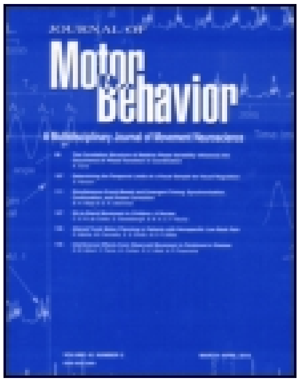

Journal of Motor Behavior
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/vjmb20

Deterministic and Stochastic Postural Processes: Effects of Task, Environment, and Age

Cedrick T. Bonnet [a], Jeffrey M. Kinsella-Shaw [b], Till D. Frank [a], Deborah J. Bubela [b], Steven J. Harrison [b] & M. T. Turvey [a]

[a] Department of Psychology, University of Connecticut, Storrs

[b] Department of Physical Therapy, University of Connecticut, Storrs

Available online: 08 Jul 2010

To cite this article: Cedrick T. Bonnet, Jeffrey M. Kinsella-Shaw, Till D. Frank, Deborah J. Bubela, Steven J. Harrison & M. T. Turvey (2009): Deterministic and Stochastic Postural Processes: Effects of Task, Environment, and Age, Journal of Motor Behavior, 42:1, 85-97

To link to this article: http://dx.doi.org/10.1080/00222890903498521

Journal of Motor Behavior, Vol. 42, No. 1, 2010

Deterministic and Stochastic Postural Processes: Effects of Task, Environment, and Age

Cedrick T. Bonnet[1], Jeffrey M. Kinsella-Shaw[2], Till D. Frank[1], Deborah J. Bubela[2], Steven J. Harrison[2], M. T. Turvey[1]
[1]Department of Psychology, University of Connecticut, Storrs. [2]Department of Physical Therapy, University of Connecticut, Storrs.

ABSTRACT. Upright standing is always environmentally embedded and typically co-occurs with another (suprapostural) activity. In the present study, the authors investigate how these facts affect postural dynamics in an experiment in which younger (*M* age = 20.23 years, *SD* = 2.02 years) and older (*M* age = 75.26 years, *SD* = 4.87 years) participants performed a task of detecting letters in text or maintaining gaze within a target while standing upright in a structured or nonstructured stationary environment. They extracted the coefficients of drift (indexing attractor strength) and diffusion (indexing noise strength) from the center of pressure (COP) time series in anteroposterior (AP) and mediolateral (ML) axes. COP standard deviation decreased with drift and increased with diffusion. The authors found that structure reduced AP diffusion for both groups and that letter detection reduced younger SD_{AP} (primarily by diffusion decrease) and increased older SD_{ML} (primarily by drift decrease). For older and younger participants, ML drift was lower during letter detection. Further, in older letter detection, larger visual contrast sensitivity was associated with larger ML drift and smaller SD_{ML}, raising the hypotheses that ML sway helps information detection and reflects neurophysiological age.

Keywords: ageing, drift-diffusion analysis, suprapostural task, visual factors

The magnitude of postural sway during ordinary standing is related to the risk of falling (Maki, Holliday, & Topper, 1994). Older adults tend to sway more than younger adults, especially when the circumstances of upright posture are more challenging (Brocklehurst, Robertson, & James-Groom, 1982; Maki & MacIlroy, 1996; Prioli, Steckelberg Cardozo, Freitas, & Barela, 2006), for example, when the surface of support is compliant (Lord & Menz, 2000; Redfern, Moore, & Yarsky, 1997) or the level of illumination is low (Kinsella-Shaw, Harrison, Colon-Semenza, & Turvey, 2006). Not surprisingly, falling increases with age.

The present experiment was aimed at furthering understanding of age-related differences in sway. We focused on posture's visual basis and manipulated the demands of standing upright through two visual factors: one of task and one of environment. Visual factors were chosen because dependency on vision for balance control increases with age (e.g., Berger, Chuzel, Buisson, & Rougier, 2005). By manipulating visual factors, we expected that differences and commonalities in postural fluctuations between older and younger adults would be rendered more easily detectable.

In respect to the visual factor of task, the term *suprapostural* has been suggested for any potentially measurable activity performed while standing (Stoffregen, Smart, Bardy, & Pagulayan, 1999). Experiments have shown that visual suprapostural activity influences postural sway (e.g., Stoffregen, Bardy, Bonnet, & Pagulayan, 2006; Stoffregen et al.) and have posed the question of whether it does so in different ways for older and younger adults (Poulain & Giraudet, 2008; Prado, Duarte, & Stoffregen, 2007).

In Poulain and Giraudet's (2008) study, each of the older (age range = 44–60 years) and younger (age range = 21–31 years) participants performed one of three visual tasks while standing in a dark room and looking at a screen in the frontal plane: a recognition task (naming off-centered pictures of objects), a detection task (reporting whether a given object picture had appeared in a sequence of rapidly presented, centrally located pictures), and a focusing task (fixating a point of light at the center of the screen). Center of pressure (COP) measures of the recognition and detection tasks obtained from force-plate data were compared with each other and to COP measures similarly obtained of the focusing task. In Prado et al.'s (2007) study, older (age range = 65–75 years) and younger (age range = 22–39 years) adults either counted the occurrences of a particular letter in a block of text or maintained their gaze within the borders of a blank sheet of paper, with text and blank presented in the frontal plane. Force-plate COP measures and kinematic measures from body segments were compared across the tasks.

Poulain and Giraudet (2008) found that COP measures (root mean square and velocity) in the recognition and detection tasks were reduced relative to the focusing task. The reduction was greater for the older participants than for the younger participants, and was primarily in the mediolateral (ML) axis. Their results were not fully consistent with those of Prado et al. (2007). Although Prado et al. had similarly reported that measures of fluctuation (COP and kinematic) were smaller in their variant of a detection task (searching text) than in their variant of a focusing task (maintaining gaze within a blank area), the observed difference was not age dependent. Moreover, whereas Prado et al. observed reduction in the anteroposterior (AP) axis, Poulain and Giraudet observed reduction, as noted, in the ML axis.

In respect to the visual factor of environment, the influence on postural fluctuation of visible structure and its degree of visibility is well substantiated (e.g., Kunkel, Freudenthaler, Steinhoff, Baudewig, & Paulus, 1998; Masson, Mestre, & Pailhous, 1995). Environmental manipulations were included in Poulain and Giraudet's (2008) and Prado et al.'s

Correspondence address: Cedrick Bonnet, LNFP, CNRS UMR 8160, Eurasanté, 150, Rue du Docteur Yersin 59120 Loos, France. E-mail: cedrick.bonnet@gmail.com

(2007) experiments. Poulain and Giraudet manipulated the orientation (0° vs. 15°) of the luminous frame enclosing the stimulus displays for their recognition and detection tasks. Prado et al. manipulated the distance (0.4 m vs. 3.0 m) of the text and blank sheets constraining their suprapostural tasks. In neither study did the environmental manipulation interact with age or task. The single main effect was the reduction in sway when targets were nearer rather than farther in Prado et al.'s experiment (see also Stoffregen et al. 1999; Stoffregen, Pagulayan, Bardy, & Hettinger, 2000).

In the present study, we used the suprapostural tasks of Prado et al. (2007) and the stationary visual environments of Kinsella-Shaw et al. (2006; see also Riley, Balasubramaniam, Mitra, & Turvey, 1998). In Kinsella-Shaw et al.'s study, an array of vertically aligned rods at different depths relative to the viewer constituted the structured environment and a thin rectangular section of white foam core board of the same vertical and horizontal dimensions as the array of rods constituted the unstructured environment. In the experiment, older and younger participants looked through the array of rods or gazed at the blank board. The results revealed that the standing posture of older adults was less variable when viewing the array of rods.

In the context of manipulated visual factors, age-related differences in visual capability should matter in explaining observed differences in postural behavior between older and younger adults. To this end, visual contrast sensitivity (VCS; Ginsburg, 2003; Ginsburg, Evans, & Cannon, 1984; Woods & Wood, 1995) was used in the present study to provide a measure of the basic visual capability to detect and distinguish environmental structure under different levels of illumination and spatial frequency.[1] VCS is a better measure for the present study's purposes than visual acuity: it is more strongly linked to postural fluctuation (Cummings et al., 1995; Lord & Dayhew, 2001) and a superior indicator of the CNS's developmental age (Anstey, Lord, & Williams, 1997; Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Skeel, Schutte, van Voorst, & Nagra, 2006).[2] To anticipate, visual acuity did not distinguish participants in the present study; their Snellen ratios ranged from 20/20 to 20/24. We note that neither Poulain and Giraudet (2008) nor Prado et al. (2007) broached the possible effect of age-dependent visual efficacy on the observed postural behavior.

