Title: Effect of competing attentional demands on perturbation-evoked stepping reactions and associated gaze behavior in young and older adults

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Running head: Attention and compensatory stepping
ABSTRACT

Background: Rapid stepping reactions are a prevalent response to sudden loss of balance and are thought to play a crucial role in preventing falls. Previous dual-task studies, involving concurrent performance of the step-reaction task and a visuomotor tracking task, indicated that online visual attention was not required to guide the step, even when nearby objects increased demands for accurate foot movement. However, the planning and execution of the step apparently required attentional resources initially allotted to the tracking task. Reallocation of these resources (‘attention switching’) was delayed in older adults. The present study examined the influence of the competition for attentional resources by comparing trials performed with and without the concurrent task.

Methods: Unpredictable platform perturbations were used to evoke rapid forward stepping reactions in healthy young and older adults. Challenging obstacles and/or step targets increased demands for accurate foot motion in some trials. A concurrent tracking task was performed in half of the trials.

Results: Although subjects looked down more frequently in the absence of the tracking task, the ability to clear the obstacle or land on the step target, and other spatio-temporal features of the stepping reactions, were largely unaffected. There was, however, one notable exception: in older adults, the duration and amplitude of the ‘anticipatory postural adjustment’ that preceded foot-lift was reduced in tracking trials, resulting in increased lateral center-of-mass motion.

Conclusion: Impaired ‘attention switching’ apparently compromised the control of lateral stability during stepping reactions in older adults, and may be an important contributor to increased risk of falling.

KEYWORDS: aging, balance, environmental constraints, eye movements, postural control, stepping, triggered reactions, vision, visual attention
INTRODUCTION

Historically, rapid perturbation-evoked balance-recovery reactions have been considered to involve ‘automatic’ processing at a sub-cortical level; however, dual-task experiments, involving concurrent performance of a cognitive task and a balance-recovery task (1-7), have established that cortical pathways and cognitive processing are also involved. While the planning and execution of a balance reaction can be attentionally demanding, reactions that involve rapid limb movement, such as stepping, impose additional demands on visual attention to acquire spatial information needed to guide the step amongst environmental constraints (i.e. objects and architectural features that place restrictions on foot movement). Such stepping reactions are a prevalent response to sudden loss of balance and likely play a crucial role in preventing falls (8).

Recent dual-task studies, by the authors, of both young adults (YA) and older (OA) adults (9, 10) demonstrated that online visual attention was not required to guide perturbation-evoked stepping reactions, even when obstacles and/or step targets intensified demands for accurate foot movement. Subjects performed a concurrent visuomotor (tracking) task that required them to look straight ahead, and typically continued to look straight ahead during the execution of the step reaction. This indicates that the step was guided using visuospatial information that was acquired and stored prior to perturbation onset. An apparent switching of attention (inferred from sudden onset of significant tracking error) occurred after perturbation onset in >95% of trials, but was not related to changes in gaze direction. This ‘attention switching’ almost always occurred prior to foot-lift, suggesting that planning and execution of the foot-lift and/or step trajectory required significant cognitive involvement. None of these previous studies, however, have examined whether the dual-task competition for cognitive resources affects the capacity to plan, initiate and execute the step reaction effectively.
ATTENTION AND COMPENSATORY STEPPING

The present study aimed to extend the previous work by determining which, if any, features of the perturbation-evoked stepping reactions were affected by the dual-task competition for attention and other cognitive resources. To accomplish this, we compared step reactions evoked while subjects did or did not perform the concurrent visuomotor tracking task, within a subset of the previously-described cohort of YA and OA (9, 10). Gaze direction was also monitored, to determine if the competing visuomotor task may have affected the step reactions by inhibiting redirection of gaze toward the floor. We hypothesized that the concurrent task would not affect the step reactions in YA, due to their ability to rapidly and effectively switch attention and reallocate cognitive resources to the task of balance recovery. It appears that OA may have a diminished ability to do this (11), yet may be more dependent on using cognitive resources to control balance (1, 2, 4, 5, 12-15). We therefore hypothesized that some features of their step reactions would be affected when OA performed the concurrent task.

