The effect of age on postural and cognitive task performance while using vibrotactile feedback

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Running title: Effect of aging on using vibrotactile feedback

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Abstract

Vibrotactile feedback (VTF) has been shown to improve balance performance in healthy people and people with vestibular disorders in a single-task experimental condition. It is unclear how age-related changes in balance affect the ability to use VTF, and if there are different attentional requirements for older and young adults when using VTF. Twenty younger and twenty older subjects participated in this two-visit study in order to examine the effect of age, VTF, sensory condition, cognitive task, duration of time, and visit on postural and cognitive performance. Postural performance outcome measures included root-mean-square of center of pressure (COP) and trunk tilt, and cognitive performance was assessed using the reaction time from an auditory choice reaction time task. The results showed that compared with young adults, older adults had an increase in COP in fixed platform conditions when using VTF, although they were able to reduce COP during sway-referenced platform conditions. Older adults also did not benefit fully from using VTF in their first session. The reaction times for the secondary cognitive tasks increased significantly while using the VTF in both younger and older adults. Older adults had a larger increase compared with young adults, suggesting greater attentional demands were required in older adults when using VTF information. Future training protocols for VTF should take into consideration the effect of aging.
Key words: Vibrotactile feedback, Dual-task, Postural sway, Aging, Reaction time, Sensory substitution, Balance
Introduction

Postural control is a perceptual-motor process involving the collection and processing of sensory information and the execution of appropriate motor responses (Schmidt 1975). Sensory information from the visual, somatosensory and vestibular systems contribute to the maintenance of human postural control (Dichgans and Diener 1989; Horak et al. 1990). Age-related declines in visual, somatosensory and vestibular function may contribute to an increase in the risk of falling in older adults (Agrawal et al. 2010; Bergin et al. 1995; Lord et al. 1992). Changes in executive function and neuromuscular function are also related to increasing fall rates in older adults (de Rekeneire et al. 2003; Kearney et al. 2013). Falls in older adults not only impact personal health, but also affect the person socially and economically (Davis et al. 2010a; Stevens et al. 2008).

Sensory substitution is a technique that uses a sensory modality to replace or augment another sensory modality (Bach-y-Rita et al. 1969). Various sensory substitution devices providing auditory, vibrotactile, and multimodal biofeedback have been proposed to counter age and disease-related imbalance and to decrease the risk of falls (Dozza et al. 2007; Honegger et al. 2013; Nanhoe-Mahabier et al. 2012; Wall et al. 2009). Vibrotactile feedback (VTF) is one feedback modality that has been developed to provide individuals with balance problems with an external cue about how their body is moving in space (Wall et al. 2001). An inertial measurement unit which is used to detect body motion, a processor and a haptic display are typically included in a VTF system. Vibration cues are provided as feedback when a person’s trunk or head exceeds a pre-defined motion-based threshold. Several studies have validated the effect of VTF applied to the trunk on reducing postural sway in young healthy subjects and people with vestibular deficits (Basta and Ernst 2011; Bechly et al. 2013; Dozza et al. 2007;
Kentala et al. 2003; Lee et al. 2012; Sienko et al. 2008; Sienko et al. 2012; Sienko et al. 2010; Wall and Kentala 2005; Wall et al. 2001; Wall et al. 2009). VTF has also been demonstrated to reduce trunk tilt and improve gait performance in older adults (Haggerty et al. 2012; Wall et al. 2009). However, it has not been determined if the use of VTF to improve balance performance in older adults differs from that of young adults.

Studies have suggested that postural control requires attention, and is affected by age-related changes in attention (Mahboobin et al. 2007; Redfern et al. 2002; Shumway-Cook and Woollacott 2000). Dual postural-cognitive task paradigms have been used to study the relationship between attention, postural control, aging and falls in the elderly. For example, older adults demonstrated slower reaction times compared with younger adults on a secondary cognition task during dual postural-cognitive task conditions, which indicates an increase in attentional demands in older adults versus young adults (Brown et al. 1999; Prado et al. 2007; Rankin et al. 2000; Redfern et al. 2001; Redfern et al. 2002; Shumway-Cook and Woollacott 2000). In addition, performance, of walking while talking has been associated with a risk of falling in elderly persons (Lundin-Olsson et al. 1997; Verghese et al. 2002).

