Published in final edited form as:

Neurosci Lett. 2007 December 18; 429(2-3): 147–151.

A Model-Based Approach to Attention and Sensory Integration in Postural Control of Older Adults

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Abstract

We conducted a dual-task experiment that involved information processing (IP) tasks concurrent with postural perturbations to explore the interaction between attention and sensory integration in postural control in young and older adults. A postural control model incorporating sensory integration and the influence of attention was fit to the data, from which parameters were then obtained to quantify the interference of attention on postural control. The model hypothesizes that the cognitive processing and integration of sensory inputs for balance requires time, and that attention influences this processing time, as well as sensory selection by facilitating specific sensory channels. Performing a concurrent IP task had an overall effect on the time delay. Differences in the time delay of the postural control model were found for the older adults. The results suggest enhanced vulnerability of balance processes in older adults to interference from concurrent cognitive IP tasks.

Keywords

Sensory integration; cognitive interaction; attention; balance; postural control

Introduction

Falls are a significant problem in older adults, resulting from a complex interaction of sensory, motor and cognitive loss. Recent research has found that attention plays a role in postural control [5,15,16,20,22], as does dynamic regulation of sensory integration [4,10,11,12,13]. Environmental changes that alter sensory orientation information tend to have a greater destabilizing effect on older adults, and older adults appear to require greater attentional resources for balance control. However, the interaction between attention and sensory integration is an open question. Studying how these two factors interact, and developing a model of that interaction, will improve our understanding of their impact on balance control and predisposing conditions for falls in older adults. This paper addresses the incorporation of the interaction of attention and the dynamic regulation of sensory integration into models of postural control. In particular, we quantitatively investigated, through experiments and model-

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based analysis, the influence of attention-requiring tasks on the dynamics of sensory integration and postural control in older adults.

Studies suggest that balance engages attentional processes to varying degrees, depending upon the postural challenge and the age and capabilities of the individual [2,5,6,8,9,14,15,16,17,18,20,21,22]. Many studies use a dual-task paradigm to examine interference between a cognitive task and a balance task. Dual-task paradigms explore attentional processes involved in sensorimotor function by requiring subjects to perform two tasks simultaneously. Different cognitive tasks have been used in dual-task paradigms involving standing and walking, including mental arithmetic [2,21], visuospatial tasks (e.g. [6]), auditory and visual reaction time tasks [9,15,16,20], word recall [7], and visuospatial memory tasks [1]. Degradation in performance of either the balance task or the cognitive (or information processing (IP) task) is believed to reflect competition for cognitive resources (i.e., attention). As challenge is varied in one task, the amount of interference created in the other task is thought to reflect the degree of attention required to perform the task. If two tasks are processed in parallel, then the interference would be nonexistent. However, dual-task interference is suggestive of the two tasks sharing some common attentional resources. This concept of attention is employed in this study of balance and concurrent information processing (IP) tasks. The hypothesis is that this sharing of attentional resources affects balance by slowing the postural control system, and would be reflected in an increased delay in our model of sensory integration.

Dual task interference between reaction time tasks and standing balance has been observed and reported in the literature (e.g., [15,16,17]). Our studies have shown increased auditory simple and choice reaction times as the postural tasks increased in difficulty, particularly during sway referencing [15,17]. In a recent dual-task study involving IP tasks (auditory and visual choice reaction time tasks) and postural perturbations, we found evidence suggesting that attention shifted away from the IP tasks while a balance-stabilizing response to the postural perturbation (sudden platform translations) was made [16]. Moreover, the study found greater interference for the auditory task than the visual task. The present study uses similar auditory IP tasks to further examine attentional influences on postural control by focusing on changes in parameters of a postural control model during dual-task paradigms, particularly comparing older adults to young adults.