METHODS

Subjects

Twelve YA (5/7 male/female; ages 22–29, height 160–181cm, mass 54–93kg), and six community-dwelling OA (2/4 male/female; ages 61-68, height 145-166cm, mass 50-80kg) were tested (the subset of the cohort described in (9, 10) that performed both tracking and no-tracking trials). Subjects were naïve (no previous balance testing) and right-side dominant, and had a minimum uncorrected Snellen visual acuity of 20/40. Exclusion criteria included a recent history of falls (≥1 in past year), diabetes, neurological or sensory disorders, recurrent dizziness or feelings of unsteadiness, use of medications that may affect balance, joint replacement, medical conditions interfering significantly with daily activities, or functional limitations of limb use.
Subjects provided written informed consent to comply with ethics approval granted by the institutional review board.

Protocol

A large (2m×2m) computer-controlled motion platform evoked step reactions via sudden unpredictable horizontal support-surface movement. Subjects assumed a standardized comfortable foot position at the center of the platform at the start of each trial. For safety, subjects wore a harness suspended from a track mounted on the ceiling. See (9) for details.

Blocks of trials were performed for four environmental-constraint conditions: (1) no constraint, (2) obstacle-only, (3) target-only, and (4) obstacle-plus-target (see Figure 1B and caption for details). In 50% of trials, subjects also performed a visuomotor ‘thumb-tracking’ task, which involved pursuit tracking of pseudorandom target motion displayed for 20s on a computer screen (3, 11); see Figure 1A and caption.

As detailed in Table 1, the main protocol comprised eight randomized trial-blocks (two blocks for each of the four constraint conditions), the order counterbalanced both within and across subjects. Trials alternated between tracking and no-tracking. The focus of the study was on forward stepping reactions evoked by large backward platform translation (LBT: 3.0m/s², 0.9m/s, 0.6s). Each randomized trial-block comprised six LBT trials interspersed with ten trials of varying perturbation direction (forward, backward, left, right) and magnitude (0.13–3.0m/s²; 0.2–0.9m/s). These ten trials were included solely to prevent subjects from predicting features of the forthcoming perturbation, and were not used in the analysis. Two additional LBT trials (one tracking, one no-tracking) were performed at the very start of the session (prior to randomized trial-block #1). These two trials were intended primarily to familiarize the subjects with the testing procedure, but were included in the analysis since no problems arose during these trials.
All YA completed the full protocol (total of eight trial-blocks, two blocks per constraint condition), as did the first three OA. However, these three OA found the session long to tolerate; therefore, the protocol was shortened in the remaining three OA (total of four trial-blocks, one block per constraint condition).

Subjects were instructed to do whatever came naturally to prevent falling, but invariably stepped in the large-perturbation trials. To increase demands on control of the step trajectory, they were told to avoid contacting the obstacle and/or to land the great toe on the step target, if they needed to step forward. For tracking trials, subjects were told to track the target on the computer screen as accurately as possible throughout the entire trial (tracking performance was analyzed previously (9, 10), but was not the focus of the current study). In no-tracking trials, they looked straight ahead at the blank computer screen until perturbation onset, but were free to look elsewhere thereafter. Subjects were also free to look about during the interval between trials (~30s); however, once a trial had started, it was not possible to see the obstacle or step targets (in central or peripheral fields) without redirecting gaze downward, away from the computer screen.

To encourage accurate performance on the tracking task, subjects were told that the individual with the smallest tracking errors would receive a monetary reward of $50. They were also informed that their tracking scores would be penalized if they failed to clear the obstacle or land on the step target.

