AGE (2012) 34:1381–1392
DOI 10.1007/s11357-011-9310-9

Age-dependent modulation of sensory reweighting for controlling posture in a dynamic virtual environment

**Diderik Jan Anthony Eikema · Vassilia Hatzitaki ·
Dimitrios Tzovaras · Charalambos Papaxanthis**

Received: 5 May 2011 / Accepted: 24 August 2011 / Published online: 6 September 2011
© American Aging Association 2011

Abstract Older adults require more time to reweight sensory information for maintaining balance that could potentially lead to increased incidence of falling in rapidly changing or cognitively demanding environments. In this study, we manipulated the visual surround information during a collision avoidance task in order to investigate how young and elderly adults engage in sensory reweighting under conditions of visual anticipation. Sixteen healthy elderly (age: 71.5±4.9 years; height: 159.3±6.6 cm; mass: 73.3±3.3 kg) and 20 young (age: 22.8±3.3 years; height: 174.4±10.7 cm; mass: 70.1±13.9 kg) participants stood for 240 s on a force platform under two experimental conditions: quiet standing and standing while anticipating randomly approaching virtual objects to be avoided. During both tasks, the visual surround changed every 60 s from a stationary virtual scene (room) to either a moving room or darkness and then back to a stationary scene to evoke sensory reweighting processes. In quiet standing, elderly showed greater sway variability and were more severely affected by the removal or degradation of visual surround information when compared to young participants. During visual anticipation, sway variability was not different between the age groups. In addition, both young and elderly participants were similarly affected by the degradation or removal of the visual surround. These findings suggest that sensory reweighting in a dynamic virtual environment that evokes visual anticipation interacts with postural state anxiety regardless of age. Elderly show less efficient sensory reweighting in quiet standing due to greater visual field dependence possibly associated with fear of falling.

Keywords Elderly · Anxiety · Balance · Collision avoidance · Visual field dependence

---

D. J. A. Eikema · V. Hatzitaki
Motor Control and Learning Laboratory,
Department of Physical Education and Sport Science,
Aristotle University of Thessaloniki,
546 24 Thessaloniki, Greece

D. Tzovaras
Informatics and Telematics Institute,
Centre for Research and Technology Hellas,
570 01 Thessaloniki, Greece

C. Papaxanthis
Université de Bourgogne, UFR STAPS,
BP 27877, 21078 Dijon, France

C. Papaxanthis
INSERM,
U887: Motricité-Plasticité, Campus Universitaire,
B.P. 27877, 21078 Dijon, France

V. Hatzitaki (✉)
Department of Physical Education and Sport Science,
Aristotle University of Thessaloniki,
Thessaloniki, Greece
e-mail: vaso1@phed.auth.gr

Introduction

Sensory reweighting is the process of dynamically updating visual, proprioceptive, and graviceptive information for controlling posture. The Central Nervous System (CNS) assigns a weight to each of these channels based on their perceived usefulness for balance maintenance (Oie et al. 2002; Peterka 2002). As environmental conditions change, the CNS may need to upweight or downweight each of the assigned weights, depending on their estimated contributions to postural control. In particular, a stationary full field visual stimulus, which accurately represents the orientation of the environment, provides a useful reference and subsequently its associated weight will increase to improve postural stability (Jeka et al. 2006; Laurens et al. 2010). In instances of visual field motion on the other hand, the visual system incorrectly signals self-motion and, therefore, the weight assigned to the visual channel needs to be reduced in order to preserve balance. Following a period of sensory ambiguity and subsequent down-weighting of the affected channel, the sensorimotor system requires time to adapt to the reinsertion of reliable sensory information (Jeka et al. 2008; Mahboobin et al. 2005). Once accurate information is restored, the involved channel is upweighted leading to an imbalance of weights, which results in excessive postural sway. The imbalance is corrected for in the following adaptation phase, in which significant postural sway oscillations are present suggesting a measure of adaptation to the altered sensory context (Peterka and Loughlin 2004). Posture is less stable and, therefore, more susceptible to falls during the postural adaptation phase.

Normal aging slows the process of sensory reweighting, and consequently, lengthens the postural adaptation phase, when a particular source of sensory information used to control posture becomes unreliable (Allison et al. 2006; Doumas and Krampe 2010; Horak et al. 1989; Jeka et al. 2006; Teasdale and Simoneau 2001). On the other hand, when a sufficiently long adaptation time is available and the environmental stimuli are gradually degraded, the sensory reweighting process of both healthy and fall-prone older adults seems to be efficient (Allison et al. 2006; Jeka et al. 2006). It should be noted, however, that real world situations, in which the elderly tend to lose their balance, are generally characterized by dynamic and more challenging sensory stimuli, such as a busy street or a suddenly appearing uneven walking surface. In such cases, the prolonged instability associated with postural adaptation to an altered sensory environment may increase the probability of a fall. Yet, how the anticipation induced by the challenges of a dynamic environment could modulate the process of sensory reweighting is not well understood.

Anticipation of unpredictable aversive events delivered through a variety of sensory channels, particularly vision, can induce postural state anxiety that is known to increase sway irrespectively of age (Brumagne et al. 2008; Ishida et al. 2010; Ohno et al. 2004). This is because an increased level of postural state anxiety imposed by sensorimotor anticipation can modulate the sensory reweighting process for controlling posture increasing the anchoring to vision when this is directly related to perceived postural threat (Bolmont et al. 2002; Hainaut et al. 2011). On the other hand, this form of anxiety is not present when vision is not available. State anxiety induced by visual anticipation is expected to affect more adversely the elderly's capacity to reweight the available sensory information since cognitive impairment associated with aging affects risk perception in balance threatening conditions (Brown et al. 2002; Hatzitaki et al. 2005; Maki et al. 1991). In addition, elderly adults experience increased trait anxiety in the form of fear of falling (Yardley and Smith 2002) that also leads to higher visual field dependence (Hainaut et al. 2011). Nevertheless, how fear of falling interacts with postural state anxiety induced by visual anticipation to impact the elderly's capacity to reweight the available sensory information is not known.