It can be argued that use of VTF represents another type of postural-cognitive task paradigm, since it requires the user to sense the vibration, process its meaning (e.g. direction and magnitude), and execute a motor response. If using VTF is a task that requires greater attentional resources, the ability of older adults to use the VTF may be hindered compared with young adults. Haggerty et al. have started to investigate this hypothesis in older adults by having them perform an auditory choice reaction time task while using VTF (Haggerty et al. 2012). Reaction times increased when subjects received VTF compared with not using VTF, indicating that VTF requires greater attention. Nonetheless, older adult participants were still able to use the VTF to
reduce RMS trunk tilt (Haggerty et al. 2012). However, Haggerty et al.’s study did not characterize the effects of age-related changes in attention on balance performance. Another study that assessed postural-cognitive task performance while using multimodal feedback discovered that in contrast with young adults, older adults were not able to use the feedback to reduce trunk sway while counting backwards and walking (Verhoeff et al. 2009).

The primary purpose of this study was to investigate the effect of age on postural and cognitive task performance while using VTF during various sensory balance conditions. A secondary aim was to assess the effect of using VTF within trials and over multiple visits. We hypothesized that older adults would have reduced postural performance (greater trunk tilt center of pressure) and reduced cognitive task performance (increased reaction time) compared with young adults when using VTF, and that performance would improve with greater use.

Methods

Subjects

Twenty healthy young adults (mean age: 24.6, SD 2.4 years; age range: 19-29 years; 8 males, 12 females) and twenty healthy older adults (mean age: 75.4 SD 6.0 years; age range: 65-84 years; 10 males, 10 females) participated. Subjects were excluded during screening if they had neurologic or orthopedic disorders, or were pregnant. In addition, subjects were excluded if they failed functional cognition and balance tests, with scores worse than 1.5 standard deviations from the norm on the Repeatable Battery for the Assessment of Neuropsychological Status, (Wilk et al. 2002), scores less than 19 on the Dynamic Gait Index (Whitney et al. 2004), and Functional Gait Assessment scores that were less than 22 (Wrisley et al. 2004). In addition, subjects who had impaired sensation with the Semmes-Weinstein monofilament test (0.07g)
(Bell-Krotoski et al. 1995), had abnormal age corrected audiometric function, or had binocular visual acuity with corrective lenses worse than 20/40 were excluded. The Institutional Review Board at the University of Pittsburgh approved the protocol.

Instrumentation

The VTF system consisted of a belt, an inertial measurement unit (IMU, Xsense Technologies B.V., Enschede, The Netherlands), eight vibrating tactors (C-2, Engineering Acoustics Inc., Casselberry, FL, USA), and a laptop computer. The belt was wrapped around the subject’s waist and two tactors were placed within the belt vertically separated by 5 cm in each of the following locations: midline front, midline back, right and left side of the body. The IMU was attached to the posterior of the belt at the level of the fourth lumbar vertebra. The IMU recorded angular velocity, linear acceleration, and magnetic field, from which the subject’s trunk angular position from vertical (i.e. trunk tilt) and angular velocity in the antero-posterior (AP) and medio-lateral (ML) directions were estimated using manufacturer provided functions in the software development kit. Static accuracy of the pitch and roll measurements, corresponding to tilt in the AP and ML directions, is 0.5 deg, and the angular velocity accuracy is 0.1 deg/s at a frequency of 0.25 Hz, which is typical for postural sway applications (Xsens Technologies B.V. 2014). Vibrotactile feedback was provided when the proportional plus derivative feedback control signal, equal to the trunk angular position value (in degrees) plus 0.5 (seconds) times the trunk angular velocity (degrees/second)(Goodworth et al. 2009; Sienko et al. 2008), exceeded defined thresholds. Because this control signal incorporated velocity as well as position error terms, it effectively reduced the tactor activation threshold, theoretically enabling the subjects to quicken their response. The threshold of the lower row tactors was set to 1.5 degrees anteriorly,
0.5 degrees posteriorly, and 0.5 degrees to the right and left. The threshold of the upper row
tactors was set to 3 degrees anteriorly, 1.5 degrees posteriorly and 1.5 degrees to right and left.
The limits of stability are larger in the anterior direction compared to the posterior direction so a
larger threshold for anterior postural sway was set (Winter et al. 1996). “The nearest neighbor”
principle was used in the feedback algorithm which activated only one tactor at a time by
determining which direction had the greatest control signal value (Sienko et al. 2008). Tactor
vibrations were at 250 Hz. Subjects were barefoot and wore a thin standard shirt so that the
vibrotactile cues could be sensed easily.