As highlighted above, the results of Poulain and Giraudet's (2008) and Prado et al.'s (2007) studies differed in respect to the effects of their manipulations on AP and ML sway. That the two sway axes may contribute in different ways to postural control as a function of age is well recognized in the literature (e.g., Berger et al., 2005; Maki et al., 1994). In the present study, we expected to gain a potentially clearer understanding of postural organization as a function of age, task, and environment by resolving AP and ML sway into deterministic and stochastic components.

Decomposing postural sway into deterministic and stochastic processes aligns the present method with other proposals for two postural processes, namely, conservative (tonus) and operative (phasic), advanced by Lestienne and Gurfinkel (1988); rambling and trembling, advanced by Zatsiorsky and Duarte (1999, 2000; but see Bottaro, Casadio, Morasso, & Sanguineti, 2005); slow and fast, advanced by Dijkstra (2000) and Kiemel, Oie, and Jeka (2006); and part-deterministic and strong stochastic processes, advanced by Rougier and Caron (2000). It is also related to the focus on the measures from recurrence quantification analysis of maxline and 1/(percent recurrence), with the former taken as indicative of stability (in a mathematical sense of response to changes in initial conditions) and the latter taken as indicative of noise (Kinsella-Shaw et al., 2006). The recognition of a deterministic component alongside a stochastic component in the preceding approaches distinguishes them as a class from other mathematical procedures used for examining COP data that have tended to presume that COP motions are purely stochastic (see review in Duarte & Zatsiorsky, 1999).

That the body, during quiet standing, sways for two reasons—not one—is captured in the present research as the understanding that COP variability results from an interaction or competition between two qualitatively different processes, drift (λ) and diffusion (Q). The methodological assumptions are (a) that it does not suffice to obtain a measure of either deterministic or stochastic processes alone, and (b) that it does not suffice to evaluate the contribution of one measure independently of the contribution of the other.

We address five specific expectations and questions by reevaluating previous studies with an eye on the distinction between putatively deterministic and random (or stochastic) underlying mechanisms. First, it was expected that older and younger adults would perform comparably in the text condition (Prado et al., 2007). Confirmation of this expectation would pose the question of whether their comparable performances were mediated by similar or different postural organizations (i.e., similar or different patterns of deterministic and stochastic processes). The subsequent ancillary expectations provide the framework for addressing this question.

Second, it was expected that both age groups would reduce COP variability in the text condition compared with COP variability in the no-text condition (Prado et al., 2007). That is, both age groups should exhibit postural stabilization of searching through text for a given letter. If such proved to be the case, then questions would arise as to whether (a) the variability reduction is expressed in the same way in the AP and ML axes for both age groups, (b) the reduction is mediated through noise reduction (reducing the contribution of random processes) or through attractor strengthening (increasing the contribution of deterministic processes), and (c) the mediating process is the same for both age groups.

Third, COP variability should be affected more by task than by environment (Riccio & Stoffregen, 1988; Smart, Mobley, Otten, Smith, & Amin, 2004). That is, for COP variability, the text versus no-text comparison should be more significant than the structure versus no-structure comparison. Confirmation would invite questions of whether task and structure effects play out in different ways with respect to the axes of fluctuation and the dynamical contributions of random and deterministic processes.

Fourth, the structure versus no structure contrast in regard to the stationary environment should prove more relevant to older than younger participants (Kinsella-Shaw et al., 2006). More specifically, structure should benefit postural control in the older participants more than in the younger participants. If so, then the question can be raised of whether the stationary environment's age-related effect is manifest through random processes, deterministic processes, or both.

Fifth, COP variability should express influences of basic visual efficacy as measured by VCS (cf., Kinsella-Shaw et al., 2006; Lord & Menz, 2000). In the context of VCS as a general index of neurophysiological age, confirmation of this expectation would encourage questions about the relations of VCS to chronological age and to random and deterministic processes.

Method

Participants

Participants were 12 younger and 12 older adults, with 7 men in each group. The mean age, weight, and body height for younger adults and older adults were 20.23 ± 2.02 years and 75.26 ± 4.87 years, 71.35 ± 17.17 kg and 73.00 ± 13.71 kg, and 172.09 ± 12.02 cm and 168.45 ± 9.25 cm, respectively. The ranges for the younger and older participants were 18–24 and 68–83 years, 52–100 and 53–100 kg, and 1.60–1.83 and 1.52–1.87 m, respectively. Participants had no history of neurological or musculoskeletal disease, vestibular problems, or recurrent dizziness. All had normal or corrected-to-normal visual acuity. All completed an informed consent procedure approved by the Institutional Review Board of the University of Connecticut.

Design

Each age group was tested in four conditions. In the text conditions, participants counted the frequency of occurrences of letters in a text target. In the no-text conditions, participants gazed at a blank target, keeping their gaze within its boundaries. For both conditions, the structure behind the target was manipulated. In the no-structure conditions the environment consisted of a blank panel and in the structure conditions the environment was enriched with the vertical rods from the depth-grating array (cf. Kinsella-Shaw et al., 2006). Each trial lasted 35 s and each condition consisted of four consecutive trials. The four conditions were run in a counterbalanced design.

Apparatus and Data Collection

Before the experiment, VCS was tested for each participant. The CST 1800 digital testing station (Vision Science Research Corp., San Ramon, CA) tested VCS for three levels of illumination (3 lx, 6 lx, 85 lx) and for five standardized spatial frequency gratings: 1.5, 3.0, 6.0, 12.0, and 18.0 cycles per degree (cpd). Participants were seated during the testing.

The experimental environment consisted of an area enclosed by white sheets, from the floor to the ceiling. The sheets (Figure 1A) were located 1.20 m to the left and right and 2.40 m forward the midpoint of the two platforms (AMTI force platforms, Advanced Mechanical Technology, Inc., Watertown, MA). Six 100-W lamps were used to provide high illumination (440 lx). Ambient illumination levels were verified with a light meter (Extent Instrument, Waltham, MA, Model 407026) before the first trial of each participant.

A table supporting the depth-grating apparatus (92.0 cm wide × 105.6 cm high) was placed at 0.8 m in front of the participants. The depth-grating array (Figure 1B) consisted of nine rows of 1.8-cm diameter aluminum rods (conduits) arrayed three deep, for a total of 27 (potentially visible) rods. The rods in each row were placed 8 cm apart; rows were separated by 18 cm. The first row (that most proximate to

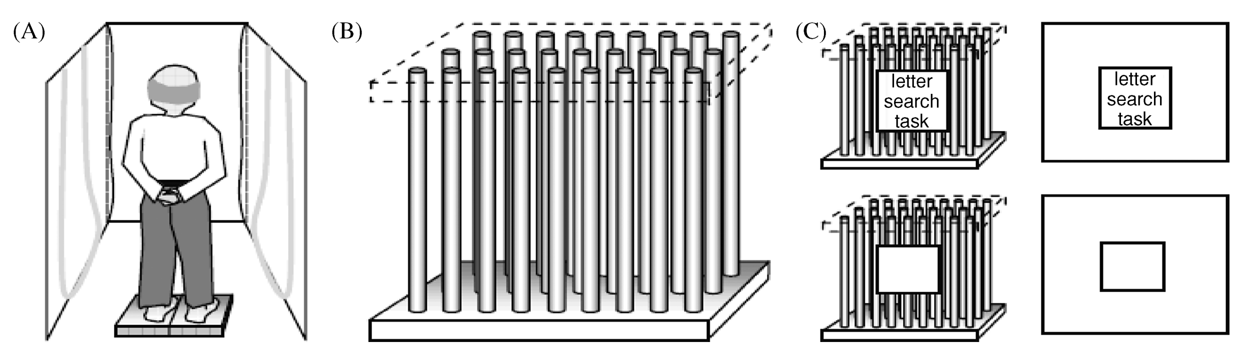

FIGURE 1. (**A**) Experimental arrangement depicting participant standing barefoot on dual-force platforms enclosed by ceiling-to-floor white sheets; (**B**) depth-grating or dowel array; (**C**) the four experimental conditions: a text or blank target attached to the dowel array or a large white board.

the participant) subtended a visual horizontal angle of 59.80° and a visual vertical angle of 66.85°.

The target (20.57 cm wide × 23.11 cm high) was attached either to the depth-grating array (Figure 1C) or to a rectangular section of white foam core board (128.3 cm wide × 100.3 cm high × 5 mm thick; Figure 1C). The target was placed at eye height. The blank target was a sheet of plain white paper. The text target was a sheet of white paper with a written paragraph of 110 English words presented in 14 lines printed using a size 26 Times New Roman font. The targets subtended a visual horizontal angle of 14.65° and a visual vertical angle of 16.44° at the participant's point of observation.