In the present study, we examined how young and elderly individuals engage in sensory reweighting under conditions of quiet standing and while anticipating randomly approaching virtual objects to be avoided. Introducing a collision avoidance task under conditions of visual uncertainty imposes a sensory conflict. On one hand, the potentially less reliable visual environment may require the downweighting of vision in order to maintain a stable posture, and on the other hand, visual information needs to remain of high priority to successfully detect and avoid the randomly approaching object. Two predictions were tested: during quiet standing, the elderly would show a greater postural sway variability and prolonged adaptation to the altered visual environment compared to the young. Second, visual anticipation of the randomly approaching objects would more adversely affect the sensory reweighting process of the elderly than that of the young individuals leading to a greater postural disturbance and a longer adaptation period to the altered visual environment.

Methods

Participants

A total number of 20 young (Young group; eight males, 12 females; age: 22.8±3.3 years; height: 174.4±10.7 cm; mass: 70.1±13.9 kg) and 16 old (Old group; four males, 12 females; age: 71.5± 4.9 years; height: 159.3±6.6 cm; mass: 73.3± 3.3 kg) adults participated in the study. Participants were free of neurological and musculoskeletal impairments and had normal or corrected to normal vision. The elderly participants were screened for cognitive function using the minimental status examination (MMSE). Scores below 22 warranted exclusion. Participants were informed of the procedures and provided written consent. All experiments were performed with the approval of the local ethics committee on human research in accordance with the Declaration of Helsinki.

Apparatus

Visual stimuli were delivered by a large (width 128 cm, height 102 cm) stereoscopic projector (Barco Baron 908, Barco N.V., Kuurne, Belgium), viewed through active shutter goggles (Chrystal Eyes 3, Stereographics) at 105 Hz. The virtual environment was developed in C++ and consisted of an empty room with walls, floor, and ceiling textured with an alternating light and dark gray bar pattern (Fig. 1). The surround environment was darkened, ensuring that only the projector provided optical stimulation. Postural sway changes in the Anterior/Posterior (AP) and Medio/Lateral (ML) directions were recorded using a 3D force plate (Balance Plate 6501, Bertec Corporation, Columbus, USA) at a sampling rate of 105 Hz. Six DoF angular kinematics were captured by a four marker electromagnetic tracking system (Nest of Birds, Ascension Inc., Burlington, USA). Markers were placed on the subject's midline on the forehead, seventh cervical vertebra (C7), hip (1st Sacral vertebra) and the left shank (posterior placement, two-thirds of shank's length from the ankle joint).

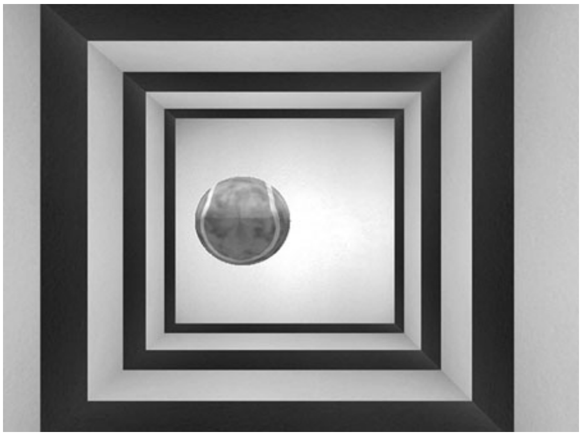

Fig. 1 An illustration of the virtual scene displayed during an object avoidance trial. The virtual scene contained a grating pattern room that was successively presented under four (4) 60-s long visual conditions: 1) Stationary Surround (SS1), 2) Moving Surround (MS) during which the scene oscillated in the anterio-posterior direction (0.33 Hz, 20 cm), 3) No Surround (NS) during which the virtual scene was removed and 4) final Stationary Surround (SS2)

Task and procedure

Prior to the experiment, all participants performed the Rod and Frame test (RFT; Reger et al. 2003) to determine the degree of visual field dependency. A rod was visible inside a frame, which would be tilted randomly at +18°, 0° or −18°. The participant was asked to rotate the bar using a dialing motion of the hand, until this was estimated to be vertical. Each participant performed six trials, two in each frame tilt condition. The angular deviation of the rod's final position from the actual vertical was recorded in degrees. Upon completion of the RFT test, participants were asked to perform two tasks: a) a quiet stance and b) a collision avoidance task.

Quiet stance (QS)

In the quiet stance (QS) task, participants stood on the force plate for 240 s under four visual conditions, each lasting 60 s. They were asked to stand quietly in a relaxed position (intermalleolar distance: 10 cm, arms freely hanging on sides) and fixate on the projection screen (positioned at a distance of 2 m from the participants' head). During a 240-s long trial, the participant was exposed to a sequence of four visual conditions (Fig. 1). In the baseline condition, the virtual Surround remained Stationary (SS1). In the No Surround condition (NS), the virtual environment was removed, thereby removing all visual information. In the Moving Surround (MS) condition, the virtual surround oscillated sinusoidally in the Anterior–Posterior (AP) direction (frequency: 0.33 Hz, amplitude: 20 cm). In the final 60 s, the virtual Surround was Stationary (SS2) again. SS1 was always presented as the first condition. The sequence of the NS and MS conditions was randomized with each participant receiving both sequences and always ending with SS2.

Collision avoidance (AV)

The collision Avoidance (AV) task consisted of 20 target stimuli that were delivered at random time intervals ranging between 4 s and 16 s, across the four 60-s visual conditions (see above), five per condition. The target stimulus was a rotating virtual sphere (10 cm in diameter, light green in color to resemble a tennis ball) traveling at a constant velocity from the center of the screen towards the participant's face (Fig. 1). The projector's height was individually adjusted to the participant's height in order to ensure that the sphere always intersected the participant's face. Participants were asked to avoid collision with the sphere by displacing the trunk in the ML direction and without moving the feet off the platform. The avoidance was successful if the sphere's end coordinates were outside a circular 20 cm range around the C7 marker's coordinates. After each avoidance response, the participant was asked to return to the initial position and wait for the next sphere. Anticipatory leaning in the ML direction was controlled for by providing a blue feedback square in the center of the screen whenever a participant was leaning to one side in between target presentations. The order of presentation of the NS and MS visual conditions was randomized with each trial always ended with the SS2.