A computerized dynamic posturography platform (EquiTest™; Neurocom, Inc.) was
used to record the center of pressure (COP). The EquiTest also provided sway referencing in the
sagittal plane about the ankle joints by estimating the body pitch from the AP COP.

A secondary attention task was delivered by a customized program (Labview, National
Instruments) providing an auditory choice reaction time task (CRT). The auditory CRT stimuli
consisted of 560 Hz and 980 Hz tones transmitted through a set of earphones (E·A·RTONE®).
The tones were played at 80 dB for 250 ms and repeated every 2 to 6 seconds during a 2 minute
period. Using one microswitch button in each hand, the subject pressed the button in the
dominant hand for a high pitch tone and the non-dominant hand for a low pitch tone. Twenty-
five to twenty-nine stimuli were presented in each trial. The onset of the switch activation
relative to the stimulus was recorded with a temporal resolution of 1 ms.

Experimental procedure

Each subject completed three study visits including one preliminary visit and two
experimental visits. The average number of days between the two experimental visits for the
young group was 6 (SD 3) days and for the older group was 6 (SD 4) days. A preliminary visit was used for screening and training the subject. The subject was briefly trained to perform the CRT tasks, use the VTF, and perform the CRT tasks while using the VTF. Five sensory integration conditions were used in the VTF training session: standing on a fixed platform with eyes open in light (Fixed/EO), standing on a fixed platform with eyes open in dark (Fixed/EOD), standing on a sway-referenced platform with eyes open with light (SR/EO), standing on a sway-referenced platform with eyes open in dark (SR/EOD), and standing on a sway-referenced platform with EO while performing the CRT tasks. The subjects were instructed to stand comfortably and to reduce the vibration as much as possible by moving in the opposite direction. Darkened goggles were used during the EOD condition to minimize visual reference cues. Each training condition lasted for 120 seconds. During the experimental visits 1 and 2, a short training session involving multiple training trials was held before the first experimental test. The one-minute training trials included one trial of the CRT task and five different sensory integration conditions which were described above. Then during each visit, a total of sixteen two-minute experimental tests were performed, including all combinations of VTF on/off, CRT task on/off, and the sensory conditions (Fixed/EO, Fixed/EOD, SR/EO and SR/EOD). The subjects performed the experimental conditions in random order during both of the experimental visits.

Outcome measures

The postural performance measures were the trunk tilt deviation from vertical and the COP in the AP and ML directions. In order to investigate within-trial performance, we divided the 120 seconds of data into four periods (Period 1: 1-30 seconds; Period 2: 31-60 seconds; Period 3: 61-90 seconds; Period 4: 91-120 seconds) (Carroll and Freedman 1993; O’Connor et al.)
The root-mean square (RMS) of trunk tilt and RMS COP were computed after subtracting the mean value, via a custom Matlab (The MathWorks, Natick, MA) program. However, because the sway-referenced platform only moved in the AP direction, ML trunk tilt and COP were not included in the data analysis. The IMU data was only recorded during the trials with VTF so that the trunk tilt was only recorded in eight out of sixteen trials. The COP was recorded during all the sixteen trials.

Cognitive task performance was assessed using the median reaction time (RT) calculated for each of the eight trials with the CRT task. The first RT response was not included in the median calculation because the subjects usually responded with an increased latency. The median RT was used to assess the influence of VTF, sensory condition and between-visit factors on attention in the young and older groups.

Statistical Analysis

A repeated measures analysis of variance (ANOVA) was conducted to investigate the aims. A secondary analysis showed that while there was an interaction between platform condition and vision conditions on the RMS COP, this effect did not appear in any other higher order interactions with any of the other factors. Consequently, we applied a simpler model using sensory condition (Condition) with four levels (fixed/SR platform x EO/EOD) instead of including the platform and vision factors. The effects of Age, Period, Visit, CRT and Condition were tested with the RMS trunk tilt data. The effects of Age, Period, Visit, VTF, CRT and Condition were tested with the RMS COP. The postural performance data (RMS trunk tilt and RMS COP) were logarithmically transformed to meet the assumption of normality of repeated measures ANOVA. A Bonferroni correction was applied if post-hoc analysis was needed for the
Condition and Period variables. The highest order interactions considered were three-way interactions. Similarly, we investigated the effect of Age, Visit, VTF and Condition on the median reaction time (RT). All statistical analyses were performed using IBM® SPSS® Statistics, Release Version 19 (IBM, Armonk, NY). A significance level of $\alpha = 0.05$ was used.

