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RESEARCH ARTICLE

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The time course of attention shifts following perturbation of upright stance

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Abstract Recent work has revealed the specific time course of attention shifts associated with balance control in a seated model using a dual-task paradigm. This work highlighted an initial "automatic" and later "attention-demanding" phase of the evoked balance reaction. The objective of the present study was to determine if comparable influences would be observed for performance of a visuomotor tracking task when responding to perturbations of upright stability. Small-amplitude floor translations were applied in the forward or backward direction to evoke stabilizing postural reactions. Balance reactions were evoked with and without the concurrent performance of a visuomotor tracking task using the right hand. Results showed significant disruptions (pauses) in tracking that invariably occurred *after* onset of the earliest balance reaction measured in ankle muscles. On average, there was a delay of 345 ms between ankle-muscle activation (average onset 144 ms) and the pause in visuomotor tracking. The concurrent tracking led to modest change in later phases of the balance reaction, as measured by an increase in center-of-pressure excursions, but did not affect the earliest phase of the reaction. These results support the view that compensatory balance reactions, even those evoked by small perturbations, are characterized by an initial "automatic" phase and subsequent control that may be more dependent on cognitive resources.

Keywords Attention · Cognitive processing · Compensatory balance reaction · Dual task · Postural control · Visual tracking

Introduction

There is convincing evidence that attention is associated with the control of upright stability. This has been revealed using dual-task paradigms in which disruptions in the performance of either the balance task or the secondary cognitive task indicate the attentional load associated with the control of upright stability. For example, the performance of cognitively demanding secondary tasks, such as the Stroop test, digit recall, reaction-time tasks or sentence completion, led to an increase in spontaneous postural sway during quiet, unperturbed stance (Geurts et al. 1991; Maylor and Wing 1996; Shumway-Cook et al. 1997; Schlesinger et al. 1998). Reciprocally, performance of the secondary cognitive task (i.e., the Brooks spatial memory test, backward counting or reaction-time tasks) has been shown to be compromised during the simultaneous control of unperturbed upright stance (Kerr et al. 1985; Teasdale et al. 1993; Lajoie et al. 1993, 1996; Andersson et al. 1998; Redfern et al. 1999; Yardley et al. 2001).

Such an interaction between the performance of cognitively demanding tasks and balance control has also been observed in studies that have explored reactions to perturbations of whole-body stability. For example, Stelmach et al. (1990) revealed a marked age-related increase in the time to return to quiescent levels of postural sway following perturbation induced by active swinging of the arms; however, this increase was only observed when the recovery was performed concurrently with a cognitively demanding task (single-digit addition). More recent studies have demonstrated that performance of concurrent attention-demanding tasks (backward

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counting by 3's) is impaired during balance recovery evoked by sudden platform translation (Woollacott and Shumway-Cook 1999; Brown et al. 1999). Reciprocal effects of cognitive task on certain features of the balancing reactions were also observed (Brown et al. 1999; Rankin et al. 2000). While these studies have revealed evidence of resource sharing, it remains unclear which phases of the postural reactions demand attentional resources, as the discontinuous nature of the cognitive tasks that have been employed precludes accurate determination of the timing of attentional shifts. The focus of the present study was on the temporal characteristics of the shifts in resource allocation associated with compensatory balance control.

A recent study from our laboratory revealed a specific pattern of resource sharing consequent to perturbations of ankle stability (McIlroy et al. 1999). In our dual-task paradigm, seated subjects were required to maintain the stability of an inverted pendulum by controlling a foot pedal and, at the same time, performed a continuous visuomotor tracking task with the hand. Imposed perturbations of the pendulum evoked what appeared to be a profound switch in attention, subsequent to the initial postural reaction. On average, a pause (average duration 600 ms) in visuomotor tracking occurred 235 ms after the onset of the perturbation-evoked muscle activity. It was proposed, on the basis of these findings, that the perturbation-evoked balance reaction comprises at least two phases: an initial automatic phase that does not require attentional resources and a later attention-demanding phase likely associated with efforts to regain a state of equilibrium. Although the view that the initial reaction is triggered automatically is certainly not new (e.g., see Nashner and Cordo 1981), no previous studies had actually characterized the attentional demands and attentional dynamics associated with the control of the different phases of the reaction.