**Measurements**

A bilateral lightweight eye tracker (model 501, Applied Science Labs) superimposed the point-of-gaze (accurate to 0.5° of visual angle) on the video images recorded by a head-mounted ‘scene’ camera (sampled at 60Hz). These images were reviewed to determine the onset of any downward gaze shifts, defined to occur when the point-of-gaze dropped below the bottom edge
of the monitor screen and continue to move downward for ≥50ms (typical saccade duration) (9).

All subjects were found to maintain gaze on the monitor during the pre-perturbation portion of each trial (as instructed); hence, the analysis focussed entirely on downward gaze shifts that occurred after perturbation onset.

Two forceplates (AMTI model OR6-5, Kistler model 9281) were used to determine step timing and displacement of the center of foot pressure (COP) and center of mass (COM), as detailed previously (16, 17). Time of foot-off and foot-contact were determined from the vertical ground-reaction force; step onset was determined from the medio-lateral (m-l) COP (excursion >4mm). The reaction was deemed to include a preparatory weight-shift phase, commonly referred to as an ‘anticipatory postural adjustment’ (APA), if the initial m-l COP displacement was toward the swing leg, and was characterized by the duration and amplitude of this COP excursion (see schematic insert in Figure 4). This APA propels the COM toward the stance leg, thereby countering the tendency of the body to fall toward the unsupported side during swing phase; hence, the stabilizing effect of the APA was characterized by determining m-l COM displacement at time of foot-off and foot-contact.

Video recordings from five overhead cameras were used to identify obstacle contact, to measure step distance and step-to-target accuracy, and to verify foot-off and foot-contact times. The spatial measures were determined by resolving (to within 1cm) the position of a reflective marker on the great toe relative to a grid marked on the platform surface.

The ‘automatic postural response’ (APR) that preceded step initiation was quantified by surface electromyographic (EMG) activity recorded bilaterally in medial gastrocnemius. Onset of activation was detected by a computerized algorithm (11) and confirmed by visual inspection. EMG magnitude was quantified by: 1) computing the time-integral of the rectified signal (first
100ms of activity); 2) ‘normalizing’ these values by dividing by the subject’s average in no-constraint/no-tracking trials; and 3) averaging the left and right normalized values.

Statistical analysis

For each of the measures described above, a repeated-measures analysis of variance (ANOVA) was performed within each age group to assess the effect of performing the tracking task (tracking versus no-tracking). To determine whether the effect of the tracking task was dependent on the level of demand for accurate control of the foot trajectory, constraint condition (no-constraint, obstacle-only, target-only, obstacle-plus-target) and constraint-by-tracking interaction were included in the ANOVA and Tukey posthoc tests were performed. Where necessary, rank transformations were used to normalize the data and/or stabilize the variance, prior to performing the ANOVA (18).

The analysis focused on the forward stepping reactions evoked by the large backward platform translations. Although multiple steps were sometimes required to restore equilibrium (7% of trials in YA, 13% in OA), we focussed on the initial step in each trial, as this was the step that had to be modulated to deal with the constraints on foot trajectory. All timing variables were defined relative to onset of platform acceleration (0.1m/s²), and all spatial variables were expressed as a percentage of subject height. For the frequency analyses, the dependent variable was the percentage of trials (determined for each task condition, within each subject) in which downward gaze shift, successful obstacle clearance or successful step-to-target occurred. All other analyses involved the data from individual trials.
RESULTS

Effect of tracking on gaze behavior

YA directed gaze downward more frequently in no-tracking trials, in comparison to tracking trials [46% (133/289) of trials versus 17% (47/279); F(1,11)=29.6, p=0.0002; Figure 2a]. A significant tracking-by-constraint interaction [F(3,33)=9.3, p=0.0001] indicated that the effect of the tracking task was limited to the three more demanding constraint conditions. OA were also more likely to look downward in no-tracking trials, in comparison to tracking trials [34% (37/110) of trials versus 8% (9/111), F(1,5)=6.7, p=0.05; Figure 2b] but there was no significant interaction between tracking and constraint condition [F(3,15)=0.5, p=0.69].