Results

Postural performance

The repeated measures ANOVA revealed numerous significant main effects and interactions on RMS COP (Table 1) and RMS trunk tilt (Table 2). Significant main effects included Age, Condition, Period and Visit on RMS COP and RMS trunk tilt. Over all conditions, older adults had approximately 33% greater RMS COP and 58% greater RMS trunk tilt than younger adults ($p < 0.001$). The sensory Condition had a dramatic effect on the magnitude of RMS COP and RMS trunk tilt, increasing by more than a factor of three from the Fixed/EO condition to the SR/EOD condition ($p < 0.001$). A significant Period effect was observed ($p < 0.001$), which was due to greater RMS COP in the initial 30 seconds compared to the final 90 seconds and greater RMS trunk tilt in the last 30 seconds compared to the middle 60 seconds. There was a modest, but significant Visit effect, with reduced RMS COP (-4%) and RMS trunk tilt (-15%) during experimental visit 2 compared with experimental visit 1 ($p < 0.005$).

Unexpectedly, there was not a significant reduction of RMS COP when VTF was used, due to interactions between VTF and other factors (as described below). The secondary CRT task did not significantly increase RMS COP or RMS trunk tilt. Furthermore, CRT did not appear in any higher order interactions.
Evidence of an age effect on ability to use VTF was revealed in significant higher order interactions that were discovered for the RMS COP data. First, there was a significant three-way interaction of Age*VTF*Condition (p < 0.001, Figure 1). Specifically, during the fixed platform conditions (Fig. 1a and 1b), greater RMS COP was observed when VTF was provided to older adults (p < 0.001), while there was no change in RMS COP during VTF in younger adults (p > 0.13). In contrast, during the SR platform conditions (Figure 1c and 1d), application of VTF reduced RMS COP in both older and younger adults (p < 0.022). Thus the use of VTF had an unexpected influence on COP in older adults on the fixed platform trials.

Tables 1, 2 about here

Figure 1 about here

A significant Age*VTF*Visit interaction also demonstrated a difference in older adults’ ability to use VTF (p = 0.018, Figure 2). Whereas the reduction in RMS COP with VTF was consistent across visits in younger adults (p = 0.46), older adults had no improvement in RMS COP with VTF on visit 1, but a significant improvement in COP with VTF on visit 2 (p = 0.003).

Figure 2 about here

The final three-way interaction from the COP analysis consisted of the factors Period, VTF, and Condition (p = 0.02, Figure 3). The three-way interaction illustrates that during the fixed platform conditions (Figure 3a and 3b), RMS COP was relatively level across all four periods when there was no VTF. When VTF was available, although the overall RMS COP increased compared with no VTF, there was a reduction of RMS COP during periods 2, 3, and 4 compared with period 1 (p < 0.007). During the SR platform conditions (Figure 3c and 3d), the reduction in RMS COP during the VTF was relatively stable across all periods.

Figure 3 about here
There were significant interactions among the factors on the RMS trunk tilt (Table 2, Figure 4). Foremost was the significant Age*Condition interaction (p = 0.028), which revealed that during the conditions when VTF was available, older adults had an impaired ability to use the VTF to control their trunk tilt compared with the young adults as the sensory conditions became more difficult (Figure 4a). Although the Condition*Visit interaction (p = 0.049) was found, the post-hoc analysis did not reveal any statistical difference between different visits among all conditions (Figure 4b). The Condition*Period interaction (p = 0.021) illustrated that in the Fixed/EOD condition, there was a decrease in RMS trunk tilt in period 3 compared with the other periods. In the SR/EO condition, period 4 had the largest RMS trunk tilt. In the SR/EOD condition, there was a decrease in RMS trunk tilt from period 1 to period 2, then an increase from period 2 to 4 (Figure 4c).

**Figure 4 about here**

Cognitive task performance

A repeated measures ANOVA of the median reaction time (RT) from each trial demonstrated significant main effects of Age, Condition, and VTF (p < 0.001, Table 3). The RTs of older adults were slower than younger adults by 109 ms (+27%). RTs increased as the challenge of the sensory condition increased. In particular, the SR/EOD condition produced RTs significantly greater than all the other conditions, and the SR/EO condition resulted in greater RTs compared with the Fixed/EO condition. When VTF was used, the RTs increased about 69 ms (+16%) compared with when VTF was not used.

