angle of 46.8° at the nearest row), and was positioned such that participants' eyes were directed roughly at its center. Participants were instructed simply to "look at the ap-

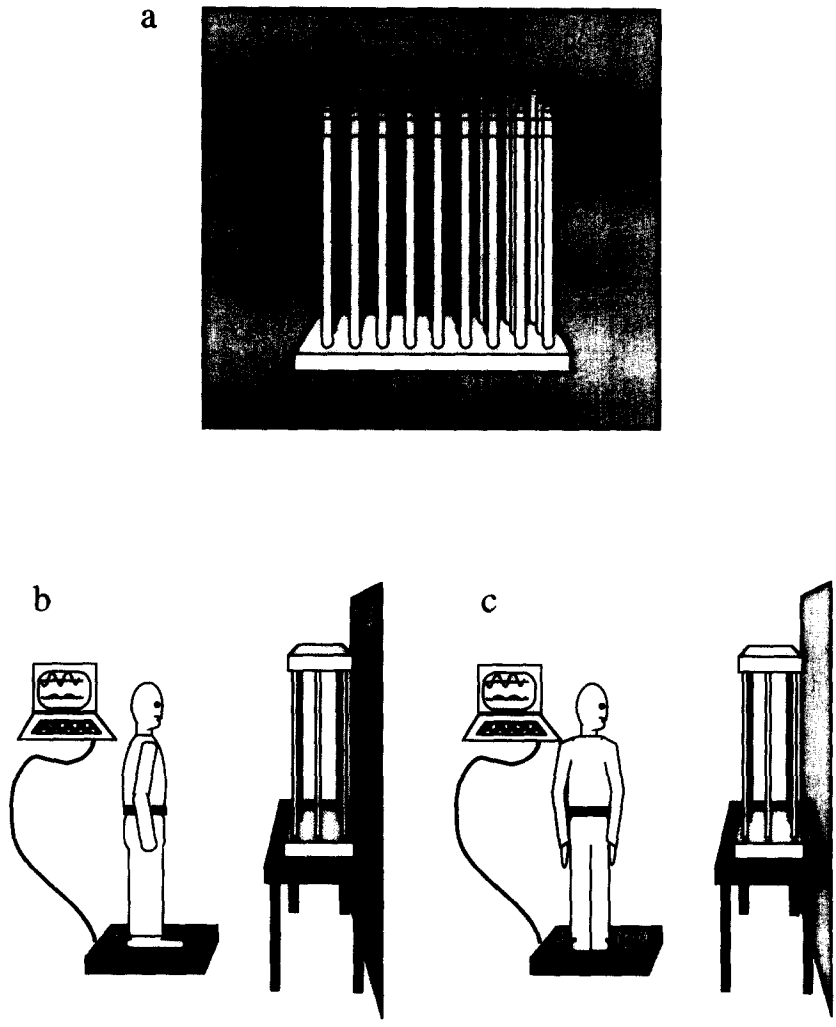

FIGURE 7 (a) Arrangement of vertical wooden dowels in depth used as the visual target in Experiment 2. (b) and (c) Viewing conditions as a function of head orientation.

paratus"; they were not instructed to focus specifically on the dowels or on the wall behind them.

Design and analysis procedure. As in Experiment 1, there were four experimental conditions: (a) eyes open and head straight, (b) eyes closed and head straight, (c) eyes open and head sideways, and (d) eyes closed and head sideways.

AP and ML sway were again analyzed separately in order to assess effects of head orientation on each component of sway. Data analysis procedure and criteria were identical to those in Experiment 1. Table 1 provides the means and standard deviations of the cutoff intervals obtained for the four experimental conditions.

Results

Two 2 × 2 × 2 × 2 ANOVAs were conducted on the factors of Vision (eyes open vs. eyes closed), Head Orientation (forward vs. side), Scaling Region (short term vs. long term), and Sway (AP versus ML). One ANOVA was directed at D and one was directed at H. There were two instances of $H > .5$ in the long-term scaling region in Experiment 2. As in Experiment 1, these anomalous values were included in all analyses.