The objective of the present study was to determine whether similar phases of control occur during balance reactions evoked by perturbation of upright stance. It was hypothesized that a significant deviation in visuomotor tracking would occur following the onset of the initial "automatic" compensatory balance reaction. We propose that this pause in tracking performance would reflect a diversion of attentional resources away from the visuomotor tracking task to control of the later elements of the compensatory balance reaction.

Materials and methods

Subjects

Six volunteers (two male, four female; ages 24–30 years) consented to participate in the study. None of the subjects reported any neurological or musculoskeletal impairments. The experimental procedures were approved by the local research ethics board.

Protocol

Each subject was tested under two task conditions: (1) "perturbation only" (no secondary task) and (2) "visuomotor tracking" (with and without balance perturbation). Within the visuomotor tracking condition, subjects were informed that they may or may not receive a perturbation. In total, each subject performed ten perturbation-only trials, ten tracking-only trials (balance unperturbed) and ten dual-task trials (balance perturbed while tracking). The order of the trials was randomized.

During all trials, subjects stood at the center of a large (2×2-m), computer-controlled, moveable platform (Maki et al. 1996), with each foot on one of two forceplates. Postural reactions were evoked by small, transient, horizontal platform motions, either forward ($0.75/ms^2$, 0.23/ms, 0.068 m) or backward ($1.25/ms^2$, 0.38/ms, 0.113 m). Equal numbers of trials were performed in each direction. The perturbation magnitudes were selected, on the basis of previous studies, to be sufficiently small to be withstood typically without stepping or moving the arms. The direction and timing of platform motion were varied in an unpredictable manner.

For visuomotor-tracking trials, subjects tracked a moving target on a computer screen (pursuit tracking), controlling the cursor movement by using the dominant hand to rotate a potentiometer (held by the non-dominant hand). The pseudorandom target waveform, the algebraic sum of four sinusoids, was 30 s in duration and featured a mean frequency of approximately 0.5 Hz. At the end of each trial, the root mean square (RMS) tracking error was presented to the subjects as feedback regarding their performance. Prior to the experiment, subjects practiced the visuomotor tracking task until there was negligible improvement in performance (usually eight to ten repetitions); an example performance is shown in Fig. 1a. In order to provide the clearest indication of deviations in tracking performance, balance perturbations were applied, in the dual-task trials, at times to coincide with intervals where the tracking target moved in a single direction. These were the intervals where the highest tracking accuracy and repeatability occurred (note the narrow confidence intervals in Fig. 1a). To allow time to reach steady-state tracking performance, perturbations were always delivered at least 4 s after the start of the target display. To allow sufficient opportunity to resume tracking, each perturbation was followed by a minimum of 7 s of target display.

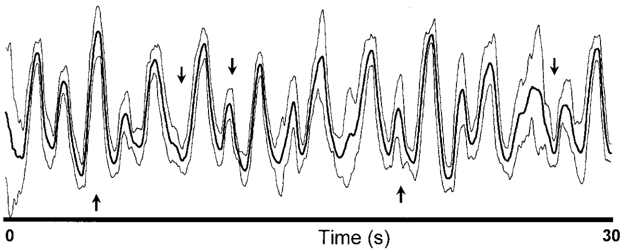
In all trials, subjects were instructed to stand as still as possible. In the dual-task condition, subjects were instructed to track the target as accurately as possible, while always maintaining their upright posture. Subjects held the tracking device in front of the abdomen in all trials.

Measures

A linear accelerometer measured the onset of the platform perturbation (onset = $0.1/ms^2$). Forceplate signals were used to determine anteroposterior (AP) center-of-pressure (CoP) excursions during the postural response. The forceplate signals were also used (in combination with video recordings) to check for failure to maintain static stance (i.e. avoid stepping). Electromyographic (EMG) recordings were obtained with surface Ag/AgCl electrodes placed approximately 2 cm apart longitudinal to the predicted path of the muscle fibers of medial gastrocnemius (MG) and tibialis anterior (TA) muscles (both lower limbs) and anterior deltoid (AD) (dominant upper limb). TA and MG EMG latency were used to characterize the timing of the perturbation-evoked reactions evoked by forward and backward platform translations, respectively. AD EMG was checked (in three of six subjects) for the presence of perturbation-evoked arm reactions that might interfere with performance of the visuomotor tracking task (McIlroy and Maki 1995).