In addition, there were three significant two-way interactions, as shown in Figure 5. The VTF*Age interaction (Figure 5a) demonstrated that the increase in RTs during VTF was greater in older adults compared with younger adults (101 ms v. 37 ms, p < 0.001). The VTF*Visit
interaction (Figure 5b) showed that the increase in RTs during VTF was greater in the first versus the second visit (78 ms v. 60 ms, p = 0.01). Finally, the Age*Visit interaction (Figure 5c) indicated that younger adults had faster RTs on second study visit while the RTs of the older group was essentially the same on both visits (-26 ms v. +6 ms, p = 0.018).

Table 3 about here

Figure 5 about here

Discussion

Our primary hypothesis was that older adults would have reduced postural and cognitive task performance compared with young adults when using VTF. In accordance, older adults demonstrated worse performance in the following ways. First, the Age*VTF*Condition interaction demonstrated that COP increased significantly when VTF was used by older adults during fixed platform conditions (EO/Fixed: + 37.4%; EOD/Fixed: + 33.1%), whereas COP changed minimally in young subjects (EO/Fixed: + 12.6%; EOD/Fixed: + 6%) (Figure 1).

Increased COP indicates that greater ankle torque was needed to control the body sway (Winter et al. 1998). Second, as shown by the Age*VTF*Visit interaction (Figure 2), older adults did not reduce COP in the first visit, indicating that they needed additional training to use the feedback appropriately. Furthermore, the results demonstrated that during the trials when trunk tilt was measured (i.e. the VTF on trials), older adults had greater increases in trunk tilt as the sensory conditions became more difficult, compared with young adults (Figure 4). Finally, older adults had worse cognitive task performance than young adults when VTF was utilized, as revealed by the Age*VTF interaction on reaction time (Figure 5).
Postural Performance

Typically, the center of pressure, reflective of ankle torque generation, is considered to be the regulator of body center of mass (COM) or center of gravity (COG) movement, represented by trunk tilt during quiet standing (Winter et al. 1998). Winter showed that during quiet standing, body movements can be approximated by an inverted pendulum model, in which the horizontal acceleration of COM is proportional to the difference between COP and COG (Winter 1995). Consequently, COG and COP are highly correlated when the acceleration is small. Thus it was no surprise that the results of both postural performance measures were consistent in showing significant main effects of Age, Condition, and Visit.

The RMS COP data demonstrated that younger and older subjects responded differently to VTF under various sensory integration tasks. When the platform was fixed, RMS COP increased when VTF was used by older adults during the first visit. However, when the platform was sway-referenced, RMS COP decreased similarly in both younger and older adults during VTF. These results suggest the use of different postural strategies between young and older adults during the fixed platform condition while VTF was provided and we speculate that older adults used a hip strategy to a greater extent during their first visit. Although the lack of kinematic data precludes confirmation of this postulation, Speers et al. have shown that the use of a hip strategy to maintain balance during a fixed platform condition in astronauts post-spaceflight significantly increased sway compared with pre-spaceflight (Speers et al. 1998). It is also possible that VTF provided a type of perturbation and/or elicited an overcorrection as the older adults were still learning to effectively use the VTF during visit 1. If the older adults attempted to make postural corrections during this condition in response to the vibrotactile cues,
they may have done so by repositioning their trunk (i.e. larger corrections and therefore larger changes in COP) as opposed to initiating a corrective response using their ankles (i.e. smaller corrections and therefore smaller changes in COP). This strategy may have resulted in “overcorrections”. As their abilities to use the feedback in a controlled manner improved, as shown by the reduction in COP during visit 2, older subjects no longer demonstrated an increase in COP during the fixed platform conditions.

Several previous studies have documented the ability of older adults to use various modalities of feedback to control their standing balance and walking (Allum et al. 2011; Verhoeff et al. 2009; Wall et al. 2009). In these studies, training periods lasted from 20 min (Haggerty et al. 2012; Wall et al. 2009) to six visits over two weeks (Allum et al. 2011). Using multimodal feedback, older adults were able to reduce trunk tilt while standing on level surfaces and foam and tandem walking, with eyes open or closed (Allum et al. 2011; Davis et al. 2010b). Similarly, using VTF, older adults reduced trunk tilt during normal and semi-tandem stance with eyes open and closed (Haggerty et al. 2012), and improved their DGI scores (Wall et al. 2009).