Prior to testing, a familiarization trial was performed to ensure learning of the task and adjust the target's velocity to the participant's avoidance skill. During the familiarization trial, feedback was provided on whether the avoidance was successful or not. In case of target collision, a red square (10× 10 cm) was visible for 3 s in the center of the screen after completion of the avoidance response. Based on feedback provided by the red square, participants performed avoidances until a 90% successful avoidance rate was achieved in a given trial. In addition, target velocity was adjusted in the learning phase and held stable in the following trials. The target velocity range in the Young group was 2.25 m/s–2.86 m/s. The target velocity range in the Old group was 1.75 m/s–2.10 m/s.

Each participant performed a total of three experimental trials: one QS and two AV trials. For the two avoidance trials, the average performance within each participant was considered for further analysis. The experiment was concluded with the administration of a short questionnaire containing items from the Immersive Tendencies Questionnaire (ITQ) and the Presence Questionnaire (PQ) to assess VR immersion effects (Table 1).

Data analysis

Ground reaction force and electromagnetic tracking signals were synchronously sampled at 105 Hz and further processed in MatLab (Mathworks Inc., USA). All data time series were low pass filtered using a fourth order zero-lag Butterworth filter with a 5 Hz cutoff frequency. Force platform recordings were processed to determine AP and ML components of

Table 1 Composition of the questionnaire administered to assess virtual reality immersion effects. PQ = Presence Questionnaire, ITQ = Immersive Tendencies Questionnaire, INV/C = involvement/control subscale, NATRL = natural subscale, representing the degree to which the experience is perceived as natural and FOCUS = focus and attentiveness subscale. ITCorr is the Item-Total correlation, the correlation between each subscale sum-score and the total score of the questionnaire

Questionnaire	Subscale	*N* items	ITCorr
PQ	INV/C	5	0.815**
PQ	NATRL	4	0.799**
ITQ	FOCUS	2	0.480*

* $p<0.01$ (statistical significance)

** $p<0.001$ (statistical significance)

the Centre of Pressure (CoP) fluctuations. The angular position signal of the C7 marker about the AP axis was differentiated to obtain the upper trunk angular velocity in the roll direction (dC7).

For the analysis of quiet stance (QS), each 240-s trial was separated in twenty 12-s time windows resulting in five QS time intervals per visual condition. Postural sway variability was quantified by calculating the Standard Deviation of the rate of the CoP displacement signal (SD dCoP) in the AP direction for each QS interval.

Similarly, the collision avoidance (AV) task was analyzed by separating each 240-s trial in twenty 12-s time windows (avoidance intervals) resulting in the analysis of five avoidances per visual condition. Postural sway variability in the AP direction during anticipation of the virtual sphere was quantified in terms of the Standard Deviation of the CoP displacement rate (SD dCoP) over a 4-s time window prior to the appearance of the sphere on the screen. Stabilization Time (ST) was the time it took for the postavoidance dCoP variability to match the premovement dCoP variability in seconds. The ST measure was only used to ensure that the participant returned to a stable posture prior to the 4-s period that was used to calculate the SD dCoP variable of the following time window. In addition, the peak to peak CoP displacement in the ML direction during the anticipatory and focal phases of the postural adjustment to the approaching sphere (Fig. 3c) was calculated as a measure of the amplitude of the avoidance response. The maximum trunk velocity (dC7max) in the ML direction for avoiding the approaching sphere was also calculated.

Statistical analysis

Performance measures were compared between the two age groups, across the four visual conditions and five time intervals of each visual condition using a 2 (Group)×4(Condition)×5(Time) repeated measures ANOVA. The analysis was run separately for the QS and the visual anticipation (AV) trials. Significant interactions were further analyzed using post hoc paired samples *t*-test comparisons between the visual conditions and time intervals within each condition separately for each age group. Age differences in visual field dependence were analyzed employing a 2(Group)×3(Tilt) repeated measures ANOVA on the RFT scores. In order to investigate the relationship between visual field dependence and postural instability, the mean (averaged across all tilting positions) RFT score was correlated with the mean SD dCoP measure averaged over the first five time intervals of the SS1 (static background) condition separately for the QS and AV trial. As the underlying distribution of measures consisted of two subgroups, nonparametric correlation analyses were performed. The ordinal nature of the Likert scale ITQ and PQ items of the questionnaire required the use of Mann–Whitney *U* test for independent samples comparisons. Within each of the subscales, comparisons were made between the age groups.

Results

Analysis of the responses to the administered questionnaire containing ITQ and PQ items confirmed that both young and elderly participants were equally immersed and engaged by the virtual environment. Mann–Whitney *U* tests performed on the sum-scores revealed only the FOCUS subscale scores were significantly different between the age groups. Significantly higher FOCUS scores were noted in the young group ($Z(46)=-3.492$, $p<0.001$).

Visual field dependence

The analysis on the RFT error scores revealed a significant Group effect on visual field dependence ($F\,(1,25)=6.463, p<0.001$). The old group participants displayed a significantly greater error in estimating verticality compared to the young group (Fig. 2). Analysis also revealed a significant effect of the Tilt ($F\,(2, 50)=3.968$, $p<0.05$) suggesting a greater error in estimation of verticality when the frame was tilted in either direction. No Group by Tilt interaction effect was noted. For this reason, a composite (averaged across tilting positions) RFT score was used in subsequent analysis.