An experimentally validated postural control model [12,13] sets forth a quantitative framework for exploring this hypothesis. We explicitly incorporate a cognitive component (i.e., attention) into the model (Fig. 1), whereby attention influences sensory integration primarily through the time delay parameter t_d and the sensory weights of the model. This model hypothesizes that the processing and integration of sensory inputs for balance requires time, and that attention influences this processing time.

In this study, a dual-task experiment was conducted to examine competition for cognitive resources and its impact on a model of postural control through increase in sensory processing time, quantified by the time delay parameter in the model. Least-squares model fits to subject data were made to quantify differences between young and older adults. We hypothesized that attentional processes would play a greater role in postural control during concurrent IP tasks, resulting in longer cognitive processing times of balance sensory information, manifest in the time delay parameter of the postural control model when fit to the experimental data. We further hypothesized that this effect would be greater in older adults.

Materials and Methods

Subjects

Ten healthy young adults ($M = 5$, $F = 5$, 25 ± 3 yrs., range: 22–33 yrs.) and ten older adults ($M = 4$, $F = 6$, 73 ± 8 yrs., range: 61–85 yrs.) participated in this study, after giving their informed, written consent. The experimental protocol was approved by the Institutional Review Board of the University of Pittsburgh Medical Center, and was performed in accordance with the Declaration of Helsinki. All subjects had no history of auditory, vestibular or neurological disorders, and were screened for normal vestibular function through caloric and rotational vestibular testing. In addition, a neurologist performed a neurological examination to confirm normal neurological function. All subjects also had a Mini-Mental Status Exam (MMSE) score of greater than 24.

Experimental Protocol

A dual-task paradigm was performed that combined postural perturbations with concurrently performed information processing (IP) tasks. Based on our past findings showing interference between postural control and auditory IP tasks, auditory stimuli were used for the IP tasks (see below). Postural challenge was provided by rotating a posture platform (EquiTest, Neurocom, Inc.) during eyes-closed stance about an axis collinear with the ankle angle in a random manner for 121 sec, at a peak-to-peak amplitude of 2 degrees. The platform was driven by computer interface using custom software. Platform motion was preceded and followed by 30 sec of no movement.

The signal used to randomly rotate the platform consisted of two consecutive 60.5 second pseudorandom ternary sequence (PRTS) time series, with peak-to-peak amplitude of 2 degrees. This platform perturbation has been used in previous studies (e.g., [12]). The 2 degree peak-to-peak amplitude was selected based on [12] to avoid saturation effects in the postural response. The PRTS has a wide spectral bandwidth, with the velocity waveform having spectral and statistical properties approximating a white noise stimulus. Hence, any concerns about subjects adapting to the platform motion, such as can occur with sinusoidal perturbations, are ameliorated by using this platform perturbation. The duration of random platform motion was chosen to ensure adequate steady-state conditions for estimation of experimental transfer functions and model parameter fits, while at the same time keeping trials short enough to avoid fatigue effects, especially in the older subjects.

The IP tasks were: 1) None, 2) an auditory choice reaction task (CRT), in which subjects had to click a hand-held microswitch with either the left hand or right hand depending on whether they heard a high- or low-pitched tone (980 Hz vs. 560 Hz, 250 msec duration, 80 dB SPL (Sound Pressure Level), mean inter-stimulus interval of 4 sec (range 2–6 sec)), and 3) an auditory vigilance task (VT), in which subjects experienced the same tone stimuli as in the CRT task but rather than pushing a button in response to the tone, for the VT task subjects had to remember the number of high or low tones they heard during the trial. Auditory stimuli were presented throughout the entire 3 minute trial every 2–6 seconds via Etymotic Research model 3A insert earphones. Note that, although the IP tasks are discrete, occurring randomly every 2–6 seconds throughout the trial, subjects need to attend to the auditory channel to listen for the stimulus, and hence attentional focus is continuous. The IP tasks were selected based on past research and to explore specific processing that might interfere with posture adjustment. The CRT task requires auditory stimulus detection, a choice decision, and a fast reaction. The emphasis is on simple, but fast, processing. Slowing of processing speed is a common finding with age [19]. In contrast, the VT emphasizes accuracy of detection and provides a sensory focus, with a memory requirement and no musculo-skeletal reaction (unlike the CRT task).