Two of the cited studies compared responses of older adults with young adults. Consistent with our results, young adults, but not older adults, were able to reduce their trunk tilt when a secondary arithmetic task was performed (Verhoeff et al. 2009). However, in contrast with our study, Davis et al. demonstrated that the reduction in trunk tilt was not different between older and young adults in most conditions (Davis et al. 2010b). However, older subjects had a greater reduction in trunk tilt than young subjects during tandem walking (Davis et al. 2010b). Thus, while Davis et al. showed that older adults have the ability to use feedback to reduce trunk tilt to the same degree as young adults (Davis et al. 2010b), there may be some limitations to this
ability that depends on secondary cognitive engagement (Verhoeff et al. 2009), sensory environment, and training, as shown in this study.

We expected that the addition of a secondary cognitive task (i.e. auditory choice reaction time task) would negatively influence the amount of reduction in trunk tilt provided by VTF, especially in older adults. However, we failed to detect a significant main effect of the CRT on the postural performance measures, independent of the state of VTF; nor did we find an interaction between the CRT and Age. Likewise, Haggerty et al. did not find that performing a concurrent auditory CRT prevented older adults from reducing their trunk tilt when using VTF. These results corresponded with the study by Redfern et al. (Redfern et al. 2002), which found that COP was unchanged by the presence of the reaction time task. In our experiment, the posture first principle may explain the negligible effect of the secondary cognitive task on COP (Lajoie et al. 1993; Shumway-Cook et al. 1997). In contrast, Verhoeff et al. reported that older adults were not able to use multimodal feedback to reduce trunk tilt and velocity while walking and counting backwards (Verhoeff et al. 2009). Thus, the ability to use VTF may depend on the type of primary or secondary task, or other factors not accounted for.

An unresolved issue is the duration of time over which VTF is effective at reducing sway. We found that older adults did not see a benefit in their first experimental visit. It has been proposed that people with balance problems will wear vibrotactile feedback systems for the purpose of balance training or as a balance aid. In many of the previous research studies, the duration of using VTF was less than a minute (Kentala et al. 2003; Sienko et al. 2012; Wall 2010; Wall et al. 2001). However, given that dynamic reweighting of sensory inputs to postural control can occur (Peterka and Loughlin 2004), and that VTF may be used for training over
longer time spans, it is necessary to evaluate in future studies if responses to VTF change over longer periods of time.

Cognitive task performance

The secondary cognitive task resulted in longer RTs in older adults compared with younger adults, consistent with previous studies (Redfern et al. 2002; Shumway-Cook and Woollacott 2000; Shumway-Cook et al. 1997). Furthermore, the use of VTF required additional attention during the sensory integration conditions, confirming the results of Haggerty et al. (Haggerty et al. 2012). However, our data also suggested that the attention requirement in utilizing VTF was greater in older adults than younger adults. Specifically, RTs increased by 101 ms (22%) in older adults and 37 ms (9%) in younger adults when VTF was present. The increase in reaction time is significant and suggests that more attentional resources are needed (Pashler 1998). The increase in attention needed to use VTF indicates that some older adults who have executive dysfunction may not be good candidates for using VTF.

Limitations

Several study limitations were identified when we tried to interpret our data. We did not measure segmental body movement and therefore were not able to quantify differences in postural control strategies that may have been present between young and older adults. In addition, we did not assess trunk tilt during the conditions when VTF was not used. As a result, we were not able to assess the effect of VTF on trunk tilt, and how VTF may have influenced COP and trunk tilt differently.
Conclusion

Our data suggest that younger and older adults use VTF differently, depending on the underlying sensory conditions and amount of training. Although the use of VTF required more attention, older adults were able to use VTF to reduce COP and trunk tilt in SR platform conditions. Designing the optimal training protocol for VTF should take these factors into consideration.

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Disclosures

All authors reported no conflict of interest.
References


Figure Legends

Figure 1: Effect of VTF*Age*Condition interaction on the root-mean-square of the anterior-posterior center of pressure (RMS COP).
- Light conditions: Eyes open (EO) and Eyes open in the dark (EOD).
- Platform conditions: Fixed platform (Fixed) and Sway-referenced platform (SR).
- VTF: Vibrotactile feedback.