Effect of tracking on obstacle clearance and step-to-target accuracy

Obstacle clearance was unaffected by tracking in YA [success in 98% (139/142) of tracking trials versus 99% (140/142) of no-tracking trials; F(1,11)=0.8, p=0.4; Figure 3a]. Ability to step to the target appeared to decline when tracking; however, the effect was relatively small. YA landed on the target in 58% (82/141) of tracking trials versus 69% (99/144) of no-tracking trials [F(1,11)=4.02, p=0.07], and the average error (m-l distance between great toe and target) increased by ~1cm when tracking [0.036±0.037m versus 0.026±0.034m; F(1,11)=14.2, p=0.003].

Like the YA, the OA exhibited no effect of tracking on ability to clear the obstacle [success in 91% (49/54) of tracking trials versus 87% (45/52) of no-tracking trials; F(1,5)=1.00, p=0.4; Figure 3b]. There was also no significant effect on step-to-target accuracy [error of 0.052±0.053m in tracking trials versus 0.037±0.040m in no-tracking trials; F(1,5)=3.08, p=0.14] or step-to-target success rate [58% (32/55) of tracking trials versus 41% (22/54) of no-tracking trials; F(1,5)=3.3, p=0.13]; however, the latter analysis showed a significant tracking-by-constraint interaction [F(3,15)=6.7, p=0.05]. The tracking task caused a decrease in the
frequency of successful target landing in obstacle-plus-target trials [23% (6/26) of tracking trials versus 56% (14/25) of no-tracking trials], but not in target-only trials [59% (27/29) of tracking trials versus 62% (18/29) of no-tracking trials].

**Effect of tracking on other features of the postural reactions**

Table 2 summarizes the results of the statistical analysis of the effect of performing the tracking task on the spatio-temporal features of the perturbation-evoked stepping reactions, as well as the preceding ankle-muscle activation that characterizes the early ‘automatic postural response’ (APR). For most variables, performance of the tracking task resulted either in no statistically significant effect (e.g. step distance) or an effect that was small in magnitude (e.g. 15ms decrease in foot-off and foot-contact times in OA, 19ms delay in step-onset time in OA, 5ms delay in step-onset in YA).

One notable exception pertains to the effect of the tracking task, within the OA, on the ‘anticipatory postural adjustment’ (APA) that preceded the lifting of the swing foot (Figure 4, Table 2). In these subjects, the tracking task caused a reduction in mean APA duration (31%) and amplitude (32%), and the frequency of APA occurrence also decreased [64% (71/111) of tracking trials versus 82% (90/110) of no-tracking trials]. No significant tracking-related effects on APA frequency, duration or amplitude were observed in the YA.

Performing the tracking task led to changes in lateral COM motion, in the OA, consistent with the APA changes. Specifically, the increased APA’s in the no-tracking trials acted to propel the COM farther toward the stance-leg side by time of foot-off, which then reduced the degree to which the COM fell laterally during the swing phase (Figure 5, Table 2). As indicated by significant tracking-by-constraint interactions, these effects were largely limited to trials that involved the obstacle.
DISCUSSION

For the most part, the results support the hypothesis that performing the concurrent task would not affect stepping reactions in YA. Only two step features were affected by the concurrent tracking task in the YA, and the tracking-related differences were likely too small to have much functional significance (mean step-to-target accuracy and step-onset timing differed by only 1cm and 5ms, respectively). In contrast, the OA did show some pronounced dual-task interference effects, as hypothesized. Most notably, generation of the ‘anticipatory postural adjustment’ (APA) was impaired when performing the tracking task, and this led to increased lateral COM motion during step execution. The effect was most pronounced in trials where prolonged single-leg support was required to step over an obstacle, a situation where the APA is known to play a critical role in countering the tendency to fall laterally (16, 17). These problems in controlling lateral COM motion when stepping over obstacles may have also contributed to the large (twofold) tracking-related increase in step-to-target error-rate that OA exhibited during obstacle-plus-target trials.