Sway variability in quiet stance (QS) on the AP axis

Exemplar traces of the CoP velocity profiles plotted for one representative old and young participant across the four visual conditions are shown in

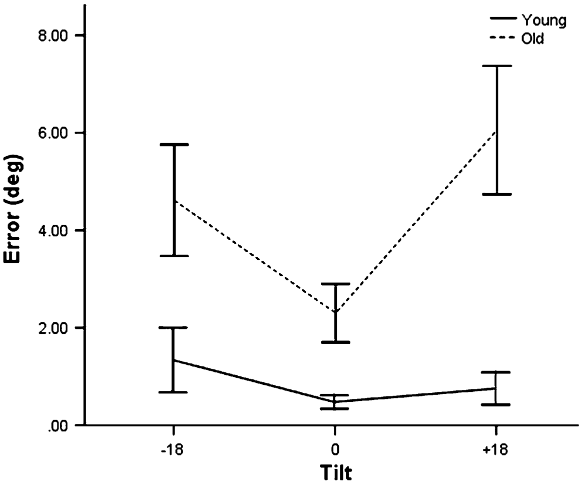

Fig. 2 Error in estimating the rod's deviation from the vertical position (in degrees) in the Rod and Frane Test (RFT) plotted across the three different tilting conditions (+18°, 0° or −18°) for the young and old group participants. Group means and ±1SE are shown

Fig. 3a. Postural performance of the old participant was characterized by more variable sway patterns that were modulated by the visual conditions in contrast to the young participant's sway patterns that remained unchanged across conditions. A significant Group × Condition × Time interaction (*F* (12,336)=1.959, $p<0.05$) on the SD of dCoP indicated that the rate of adaptation across the successive time intervals was dependent on both the age group and the visual condition (Fig. 4a). Specifically, the reduction of sway variability over successive time intervals was significant for the old but not for the young group as also confirmed by a significant Group × Time interaction (*F* (4,112)=2.477, $p<0.05$) and a significant Time effect for the old group (*F* (4, 56)=4.645, $p<0.01$). Moreover, the age-associated decrease of the SD of dCoP over successive time intervals was significant only in the degraded visual conditions (NS, MS) as confirmed by a significant Condition×Time interaction effect (*F* (12,168)=1.906, $p<0.05$). Post hoc comparisons performed between the four visual conditions indicated that the old group's sway variability was greater in the NS ($p<0.001$) and MS ($p<0.001$) relative to the SS1 visual condition. The difference between SS1 and SS2 was not significant suggesting that the elderly were able to reduce sway variability to baseline levels once the static visual scene was reinserted. In the young group, sway variability was not affected by the visual scene manipulation as this was confirmed by the absence of significant differences across the visual conditions and between the successive time intervals within each condition. Overall, during quiet stance, old group participants displayed significantly greater SD of dCoP compared to the young group (*F* (1, 28)=9.182, $p<0.01$; Fig. 4a).

Sway variability in visual anticipation (AV) on the AP axis

The CoP velocity traces during the successive 4-s intervals of visual anticipation prior to the appearance of the sphere in the visual scene are plotted in Fig. 3b for one young and one old participant. Sway variability while anticipating for the sphere was not significantly different between the age groups as confirmed by the absence of a main effect for the Group on the SD of dCoP measure (Fig. 4b). On the other hand, this significantly increased for both groups in the NS ($p<0.05$) and MS ($p<0.001$) visual condition but returned to baseline in SS2 (Fig. 4b) as also shown by a significant visual Condition effect (*F* (3, 78)=12.236, $p<0.001$). A Time effect on SD of dCoP was also noted suggesting that variability decreased across successive time intervals within each visual condition (*F* (4,104)=6.507, $p<0.001$). Specifically, post hoc comparisons between the time intervals revealed that SD of dCoP decreased significantly between intervals 1–3, 1–4, and 1–5 ($p<0.05$) while this was not significantly different between intervals 1 and 2. This pattern of change was common in both age groups.

Collision avoidance on the ML axis

The collision avoidance response was depicted in the peak to peak CoP displacement in the ML direction and the maximum upper trunk roll velocity. Figure 3c shows a representative CoP displacement trace in the ML direction during one avoidance trial for one old and one young participant. The statistical analysis revealed that elderly participants had a significantly smaller peak to peak CoP displacement (*F* (1, 32)=7.842, $p<0.01$; Fig. 5a) and a slower upper trunk velocity (*F* (1, 34)=24.351, $p<0.001$; Fig. 5b) when avoiding the virtual sphere compared to their young counterparts. On the other