Procedure and Data Analysis

Participants stood barefoot in a comfortable, self-selected position with feet equidistant from the inside edges of the force platforms. This self-selected position of the feet was held constant across the trials. Participants' hands could be in pockets, or grasped behind or in front of the body. Although participants were told that they could adjust the hands and upper limbs slowly if necessary for comfort reasons, they were encouraged to avoid making any voluntary movements during the course of a trial. Older adults wore a gait training safety belt that could be grasped by a physical therapist who stood approximately 5 ft behind them, outside of their field of view. Younger adults wore the belt, but the physical therapist was not present.

In the text conditions, participants were instructed to count the number of times the experimenter-specified letter occurred in the text and to do so as accurately as possible. They were also instructed to return to the beginning of the text if they finished scanning prior to the end of the trial and to continue counting until the trial terminated. On each trial, a new letter was given. After each trial, the experimenter recorded how many letters had been counted and where in the text the participant had stopped. Success on the task was defined as the reported number of instances relative to the actual number of instances encountered by the participant, expressed as a percentage. Speed was defined as the mean number of letters scanned per trial duration. In the no-text conditions the instructions were to maintain the gaze within the boundaries of the blank sheet of paper.

The sampling frequency of the force platforms was set at 100 Hz. We reconstructed COP over the two force plates in the AP and ML axes following Winter (1995):

$$COP(t) = COP_l(t)\frac{R_{vl}(t)}{R_{vl}(t)+R_{vr}(t)} + COP_r(t)\frac{R_{vr}(t)}{R_{vl}(t)+R_{vr}(t)}, \tag{1}$$

in which subscripts l, r, and v designate left, right, and vertical, respectively, and R designates reaction force. The initial 5 s of each trial was removed to avoid initial transients (Kinsella-Shaw et al., 2006). Time series of the COP in the two axes were smoothed with a 7-point triangular moving-window time-domain filter (Abarbanel, 1996).[3]

In what follows, we denote the COP trajectories in the ML and AP directions by $X_{ML}(t)$ and $X_{AP}(t)$, respectively. As highlighted above, observed variability was assumed to arise from the interplay between drift and diffusion or deterministic and random mechanisms, respectively.

For the purposes of deriving quantitative measures of drift and diffusion for COP trajectories,[4] we assumed that COP could be described approximately by Ornstein-Uhlenbeck processes (see Newell, Slobounov, Slobounova, & Molenaar, 1997) and could be defined, therefore, by Langevin equations (Frank, 2005; Risken, 1989) of the form:

$$\frac{d}{dt}X_{ML} = -\lambda_{ML}\, X_{ML} + \sqrt{Q_{ML}}\;\Gamma_{ML}(t) \tag{2}$$

$$\frac{d}{dt}X_{AP} = -\lambda_{AP}\, X_{AP} + \sqrt{Q_{AP}}\;\Gamma_{AP}(t) \tag{3}$$

For $Q_{ML} = Q_{AP} = 0$, the Langevin Equations 2 and 3 reduce to deterministic evolution equations of the form:

$$\frac{d}{dt}X_{ML} = -\lambda_{ML}\, X_{ML} \tag{4}$$

$$\frac{d}{dt}X_{AP} = -\lambda_{AP}\, X_{AP} \tag{5}$$

These equations are solved by exponentially decaying functions. Accordingly, postural sway decays to zero. In other words, there is a drift that results in a decay of postural sway. The decay rates are measured in terms of the parameters λ_{ML} and λ_{AP}. A large parameter indicates a rapid decay. From a dynamic systems perspective, we considered the origin as a fixed point of the postural sway dynamics. Therefore, the parameters λ_{ML} and λ_{AP} described how strong the postural sway is attracted to the fixed point due to the drift dynamics. Consequently, we refer to λ_{ML} and λ_{AP} as measures of attractor strength or simply as drift parameters.

For $\lambda_{ML} = \lambda_{AP} = 0$, the Langevin equations 2 and 3 become:

$$\frac{d}{dt}X_{ML} = \sqrt{Q_{ML}}\;\Gamma_{ML}(t) \tag{6}$$

$$\frac{d}{dt}X_{AP} = \sqrt{Q_{AP}}\;\Gamma_{AP}(t) \tag{7}$$

In this, Γ_{ML} and Γ_{AP} describe fluctuating forces (i.e., time-dependent functions that have random numbers as function values). The preceding fluctuating forces are defined in the present context by so-called Langevin forces (Frank, 2005; Risken, 1989). For Q_{ML} and Q_{AP} equal to unity the solutions of Equations 6 and 7 correspond to standard Wiener processes $W_{ML}(t)$ and $W_{AP}(t)$. That is, $X_{ML} = W_{ML}$ and $X_{AP} = W_{AP}$, and the variances of X_{ML} and X_{AP} increase linearly in time as $\mathrm{Var}(X_{ML}) = t$ and $\mathrm{Var}(X_{AP}) = t$. In this case, postural sway would correspond to a purely diffusive nonstationary process.

The parameters Q_{ML} and Q_{AP} measure the strength of the impact of the fluctuating forces. A large parameter indicates a rapidly diffusing process. For Q_{ML} and Q_{AP} different from unity we have $\mathrm{Var}(X_{ML}) = Q_{ML}t$ and $\mathrm{Var}(X_{AP}) = Q_{AP}t$. In line with dynamics systems theory, we interpreted Q_{ML} and Q_{AP} as amplitudes of the fluctuating forces Γ_{ML} and Γ_{AP} or as diffusion parameters. For the total postural sway, the dynamics as defined by Equations 2 and 3 describe stationary processes. The standard deviations in ML and AP directions of these processes are given by the following:

$$SD_{ML,\,THEORETICAL} = \sqrt{\frac{Q_{ML}}{2\lambda_{ML}}} \tag{8}$$

$$SD_{AP,\,THEORETICAL} = \sqrt{\frac{Q_{AP}}{2\lambda_{AP}}}. \tag{9}$$

Qualitatively, the standard deviations are large if diffusion dominates drift (i.e., if diffusion is strong and the drift dynamics is weak). Likewise, standard deviations are small if drift dominates diffusion. (For details of how the measures of drift and diffusion were calculated, see Appendix.)

Results

The preanalyses showed one outlier for one trial in a text condition.[5] For the participant in question, the averages for the different variables were made by omitting the problematic trial.

Performance in the Letter-Counting Task (Text Condition)

In the text condition, participants had to determine how many times an experimenter-specified letter occurred. Percent correct detection and its standard deviation were similar in the two groups, all ts(22) < 0.35, all ps $> .05$ (Table 1). However, older adults performed the task more slowly, $t(22) = -2.33$, $p < .05$ (Table 1). In the period of a trial, younger adults, on average, scanned more of the text and encountered more instances of a given target letter than did older adults.

TABLE 1. Text-Scanning Performance of Younger and Older Adults: Measures of Mean Accuracy (%) and Rate (Number Detected within Trial Duration) on the Letter-Detection Task for the Two Age Groups

Group	Accuracy	Rate
Old	87.71±11.08	18.30±3.33
Young	88.81±10.11	21.92±4.21

COP Variability in the Different Conditions

A three-factor analysis of variance (ANOVA) was conducted on each of the 6 COP measures with the factors of age (old vs. young), task (text vs. no text), and environment (structure vs. no structure), and with repeated measures on the second and third factors.

COP SD

For COP *SD* in the AP and ML axes, separate ANOVAs revealed a significant age by task interaction effect, all Fs(1, 22) > 4.33, all ps $< .05$, partial $\eta^2 > .17$ (Figure 2, Panels A and B); a significant main effect of task, all Fs(1, 22) $>$ 6.54, all ps $< .05$, partial $\eta^2 > .23$ (Figure 2, Panels A and B); and a significant main effect of age, all Fs(1, 22) = 4.68, all ps $< .05$, partial $\eta^2 > .18$ (Table 2). Younger COP SD_{AP} was smaller for the text condition than for no-text condition and older COP SD_{ML} was larger for text condition than for no-text condition. The first result was expected but not the second.

COP Q

For Q_{AP}, the ANOVA revealed a significant age by environment interaction effect, $F(1, 22) = 10.59$, $p < .05$, partial $\eta^2 = .33$ (Figure 3B); a significant main effect of environment, $F(1, 22) = 6.77$, $p < .05$, partial $\eta^2 = .24$ (Figure 3B); and a significant main effect of age, $F(1, 22) > 6.82$, $p < .05$, partial $\eta^2 = .24$ (Table 2). No effect was significant for Q_{ML}. Older Q_{AP} was larger than younger Q_{AP} and older Q_{AP} was smaller for structure than no structure.

COP λ

For λ_{AP}, the ANOVA revealed a significant age by environment interaction effect, $F(1, 22) = 6.89$, $p < .05$, partial $\eta^2 = .24$. Older λ_{AP} was less than younger λ_{AP} for structure and more than younger λ_{AP} for no structure (Figure 3A). For λ_{ML}, the ANOVA revealed significant main effects of task, $F(1, 22) = 14.15$, $p < .05$, partial $\eta^2 = .39$ (Figure 2C), and age, $F(1, 22) = 4.55$, $p < .05$, partial $\eta^2 = .17$ (Table 2). Older λ_{ML} was smaller than younger λ_{ML} and both older λ_{ML} and younger λ_{ML} were smaller for text than no text.