OA also exhibited some small (~15-20ms) but statistically significant changes in step timing when performing the tracking task. Tracking-related reduction in foot-off and foot-contact times was likely due, in large part, to the tracking-related reduction in the duration of the preceding APA, whereas the delay in step-onset times could possibly reflect dual-task interference with the planning of the step initiation.

The absence of dual-task interference effects, for other features of the postural reactions, implies that either: 1) control of the features in question does not require attentional resources, or 2) the switching of attention that occurs after perturbation onset effectively reallocates the resources that are required. Although it is possible that we failed to see such effects because the
secondary task was not sufficiently difficult, this seems unlikely. Subjects found the tracking
task to be very challenging, and required considerable practice to achieve high levels of tracking
accuracy. Furthermore, the tracking involves visuospatial processing, and is therefore more
likely than non-visuospatial tasks (e.g. counting, mental arithmetic, verbal fluency) to compete
for the cognitive resources required to plan the step. The lack of effect on the ‘automatic postural
response’ (APR) supports previous reports that this early component of the postural reaction
requires little or no cognitive processing, and that cognitive resources are not engaged until later
phases of the response (7, 11). Consistent with this conclusion, the onset of attention switching
in the present cohort (as reported previously (9)) consistently occurred well after APR onset.
Conversely, the fact that the attention switching usually occurred prior to foot-off (88% of trials)
suggests that cognitive resources were required to plan and execute at least some phases of the
stepping reactions, and other dual-task studies have provided further evidence to support this (1, 4, 11).

Based on the dual-task interference observed in the OA, it appears that effective scaling
of the APA is one aspect of the stepping reaction that requires cognitive resources. This agrees
with past work that has attributed anticipatory postural control to supraspinal structures (19).
Potentially, the APA disruption observed in the OA, and the absence of such disruption in the
YA, can be attributed to age-related impairment in the capacity to rapidly reallocate the required
cognitive resources. The similarity, in the YA, in mean onset timing of the APA (~210ms) and
attention switching (~230ms (9)) is consistent with this proposition. In a previous dual-task
study, OA exhibited a very substantial delay in attention switching (~120ms (11)). The mean
delay in the present cohort was smaller (~30ms (7)), and it is not clear whether such a delay
could, in itself, cause the impaired APA scaling; however, it is possible that other age-related
impairments in ability to reallocate the required cognitive resources may have also contributed. The susceptibility of OA to dual-task interference could thus be due not only to increased reliance on cognitive control of balance, as suggested previously \((12, 20, 21)\), but also impaired ‘attentional dynamics’ \((5, 21)\).

The effect of the concurrent task on gaze behavior did not appear to be an important factor. Although the tracking task inhibited downward redirection of gaze during the step reaction, subjects still stepped without looking down in the majority of trials, and were often able to step over an obstacle and/or land the foot on a target without looking down. Thus, it appears that ‘stored’ visuospatial information was commonly used to guide the stepping reactions, even when subjects were free to look down during the reaction, and the increased frequency of downward gaze shifts that occurred in the no-tracking trials provided little benefit (other than slightly improving step-to-target accuracy). The attentional demands of performing the concurrent visuospatial task apparently did not compromise the ability to store, retrieve and utilize the salient visuospatial information needed to guide the step, in either age group.