EMG signals were amplified (×1,000), bandpass filtered (3–300 Hz) and sampled at a rate of 1,000 Hz; forceplate and accelerometer signals were lowpass filtered (10 Hz) and sampled at a rate of 200 Hz. For each tracking trial, all signals were sampled throughout the 30-s duration of the trial. For perturbation-only

A) Hand tracking (average and 95%CI)



B) Example perturbation trial with tracking pause

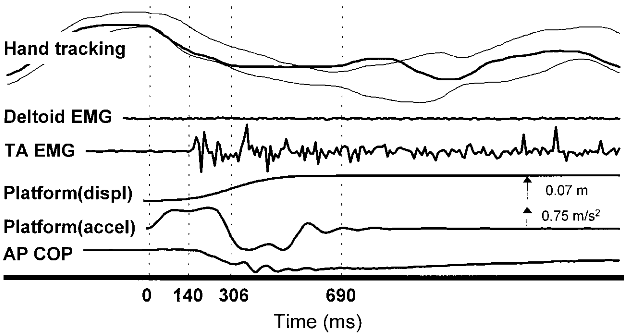


Fig. 1 A Average hand tracking performance from a single subject collected during non-perturbation trials. The average time series for a total of ten tracking trials, all featuring the same target waveform, is shown (*bold line*) along with the upper and lower 95% confidence interval (*CI, thin lines*). *Arrows* indicate the intervals of the waveform during which perturbations were applied in the dual-task trials. **B** Example perturbation trial revealing the balance response and change in hand tracking in response to an applied perturbation to stability (onset at time 0). The perturbation was a forward floor translation (0.75 m/s^2) evoking a measurable balance reaction in tibialis anterior (TA, onset 140 ms after onset of perturbation). Change in tracking (*bold line*) relative to the 95% CI (*thin lines*) is characterized by the onset of a pause (onset 306 ms) which continued until 690 ms after onset of perturbation. The pause onset was determined by finding the sudden change in tracking that preceded the exit of the tracking signal from the confidence band. Note that the deltoid EMG shows no evidence of a postural arm reaction that could have affected tracking performance

trials, the data were sampled for 2 s prior to perturbation onset, and for 5 s following perturbation onset.

Analysis

The baseline tracking response was determined for each subject by averaging across non-perturbed tracking trials (n=10). The 95% confidence interval about the average performance was then determined. Significant shifts in attention, during perturbed dual-task trials, were inferred to occur whenever the tracking deviated outside this 95% confidence band. The onset of the deviation was noted by the sudden change in tracking behavior that immediately preceded the breaking of the 95% confidence band. Balance reactions to evoked perturbations were also compared between the tracking and non-tracking trials, using the AP CoP excursion. The initial response was characterized by the rate of the initial CoP excursion. The latter phase of the reaction was characterized by the amplitude of the peak CoP excursion, frequency of CoP oscillations (i.e., number of crossings of the initial AP CoP position following the initial CoP peak), and time required to restabilize (defined to occur when the AP CoP excursion entered and persisted within a 95% confidence band constructed about the last 500 ms of the trial).

A repeated-measures analysis of variance (ANOVA) was used to test the hypothesis that the onset of the perturbation-evoked muscle activation would precede the onset of tracking deviation; direction of platform motion was included as a factor in the ANOVA. Repeated-measures ANOVA was also performed to compare the influence of the different task conditions on the evoked balance reactions.