Figure 2: Effect of VTF*Age*Visit interaction on the root-mean-square of the anterior-posterior center of pressure (RMS COP).
- VTF: Vibrotactile feedback.

Figure 3: Effect of Period*VTF*Condition interaction on the root-mean-square of the anterior-posterior center of pressure (RMS COP).
- Light conditions: Eyes open (EO) and Eyes open in the dark (EOD).
- Platform conditions: Fixed platform (Fixed) and Sway-referenced platform (SR).
- VTF: Vibrotactile feedback.
- Period 1: 1-30 s; Period 2: 31-60 s; Period 3: 61-90 s; Period 4: 91-120 s

Figure 4: Age*Condition, Condition*Visit and Condition*Period interaction on the root-mean-square of the anterior-posterior trunk tilt (RMS trunk tilt) when VTF was applied.

Figure 5: Effect of a. VTF*Age interaction, b. VTF*Visit interaction and c. Age*Visit interaction on median reaction time.
- VTF: Vibrotactile feedback.
a. Fixed/EO

b. Fixed/EOD

c. SR/EO
d. SR/EOD

Figure 1
Figure 2

a. Experimental Visit 1

b. Experimental Visit 2
Figure 3

(a) Fixed/EO
(b) Fixed/EOD
(c) SR/EO
(d) SR/EOD
a. Age*Condition interaction

b. Condition*Visit interaction

c. Condition*Period interaction

Figure 4
Figure 5

a. Age*VTF interaction

b. VTF*Visit interaction

c. Age*Visit interaction
Table 1: Effects of age, sensory condition, vibrotactile feedback (VTF), performance of auditory choice reaction time (CRT) tasks, period and visit on the root-mean-square of the anterior-posterior center of pressure (RMS COP).

<table>
<thead>
<tr>
<th>Main Effects</th>
<th>RMS COP (mean ± SD)</th>
<th>F and P values</th>
<th>Interaction(s)</th>
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<td></td>
<td>F1, 38 = 19.6, p &lt; 0.001</td>
<td></td>
<td>Age*VTF</td>
<td>F1, 38 = 5.5, p = 0.02</td>
</tr>
<tr>
<td></td>
<td>F2.1, 80.0 = 60.6, p &lt; 0.001</td>
<td></td>
<td>VTF*Condition</td>
<td></td>
</tr>
<tr>
<td>Conditiona</td>
<td>Fixed/EO: 0.45 ± 0.16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fixed/EOD: 0.56 ± 0.18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SR/EO: 1.03 ± 0.42</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SR/EOD: 1.57 ± 0.39</td>
<td></td>
<td>Age<em>VTF</em>Visit</td>
<td>F1, 38 = 6.1, p = 0.018</td>
</tr>
<tr>
<td></td>
<td>F1.9, 71.2 = 564.1, p &lt; 0.001</td>
<td></td>
<td>Age*VTF</td>
<td>F1, 38 = 5.5, p = 0.02</td>
</tr>
<tr>
<td></td>
<td>F1.38 = 3.8, p = 0.058</td>
<td></td>
<td>VTF*Visit</td>
<td>F1, 38 = 14.1, p = 0.001</td>
</tr>
<tr>
<td>VTF</td>
<td>Off: 0.93 ± 0.27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>On: 0.87 ± 0.27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRT</td>
<td>Off: 0.92 ± 0.27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>On: 0.89 ± 0.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Periodb</td>
<td>1: 0.98 ± 0.28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2: 0.86 ± 0.25</td>
<td></td>
<td>Period<em>VTF</em>Condition</td>
<td>F9.342 = 2.2, p = 0.02</td>
</tr>
<tr>
<td></td>
<td>3: 0.86 ± 0.26</td>
<td></td>
<td>Period*VTF</td>
<td>F3.114 = 11.6, p &lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>4: 0.89 ± 0.27</td>
<td></td>
<td>Period*Condition</td>
<td>F6.3.240.0 = 4.4, p &lt; 0.001</td>
</tr>
<tr>
<td>Visit</td>
<td>1st: 0.92 ± 0.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2nd: 0.88 ± 0.28</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Platform conditions: Fixed platform (Fixed) and Sway-referenced platform (SR).
- Light conditions: Eyes open (EO) and Eyes open in the dark (EOD).
- Post-hoc test for Condition: all conditions were significantly different, p < 0.001.
- Post-hoc test for Period: Period 1 significantly greater than Periods 2, 3 and 4, p < 0.001.
Table 2: Effects of age, sensory condition, performance of auditory choice reaction time (CRT) task, period and visit on the root-mean-square of the anterior-posterior trunk tilt (RMS trunk tilt).