A potential limitation of the study pertains to the relatively small number of OA tested. The tested numbers of subjects and trials did, however, provide sufficient statistical power to detect very small task-related differences (e.g. mean differences of ~15ms in foot-off and foot-contact times, in comparing tracking and no-tracking trials; see Table 2). Moreover, the most important new finding of the study, regarding APA scaling, was very robust. For example, all six OA exhibited a substantial decrease in mean APA duration in tracking trials, with percentage decreases in individual subjects ranging from 22 to 45%. The consistency across subjects suggests that this impairment may be a common occurrence in senior populations; however, further testing with larger samples is needed to confirm this.
Although the influence of environmental constraints on stepping behavior was not the primary focus of the present study, the findings raise questions about the ability of OA to modulate preparatory weight shifts effectively. Whereas YA increased APA frequency, duration and amplitude when faced with the challenge of stepping over the obstacle (16, 17), such up-regulation was much less evident in the OA, and these deficiencies were exacerbated when the OA were distracted by the concurrent visuomotor task. Moreover, the age-related deficiencies in APA control impacted functional stability (i.e. increased lateral COM motion), and likely also contributed to a diminished ability to land the foot on the target. Previous studies of unobstructed stepping reactions have also demonstrated impaired control of lateral stability in OA (22), and associations with balance impairment (23), fall history (24) and future fall risk (25). APA control is critical when the step must be prolonged in order to step over objects (16, 17); hence, the lateral-instability problem is likely to be exacerbated in the ‘cluttered’ environments of daily life. Given the links between lateral instability and risk of hip fracture (26), the current findings may thus have important implications for prevention of such injuries, indicating a need to improve APA control and suggesting that interventions to target ‘attentional dynamics’ may also merit investigation.
ACKNOWLEDGMENTS

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REFERENCES


Table 1: Details of the experimental protocol

<table>
<thead>
<tr>
<th>Block #</th>
<th>Constraint condition</th>
<th># of LBT trials ([large forward steps])</th>
<th># of ‘wildcard’ trials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Full protocol</td>
<td>Shortened protocol</td>
</tr>
<tr>
<td></td>
<td></td>
<td>track</td>
<td>no-track</td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>3</td>
<td>3</td>
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<tr>
<td>3</td>
<td>C</td>
<td>3</td>
<td>3</td>
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<td>3</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>A</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Total # of trials</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

§ A, B, C and D are used to indicate the order in which the four constraint conditions were tested. For example, in one order pattern: A=no-constraint, B=obstacle-only, C=target-only and D=obstacle-plus-target. Each subject was randomly assigned to one of four different order patterns.

¶ These trials, which involved forward steps evoked by large backward platform translation (LBT; acceleration 3.0 m/s², velocity 0.9 m/s, duration 0.6 s), were the focus of the analysis. The total number of trials available for analysis was 600 for the young adults (12 subjects x 50 trials per subject) and 228 for the older adults (3 subjects x 50 trials + 3 subjects x 26 trials). Exclusion of trials with technical problems left 568 YA-trials and 221 OA-trials available for analysis.

£ The ‘wildcard’ trials were pseudo-random selections of various perturbation directions (forward, backward, left, right) and magnitudes (acceleration 0.13–3.0 m/s²; velocity 0.2–0.9 m/s) and were randomly interspersed with the LBT trials to increase unpredictability (no-perturbation ‘catch’ trials were also included).