Validity of the Model and the Text Effect on Older and Younger SD

The results satisfied $SD_{i,THEORETICAL} = \sqrt{Q_i/(2\lambda_i)}$ given by the Ornstein-Uhlenbeck approach: For all participants in all conditions, the difference between (a) experimental SD_{AP} and predicted (theoretical) SD_{AP} and (b) experimental SD_{ML} and predicted (theoretical) SD_{ML} did not differ from 0, all ts(23) $< .001$, all ps $> .05$. The maximum difference was less than 0.6%.

For the younger adults, text was associated with a significant reduction in SD_{AP} (text = .28, no text = .39). For the older adults, text was associated with a significant

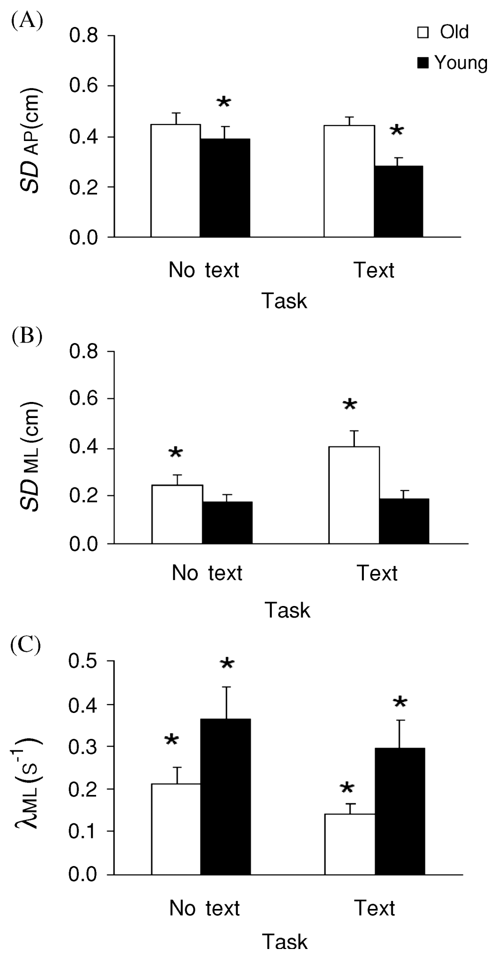

FIGURE 2. Effects of text versus no text. (**A**) Standard deviation (cm) in the anteroposterior (AP) axis; (**B**) standard deviation (cm) in the mediolateral (ML) axis; (**C**) attractor strength (λ [s^{-1}]) in the ML axis. Significant age by task interaction effects are reported for **(A)** and **(B)**, and significant main effects of task are reported for **(A)**, **(B)**, and **(C)**. Significant differences between factor target within age groups are reported (*p <.05).

increase in SD_{ML} (text = .40, no text = .25). It is important to ask whether these significant effects arose through λ, Q, or both. For the younger adults, a repeated measures ANOVA revealed that Q_{AP} was weaker for text (.02) than for no text (.03), $F(1, 11) = 5.14$, $p < .025$, partial $\eta^2 = .32$. For the older adults, a repeated measures ANOVA revealed that λ_{ML} was weaker for text (.14) than for no text (.21), $F(1, 11) = 6.94$, $p < .025$, partial $\eta^2 = .39$ (Figure 2C).

Influence of VCS on COP Variability

A multivariate ANOVA was conducted to compare age-related changes in VCS at each spatial frequency. The analysis was run only for the five variables at 85 lx because 85 lx is the highest illumination in the VCS test and because it is

TABLE 2. Significant Main Effects of Age on Center of Pressure (COP) Standard Deviation in the Anteroposterior (AP) and Mediolateral (ML) Axes

Group	SD_{AP} (cm)	SD_{ML} (cm)	Q_{AP} (cm^2 s^{-1})	λ_{ML} (s^{-1})
Old	.44±.14	.32±.21	.04±.02	.18±.12
Young	.33±.15	.18±.10	.02±.02	.33±.25

Note. Q = diffusion coefficient AP axis; λ = drift coefficient in ML axis.

consistent with the high illumination used in our experimental trials (Kinsella-Shaw et al., 2006). Moreover, it is the case that the levels of illumination during VCS testing and data collection supported full photopic (cone dominant) vision, as is optimal for letter identification (Ginsburg, 2003). The analysis revealed that older adults had significantly lower VCS than did younger adults at each spatial frequency, all Fs$(1, 22) > 7.68$, all ps $< .05$ (Figure 4).

Linear regression was used to assess the relation between VCS and COP variability. We focused on the dependence of COP SD_{ML} on VCS assessed at 85 lx for the following reasons: (a) the age factor was most pronounced for COP SD_{ML} and (b) 85 lx is representative of the visual conditions most

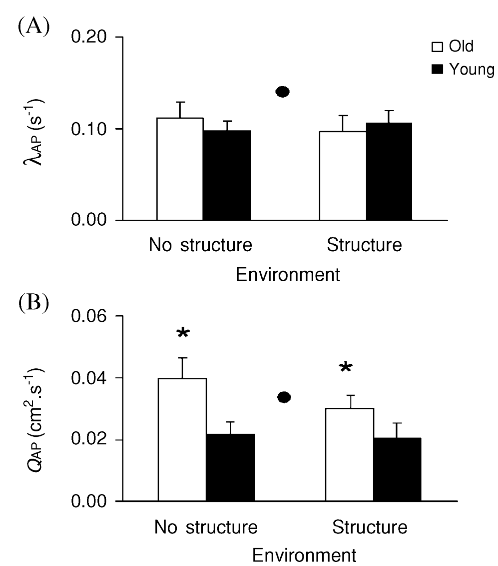

FIGURE 3. Effects of structure versus no structure: (**A**) attractor strength (λ [s^{-1}]) in the anteroposterior (AP) axis and (**B**) fluctuating force (Q) in the AP axis. Significant age by structure interaction effects are reported for (**A**) and significant main effects of structure are reported for (**A**) and (**B**). Significant differences between factor environment within age groups (*p <.05) and significant age by environment interaction effect are reported (•p <.05).

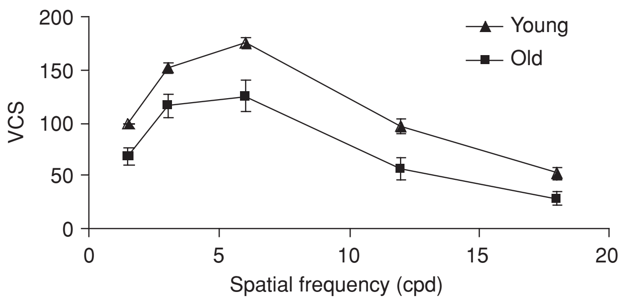

FIGURE 4. Visual contrast sensitivity (VCS) of older and younger adults at the five spatial frequencies (cycles per degree [cpd]) under the 85lx level of illumination. Error bars represent standard errors of the mean.

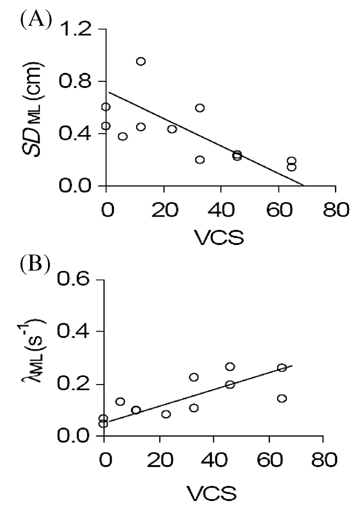

FIGURE 5. Relation between (**A**) visual contrast sensitivity (VCS; at 85lx and 18 cycles per degree [cpd]) and center of pressure standard deviation in the mediolateral (ML) axis (COP SD_{ML}) for older adults in the text conditions, adjusted $R^2(11) = .46$, $p < .025$ and (**B**) VCS (at 85lx and 18 cpd) and COP attractor strength in the ML axis (λ_{ML}) for older adults in the text conditions, adjusted $R^2(11) = .56$, $p < .005$.