Short-term and long-term diffusion coefficients. Short-term D ($M = 10.7$) was greater than long-term D ($M = 2.1$), $F(1, 9) = 37.87$, $p < .001$; and D with eyes closed ($M = 8.0$) exceeded D with eyes open, ($M = 4.8$), $F(1, 9) = 98.08$, $p < .0001$. In replication of Experiment 1, the relative increase in D with eyes closed was greater in the short term than in the long term, $F(1, 9) = 58.77$, $p < .0001$ (see Figure 6c). The three-way interaction of vision, scaling region, and sway was also significant, $F(1, 9) = 16.14$, $p < .01$. As in Experiment 1, this interaction reflected the greater influence of vision on the difference between AP and ML in the short term than in the long term. Head position was not significant, $F(1, 9) = 2.28$, $p > .05$, and did not interact with any factor (all Fs < 1).

Short-term and long-term scaling exponents. Short-term H ($M = .74$) was greater than long-term H ($M = .28$), $F(1, 9) = 668.11$, $p < .0001$; and H was greater in the head-sideways ($M = .52$) than in the head-straight condition ($M = .50$), $F(1, 9) = 6.13$, $p < .05$. In replication of Experiment 1, vision and scaling region interacted significantly, $F(1, 9) = 5.08$, $p < .05$ (Figure 6d). Means comparisons showed that long-term H was less for eyes closed than for eyes open, $F(1, 9) = 7.23$, $p < .05$, but there was no difference in short-term H (for either AP or ML). Vision and sway also interacted significantly, $F(1, 9) = 5.97$, $p < .05$; means comparisons showed that H for AP was greater with eyes open than with eyes closed, $F(1, 9) = 9.40$, $p < .05$, with no corresponding effect for ML.

There was a reliable three-way interaction of Vision × Scaling Region × Sway, $F(1, 9) = 6.29$, $p < .05$, indicating that the important interaction between vision and region was restricted to the AP data. Means comparisons showed a difference between eyes open and eyes closed in long-term AP sway, $F(1, 9) = 21.731$, $p < .01$, while no such difference appeared in either short-term AP or

short- and long-term ML sway. Other significant interactions were Vision × Sway × Head Orientation, $F(1, 9) = 10.75$, $p < .01$; and Vision × Sway × Head Orientation × Scaling Region, $F(1,9) = 8.65$, $p < .05$. The four-way interaction was due to the lack of any effects in the short term. The residual three-way interaction was due to a larger H (i.e., closer to .5, indicating weakened correlations) for long-term AP with eyes open than eyes closed when the head was turned sideways, $F(1, 9) = 36.33$, $p < .001$. No other differences in the long-term scaling region were significant.

Discussion

Experiment 2 differed from Experiment 1 only with respect to what participants looked at. In Experiment 2, they looked at a layout of objects arranged in depth designed to enhance motion perspective and parallax. In Experiment 1, they looked at a closed contour flush with a wall. Did the more structured visible environment of Experiment 2 affect vision's influence at the two time scales? As shown in Figures 6c and 6d, Experiment 2 reproduced the interactions between vision and scaling region found in Experiment 1. In Figure 6c, the eyes-closed effective diffusion coefficient exceeded that for eyes open in the short-term region but was of the same magnitude as the eyes-open effective diffusion coefficient in the long-term region. In Figure 6d, the eyes-closed Hs were further from .5 than the eyes-open Hs in both scaling regions. As in Experiment 1, the two interactions fit. Given that short-term D with eyes closed is so much greater than with eyes open (see Figures 6a and 6c), any small difference in short-term H would have to translate into a larger difference in long-term H (see Figures 6b and 6d) if long-term D with eyes closed is to be the same as long-term D with eyes open.