Results

A total of 120 perturbation trials (60 with concurrent tracking and 60 with no tracking) were collected from the 6 subjects. The present analysis focussed on feet-in-place reactions; therefore, 15 trials were excluded because subjects executed a step. Ten of these stepping trials occurred in one subject, who stepped in response to all forward platform translations (five tracking and five non-tracking). This unexpected occurrence likely reflects a particularly low threshold for stepping when swaying backwards in this specific subject. Of the remaining five steps, four occurred during tracking tasks, suggesting a possible trend toward increased likelihood of stepping in the tracking task. An additional 14 tracking trials were excluded because the timing of the perturbation led to a change in tracking that could not be distinguished from the natural pause in tracking that occurs whenever the target motion reverses direction. In total, 91 trials were analyzed: 37 tracking trials (5–10 trials/subject) and 54 non-tracking trials (5–10 trials/subject).

Typically, a very clear disturbance in visuomotor tracking was observed subsequent to postural perturbation. Across the six subjects, 83.8% of the trials (31 of 37) were characterized by a profound deviation in the performance of the tracking task as compared to the tracking behavior occurring prior to the perturbation. Interestingly, in 77.4% of these trials (24 of 31), the deviation in visuomotor tracking was characterized as a pause, i.e., an absence of tracking (see Fig. 1b). Such significant deviations in tracking were not seen in trials where balance was unperturbed.

The subsequent visuomotor tracking and EMG analysis considered the 24 trials featuring a pause in tracking. In all 24 trials, the onset of the pause in tracking occurred well after the onset of the balance reaction evoked by the perturbation. On average, onset of the balance reaction (measured from either TA or MG EMG) occurred at a latency of 144 ms (SD 31, range 104–179 ms), whereas the pause in tracking began 479 ms (SD 186, range 161–807 ms) after the onset of the perturbation. Thus, there was an average interval of 346 ms (SD 186, range 90–687 ms) between the earliest balance reaction and the pause in visuomotor tracking (p<0.0001). On average, the pause lasted for 302 ms (SD 125, range 135–621 ms). Mean values for individual subjects and for the group are shown in Fig. 2.

No statistical difference in the onset or duration of the visuomotor tracking pause was observed between forward and backward platform translations. On average, the onset of the pause occurred at 475 ms (SD 196 ms) following

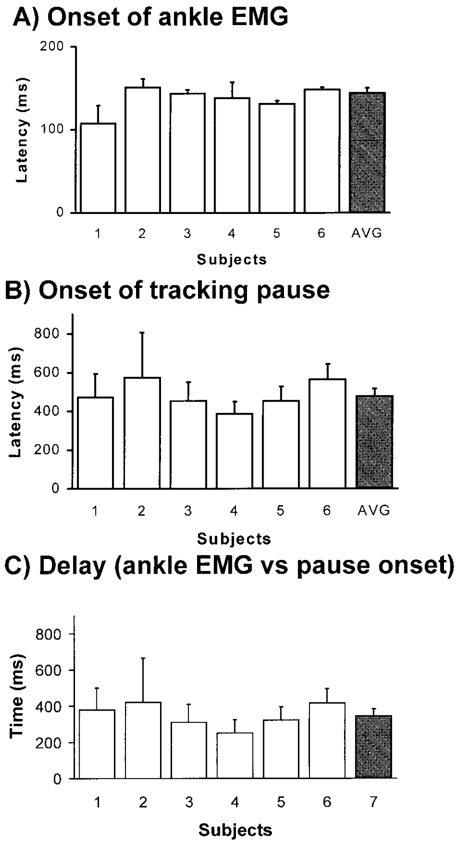


Fig. 2A–C Average temporal characteristics of the earliest postural response and the pause in tracking, in dual-task trials. **A** Average onset and standard error (SE) of evoked EMG reactions from ankle muscles, relative to onset of perturbation. **B** Average onset (and SE) of pause in visuomotor tracking, relative to onset of perturbation. **C** Average delay (and SE) in onset of pause in tracking, with respect to onset of ankle EMG. (In all trials, the onset of the pause occurred after the onset of ankle EMG.) Results are shown for individual subjects (*unfilled bars*); overall averages, across trials and subjects, are also shown (*filled bars*)