Subjects stood, with eyes closed and arms folded across their chest, on the posture platform while performing the IP task conditions, which persisted throughout the entire trial duration. The eyes closed condition was chosen to enhance the postural challenge, to simplify the sensory integration and sensory re-weighting strategy for modeling (presumably limited to proprioceptive and vestibular channels), and to focus attentional resources on fewer sensory channels. Three trials for each IP task were performed, with one IP task per visit, selected randomly. The tasks were completed within 4 weeks, with 2–7 days between visits. The IP tasks were performed on separate days rather than in one visit in order to minimize any possible fatigue effects across the conditions, particularly in our older subjects.

A training session prior to testing was conducted to familiarize subjects with the IP tasks; subjects were seated for the training session. Subjects were naïve to the posture platform condition prior to the first testing session. Instructions to the subjects during testing were: “With your eyes closed and arms folded across your chest, maintain a relaxed upright stance position while reacting as fast as possible to the tone” for the CRT task and “With your eyes closed and arms folded across your chest, maintain a relaxed upright stance position while mentally counting the number of (high or low) tones you hear” for the VT IP task.

Data Measurement and Analysis

Anterior-posterior (AP) body sway (center-of-pressure (COP) under the feet) was recorded at 100 Hz from the force platform. COP were collected with two load cells (one anterior and one posterior) and then combined to estimate AP-COP. For small body angles and velocities of motion as obtained here, AP-COP tracks AP center-of-mass but has more high frequency power [24]. Therefore, we approximated AP body center-of-mass ($\hat{C}\hat{O}\hat{M}$) by digitally low-pass filtering the AP-COP data at 0.5 Hz using a zero-phase first-order Butterworth filter, then down-sampled to 20 Hz to match the platform motion sampling rate. Assuming a linearized (small angle) inverted pendulum model, AP body angle (in radians) was estimated from the

processed AP-COP data by computing $\theta = \frac{\hat{C}\hat{O}\hat{M}}{h}$, where h is the height of the subject's center-of-mass, determined from anthropometric measurements [23].

A steady-state analysis using linear systems techniques was applied to the estimated body angle data to quantify postural responses and estimate model parameters. Specifically, experimental transfer functions of body sway angle to support surface motion were computed, and fit to a feedback model of postural control. For the eyes-closed stance, the model transfer function is [12]

$$M(s) = \frac{BS(s)}{SS(s)} = \frac{W_p(K_D s^2 + K_P s + K_I) e^{-s t_d}}{J s^3 - m g h s + \mathbf{W}(K_D s^2 + K_P s + K_I) e^{-s t_d}}, \quad (1)$$

where s is the Laplace variable; BS and SS denote body sway and support surface angles, respectively, in the Laplace domain; W_p is the proprioceptive sensory weight, which according to the sensory re-weighting hypothesis can change with environmental conditions; t_d is the overall time delay that includes neural conduction times as well as cognitive processing time; and K_P , K_I and K_D are the fixed gains of a PID controller that generates the corrective ankle torque T_a to maintain upright balance. The parameters K_P and K_D represent the active stiffness and damping, respectively, of the postural control system. The parameter $\mathbf{W}$ represents the total sensory contribution, which during eyes-closed stance is $W_p + W_g$, and under steady-state is taken to be $\mathbf{W} = 1$ [12].

Experimental transfer functions were computed by taking a Discrete Fourier transform (DFT) of each 60.5 second cycle of each trial's platform stimulus and the corresponding measured

body sway (filtered AP-COP). The DFT was calculated at 150 equi-spaced frequencies ranging from $f = 0.0165$ Hz to $f = 2.48$ Hz. A property of the PRTS stimulus is that all even frequency components have zero amplitude [12], therefore, these even frequencies are discarded leaving 75 frequency points. Power and cross-power spectral densities were computed for each 60.5 second cycle and then averaged together. High-frequency portions of these spectra were further smoothed, by averaging adjacent spectral points as in [12], to produce the final spectra at 16 frequencies ranging from 0.0165 to 1.90 Hz.