¥ All 12 young adults and 3 of the older adults performed the full protocol. The remaining 3 older adults performed the shortened protocol.
Table 2: Influence of tracking task on features of the postural reactions (results of 2-way repeated-measures ANOVA, with constraint condition included as the second factor; statistically significant p-values are highlighted in bold)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Age group</th>
<th>Mean ± std dev</th>
<th>Tracking effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Track</td>
<td>No-track</td>
</tr>
<tr>
<td><strong>STEP TIMING:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>step onset (ms)</td>
<td>young</td>
<td>207 ± 44</td>
<td>202 ± 47</td>
</tr>
<tr>
<td></td>
<td>older</td>
<td>227 ± 44</td>
<td>208 ± 46</td>
</tr>
<tr>
<td>foot-off (ms)</td>
<td>young</td>
<td>401 ± 66</td>
<td>416 ± 88</td>
</tr>
<tr>
<td></td>
<td>older</td>
<td>384 ± 53</td>
<td>398 ± 65</td>
</tr>
<tr>
<td>foot-contact (ms)</td>
<td>young</td>
<td>652 ± 150</td>
<td>659 ± 160</td>
</tr>
<tr>
<td></td>
<td>older</td>
<td>630 ± 137</td>
<td>645 ± 148</td>
</tr>
<tr>
<td><strong>STEP DISTANCE:</strong></td>
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<td></td>
</tr>
<tr>
<td>forward *</td>
<td>young</td>
<td>28.1 ± 5.6</td>
<td>28.0 ± 5.8</td>
</tr>
<tr>
<td></td>
<td>older</td>
<td>26.0 ± 6.2</td>
<td>27.2 ± 5.8</td>
</tr>
<tr>
<td>lateral *</td>
<td>young</td>
<td>2.0 ± 3.6</td>
<td>2.1 ± 3.1</td>
</tr>
<tr>
<td></td>
<td>older</td>
<td>4.4 ± 5.3</td>
<td>3.8 ± 4.2</td>
</tr>
<tr>
<td><strong>‘ANTICIPATORY POSTURAL ADJUSTMENT’:</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>frequency (% of trials)</td>
<td>young</td>
<td>84 ± 19</td>
<td>86 ± 22</td>
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<tr>
<td></td>
<td>older</td>
<td>64 ± 27</td>
<td>81 ± 29</td>
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<tr>
<td>duration (ms)</td>
<td>young</td>
<td>138 ± 75</td>
<td>149 ± 81</td>
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<td></td>
<td>older</td>
<td>85 ± 77</td>
<td>124 ± 73</td>
</tr>
<tr>
<td>amplitude *</td>
<td>young</td>
<td>3.2 ± 2.5</td>
<td>3.2 ± 2.5</td>
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<tr>
<td></td>
<td>older</td>
<td>1.4 ± 2.1</td>
<td>2.1 ± 2.1</td>
</tr>
<tr>
<td><strong>LATERAL CENTER-OF-MASS DISPLACEMENT:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at foot-off *</td>
<td>young</td>
<td>-0.45 ± 0.50</td>
<td>-0.48 ± 0.60</td>
</tr>
<tr>
<td></td>
<td>older</td>
<td>-0.08 ± 0.37</td>
<td>-0.18 ± 0.50</td>
</tr>
<tr>
<td>at foot-contact *</td>
<td>young</td>
<td>0.73 ± 1.65</td>
<td>0.69 ± 1.30</td>
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<tr>
<td></td>
<td>older</td>
<td>1.89 ± 1.93</td>
<td>1.28 ± 1.68</td>
</tr>
<tr>
<td><strong>AUTOMATIC POSTURAL RESPONSE:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>time-integral (%) ‖</td>
<td>young</td>
<td>104 ± 34</td>
<td>99 ± 31</td>
</tr>
<tr>
<td></td>
<td>older</td>
<td>101 ± 21</td>
<td>100 ± 24</td>
</tr>
<tr>
<td>latency (ms)</td>
<td>young</td>
<td>102 ± 13</td>
<td>107 ± 15</td>
</tr>
<tr>
<td></td>
<td>older</td>
<td>111 ± 15</td>
<td>112 ± 14</td>
</tr>
</tbody>
</table>

† F_{1,11} for young adults, F_{1,5} for older adults.
‡ Effect of tracking was dependent on the constraint condition, as indicated by a significant (p<0.05) tracking-by-constraint interaction in the ANOVA (in each case, the tracking-related change was most predominant in the obstacle-only and obstacle-plus-target tasks).
§ Data were rank-transformed prior to ANOVA (the rank-transform was also used in the analyses of frequency of downward gaze shift and step-to-target success in YA).
* Expressed as a percentage of subject height.
ǁ Time-integral of the rectified EMG (100ms interval after EMG onset) in medial gastrocnemius, expressed as a percentage of the subject’s mean score for no-constraint/no-tracking trials.
CAPTIONS FOR FIGURES