significant to letter identification (Ginsburg, 2003). Regressions for old and young in the text and no-text conditions revealed a dependency of COP SD_{ML} on VCS only for the older participants when performing the letter-identification task. A full regression analysis was conducted on the five spatial frequencies and the COP SD_{ML} values of the 12 older adults. Simple linear regressions of COP SD_{ML} on spatial frequency were significant for 3.0, 6.0, 12.0 and 18.0 cpd: adjusted $R^2 = .30$, $F(1, 11) = 5.72$, $p = .038$; adjusted $R^2 = .261$, $F(1, 11) = 4.88$, $p = .052$; adjusted $R^2 = .426$, $F(1, 11) = 9.15$, $p = .013$; and adjusted $R^2 = .392$, $F(1, 11) = 8.1$, $p = .017$, respectively. At each spatial frequency the dependency was a decline in COP SD_{ML} with increasing VCS (Figure 5A shows the regression for 18.0 cpd). Twenty-four sequential (hierarchical) regressions of COP SD_{ML} on spatial frequency were then conducted employing all possible orders of entry using 3.0, 6.0, 12.0 and 18.0 cpd. This allowed a check on all possible additive combinations of the regressors, evaluating both the incremental F values—with the appropriately reduced degrees of freedom at each step—and the overall F value of each possible model. Adding a regressor or combining regressors did not improve the predictive power of any model obtained using any of the four spatial frequencies. Thus, participants' VCS values at each of the four spatial frequencies are independently predictive of postural variability in the ML direction while viewing the text on the dowel array. The lack of predictive power of 1.5 cpd, the lowest spatial frequency tested, is consistent with the task requirement of looking into the center of the dowel array at the text. VCS at 1.5 cpd corresponds most closely to the contour of the dowel array, not the multispatial frequency, nested structure over which visual searching was conducted.

Further regressions restricted to the older participants evaluated the relation of COP λ_{ML} and COP Q_{ML} to VCS in the text and no-text conditions. The only significant regressions were those involving COP λ_{ML} in the text condition, revealing COP λ_{ML} increased with VCS. As with COP SD_{ML}, full regression analysis was conducted on the five spatial frequencies and λ_{ML} values of the 12 older adults. Simple linear regressions of λ_{ML} on spatial frequency were significant for 18.0 cpd and 12.0 cpd: adjusted $R^2 = .52$, $F(1, 11) = 12.79$, $p = .005$; and adjusted $R^2 = .40$, $F(1, 11) = 8.26$, $p = .017$, respectively. The simple regression was marginal for 6.0 cpd: adjusted $R^2 = .23$, $F(1, 11) = 4.35$, $p = .064$. Nine sequential (hierarchical) regressions of λ_{ML} on spatial frequency were then conducted employing all possible orders of entry using 18.0, 12.0 and 6.0 cpd. Again, to evaluate all possible additive combinations of the regressors, the incremental F values—with the appropriately reduced degrees of freedom at each step—and the overall F value of each possible model. Adding a regressor or combining regressors did not improve the predictive power of the model obtained using 18.0 cpd at 85 lx. Also, 18.0 cpd is the tested spatial frequency most relevant to the visual search task, in relation to the dynamical stability index provided by the drift-diffusion analysis. The results of the VCS regression analyses are consistent with the result (Figures 2 and 3) that more significant differences in COP dynamics were induced by task versus no task than by structure versus no structure. As anticipated by Riccio (1993) and confirmed by Smart et al. (2004), the requirements of the task, not the simple availability of visual structure, appear to configure the assembled postural dynamics.

Figure 5 summarizes the primary finding for the older participants: In the letter-detection task, higher VCS values were associated with less variable and more deterministic ML postural dynamics. As Figure 5B makes apparent, COP λ_{ML} was least for two participants who exhibited VCS =

0 at 18.0 cpd.[6] This observation should be considered in light of (a) the normal or corrected to normal 20/20 vision of the older participants and (b) evidence that VCS is an index of neurophysiological age (Anstey et al, 1997; Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Skeel et al., 2006). In that light, Figure 5B suggests that the older the nervous system, the lower is ML sway stability.

Possible Contributions of Differences in Body Lean and Scanning Behavior

The main effect of age was significant for most variables (Table 2). However, one-way ANOVAs in the no-text, no-structure condition did not reveal any significant age-related effects, all Fs(1, 22) < 4.18, all ps >.025. Thus, the differences in COP dynamics between the two groups were not tied to their age difference as such but rather to how the age difference played out through either one or both of the visual manipulations.

In respect to the effects of the visual task, two alternative explanations need to be addressed, one in respect to stance asymmetries and one in respect to visual scanning. Younger and older adults could have stood with different degrees of body lean in the AP or ML axes. Also, they could have chosen different stance widths from one condition to another (although they could not move their feet from one trial to another within each condition). Multivariate ANOVAs were conducted comparing the average position of the COP of younger and older adults in the four conditions and in the AP and ML axes separately. A subsequent multivariate ANOVA was conducted comparing the distance between the COP coordinates of the two force platforms for the two groups in the four conditions. There was no significant difference in any of the variables, all Fs(1, 22) < 2.65, all ps >.025. Thus, the age-related differences in COP dynamics were not caused by an age-related difference in body lean or stance width.

The increase in older SD_{ML} for text versus no text might have arisen from the modified left-to-right reading needed to detect the specified letter. In the subsequent analyses, we controlled for any potential effect of the text in the horizontal axis on SD_{ML} whatever the origin of such an effect (e.g., eye movement, head movement, body movement). We counted the number of beginnings and endings of lines of text read by the 24 participants. They totaled 2,896. Then, we calculated the number of times the 24 participants loaded one foot and then the other foot above a certain threshold of their personal weight (number of weight loads). We tried to find the weight threshold for which we could approximate the number 2,896. We found 3,508, 2,827, and 2,361 load–unload when we used the thresholds of 0.5%, 0.75%, and 1% of participants' weight, and we thus chose the middle threshold. We computed the number of text corners and the number of weight loads for each participant, and ran one correlation for each group. The two correlations were not significant, all ts(96) < 0.17, all ps >.025. This suggests that the significant findings for SD_{ML} were not because of lateral movements of the body caused by the visual scan of the text. The conclusion is consistent with the findings of Stoffregen et al. (2006) for eye movements confined to the range that typically elicits shifting of gaze without rotation of the head (see White, Post, & Leibowitz, 1980). Stoffregen et al. found that the requirement to shift gaze in accordance with a horizontally oscillating target did not induce a magnification of SD_{ML}. For their participants (younger adults), SD_{ML} decreased rather than increased.

Discussion

The introduction identified five experimental outcomes expected on the basis of previous investigations, and specific questions concerning the deterministic (λ) and stochastic (Q) underpinnings of the outcomes if confirmed. In the subsequent section, the expectations and questions are addressed in succession.

Evaluation of Expectations and Questions

On the basis of the results reported by Prado et al. (2007), we expected that, in performing the suprapostural task of detecting letters in text, the older adults would match the younger adults on mean proportion correct but not on the pace of detection. These expectations were confirmed. It was also expected from the results reported by Prado et al. that older and younger adults would reduce COP SD in the text condition relative to the no-text condition. This expectation was not confirmed. Whereas younger COP SD was less for text than no text (with younger COP SD_{ML} equal for text and no text), older COP SD_{ML} was greater for text than no text (with older COP SD_{AP} equal for text and no text).[7]

Behind the older and younger participants' achievement of a common outcome (equal proportion correct in the text condition) through different patterns of COP variability were organizations of postural dynamics marked by common deterministic and stochastic adjustments. In the text condition, older and younger participants reduced COP λ_{ML}. That is, the older and younger postural organizations were alike in that the suprapostural activity of letter detection entailed weakening the attractor for ML sway. That older and younger postural organizations for text were different from that for no text is in agreement with the proposal by Stoffregen and colleagues (e.g., Stoffregen et al., 2006; Stoffregen, Hove, Bardy, Riley, & Bonnet, 2007) that postural organization is adaptive to suprapostural tasks, facilitating their performance, even when very little if any deliberate movement is involved. Whereas prior research has looked to reduction of COP variability for evidence favoring the proposal, the present research suggests that, for the general case, the evidence may be better sought in the underlying deterministic and stochastic processes that fashion COP variability. To reiterate, COP $SD^2 = 1/2\lambda \times Q$. In respect to rambling and trembling, Danna-Dos-Santos, Degani, Zatsiorsky, and Latash (2008) reported that maintaining gaze within a smaller target required a different relation between the two postural processes than maintaining gaze within a larger target.

On the basis of results reported by Kinsella-Shaw et al. (2006), it was expected that a stationary environment as background for the text versus no-text manipulation would influence postural dynamics, with the influence more pronounced for older than younger participants. That the structure of a stationary environment might benefit older adults more than younger adults is supported by the results summarized in Figure 3B. Whereas younger Q_{AP} was the same in the two environmental conditions, older Q_{AP} was smaller for structure than no structure.

Theoretical arguments (Riccio, 1993) and experimentation (Smart et al., 2004) have suggested that COP variability is affected more by task than by environment. In partial confirmation, more significant differences in COP dynamics were induced by task versus no task than by structure versus no structure. Overall, the two visual factors had complementary effects on COP dynamics as is evident in the comparison of Figures 2 and 3.