Model fits to the experimental transfer functions were made via a constrained minimization of the cost function

$$C = \sum_{i=1}^N |M(j\omega_i) - H(j\omega_i)|^2, \quad (2)$$

where $H(j\omega)$ is the computed frequency response of the body sway to surface motion, and $M(j\omega)$ is the frequency response of the model, obtained from Eq. (1) with $s = j\omega$ and $\mathbf{W} = 1$. N is the number of frequency points ($N = 16$) over which the transfer function curve fits were made (ranging from 0.0165 to 1.9 Hz). Experimental transfer functions were smoothed as in [12] by averaging neighboring frequency bins. Each IP condition produced three experimental transfer functions (one per trial) per subject, and these three were averaged to obtain the mean experimental transfer function per IP condition per subject. This experimental transfer function was then fit by the model transfer function via the least squares procedure above.

The model fits produced five parameters [W_p , K_P , K_D , K_I , t_d] per subject per IP condition. Statistical analysis of the parameters was performed to test the impact of concurrent information processing tasks. The within-subject differences between the no-task condition and the IP task conditions were found. Then, a repeated-measures ANOVA was conducted on the differences with the independent variables being: AGE (YOUNG, OLD), TASK (CRT, VT), and TASKxAGE. The overall mean was included in each statistical model to examine the overall effect of performing the task on the model parameters. Secondary analyses were performed within group using t-tests to determine if the time delays within group were greater than zero during the IP tasks. A p -value of 0.05 was used for significance.

Results

Effects were found on the time delay and proprioceptive weight parameters, shown in Table 1, for the two age groups during each IP task condition. Fig. 2 (left graph) shows the changes in time delay (t_d) from the no-task condition for each group and task. Results of the ANOVA for the time delay showed that performing a concurrent IP task had an overall increase on the time delay ($p = 0.02$, $t = 2.56$). There was no significant effect of TASK, AGE, or their interaction (TASKxAGE). The overall mean increase in time delay when performing the IP tasks compared to no-task across groups was 5 msec. Secondary t-tests were performed to test whether the time delay was significantly greater than zero within each age group. This analysis showed that the increase in time delay during IP tasks for the elderly (mean increase of about 7 msec) was significantly greater than zero ($p = 0.028$, $t = 2.04$), but not for the young.

Analysis of the proprioceptive weight indicated that there was an overall decrease in W_p across groups when the IP tasks were performed ($p < 0.01$, $t = 3.92$). The AGE effect was significant ($p = 0.04$, $F(1,18) = 4.0$). There was no significant TASK effect or TASKxAGE interaction. Secondary analyses within AGE showed that the decrease in W_p for the older subjects was significantly different from zero ($p < 0.02$, $t = 2.82$), while there was no significant difference from zero for the young subjects. Thus, W_p decreased for the older subjects but not for the

younger subjects. This decrease was approximately 5 percent of the original values (see Table 1 and Fig. 2, right graph).

Analysis of the neural controller parameters (K_D , K_P , and K_I) showed no significant effects of TASK, AGE, or TASKxAGE. Accordingly, we pooled individual subject values across TASK and AGE to obtain the mean values of these parameters: $K_D=143.2$ [N.m.s/rad] (± 60.2 SD), $K_P = 1012.0$ [N.m/rad] (± 212.5 SD), and $K_I = 288.6$ [N.m/s.rad] (± 73.0 SD).