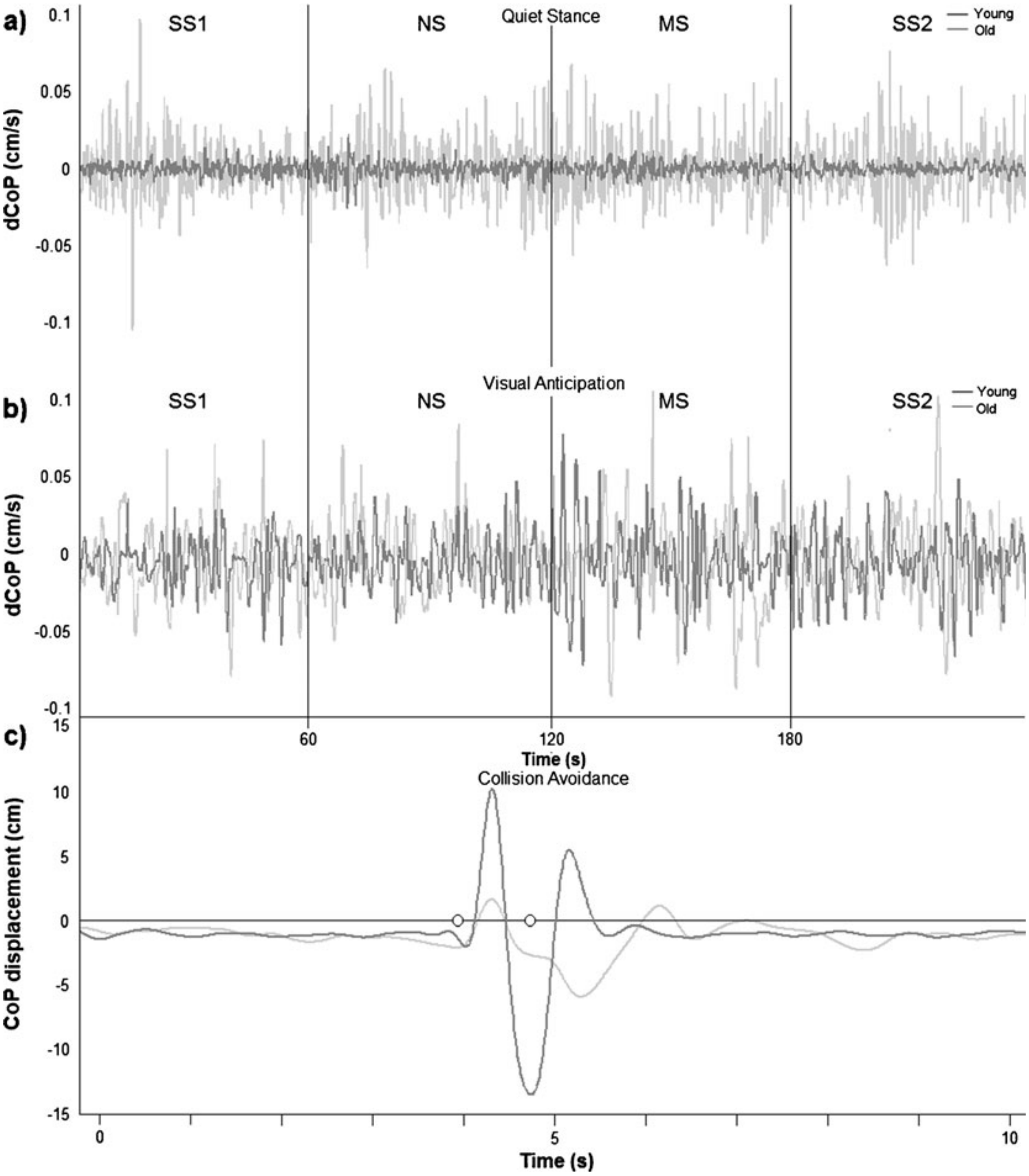

Fig. 3 Exemplar Centre of Pressure velocity (dCoP, cm/s) traces of one young (*black line*) and one old (*grey line*) participant plotted over the course of the four visual conditions (*SS1* Stationary Surround, *NS* No Surround, *MS* Moving Surround, *SS2* Stationary Surround) of quiet stance (**a**) and visual anticipation (**b**). Centre of Pressure displacement trace (CoP, cm) in the Medio/Lateral (ML) direction during a representative collision avoidance response for one young (*black line*) and one old (*grey line*) participant (**c**)

hand, the visual surround manipulation did not significantly affect the avoidance response in either of the two groups as confirmed by the absence of a main Condition, Time effect and interaction effects on either the amplitude of the CoP response or upper trunk velocity.

Relationship between visual field dependence and sway variability

In QS, the Spearman ρ between the RFT score and the SD of dCoP measure was significant ($\rho=0.459$, $p<0.05$). This suggests the degree of visual field

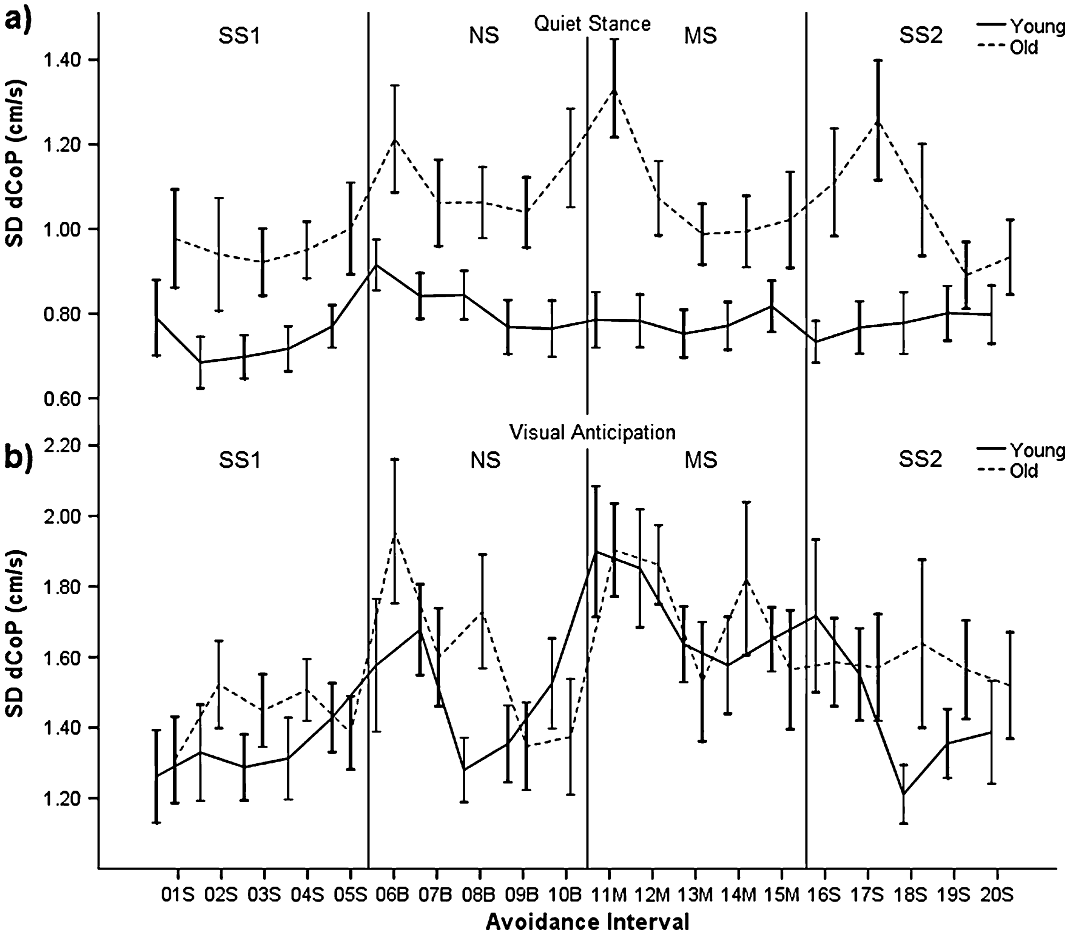

Fig. 4 Standard Deviation of CoP displacement rate (SD dCoP, cm/s) plotted for the five time intervals of each visual condition (*SS1* Stationary Surround, *NS* No Surround, *MS* Moving Surround, *SS2* Stationary Surround) of quiet stance (**a**) and visual anticipation (**b**). Group mean ± SE values are plotted for the young (*solid line*) and the old (*dotted line*) groups