Did the more structured visible environment of Experiment 2 affect the dependency of vision's influence on the conjunction of eye–head orientation and sway? Because head position did not influence the relation between vision and D, it must be concluded that the particular correspondence between optical transformations and direction of sway in Experiment 2 was immaterial to vision's effect on D. This conclusion is reinforced by the match between these results and those of Experiment 1. For unperturbed stance, it seems that vision's influence on the level of stochastic activity (i.e., effective diffusion) is very general. Any expropriospecific optical transformations due to the moving eye–head system will suffice to reduce the jump frequency or amplitude, or both, of the COP at the short-term time intervals. There was, however, an effect of head orientation on H. H was greater (closer to .5) in the long term for AP sway for eyes open relative to eyes closed, but only for the head-to-side condition; because the interaction depended on having the eyes open, this is likely not due to a purely biomechanical effect of turning the head to the side. Thus, the differential optical structure (motion parallax generated by AP sway) with the head facing to the side did have a small effect on long-term H for AP

sway. (Antipersistence was decreased in strength with eyes open, indicating that with eyes open, the instantaneous postural state was less dependent upon previous postural states relative to eyes closed.) With this exception, the results of the two experiments for *H* are very similar, and suggest that the general effect of optical transformations due to the moving eye–head system is to render the COP trajectories less negatively correlated over long-term intervals.

Finally, the data of Experiment 2 also allow for a further evaluation of the two-groups hypothesis (Collins & De Luca, 1995). Inspection of the data revealed that stochastic activity was neither uniformly larger for eyes closed nor uniformly larger for eyes open for any of the participants. The number of times (out of 4) that *D* for eyes open exceeded *D* for eyes closed were: 2, 2, 1, 1, 3, 2, 1, 2, 1, and 2 for Participants 1 through 10, respectively. As in Experiment 1, there was no indication of a division into two groups.

GENERAL DISCUSSION

The goal of this research has been to clarify vision's contribution to postural control with respect to short- and long-term regions of stabilogram–diffusion plots. Both experiments showed that, relative to eyes closed, eyes open reduced the level of stochastic activity in the short term and decreased the level of long-term negatively correlated activity. The general contribution of vision is defined compactly and consistently by the interactions depicted in Figure 6. However, there was one exception in Experiment 2 that indicates that the particulars of optical structure may, in some cases, have a more specific effect. With the head to the side (but not with the head facing straight) and for AP sway (but not ML sway), there was a difference in long-term *H* across conditions of eyes open and eyes closed. (There was decreased correlated activity with the eyes open.) Furthermore, whereas Collins and De Luca (1995) concluded that vision might be integrated into the postural control system in two different ways for different individuals, our experiments, in agreement with Riley, Mitra, et al. (1997) and Riley, Wong, et al. (1997), found no evidence that participants comprise two distinct functional groups and yielded a simple pattern of results suggestive of a common, single strategy.

As Collins and De Luca (1993) underscored, the fact of persistence and the implied open-loop mechanism run counter to the standard view of continuous sensory corrections of the postural system. The mechanical fluctuations due to open-loop activation of muscles and their displacement effects seem to be left unchecked until a certain threshold is exceeded—then, and only then, are sensory influences brought into play. The rationalization given by Collins and De Luca (1993, 1995) for an open-loop contribution to postural control is that it would take care of inherent time delays and would simplify the task of incorporating sensory corrections from multiple sources, essentially ignoring them when postural stability is not threatened. Although our experiments are supportive of the preceding interpretation, they also give reason to pursue the perceptual, exploratory account of

movement variability. If persistence does involve perception, it would seem to do so in a way that is different from the way that antipersistence involves perception. The difference may be that persistence reflects, in part, obtaining information, whereas antipersistence reflects information use. Considered in these terms, this study might be further evidence for the view that unperturbed stance is a perception–action cycle in which actively generated sway plays a fundamental role (Riccio et al., 1992; Riccio, 1993; Riley, Mitra, et al., 1997).