Finally, it was expected on the basis of previous research that differences in the organization of postural dynamics reflect differences in VCS (Kinsella-Shaw et al., 2006). The VCS is a measure of the ability to distinguish details of environmental layout and is a major index of neurophysiological aging. It need not be strictly correlated with chronological age. The confirmatory observation of a VCS effect was in respect to COP SD_{ML} (decreasing with VCS) and COP λ_{ML} (increasing with VCS) in the older adults.

On the Role of COP SD_{ML} in Older Adults' Postural Dynamics

In our experiment, older adults' COP SD_{ML} was significantly greater for text than for no text. Typically, magnification of lateral sway in older adults is viewed as a sign of reduced postural control and a viable predictor of the likelihood of falling (e.g., Lord, Rogers, Howland, & Fitzpatrick, 1999; Maki et al., 1994). However, the magnification of lateral fluctuation in the text conditions suggests that the lateral fluctuation of older adults may not necessarily or solely reflect destabilization due to sensory decline—it may reflect an adaptation to sensory decline (compare with Berger et al., 2005; Mitchell, Collins, De Luca, Burrows, & Lipsitz, 1995; Schieppati, Hugon, Grasso, Nardone, & Galante, 1994).

In favor of an adaptation interpretation of increased lateral fluctuation are the following observations. First, the older adults were comparable to the younger adults in performing the letter-detection task despite their notably lower VCS (Table 1; Figure 4). Second, in performing the letter-detection task they needed to be visually anchored to the target—presumably to control and stabilize the reading-like behavior. The control and stabilizing demands would have been much less in the no-text condition (Stoffregen et al., 2000). The observations suggest that the older participants' amplification of lateral fluctuation from no text to text was a beneficial, task-specific adjustment. The questions then become: Why did the older adults make the adjustment in COP SD_{ML} (and not in COP SD_{AP} as the younger adults did)? And why was their adjustment an increase in COP *SD* (rather than a decrease in COP *SD*, similar to the younger adults)?

In respect to the second question, it has been argued that more postural fluctuation relative to less postural fluctuation can be functional (Riccio, 1993; Riley & Turvey, 2002; Van Emmerik & van Wegen, 2000, 2002). Imposing limits on postural fluctuations impairs the visual perception of action possibilities (e.g., Mark, Balliet, Craver, Douglas, & Fox, 1990). The notion is that postural fluctuations can serve an exploratory function with respect to propriospecific and exterospecific information detection (Riley, Mitra, Stoffregen, & Turvey, 1997). That older adults may need such a mechanism is suggested by the observation that their visual attentional fields tend to be of smaller radii than those of younger adults (Lott et al., 2001), an age-related reduction that has been found to correlate with both reduced reading speeds and contrast sensitivity (Lott et al., 2001). The regressions reported in Figure 5 are consistent with this a posteriori hypothesis of postural fluctuations aiding information detection. Within the older group, COP SD_{ML} increased with decreasing VCS. A possibly more direct evaluation of the hypothesis is whether the older adults' greater lateral fluctuation affected performance on the letter-detection measures summarized in Table 1. The outcome of a regression analyses on these measures did not lend support to the hypothesis: There was no significant dependency of either measure on either of COP SD_{ML} or COP λ_{ML} (all ps $>.05$). Unfortunately, little can be concluded from the latter outcome given the crudeness of the task (chosen primarily for ease of understanding by the participants). Recall that on a trial the participant searched the text at a self-selected pace with the goals of reporting simply (a) where he or she was in the text when the trial ended and (b) the number of target letters detected. Absent a controlled manipulation of rate of presentation and a measure of false alarms, determinations of sensitivity to speed demands, and accuracy of performance were less than ideal. In Stoffregen et al.'s (2007) study, these limitations were overcome by the use of a signal-detection task.

In respect to the first question, older adults might find it easier to explore in the ML axis than in the AP axis, especially in the letter detection task. COP SD_{AP} originates primarily at the ankles, whereas COP SD_{ML} originates primarily at the hips (Balasubramaniam, Riley, & Turvey, 2000; Winter, Prince, Stergiou, & Powell, 1993). Older adults may defer to a hip mechanism for facilitating information detection to accommodate for age-related physiological degradation in the peripheral segments of the lower limbs. Bonnet, Carello, and Turvey (2009) have suggested that sensory decline such as diabetic neuropathy[8] disposes a person toward exploration through lateral sway. The latter sway about the hips is more controllable and more able to detect information than forward–backward sway about the ankles. The basis of

Bonnet et al.'s claim is that neuropathy generally occurs distally before occurring proximally (Cavanagh, Simoneau, & Ulbrecht, 1993).

In sum, with respect to the two questions above, our conjecture is that reduced VCS may be considered the primary reason for increased fluctuations-qua-exploration in the text versus no-text conditions in the present experiment, with the exploration practically easier in the ML axis.

Influence of the Visual Environment on COP Dynamics

Finally, we note that although environment was less influential than task, environment had an important effect on COP dynamics. Both age groups exhibited lowered COP Q_{AP} within the structured stationary environment. The interaction of age and environment for COP Q_{AP} suggests that structure reduces fluctuating forces in older adults more so than in younger adults. The positive effect of a structured visual environment on COP fluctuations is consistent with an observation of Kinsella-Shaw et al.'s (2006) study. In their study, older adults in the presence of structure decreased COP root mean square and increased the recurrence analysis quantity of COP maxline in the AP axis. Overall, the effect of the structure manipulation on COP dynamics in the present experiment is noteworthy given that participants' attention was directed to the task, not to the environment.

Postscript on Deterministic Processes (Drift), Stochastic Processes (Diffusion) and Movement Variability

A key issue in the study of the emergence of postural variability, and motor behavior variability in general, is that of the nature of the dynamical processes giving rise to the variability (Frank, Friedrich, & Beek, 2006; Riley & Turvey, 2002). In the present investigation, an increase in postural variability has been related to a decrease in the strength of a deterministic attractor or to an increase in the amplitude of fluctuating forces, paralleling an earlier and productive identification of the origins of rhythmic movement variability as jointly deterministic and stochastic (Kelso, 1995; Schöner, Haken, & Kelso, 1986). The present findings, in respect to how task, environment, and age affect the variance of COP, have highlighted the potential significance of deterministic-stochastic, drift-diffusion decomposition. Future applications of this decomposition to the study of postural control warrant consideration of the sufficiency of Equations 2 and 3—a linear drift model with an additive noise term. For the more general case, COP fluctuations would be expected to be non-Gaussian (e.g., abiding a power law distribution), arising from nonlinear drift and multiplicative noise. In the present experiment, with its fairly standard short-duration trials (around 30 s), COP motions occurred within a single region, presumably close to a fixed point. In the vicinity of a fixed point, influences of nonlinearities and multiplicative noise would be small and Equations 2 and 3 would be appropriate. For an experimental protocol that promotes less probable COP motions, such as prolonged unconstrained standing and the shifting and fidgeting of COP (Duarte & Zatsiorsky, 1999), a generalization of Equations 2 and 3 incorporating nonlinear drift terms and multiplicative noise terms may well be required (see Frank et al., Table II).

ACKNOWLEDGMENT

This research was supported by the Collaboratory for Rehabilitation Research through a grant from the Provost's Office at the University of Connecticut.

NOTES

1. In respect to the clinical evaluation of visual detection capability, *contrast* (specifically Michelson Contrast) is a measure of the difference between the luminance of an object and the luminance of its surround. It is calculated as the luminance difference between adjacent regions divided by the luminance summed across the adjacent regions. This yields a dimensionless number, typically reported as a percentage. *Threshold contrast* is that amount of contrast where a participant cannot discriminate between adjacent regions, typically between a sine wave and a patch of uniform grey (50% point on the psychometric function). *Contrast sensitivity* is defined as the inverse of the threshold contrast. Thus, the lower the contrast detectable by a participant over any region of the visual environment, the higher is their contrast sensitivity in that setting. Contrast sensitivity differs as a function of the spatial frequencies available. Spatial frequency is specified in terms of the size of sine wave grating over the back of the eye using cpd of visual angle.

2. Visual acuity (as measured with a standard Snellen chart) is a special case of VCS under high illumination and spatial frequency conditions that are relevant to the detection of refractive errors but less relevant to visually guided tasks in other embedding environments (for an extensive review, see Ginsburg, 2003).

3. Analysis of the voltage output from the dual-force plate system revealed high frequency spikes, most likely due to measurement noise. A triangular filter with a seven-point width was sufficient to eliminate them. Our prior comparisons of filtered and unfiltered postural sway have not revealed effects of the triangular filter on the pattern of results. An exception is applications of recurrence quantification and detrended fluctuation analyses in which triangular filtering has brought patterns in the unfiltered data into sharper relief. A concern with respect to frequency domain filters is that when recovery of temporal structure is the goal, their use to address measurement noise may inject complexities into the time domain.