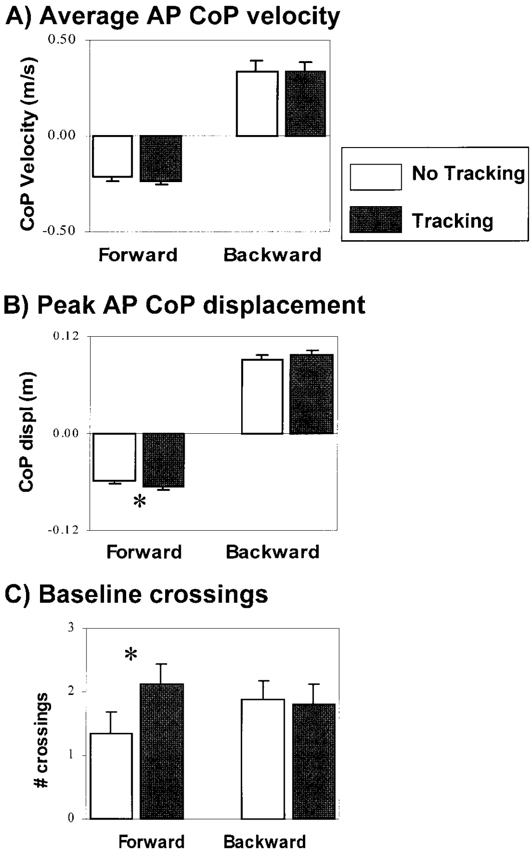


Fig. 3A–C Task related differences in anteroposterior center of pressure (*AP CoP*) excursion induced by applied perturbations (forward or backward platform translations). Average data and standard errors are shown for: **A** average initial CoP velocity (measured between response onset and the first peak in CoP displacement), **B** amplitude of the first peak in CoP displacement, and **C** number of baseline crossings after the first CoP peak. Anterior-directed CoP changes are shown as positive values (*denotes statistically significant difference, $p<0.05$)

forward translations and 482 ms (SD 183 ms) following backward translations (p=0.928). The duration of the pause lasted on average for 274 ms (SD 102 ms) and 322 ms (SD 139 ms) for forward and backward translations, respectively (p=0.372).

It appears unlikely that perturbation-evoked arm reactions interfered with performance of the tracking task. Inspection of video recordings showed no evidence of overt upper-limb movement associated with the imposed perturbation. This was not surprising since the subjects were well practiced and the imposed perturbations were small. In addition, there was no evidence of upper-limb muscle activity in the majority of trials featuring a pause (75% of trials, in the three subjects where arm-muscle activity was monitored). In the remaining trials, the arm EMG activity was very small and the EMG onset time was not associated temporally with the onset of the pause (p=0.65).

Figure 4 displays anteroposterior CoP excursions for tracking and non-tracking trials for two different subjects (both for backward directed platform translations). One feature evident from such data is the similarity of the initial phase of the evoked CoP reactions comparing the two task conditions. On average (across all subjects) the initial phase of the response to perturbation, as characterized by the initial rate of change in AP CoP, was not affected by performing the tracking task (p=0.75, Fig. 3), nor was there any effect on the latency of the initial activation of TA or MG (p=0.54). In contrast, later components (>250 ms after onset of perturbation) of the AP CoP excursion did appear to be affected. During the dual-task condition, the CoP excursion immediately following perturbation tended to be larger than during the perturbation-only trials: the CoP traveled 13.6% (8.4 mm) farther backwards following forward platform translation (p=0.007) and 4.7% (4.6 mm) farther forward following backward platform translation (p=0.184). In addition, in forward-translation trials, there was greater oscillation of the CoP during tracking as compared to non-tracking trials (1.3 vs 2.0 crossings of the initial AP