Finally, the application of stabilogram–diffusion analysis provides further confirmation that COP movements possess different characteristics in the fine details of their temporal structure over different time scales (Riley, Mitra, et al., 1997). However, our data do not necessarily suggest different control mechanisms operating over different time scales (see Newell et al., 1997). With respect to the criticisms raised by Newell et al. of the model of postural control put forth by Collins and De Luca (1993), we concede that the differential structure in COP trajectories may reflect continuous processes that act differentially over various time scales and that the existence of a well-defined critical point in COP trajectories, which would delineate the domains of control of two separate processes, may be questionable. However, we contend that the division of stabilogram–diffusion series into two segments using reliably repeatable statistical procedures is necessary in order to characterize the extent to which the correlational structure of COP trajectories differs across the short- and long-term regions under experimental manipulations. While the OU model put forth by Newell et al. is perhaps a more parsimonious account of diffusion (variability) in COP trajectories, the model is mute with respect to correlated COP activity. In Experiment 2 in this article, the effect of optical structure on the different sway components observed in H was not observed in D. Recent work (e.g., the leaning vs. standing upright, with eyes open or closed conditions of Riley, Mitra, et al., 1997), as well as this result, suggests that analysis of postural fluctuations in terms of correlated structure in COP signals may provide a deeper account of postural control than simple characterizations of variability. It also suggests that inferences regarding the nature of postural control based only on the magnitude of observed variability may suffer if not considered in conjunction with the structure of the variability. The same argument applies to restricting analysis solely to the correlation structure of COP signals. In short, both the magnitude and nature of postural fluctuations should be considered together.

ACKNOWLEDGMENTS

M.T. Turvey is also at Haskins Laboratories, New Haven, CT. S. Mitra is now at Warwick University, UK.

This research was partly supported by NSF Research Grant SBR 97–28970 (M. T. Turvey). R. Balasubramaniam and S. Mitra were partly supported by research fellowships from the Taylor L. Booth Research Center at the University of Connecticut.

We thank Jim Collins, Claudia Carello, Elliot Saltzman, Len Katz, George Lukatela, Tom Stoffregen, Gary Riccio, Steven Boker, Dave Collins, and an anonymous reviewer.

REFERENCES

Andersen, G. J., & Dyre, B. P. (1989). Spatial orientation from optical flow in the central visual field. *Perception & Psychophysics, 45,* 453–458.

Beran, J. (1994). *Statistics for long memory processes.* New York: Chapman & Hall.

Berthoz, A., Lacouer, M., Soechting, J. F., & Vidal, P. P. (1979). The role of vision in the control of posture during linear motion. *Progress in Brain Research, 50,* 197–209.

Bingham, G. P., & Stassen, M. G. (1994). Monocular egocentric distance information generated by head movements. *Ecological Psychology, 6,* 219–238.

Black, F. O., Wall, C., Rockette, H. E., & Kitch, R. (1982). Normal subject postural sway during the Romberg Test. *American Journal of Otolaryngology, 3,* 309–318.

Carroll, J. P., & Freedman, W. (1993). Nonstationarity properties of postural sway. *Journal of Biomechanics, 26,* 409–416.

Collins, J. J., & De Luca, C. J. (1993). Open-loop and closed-loop control of posture: A random-walk analysis of center-of-pressure trajectories. *Experimental Brain Research, 95,* 308–318.

Collins, J. J., & De Luca, C. J. (1995). The effect of visual input on open-loop and closed-loop postural control mechanisms. *Experimental Brain Research, 103,* 151–163.

Edwards, A. S. (1946). Body sway and vision. *Journal of Experimental Psychology, 36,* 526–535.

Einstein, A. (1905). Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flussigkeiten suspendierten Teilchen [On the movement of suspended particles in calm liquid from the molecular kinetic theory of heat]. *Annalen der Physik, 322,* 549–560.

Feder, J. (1988). *Fractals.* New York: Plenum.

Gardiner, C. W. (1985). *Handbook of stochastic methods for physics, chemistry, and the natural sciences.* Berlin: Springer-Verlag.

Gibson, J. J. (1986). *The ecological approach to visual perception.* Hillsdale, NJ: Lawrence Erlbaum Associates, Inc. (Original work published 1979)

Hosking, J. R. M. (1981). Fractional differencing. *Biometrika, 68,* 165–176.

Jeka, J. J., & Lackner, J. R. (1994). Fingertip contact influences human postural control. *Experimental Brain Research, 100,* 495–502.

Jeka, J. J., & Lackner, J. R. (1995). The role of haptic cues from rough and slippery surfaces in human postural control. *Experimental Brain Research, 103,* 267–276.