dependence is an indicator of the level of postural instability in quiet stance. On the other hand, the correlation between the RFT score and mean SD dCoP in the first five intervals (SS1) of the AV trial was not significant suggesting the possible link between visual field dependence and postural instability is not present in conditions of visual anticipation.

Discussion

The current study investigated how young and elderly adults reweight the available visual surround information under conditions of quiet standing and while anticipating randomly approaching virtual objects to be avoided. Whereas an age-induced decrement in sensory reweighting was evident in quiet stance, under conditions of visual anticipation induced by the randomly approaching virtual objects, young and old individuals were similarly affected by the removal or degradation of visual surround information.

Sensory reweighting in quiet stance

Elderly participants increased sway variability when the visual surround became ambiguous (room oscillations) or was removed (no virtual scene). Within each 60-s long visual condition though, they were able to reduce sway variability over time suggesting an effective adaptation process to the particular visual manipulation. Note, however, that they required more than 30 s after reinsertion of the

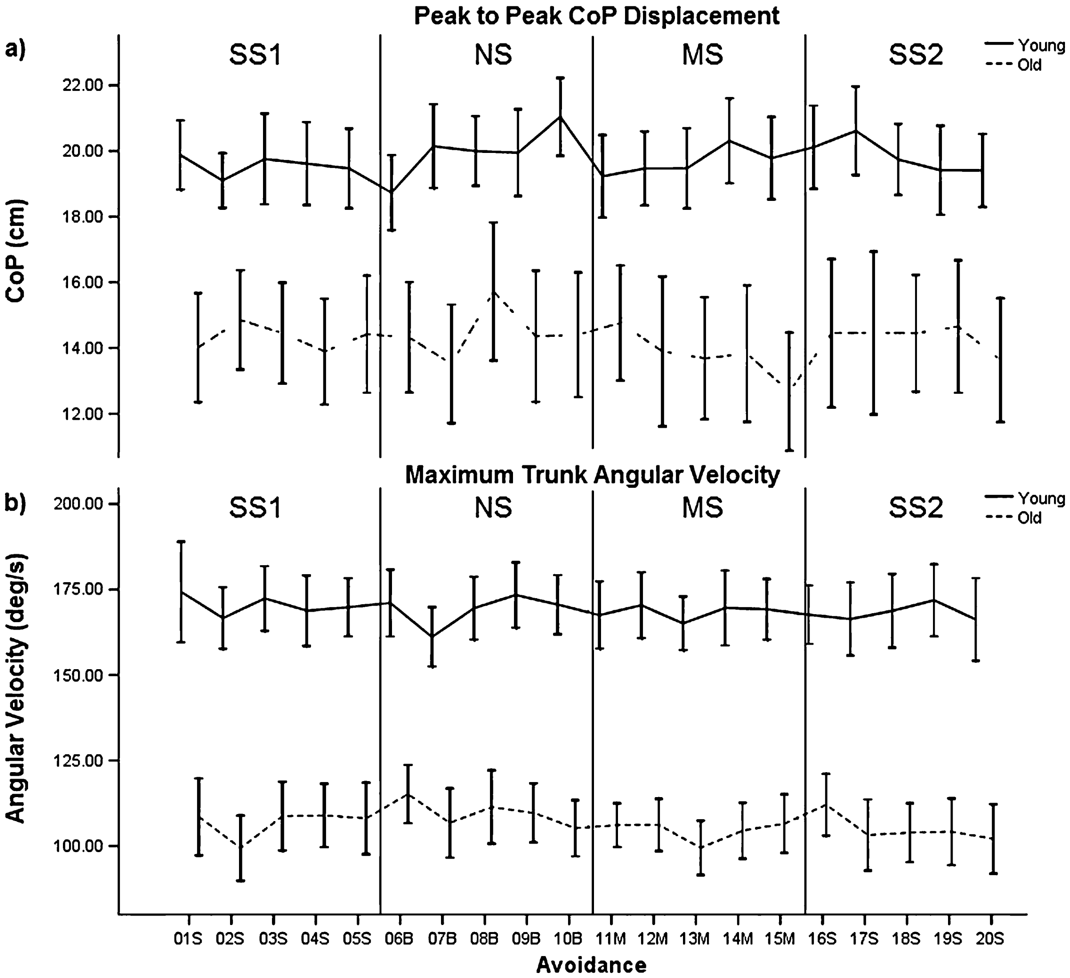

Fig 5 Peak to Peak Centre of Pressure (CoP) displacement (**a**) and maximum upper trunk angular velocity (**b**) in the Medio/Lateral direction during the collision avoidance response performed under the 5-time intervals of each visual condition (*SS1* Stationary Surround, *NS* No Surround, *MS* Moving Surround, *SS2* Stationary Surround). Group mean ± SE values are plotted for the young (*solid line*) and the old (*dotted line*) groups

stationary visual surround to decrease their sway variability to baseline levels. These observations are in agreement and extend those of previous studies showing an age-induced slowing of the sensory reweighting process as this is evident in a longer adaptation phase when the accurate sensory information for controlling posture is either degraded or reinserted (Allison et al. 2006; Doumas and Krampe 2010; Jeka et al. 2006; Teasdale and Simoneau 2001). This age-associated slowness can be attributed to a reduction of the available cognitive resources and to an overall slowness of information processing (Salthouse 2000) that makes the reweighting of the available sensory information a cognitively demanding task that is subject to prioritization and competition effects. This in turn, could compromise the automatic control of posture resulting in a longer postural adaptation phase (Teasdale and Simoneau 2001). Young participants on the other hand, were less affected by the visual surround manipulation suggesting an effective sensory reweighting process when standing quietly. The almost invariable sway patterns across the visual conditions suggest a rapid downscaling of the visual channel in concert with upweighting of the proprioceptive and graviceptive channel in order to minimize the excessive sway induced by the imbalance of weights.