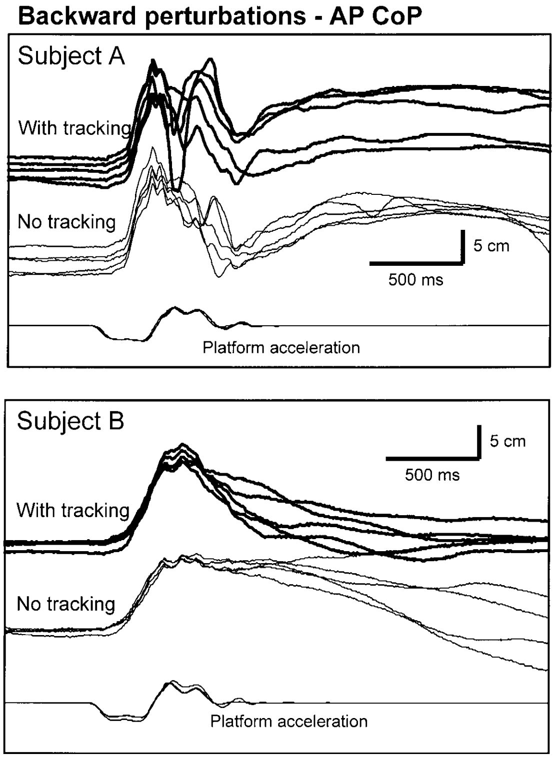


Fig. 4 Anterior-posterior center-of-pressure (*AP CoP*) excursion evoked by backward platform translations for all trials from two different subjects. The *thin line* represents data from non-tracking trials and the *thick line* represents data from tracking trials. Measures of platform acceleration from all trials (including both tracking and non-tracking tasks) are overlaid to provide a temporal reference (positive values indicate forward acceleration and CoP displacement)

CoP position; p=0.04) (see Fig. 3). In terms of time required to regain quiescent levels of CoP excursion, it appeared that static equilibrium was reattained more rapidly in the non-tracking trials (4.47 s, vs 4.62 s for the dual-task condition), although this difference was not statistically significant (p=0.12). In addition to the modest task-related differences in later stages of the response that were revealed by the statistical analyses, more pronounced effects were often evident in individual subjects. One distinguishing characteristic of perturbation responses during tracking, observed in several subjects, was increased trial-to-trial variability in the latter components of the CoP excursion (see data for subject A in Fig. 4). Other subjects (such as subject B in Fig. 4) appeared to exhibit task-related differences in the rate at which the CoP returned to baseline, immediately after the initial peak in CoP displacement.

Discussion

The present study supported the experimental hypothesis. We observed, following rapid translational perturbations to upright stance, a profound deviation in visuomotor tracking that always occurred *after* the initial balance reaction (TA or MG EMG). Typically, this initial disruption of attention manifested as a complete absence of tracking activity (a pause), which began approximately 345 ms after the onset of EMG activity at the ankle and persisted for about 300 ms.

These results suggest that the evoked balance reactions are characterized by an initial "automatic" phase that is initiated with minimal cognitive requirements, and subsequent control during which cognitive resources are apparently shifted toward the control of stability. This view is further supported by the findings that the earliest phase of the postural reaction was not affected by performing the tracking task, whereas later components of the reaction (>250 ms after perturbation onset) showed evidence of heightened instability (increased CoP excursion), on average, in comparison to non-tracking trials. Presumably, temporal requirements for cognitive processing would preclude a cognitive contribution to the initial triggering of the balance reaction; however, timing considerations alone do not rule out the possibility that cognitive processing could have been involved in modulating or programming features of the response immediately following the initial burst of muscle activation (e.g., as early as 150–200 ms after perturbation onset). The present findings, however, suggest that the cognitive involvement does not occur this early, i.e., that the "automatic" phase of the reaction typically continues for several hundred milliseconds before cognitive resources are diverted to the control of the balancing reaction.

The present findings are consistent with those of Rankin et al. (2000), who found that simultaneous performance of a counting task did not affect the earliest ankle EMG activity evoked by postural perturbation, but did affect later components of the EMG response. Our findings are also consistent with the results of Brown et al. (1999), who demonstrated delays in performing a counting task during the execution of a compensatory balancing reaction. Our findings suggest that a temporary switching of attention, away from the cognitive task, may have been responsible for these performance delays. In comparing our results to other studies, however, it is important to recognize that the disruption in tracking may reflect competition for other cognitive resources, e.g., resources allocated to sensorimotor processing (Yardley et al. 2001), as well as competition for attentional resources. Indeed, Yardley et al. (1999) concluded that it was the verbal articulation, rather than the attentional demands per se, that affected postural sway during a spoken counting task.