Lee, D. N. (1978). On the functions of vision. In H. Pick & E. L. Saltzman (Eds.), *Modes of perceiving* (pp. 159–170). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Lee, D. N, & Lishman, J. R. (1975). Visual proprioceptive control of stance. *Journal of Human Movement Studies, 1,* 87–95.

Liebovitch, L. S., & Todorov, A. T. (1996). Invited editorial on "Fractal dynamics of human gait: Stability of long-range correlations in stride interval fluctuations." *Journal of Applied Physiology, 80,* 1446–1447.

Mandelbrot, B. B. (1983). *The fractal geometry of nature.* New York: Freeman.

Mandelbrot, B. B., & van Ness, J. W. (1968). Fractional Brownian motions, fractional noises, and applications. *SIAM Review, 10,* 422–437.

Marotta, J. J., Kruyer, A., & Goodale, M. A. (1998). The role of head movements in the control of manual prehension. *Experimental Brain Research, 120,* 134–138.

Newell, K. M., Slobounov, S. M., Slobounova, E. S., & Molenaar, P. C. M. (1997). Stochastic processes in center of pressure profiles. *Experimental Brain Research, 113,* 158–164.

Paulus, W. M., Straube, A., & Brandt, T. (1984). Visual stabilization of posture: Physiological stimulus characteristics and clinical aspects. *Brain, 107*, 1143–1163.

Paulus, W. M., Straube, A., Krafczyk, S., & Brandt, T. (1989). Differential effects of retinal target displacement, changing size and changing disparity in the control of anterior/posterior and lateral body sway. *Experimental Brain Research, 78*, 243–252.

Riccio, G. E. (1993). Information in movement variability about the qualitative dynamics of posture and orientation. In K. M. Newell & D. M. Corcos (Eds.), *Variability in motor control* (pp. 317–357). Champaign, IL: Human Kinetics.

Riccio, G. E., Martin, E. J., & Stoffregen, T. A. (1992). The role of balance dynamics in the active perception of orientation. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 624–644.

Riccio, G. E., & Stoffregen, T. A. (1988). Affordances as constraints on the control of stance. *Human Movement Science, 7*, 265–300.

Riccio, G. E., & Stoffregen, T. A. (1991). An ecological theory of motion sickness and postural instability. *Ecological Psychology, 3*, 195–240.

Riley, M. A., Mitra, S., Stoffregen, T. A., & Turvey, M. T. (1997). Influences of body lean and vision on unperturbed postural sway. *Motor Control, 1*, 229–246.

Riley, M. A., Wong, S., Mitra, S., & Turvey, M. T. (1997). Common effects of touch and vision on postural parameters. *Experimental Brain Research, 117*, 165–170.

Schöner, G. (1991). Dynamic theory of action–perception patterns: The "moving room" paradigm. *Biological Cybernetics, 64*, 455–462.

Stoffregen, T. A., Smart, L. J., & Bardy, B. G. (1998). *Postural stabilization of looking*. Manuscript submitted for publication.

Travis, R. C. (1945). An experimental analysis of dynamic and static equilibrium. *Journal of Experimental Psychology, 35*, 216–234.

Warren, W. H., Kay, B. A., & Yilmaz, E. H. (1996). Visual control of posture during walking: Functional specificity. *Journal of Experimental Psychology: Human Perception and Performance, 22*, 818–838.

Watanabe, Y., Yokoyama, K., Takata, K., and Takeuchi, S. (1987). An evaluation of control mechanisms in a standing posture using velocity and acceleration of body sway. In B. Jonsson (Ed.), *Biomechanics X–B* (pp. 1005–1010). Champaign, IL: Human Kinetics.

Winter, D. A., Prince, F., Frank, J. S., Powell, C., & Zabjek, K. F. (1996). Unified theory regarding A/P and M/L balance in quiet stance. *Journal of Neurophysiology, 75*, 2334–2343.

Woollacott, M. H., Shumway-Cook, A., & Nashner, L. M. (1986). Postural reflexes and aging. In J. Mortimer, F. J. Pirozolo, & J. G. Maletta (Eds.), *The aging motor system* (pp. 98–119). New York: Praeger.