The greater impact of the visual surround manipulation on the elderly sway patterns could be due to their greater visual field dependence for controlling quiet standing. Higher field dependence scores correlate with postural instability (Isableu et al. 1998). Our RFT results indicated that elderly participants were more reliant on visual surround information for establishing verticality compared to their younger counterparts. This suggests a greater reliance on external and contextual visual cues for controlling posture and subsequently a greater impact of the visual surround manipulations on their sway. This is not uncommon when considering the faster age-induced degeneration of the proprioceptive and vestibular systems, over the years, which inevitably increase the weights assigned to vision for controlling posture (Jamet et al. 2004; Lord et al. 1991).

Sensory reweighting during visual anticipation

While anticipating for the approaching objects, both young and old participants increased sway to similar levels of instability as soon as the visual surround was removed or started oscillating. One possible explanation for the greater impact of the visual surround degradation on the reweighting process could be visual anchoring induced by the anticipation task. It is possible that visual anticipation of the randomly approaching objects increased visual anchoring and may have upweighted the visual contribution to the control of posture resulting in excessive sway variability. Visual fixation or anticipation of an unpredictable event in the visual domain strengthens the anchoring of vision to the environment with positive effects on postural stability when the visual environment is reliable (Guerraz et al. 2000; Laurens et al. 2010). However, when the visual input is attenuated, i.e., during visual field oscillations or in the absence of peripheral visual cues, this anchoring process may compromise postural stability (Glasauer et al. 2005; Laurens et al. 2010). A similar increase in sway variability was observed in our study when the visual surround was removed or became ambiguous. A comparable increase in sway variability between the age groups though suggest that both young and old participants could not downweight the visual coefficient when visual ambiguity was introduced possibly because they were required to maintain focal vision to the screen in order to effectively detect and avoid the randomly approaching objects. It should be noted, however, that a relative (almost 50% when compared to quiet standing) increase in sway variability was noted in the stationary visual environment (SS1) as well under conditions of visual anticipation. For the visual anchoring hypothesis to hold, postural sway should have been reduced in the stationary visual environment to levels similar to quiet standing, which was not the case.

An alternative explanation of the increase in sway variability observed in response to the visual surround manipulation in both age groups could be the anticipatory anxiety induced by the collision avoidance task. Anticipation and anxiety are mediated by the same neural pathways, suggesting the concepts are interrelated (Herry et al. 2007). Anxiogenic conditions, i.e., performance on a visual stroop test, could induce faster and larger body sways while standing (Hainaut et al. 2011). When anxiety is directly related to perceived postural threat, elderly adults could adopt an ankle stiffening strategy that results in smaller amplitude and higher frequency of sway (Adkin et al. 2000; Brown et al. 2006; Carpenter et al. 2001). Postural state anxiety in this case could influence the interactions of visual with vestibular and somatosensory cues resulting in increased sway due to the greater visual anchoring induced by the perceived postural threat (Adkin et al. 2000; Ohno et al. 2004; Wada et al. 2001). In the current study, we assumed that the collision avoidance task required a trunk roll response sufficiently challenging to evoke a postural threat perception. This assumption was confirmed by the emergence of an ankle stiffening strategy in the elderly participants as this was reflected in the age-induced reduction of the CoP amplitude and upper trunk's velocity during the avoidance response. Contrary to what was expected, however, the relative impact of the state anxiety possibly evoked by anticipation of the colliding objects was greater in the young than in the old participants' capacity to effectively reweight the available sensory information.

One possible explanation for the reduced impact of state anxiety on the old compared to young participants' reweighting capacity could be an additional aged-induced trait anxiety that is present in the form of fear of falling. While trait anxiety was not directly measured in the current study, the RFT scores, revealing greater visual field dependence in the elderly participants, provide an indirect support of the presence of postural trait anxiety in our elderly group. Elderly's higher visual field dependence was also confirmed by their more variable sway responses to the ambiguous visual conditions in the quiet stance task. Moreover, our correlation analysis revealed a significant relationship between visual field dependence and sway variability in quiet standing. It has recently been shown that state anxiety disturbs the ability to use vestibular and/or somatosensory inputs in individuals with low trait anxiety but not in individuals with moderate trait anxiety, characterized by higher levels of field dependence (Hainaut et al. 2011). This finding is in concordance with Holmberg et al. (2009), who found that normal postural sway differences between healthy individuals and phobic postural vertigo patients were significantly attenuated under conditions of increased postural threat induced by Achilles tendon vibration. It has been suggested that sway responses in anxiety inducing specific contexts are not increased in individuals with postural trait anxiety as a further increase in sway is judged to be a danger to the individual's well-being (Balaban and Thayer 2001). Based on these findings, it could be speculated that due to their postural trait anxiety, elderly adults were less vulnerable to the anticipatory anxiety induced by the collision avoidance task, and therefore, their reweighting capacity was no more adversely affected when compared to their young counterparts.

In summary, the results of the current study suggest the sensory reweighting for controlling posture in a dynamic virtual environment is affected by state anxiety induced by the visual anticipation of aversive events that could directly threaten balance. Age-associated trait anxiety in the form of fear of falling interacts with state anxiety to reduce the aversive effect of visual anticipation on the older adults' capacity to effectively reweight the available sensory information in a dynamic environment. It should be noted, however, that trait anxiety in the form of fear of falling was not directly measured in the group of elderly participating in the present study. Through what mechanisms anticipation and anxiety influence balance performance and its relation to falls in a real life environment is not yet well understood and warrants further investigation.