Figure 1. Photographs of the tracking-task apparatus (A.1 computer display, A.2 thumb tracker) and environmental-constraint conditions (B.1 no-constraint, B.2 obstacle-only, B.3 target-only, B.4 obstacle-plus-target). In tracking trials, subjects controlled a cursor to track a target as it moved continuously and unpredictably up and down on a computer screen mounted at eye level, 1.2m in front of the subject (A.1). The cursor was controlled by using the right thumb to rotate a potentiometer attached to a splint that was supported by a sling and strapped securely to the abdomen (A.2). In step-target trials (B.3, B.4), subjects were instructed to land the great toe on the line of red tape (2x75cm) extending forward from each foot (this restricted medio-lateral step placement without affecting ability to achieve the forward step length needed to arrest the forward perturbation-induced body motion). In obstacle trials (B.2, B.4), the step had to clear a black obstacle (12.5% of subject height) mounted transversely in front of the subject (2.5% of body height from toes). The medio-lateral length of the obstacle was 1.5m; the antero-posterior depth was 2.4cm.

Figure 2. Relative frequency of downward gaze shift in the young adults (A) and older adults (B) in tracking (filled bars) trials and no-tracking trials (unfilled bars). Note that the percentage of trials in which downward gaze shift occurred increased significantly, in both age groups, when the visuomotor tracking task was not performed; however, there remained substantial numbers of no-tracking trials where downward gaze shift did not occur.

Figure 3. Relative frequency of successful step-to-target (A: young; B: older) and obstacle clearance (C: young; D: older) in tracking trials (filled bars) and no-tracking trials (unfilled bars). Note that the tracking task had no effect on the frequency of successful obstacle clearance in
either age group (C, D), despite the lower frequency of downward gaze shift in the tracking trials (see Figure 2). The tracking task did reduce step-to-target success rate (A, B); however, the effect in the young adults was small (9%). A more substantial effect was seen in the older adults, but only in the obstacle-plus-target trials.

**Figure 4.** Characteristics of the ‘anticipatory postural adjustment’ (APA) that preceded the lifting of the swing foot, for tracking trials (filled bars) and no-tracking trials (unfilled bars). Means and standard deviations are shown for the APA duration (A: young, B: older) and amplitude (C: young, D: older). The schematic drawings indicate how each parameter was derived from the initial medio-lateral (m-l) center-of-pressure (COP) displacement (directed toward the swing leg). The tracking task had no statistically significant effect on either of the APA measures in the young adults. However, both APA duration and amplitude declined by nearly a third in older adults when performing the concurrent tracking task.

**Figure 5:** Medio-lateral center-of-mass (COM) displacement in tracking trials (filled bars) and no-tracking trials (unfilled bars). Means and standard deviations are shown for COM displacement at time of foot-off (A: young, B: older) and foot-contact (C: young, D: older). Positive values denote displacement toward the unsupported (swing-limb) side, and negative values indicate displacement towards the supported (stance-limb) side. Note that the tracking task did not affect the COM displacement in the young adults; however, there was an effect in the older subjects, during obstacle trials. Here, the reduced ‘anticipatory postural adjustment’ in the tracking trials (see Figure 4) led to reduced propulsion of the COM toward the stance limb prior to foot-off (B), and this translated into a much greater tendency for the COM to fall toward the unsupported side by the end of the swing phase (D).
Figure 1: Tracking task (A) and environmental constraints (B)
Figure 2: Downward gaze shifts in young (A) and older (B) adults

A. Young gaze deviation

B. Older gaze deviation
Figure 3: Step-target (A,B) and obstacle (C,D) success in young (A,C) and older (B,D) adults.
Figure 4: APA duration (A, B) and amplitude (C, D) in young (A,C) and older (B,D) adults.
Figure 5: COM displacement at foot-off (A,B) and foot-contact (C,D) for young (A,C) and older (B,D) adults.

A. Young COM displacement at foot-off

B. Older COM displacement at foot-off

C. Young COM displacement at foot-contact

D. Older COM displacement at foot-contact