Discussion

These results suggest that our model of postural control, including attentional influences in the time delay, are sensitive to the effect of dual-task interference. The model implies that the time for sensorimotor processing involved in maintaining balance is impacted by dual-task interference. The similarities and differences between age groups in time delay changes suggest that healthy older adults have similar postural control function as young adults during mild postural challenges without concurrent IP tasks, but different postural control function during dual-task conditions. These differences likely reflect the enhanced vulnerability of balance processes in the older adults to interference from cognitive processes. The results also suggest that certain perceptual-motor tasks requiring speeded motor responses (i.e. pushing a button in response to a stimulus) slows balance processing in the old but not the young.

The increase in time delay with a concurrent IP task of about 7 msec for the older adults represents about 5 percent of the total time delay of the postural control system. Although this seems to be a small increase, it was statistically significant. Moreover, much of the time delay is “fixed” due to peripheral neural conduction velocity limitations, which is presumably not impacted by IP task. The total time delay includes this peripheral (sensory and motor) conduction delay, and central processing delay. It is the central processing delay that is hypothesized to be affected by interference from the IP tasks. The peripheral time delay is approximately 80 msec, assuming a conduction velocity of 50 m/sec [3] and a height of 1 m from ankle proprioceptors to the brain. Thus, approximately 70 msec of the total time delay is estimated to be due to central nervous processing (cortical and sub-cortical), such that the increase of 7 msec seen in the time delay represents roughly 10 percent of the central processing delay.

The changes in sensory weighting suggest a potentially significant strategic shift in posture control in the elderly that calls for further investigation. This finding regarding sensory re-weighting during IP task in the older subjects but not the young subjects can be interpreted in terms of the idea proposed in [16], that attention influences sensory selection. In particular, attentional resources drawn to the auditory task serve to enhance the auditory channel. If older adults have greater limits on cognitive resources compared to young adults as evidence suggests, then this shifting of attention to enhance one sensory channel comes at the expense of other sensory channels, namely the proprioceptive channel in this case. This decrease in the proprioceptive weight would also have a stabilizing effect, as it would reduce the influence of the platform perturbation coming in through the proprioceptive channel (SS in Fig. 1). This, too, is consistent with previous findings that older adults are challenged to a greater degree to postural perturbations compared to young adults [16].

In conclusion, this initial study supports the main postulate of our model, that attention, in part, impacts processing speed of the sensory integration process. This effect appears to be true across ages under some conditions (i.e. during our VT task), but greater in older adults under other conditions (i.e. during our CRT task). Further studies in a larger population are warranted.

Acknowledgements

Funding provided by the Pittsburgh Claude D. Pepper Older Americans Independence Center [P30AG024827 (NIA)], and the National Institutes of Health (R01 AG29546, P30 DC005205).

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Fig. 1.

Feedback model of postural control for eyes-closed stance. The body is modeled as a linearized inverted pendulum. Sensory pathways include weights (W_g , W_p) that can change as environmental factors change (the “sensory re-weighting” hypothesis). Corrective ankle torque, T_a , is generated by a fixed-gain proportional-integral-derivative controller acting on the combined delayed error signal E from the sensory systems. Attentional tasks that interfere with balance are hypothesized to increase cognitive processing time involved in balance, manifest in the model as an increase in the time delay of the system. Attention may also influence sensory integration, as manifest in the model via the sensory weights (W_g , W_p). Modified from [12,13].

Fig. 2.

Normal change in postural control time delay (left graph) and proprioceptive weight (right graph) (MEAN $\pm$ SD) during IP tasks relative to no-IP task condition (CRT -NONE and VT -NONE), for young (black) and older (white) subjects.

Table 1

Postural Control Time Delay for Young and Older Adults during IP tasks vs. no-task (MEAN±SD)

IP Task	t_d [msec], YOUNG	t_d [msec], OLDER	w_p , YOUNG	w_p , OLDER
NONE	153±13	153±10	0.52±0.09	0.62±0.12
CRT	153±18	160±18	0.50±0.10	0.56±0.07
VT	162±13	158±18	0.54±0.10	0.57±0.12