Acknowledgements The research leading to these results has received funding from the European Community's Seventh Framework Programme FP7/2007–2013 under grant agreement number 214728–2.

References

Adkin AL, Frank JS, Carpenter MG, Peysar GW (2000) Postural control is scaled to level of postural threat. Gait Posture 12:87–93

Allison LK, Kiemel T, Jeka JJ (2006) Multisensory reweighting of vision and touch is intact in healthy and fall-prone older adults. Exp Brain Res 175:342–352

Balaban CD, Thayer JF (2001) Neurological bases for balance–anxiety links. J Anxiety Disord 15:53–79

Bolmont B, Gangloff P, Vouriot A, Perrin PP (2002) Mood states and anxiety influence abilities to maintain balance control in healthy human subjects. Neurosci Lett 329:96–100

Brown LA, Sleik RJ, Polych MA, Gage WH (2002) Is the prioritization of postural control altered in conditions of postural threat in younger and older adults? J Gerontol A Biol Sci Med Sci 57:785–792

Brown LA, Polych MA, Doan JB (2006) The effect of anxiety on the regulation of upright standing among younger and older adults. Gait Posture 24:397–405

Brumagne S, Janssens L, Janssens E, Goddyn L (2008) Altered postural control in anticipation of postural instability in persons with recurrent low back pain. Gait Posture 28:657–662

Carpenter MG, Frank JS, Silcher CP, Peysar GW (2001) The influence of postural threat on the control of upright stance. Exp Brain Res 138:210–218

Doumas M, Krampe RT (2010) Adaptation and reintegration of proprioceptive information in young and older adults' postural control. J Neurophysiol 104(4):1969–1977

Glasauer S, Schneider E, Jahn K, Strupp M, Brandt T (2005) How the eyes move the body. Neurology 65:1291–1293

Guerraz M, Sakellari V, Burchill P, Bronstein AM (2000) Influence of motion parallax in the control of spontaneous body sway. Exp Brain Res 131:244–252

Hainaut JP, Caillet G, Lestienne FG, Bolmont B (2011) The role of trait anxiety on static balance performance in control and anxiogenic situations. Gait Posture 33:604–608

Hatzitaki V, Amiridis IG, Arabatzi F (2005) Aging effects on postural responses to self-imposed perturbations. Gait Posture 22:250–257

Herry C, Bach DR, Esposito F, Di Salle F, Perrig WJ, Scheffler K, Lüthi A, Seifritz E (2007) Processing of temporal unpredictability in human and animal amygdala. J Neurosci 27:5958–5966

Holmberg J, Tjernström F, Karlberg M, Fransson PA, Magnusson M (2009) Reduced postural differences between phobic postural vertigo patients and healthy subjects during a postural threat. J Neurol 256:1258–1262

Horak FB, Shupert CL, Mirka A (1989) Components of dyscontrol in the elderly: a review. Neurobiol Aging 10:727–738

Isableu B, Ohlmann T, Crémieux J, Amblard B (1998) How dynamic visual field dependence–independence interacts with the visual contribution to postural control. Hum Mov Sci 17:367–391

Ishida M, Saitoh J, Wada M, Nagai M (2010) Effects of anticipatory anxiety and visual input on postural sway in an aversive situation. Neurosci Lett 474:1–4

Jamet M, Deviterne D, Gauchard GC, Vançon G, Perrin PP (2004) Higher visual dependency increases balance control perturbation during cognitive task fulfilment in elderly people. Neurosci Lett 359:61–64

Jeka J, Allison L, Saffer M, Zhang Y, Carver S, Kiemel T (2006) Sensory reweighting with translational visual stimuli in young and elderly adults: the role of state dependent noise. Exp Brain Res 174:517–527

Jeka JJ, Oie KS, Kiemel T (2008) Asymmetric adaptation with functional advantage in human sensorimotor control. Exp Brain Res 19:453–463

Laurens J, Awai L, Bockish CJ, Hegemann S, van Hedel HJA, Dietz V, Straumann D (2010) Visual contribution to postural stability: interaction between target fixation or tracking and static or dynamic large-field stimulus. Gait Posture 31:37–41

Lord SR, Clark RD, Webster IW (1991) Physiological factors associated with falls in an elderly population. J Am Geriatr Soc 39:1194–1200

Mahboobin A, Loughlin PJ, Redfern MS, Sparto PJ (2005) Sensory re-weighting in human postural control during moving-scene perturbations. Exp Brain Res 167:260–267

Maki BE, Holliday PJ, Topper AK (1991) Fear of falling and postural performance in the elderly. J Gerontol 46:123–131

Ohno H, Wada M, Saitoh J, Sunaga N, Nagai M (2004) The effect of anxiety on postural control depends on visual information processing. Neurosci Lett 364:37–39

Oie KS, Kiemel T, Jeka JJ (2002) Multisensory fusion: simultaneous re-weighting of vision and touch for the control of human posture. Cogn Brain Res 14:164–176

Peterka RJ (2002) Sensorimotor integration in human postural control. J Neurophysiol 88:1097–1118

Peterka RJ, Loughlin PJ (2004) Dynamic regulation of sensorimotor integration in human postural control. J Neurophysiol 91:410–423

Reger GM, McGee JS, van der Zaag C, Thiebaux M, Buckwalter JG, Rizzo AA (2003) A 3D virtual environment rod and frame test: the reliability and validity of four traditional scoring methods for older adults. J Clin Exp Neuropsychol 25:1169–1177

Salthouse TA (2000) Aging and measures of processing speed. Biol Psychol 54:35–54

Teasdale N, Simoneau M (2001) Attentional demands for postural control the effects of aging and sensory integration. Gait Posture 14:203–210

Wada M, Sunaga N, Nagai M (2001) Anxiety affects the postural sway of the antero-posterior axis in college students. Neurosci Lett 302:157–159

Yardley L, Smith H (2002) A prospective study of the relationship between feared consequences of falling and avoidance of activity in community-living older people. Gerontol 42:17–23