As in previous dual-task experiments, we propose that the change in cognitive-task performance represents a reallocation of cognitive resources, away from the cognitive task and toward the control of stability. However, it is possible that the pause occurred due to mere distraction from the visuomotor tracking task rather than representing a shift in resources to the control of balance. Although the pause in tracking appeared to be time-locked to the balance correction, this tracking disruption could similarly be related to perceptual awareness of the platform movement. It would, however, be difficult to explain why the tracking task affected features of the balancing reaction if there were no demands for cognitive resources.

The observed pause in tracking behavior is unlikely to represent a startle response. Startle responses have been well characterized as very rapid responses (less than 80 ms) to auditory stimulation that consistently follow a proximal-to-distal pattern of muscle activation (Valls-Solé et al. 1999). Importantly, startle responses are only exhibited when the startle is unexpected; these responses then habituate quickly over repeated trials (Brown et al. 1991). In the present study, the onset of the pause in tracking did not occur in most trials until at least 300 ms after the perturbation, and persisted over repeated trials. Arm EMG activity (anterior deltoid) that did occur was observed on average 320 ms after the onset of the perturbation, significantly longer than a startle response. It is also unlikely that the pause was the result of the initiation of upper-limb balance reactions, due to the absence of significant EMG activity and associated arm movement. In addition, there were many trials in which pauses occurred without evidence of any EMG activity of proximal muscles of the upper limb. Although we did not measure activity in distal arm and hand muscles, it has been shown that activation of proximal arm muscles precedes activation of more distal muscles during postural arm reactions (Maki and McIlroy 1997).

The present study confirms previous observations from a seated-balance study (McIlroy et al. 1999). As noted earlier, the pause in tracking in that study occurred on average 235 ms after the onset of ankle EMG activity (90 ms) and persisted for an average of 600 ms. Interestingly, the pause tended to occur later in the present study than in the seated-balance study (480 vs 325 ms), and was shorter in duration (300 vs 600 ms). It appears that the standing subjects were able to recover from the perturbations with less disruption in visuomotor tracking performance. It is possible that these differences are associated with the greater challenge of restabilizing after the imposed perturbation in the seated task, given the novelty of that task and the larger size of the perturbations used. There remains a question as to the specific role of the apparent attention shift. One view is that the ability to rapidly shift attention reduced the potential disruptions to stability control that might have occurred had shifting of attention not been possible. Recent findings that suggest delay in attention switching is associated with delay in generating the peak stabilizing reaction (Maki et al. 2001b) support the view that the reallocation of cognitive resources contributes to the control of the postural reaction. It is noteworthy that efforts to prioritize the tracking task (instructing subjects to continue tracking after perturbation onset) have shown little difference from the present results (Maki et al. 2001a, 2001b): a rapid attention shift still occurs shortly after initiation of the postural reaction. There appears to be an inherent bias to prioritize the task of maintaining upright stability regardless of the instruction given to the subjects.

Despite the fact that cognitive resources were apparently redirected to the task of maintaining balance, there was evidence of greater instability, during later stages of the response, when simultaneously performing the tracking task. The fact that changes in stability did occur in the tracking task, despite the switching of attention, may reflect limits in the capacity to rapidly reallocate resources, or possibly a strategy of sharing, rather than a complete reallocation, of cognitive resources. This latter explanation could apply to later stages of the response, i.e. after the end of the pause in tracking, and could also apply to those trials in which the tracking deviation did not involve a complete cessation of tracking effort.

In conclusion, the present results reinforce the view that later elements of compensatory balance reactions, but not the rapid initial stages, are dependent on cognitive resources. Although it has been shown that phases can be distinguished, in part, by the behavioral characteristics (Allum et al. 1993), the present study reveals that the later phases may also be distinguished by an increased reliance on cognitive resources. The finding that disturbances in control of stability occurred despite rapid switching of attention in healthy young adults suggests that the stability of individuals with compromised balance control or impaired ability to shift central resources is likely to be even more profoundly influenced when engaging in concurrent cognitive activities.