<table>
<thead>
<tr>
<th>Main Effects</th>
<th>RMS trunk tilt (deg) (mean ± SD)</th>
<th>F and P values</th>
<th>Interaction(s)</th>
<th>F and P values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>Younger: 0.38 ± 0.10 Older: 0.60 ± 0.18</td>
<td>F1,38 = 14.5, p &lt; 0.001</td>
<td>Age*Condition</td>
<td>F2.4,85.2 = 3.5, p = 0.028</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Condition*Visit</td>
<td>F3,108 = 2.7, p = 0.049</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Condition*Period</td>
<td>F5.9,213.0 = 2.6, p = 0.021</td>
</tr>
<tr>
<td>Condition&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>Fixed/EO: 0.32 ± 0.14 Fixed/EOD: 0.37 ± 0.17 SR/EO: 0.51 ± 0.21 SR/EOD: 0.76 ± 0.28</td>
<td>F2.4,85.2 = 284.2, p &lt; 0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRT</td>
<td>Off: 0.49 ± 0.20 On: 0.49 ± 0.18</td>
<td>F1,36 = 0.2, p = 0.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Period</td>
<td>1: 0.50 ± 0.20 2: 0.48 ± 0.19 3: 0.48 ± 0.20 4: 0.53 ± 0.20</td>
<td>F2.1,75.1 = 8.3, p &lt; 0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visit</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;: 0.53 ± 0.24 2&lt;sup&gt;nd&lt;/sup&gt;: 0.45 ± 0.14</td>
<td>F1,36 = 10.6, p = 0.002</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- <sup>a</sup>Post-hoc test for Condition: all conditions were significantly different, p < 0.001.
- <sup>b</sup>Post-hoc test for Period: Period 4 significantly greater than Periods 2 and 3, p < 0.001.
Table 3: Effects of age, sensory condition, vibrotactile feedback (VTF), and visit on the median reaction time during performance of an auditory choice reaction time task.

<table>
<thead>
<tr>
<th>Main Effects</th>
<th>Reaction Time (ms) (mean ± SD)</th>
<th>F and P values</th>
<th>Interaction(s)</th>
<th>F and P values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>Younger: 411 ± 84 Older: 520 ± 96</td>
<td>F&lt;sub&gt;1,38&lt;/sub&gt; = 14.5, p &lt; 0.001</td>
<td>Age*VTF</td>
<td>F&lt;sub&gt;1,38&lt;/sub&gt; = 17.1, p &lt; 0.001</td>
</tr>
<tr>
<td>Condition&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>Fixed/EO: 447 ± 104 Fixed/EOD: 454 ± 106 SR/EO: 465 ± 104 SR/EOD: 497 ± 114</td>
<td>F&lt;sub&gt;3,114&lt;/sub&gt; = 29.1, p &lt; 0.001</td>
<td>VTF*Visit</td>
<td>F&lt;sub&gt;1,38&lt;/sub&gt; = 7.1, p = 0.009</td>
</tr>
<tr>
<td>VTF</td>
<td>Off: 431 ± 85 On: 500 ± 128</td>
<td>F&lt;sub&gt;1,38&lt;/sub&gt; = 80.2, p &lt; 0.001</td>
<td>Age*Visit</td>
<td>F&lt;sub&gt;1,38&lt;/sub&gt; = 6.1, p = 0.018</td>
</tr>
<tr>
<td>Visit</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;: 471 ± 101 2&lt;sup&gt;nd&lt;/sup&gt;: 461 ± 113</td>
<td>F&lt;sub&gt;1,38&lt;/sub&gt; = 2.4, p = 0.13</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Platform conditions: Fixed platform (Fixed) and Sway-referenced platform (SR).
- Light conditions: Eyes open (EO) and Eyes open in the dark (EOD).
- <sup>a</sup>Post-hoc test for Condition: SR/EOD significantly greater than Fixed/EO, Fixed/EOD and SR/EO, p < 0.001.
- <sup>b</sup>Post-hoc test for Condition: SR/EO significantly greater than Fixed/EO, p = 0.006.