4. For examples of the quantitative development of drift-diffusion analyses for other purposes, see Friedrich and Peinke (1997), Frank, Friedrich, and Beek (2006), and van Mourick, Daffertshofer, and Beek (2006, 2008).

5. After averaging the four trials in each condition, the box plot showed an outlier for SD_{AP} in the no-structure–text condition. It resulted from a single trial. In this trial, SD_{AP} was more than 7.5 times above the average of all the conditions. The outlier disappeared when this trial was removed from the analysis.

6. That two participants with near 20/20 Snellen acuity exhibited zero contrast sensitivity at 18.0 cpd was most probably due to illumination differences across the test sessions. The clinical protocol to assess contrast sensitivity using the VSRC test station calls for an illumination level that is at the low end of that supporting photopic vision (85 lx, per the manufacturer's benchmarking, Ginsberg's research, and the standards accepted by the United States Air Force in the 1980s). The Snellen acuity assessment, when appropriately standardized, is conducted at 400–480 lux.

7. One possibility for the difference is that the older participants in Prado et al.'s (2007) experiment were younger neurophysiologically than were the older participants in the present experiment.

That is, their VCS placed them at the higher end of the VCS axis in Figure 5A.

8. *Neuropathy* means damage to sensory or motor nerves. Neuropathy thus reduces perception and action capabilities.

REFERENCES

Abarbanel, H. D. I. (1996). *Analysis of observed chaotic data*. New York: Springer-Verlag.

Anstey, K. J., Lord, S. R., & Williams, P. (1997). Strength in the lower limbs, visual contrast sensitivity, and simple reaction time predict cognition in older women. *Psychology and Aging*, *12*, 137–144.

Balasubramaniam, R., Riley, M. A., & Turvey, M. T. (2000). Specificity of postural sway to the demands of a precision task. *Gait & Posture*, *11*, 12–24.

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: A new window at the study of cognitive aging? *Psychology and Aging*, *12*, 12–21.

Berger, L., Chuzel, M., Buisson, G., & Rougier, P. (2005). Undisturbed upright stance control in the elderly: Part 1. Age-related changes in undisturbed upright stance control. *Journal of Motor Behavior*, *37*, 348–358.

Bonnet, C. T., Carello, C., & Turvey, M. T. (2009). Diabetes and postural stability: Review and hypotheses. *Journal of Motor Behavior*, *41*, 172–190.

Bottaro, A., Casadio, M., Morasso, P. G., & Sanguineti, V. (2005). Body sway during quiet standing: Is it the residual chattering of an intermittent stabilization process. *Human Movement Science*, *24*, 588–615.

Box, G. E. P., Jenkins, G. M., & Reinsel, G. C. (1994). *Time series analysis, forcasting and control*. Englewood Cliffs, NJ: Prentice Hall.

Brocklehurst, L., Robertson, D. D., & James-Groom, P. (1982). Clinical correlates of sway in old age sensory modalities. *Age and Aging*, *11*, 1–10.

Cavanagh, P. R., Simoneau, G. G., & Ulbrecht, J. S. (1993). Ulceration, unsteadiness, and uncertainty: The biomechanical consequences of diabetes mellitus. *Journal of Biomechanics*, *26*(Suppl. 1), 23–40.

Cummings, S. R., Nevitt, M. C., Warren, S., Browner, S., Stone, K., Kathleen, M. A., et al. (1995). Risk factors for hip fracture in white women. *The New England Journal of Medicine*, *332*, 767–773.

Danna-Dos-Santos, A., Degani, A. M., Zatsiorsky, V. M., & Latash, M. L. (2008). Is voluntary control of postural sway possible? *Journal of Motor Behavior*, *40*, 179–185.

Dijkstra, T. M. H. (2000). A gentle introduction to the dynamic setpoint model of human postural control during perturbed stance. *Human Movement Science*, *19*, 567–595.

Duarte, M., & Zatsiorsky, V. M. (1999). Patterns of center of pressure migration during prolonged unconstrained standing. *Motor Control*, *3*, 12–27.

Frank, T. D. (2005). *Non-linear Fokker-Planck equations*. Berlin: Springer.

Frank, T. D., Friedrich, R., & Beek, P. J. (2006). Stochastic order parameter equation of isometric force production revealed by drift-diffusion estimates. *Physical Review E*, *74*, 051905.

Friedrich R., & Peinke, J. (1997). Description of a turbulent cascade by a Fokker-Planck equation. *Physical Review Letters*, *78*, 863–866.

Ginsburg, A. P. (2003). Contrast sensitivity and functional vision. *International Ophthalmology Clinics*, *43*(2), 5–15.

Ginsburg, A. P., Evans, D. W., & Cannon, M. W. (1984). Large-sample norms for contrast sensitivity. *American Journal of Optometry & Physiological Optics*, *61*, 80–84.

Kelso, J. A. S. (1995). *Dynamic patterns: The self-organization of brain and behavior*. Cambridge, MA: MIT Press.

Kiemel, T., Oie, K. S., & Jeka, J. J. (2006). Slow dynamics of postural sway are in the feedback loop. *Journal of Neurophysiology*, *95*, 1410–1418.

Kinsella-Shaw, J. M., Harrison, S. J., Colon-Semenza, C., & Turvey, M. T. (2006). Effects of visual environment on quiet standing by young and old adults. *Journal of Motor Behavior*, *38*, 251–264.

Kunkel, M., Freudenthaler, N., Steinhoff, B. J., Baudewig, J., & Paulus, W. (1998). Spatial-frequency-related efficacy of visual stabilization of posture. *Experimental Brain Research*, *121*, 471–477.

Lestienne, F. G., & Gurfinkel, V. S. (1988). Posture as an organizational structure based on a dual process: A formal basis to interpret changes of posture in weightlessness. In O. Pompeiano & J. H. J. Allum (Eds.), *Progress in brain research* (vol. 76, pp. 307–313). Amsterdam: Elsevier.

Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: A strong connection. *Psychology and Aging*, *9*, 339–355.

Lord, S. R., & Dayhew, J. (2001). Visual risk factors for falls in older people. *Journal of the American Geriatrics Society*, *49*, 508–515.

Lord, S. R., & Menz, H. B. (2000). Visual contributions to postural stability in older adults. *Gerontology*, *46*, 306–310.

Lord, S. R., Rogers, M. W., Howland, A., & Fitzpatrick, R. (1999). Lateral stability, sensorimotor function and falls in older people. *Journal of American Geriatrics Society*, *47*, 1077–1081.

Lott, L. A., Schneck, M. E., Hagerstrom-Portnoy, G., Brabyn, J. A., Gildengorin, G. L., & West, C. G. (2001), Reading performance in older adults with good acuity. *Optometry and Vision Science*, *78*, 316–324.

Maki, B. E., Holliday, P. J., & Topper, A. K. A. (1994). Prospective study of postural balance and risk of falling in an ambulatory and independent elderly population. *Journal of Gerontology*, *49*, M72–M84.

Maki, B. E., & McIlroy, W. E. (1996). Postural control in the older adult. *Clinics in Geriatric Medicine*, *12*, 635–658.

Mark, L. S., Balliet, J. A., Craver, K. D., Douglas, S. D., & Fox, T. (1990). What an actor must do in order to perceive the affordance for sitting. *Ecological Psychology*, *2*, 325–366.

Masson, G. S., Mestre, D. R., & Pailhous, J. (1995). Effects of the spatio-temporal structure of the optic flow on the postural readjustments in man. *Experimental Brain Research*, *103*, 137–153.

Mitchell, S. L., Collins, J. J., De Luca, C. J., Burrows, A., & Lipsitz, L. A. (1995). Open-loop and closed-loop postural control mechanisms in Parkinson's disease: Increased mediolateral activity during quiet standing. *Neuroscience Letters*, *197*, 133–136.

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

Poulain, I., & Giraudet, G. (2008). Age-related changes of visual contribution in posture control. *Gait & Posture*, *27*, 1–7.

Prado, J. M., Duarte, M., & Stoffregen, T. A. (2007). Postural sway during dual tasks in young and elderly adults. *Gerontology*, *53*, 274–281.

Prioli, A. C., Steckelberg Cardozo, A., Freitas, P. B. Jr., & Barela, J. A. (2006). Task demand effects on postural control in older adults. *Human Movement Science*, *25*, 435–446.

Redfern, M. S., Moore, P. L., & Yarsky, C. M. (1997). The influence of flooring on standing balance among older persons. *Human Factors*, *39*, 445–455.

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 and motor control* (pp. 317–357). Champaign, IL: Human Kinetics.