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References

Allum JHJ, Honegger F, Schicks HJ (1993) Vestibular and proprioceptive modulation of postural synergies in normal subjects. J Vestib Res 3:59–85

Andersson G, Yardley L, Luxon L (1998) A dual-task study of interference between mental activity and control of balance. Am J Otol 19:632–637

Brown LA, Shumway-Cook A, Woollacott MH (1999) Attentional demands and postural recovery: the effects of aging. J Gerontol 54A:M165–M171

Brown P, Rothwell JC, Thompson PD (1991) New observation on the normal auditory startle reflex in man. Brain 114:1981–1902

Geurts ACH, Mulder TW, Nienhuis B, Rijken RAJ (1991) Dual-task assessment of reorganization of postural control in persons with lower limb amputation. Arch Phys Med Rehab 72:1059–1064

Kerr B, Condon SM, McDonald LA (1985) Cognitive spatial processing and the regulation of posture. Hum Percept Perform 11:617–622

Lajoie Y, Teasdale N, Bard C, Fleury M (1993) Attentional demands for static and dynamic equilibrium. Exp Brain Res 97:139–144

Lajoie Y, Teasdale N, Bard C, Fleury M (1996) Upright standing and gait: are there changes in attentional requirements related to normal aging? Exp Aging Res 22:185–198

Maki BE, McIlroy WE (1997) The role of limb movements in maintaining upright stance: the “change-in-support” strategy. Phys Ther 77:488–507

Maki BE, McIlroy WE, Perry SD (1996) Influence of lateral destabilization on compensatory stepping responses. J Biomech 29:343–353

Maki BE, Norrie RG, Zecevic A, Quant S, Kirshenbaum N, Bateni H, McIlroy WE (2001a) Initiation and execution of rapid postural reactions and stepping movements: which phases require visuospatial attention? In: Duysens J, Smits-Engelsman BCM, Kingma H (eds) Control of posture and gait. International Society for Postural and Gait Research, Maastricht, Netherlands, pp 573–576

Maki BE, Zecevic A, Bateni H, Kirshenbaum, N, McIlroy WE (2001b) Cognitive demands of executing rapid postural reactions: does aging impede attentional switching? Neuroreport 12:3583–3587

Maylor EA, Wing AM (1996) Age differences in postural stability are increased by additional cognitive demands. J Gerontol 51:P143–P154

McIlroy WE, Maki BE (1995) Early activation of arm muscles follows external perturbations of upright stance. Neurosci Lett 184:177–180

McIlroy WE, Norrie RG, Brooke JD, Bishop DC, Nelson AJ, Maki BE (1999) Temporal properties of attention sharing consequent to disturbed balance. Neuroreport 10:2895–2899

Nashner LM, Cordo PJ (1981) Relation of automatic postural responses and reaction-time voluntary movements of human leg muscles. Exp Brain Res 43:395–405

Rankin J, Woollacott MH, Shumway-Cook A, Brown L (2000) Cognitive influence on postural stability: a neuromuscular analysis in young and elders. J Gerontol 55A:M112–M119

Redfern MS, Jennings JR, Furman JM (1999) The influence of attention on postural control during stance. Gait Posture 9:S11

Schlesinger A, Redfern MS, Dahl RE, Jennings JR (1998) Postural control, attention and sleep deprivation. Neuroreport 9:49–52

Shumway-Cook A, Woollacott M, Kerns KA, Baldwin M (1997) The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. J Gerontol 52A:M232–M240

Stelmach GE, Zelaznik HN, Lowe D (1990) The influence of aging and attentional demands on recovery from postural instability. Aging 2:155–161

Teasdale N, Bard C, LaRue J, Fleury M (1993) On the cognitive penetrability of posture control. Exp Aging Res 19:1–13

Valls-Solé J, Rothwell JC, Goulart F, Giovanni C, Munoz E (1999) Patterned ballistic movements triggered by a startle in healthy humans. J Physiol 516.3:931–938

Woollacott M, Shumway-Cook A (1999) Attentional demands in postural tasks: changes in both healthy and balance impaired adults. Gait Posture 9:S12

Yardley L, Gardner M, Leadbetter A, Lavie N (1999) Effect of articulatory and mental tasks on postural control. Neuroreport 10:215–219

Yardley L, Gardner M, Bronstein A, Davies R, Buckwell D, Luxon LL (2001) Interference between postural control and mental task performance in patients with vestibular disorder and healthy controls. J Neurol Neurosurg Psychiatr (in press)