Riccio, G. E., & Stoffregen, T. A. (1988). Affordances as constraints on the control of stance. *Human Movement Science*, *7*, 265–300.
Riley, M. A., Balasubramaniam, R., Mitra, S., & Turvey, M. T. (1998). Visual influences on center of pressure dynamics in upright posture. *Ecological Psychology*, *10*, 65–92.
Riley, M. A., Mitra, S., Stoffregen, T. A., & Turvey, M. T. (1997). Influences of body lean and vision on postural fluctuations in stance. *Motor Control*, *1*, 229–246.
Riley, M. A., & Turvey, M. T. (2002). Variability and determinism in motor behavior. *Journal of Motor Behavior*, *34*, 99–125.
Risken, H. (1989). *Fokker-Planck equation: Methods of solution and applications*. Berlin: Springer-Verlag.
Rougier, P., & Caron, O. (2000). Center of gravity motions and ankle joint stiffness control in upright undisturbed stance modeled through fractional Brownian motion. *Journal of Motor Behavior*, *32*, 405–413.
Schieppati, M., Hugon, M., Grasso, M., Nardone, A., & Galante, M. (1994). The limits of equilibrium in young and elderly normal subjects and in parkinsonians. *Electroencephalography and Clinical Neurophysiology*, *93*, 286–298.
Schöner, G. S., Haken, H., & Kelso, J. A. S. (1986). A stochastic theory of phase transitions in human hand movements. *Biological Cybernetics*, *53*, 247–257.
Skeel, R. L., Schutte, C., van Voorst, W., & Nagra, A. (2006). The relationship between visual contrast sensitivity and neuropsychological performance in a healthy elderly sample. *Journal of Clinical and Experimental Neuropsychology*, *28*, 696–705.
Smart, L. J., Mobley, B. S., Otten, E. W., Smith, D. L., & Amin, M. R. (2004). Not just standing there: The use of postural coordination to aid visual tasks. *Human Movement Science*, *22*, 769–780.
Stoffregen, T. A., Bardy, B. G., Bonnet, C. T., & Pagulayan, R. J. (2006). Postural stabilization of visually guided eye movements. *Ecological Psychology*, *18*, 191–222.
Stoffregen, T. A., Hove, P., Bardy, B. G., Riley, M., & Bonnet, C. T. (2007). Postural stabilization of perceptual but not cognitive performance. *Journal of Motor Behavior*, *39*, 126–139.
Stoffregen, T. A., Pagulayan, R. J., Bardy, B. G., & Hettinger, L. J. (2000). Modulating postural control to facilitate visual performance. *Human Movement Science*, *19*, 203–230.
Stoffregen, T. A., Smart, L. J., Bardy, B. G., & Pagulayan, R. J. (1999). Postural stabilization of looking. *Journal of Experimental Psychology: Human Perception and Performance*, *25*, 1641–1658.
Van Emmerik, R. E. A., & van Wegen, E. E. H. (2000). On variability and stability in human movement. *Journal of Applied Biomechanics*, *16*, 394–406.
Van Emmerik, R. E. A., & van Wegen, E. E. H. (2002). On the functional aspects of variability in postural control. *Exercise and Sport Sciences Reviews*, *30*, 177–183.
Van Mourik, A. M., Daffertshofer, A., & Beek, P. J. (2006). Deterministic and stochastic features of rhythmic human movement. *Biological Cybernetics*, *94*, 233–244.
Van Mourik, A. M., Daffertshofer, A., & Beek, P. J. (2008). Extracting global and local dynamics from the stochastics of rhythmic forearm movements. *Journal of Motor Behavior*, *40*, 214–231.
White, K. D., Post, R. B., & Leibowitz, H. W. (1980). Saccadic eye movements and body sway. *Science*, *208*, 621–623.
Winter, D. A. (1995). *A. B. C. (Anatomy, biomechanics and control) of balance during standing and walking*. Waterloo, Ontario, Canada: Waterloo Biomechanics.
Winter, D. A., Prince, F., Stergiou, P., & Powell, C. (1993). Medial-lateral and antero-posterior motor responses associated with center of pressure changes in *Q* uiet standing. *Neuroscience Research Communications*, *12*, 141–148.
Woods, R. L., & Wood, J. M. (1995). The role of contrast sensitivity charts and contrast letter charts in clinical practice. *Clinical and Experimental Optometry*, *78*(2), 43–57.
Zatsiorsky, V. M., & Duarte, M. (1999). Instant equilibrium point and its migration in standing tasks: Rambling and trembling components of the stabilogram. *Motor Control*, *3*, 28–38.
Zatsiorsky, V. M., & Duarte, M. (2000). Rambling and trembling in quiet standing. *Motor Control*, *4*, 185–200.

Submitted January 4, 2009
Revised April 4, 2009
Second revision June 2, 2009
Accepted July 18, 2009

APPENDIX

Statistical Parameters

To estimate the parameters λ_{ML} and λ_{AP} and Q_{ML} and Q_{AP}, we considered the time-discrete counterparts of Langevin Equations 2 and 3 (e.g., Frank, 2005; Risken, 1989) defined by

$$\begin{aligned} X_{ML}(t_n+\tau) - X_{ML}(t_n) \\ = -\tau\lambda_{ML}\, X_{ML}(t_n) + \sqrt{\tau} q_{ML}\Gamma_{ML}(t_n) \quad \text{(A1)} \end{aligned}$$

$$\begin{aligned} X_{AP}(t_n+\tau) - X_{AP}(t_n) \\ = -\tau\lambda_{AP}\, X_{AP}(t_n) + \sqrt{\tau} q_{AP}\Gamma_{AP}(t_n) \quad \text{(A2)} \end{aligned}$$

Here τ denotes the sample interval and t_n is the nth observation time: $t_n = n\tau$ with $n = 1, 2, 3, 4\ldots$. In addition, we have introduced the parameters $q_{\text{ML}} = \sqrt{Q_{\text{ML}}}$ and $q_{\text{AP}} = \sqrt{Q_{AP}}$. Note that the time step τ occurs in the diffusion terms under the square root that is related to the aforementioned fact that the variances (but not the standard deviations) in the purely diffusive case scale linearly with time. Given the observations $X_{\text{ML}}(t_1), X_{\text{ML}}(t_2), X_{\text{ML}}(t_3), \ldots$ and likewise $X_{\text{AP}}(t_1), X_{\text{AP}}(t_2), X_{\text{AP}}(t_3), \ldots$ the parameters λ_{ML} and λ_{AP} and q_{ML} and q_{AP} (and consequently Q_{ML} and Q_{AP}) can be estimated using the maximum likelihood function L (Box, Jenkins, & Reinsel, 1994) defined by $L = ln\, P_{tot}$ with

$$P_{tot} = \Pi_{n=1}^{N-1}\, p\,(X(t_n+\tau), X(t_n)|\lambda, q) \quad \text{(A3)}$$

in which N corresponds to the number of data points of a single trial. In this, X, λ, and q correspond to the corresponding variables and parameters of the ML or AP cases. The function $p(\cdot)$ is the conditional probability density of the Ornstein-Uhlenbeck process defined by

$$p = \frac{1}{\sqrt{2\pi\tau q^2}} \exp\left(-\frac{(X(t_n+\tau) - X(t_n) + \tau\lambda X(t_n))^2}{2\tau q^2}\right) \quad \text{(A4)}$$

(e.g., Frank, 2005; Risken, 1989). According to the maximum likelihood parameter estimation method, the parameters λ and q are chosen such that L becomes maximal for the data at hand.

To implement the maximum likelihood method, we used the Yule-Walker method that is known to yield maximum likelihood estimates in good approximation (Box, Jenkins, & Reinsel, 1994). We used the software package MATLAB (Mathworks Inc., Natick, MA, USA), which offers the command aryule(·). As input vectors, we used the time series $X_{ML}(t_1)$, $X_{ML}(t_2)$, $X_{ML}(t_3)$,... and likewise $X_{AP}(t_1)$, $X_{AP}(t_2)$, $X_{AP}(t_3)$,...The aryule(·) command yields the two output parameters a and e, which are related to λ and q in the manner $a = 1—\tau\ \lambda$ and $e = \tau\ q^2$. Using these relations, we computed λ and q (and Q). For every condition we obtained the quantities COP SD_{ML} and COP SD_{AP} from the experimental data and $SD_{ML,\ THEORETICAL}$ and $SD_{AP,\ THEORETICAL}$, across blocks of four trials for every participant. We then compared the averaged empirical and predicted (theoretical) standard deviations. Finding that $SD_{THEORETICAL} \neq SD_{EXPERIMENTAL}$ would be reason to assume either or both of the following: (a) that Equation 2 does not hold for COP migration, (b) that COP migration was sufficiently nonstationary to compromise the implementation of Equation 2. Finally, we computed for every condition the population averages of the drift and diffusion parameters by averaging the single trial λ and Q parameters across blocks of 4 trials and across participants.