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Successful balance training is associated with improved multisensory function in fall-prone older adults

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ABSTRACT

Balance maintenance relies on a complex interplay between many different sensory modalities. Although optimal multisensory processing is thought to decline with ageing, inefficient integration is particularly associated with falls in older adults. We investigated whether improved balance control, following a novel balance training intervention, was associated with more efficient multisensory integration in older adults, particularly those who have fallen in the past. Specifically, 76 healthy and fall-prone older adults were allocated to either a balance training programme conducted over 5 weeks or to a passive control condition. Balance training involved a VR display in which the on-screen position of a target object was controlled by shifts in postural balance on a Wii balance board. Susceptibility to the sound-induced flash illusion, before and after the intervention (or control condition), was used as a measure of multisensory function. Whilst balance and postural control improved for all participants assigned to the Intervention group, improved functional balance was correlated with more efficient multisensory processing in the fall-prone older adults only. Our findings add to growing evidence suggesting important links between balance control and multisensory interactions in the ageing brain and have implications for the development of interventions designed to reduce the risk of falls.

1. Introduction

Falls represent a major problem for many older people and are a leading cause of disability in the older population. The prevalence of falling can vary but it is typically assumed that one third of community-dwelling older adults will experience a fall each year (Tinetti, Speechley, & Ginter, 1988). For example, a longitudinal study currently being conducted in Ireland, known as The Irish Longitudinal study on Ageing (TILDA) revealed that of a population representative sample of over 8000 community-dwelling, older participants tested, approximately 20% reported having a fall in the previous year (Barrett et al., 2011). This prevalence increases with age such that 18% of adults between the ages of 50–64 years experienced a fall, whereas over 24% of adults older than 75 years reported experiencing a fall. Within this cohort, 9% reported experiencing recurrent falls. Finally, the TILDA study revealed that one in four older adults reported having a fear of falling and restricted their activities accordingly. Whilst restricted activities can prevent the occurrence of a fall, this strategy may impact negatively on an older adult's mobility (Donoghue, Cronin, Savva, O'Regan, & Kenny, 2013a; Donoghue et al., 2013b), physical health and cognition (Barrett et al., 2011) and may even increase the risk of the occurrence of falls in the future (Delbaere, Crombez, Vanderstraeten, Willems, & Cambier, 2004).

Due to its multifaceted nature, the primary causal factors related to the pathology of falls have yet to be identified although several risk factors have been suggested. These include physical frailty (e.g. Li et al., 2014) and other age-related changes in physiological function such as orthostatic hypotension and cardiovascular disorders (Davies & Kenny, 1996). However, interventions designed to alleviate these risk factors have been moderately successful only at reducing the recurrence of falls (Parry et al., 2008). Further research is therefore required to not only understand why older people are more at risk of falling but also to put in place therapeutic measures that will decrease the incidence of falling and aid the rehabilitation of those who have experienced a fall. Moreover, given the rapid increase in the size of the older population worldwide (World Health Organization., 2012), novel and cost effective approaches to prevent, or delay, age-related disability are societal imperatives.

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Recent studies have suggested that perceptual processing may be associated with an increased risk of falls in older persons. For example, an age-related reduction in visual function, such as contrast sensitivity and depth perception, has been associated with a risk of falls (Lord & Menz, 2000; Menant, Smith, & Lord, 2008) as well as an increase in a fear of falling in older adults (Donoghue et al., 2013a; Donoghue et al., 2013b). However, the ability to maintain balance and postural control depends on the efficient processing of information encoded by several sensory modalities. Specifically, balance control depends on a complex process that involves a coordinated set of sensorimotor interactions which continually integrate information from the relevant senses, particularly the vestibular, proprioceptive, auditory and visual modalities (Angelaki & Cullen, 2008; Chang, Uchanski, & Hullar, 2012; Lord & Sturnieks, 2005).

The vestibular system plays a crucial role in balance maintenance and postural control (e.g. St. George & Fitzpatrick, 2011). There is growing evidence to suggest multisensory interactions in candidate regions of the brain that have previously been identified as being involved in posture and balance control. For example multisensory neurons which code for vestibular, somatosensory and visual stimuli have been found in the primate ventral intraparietal area (VIP; Bremmer, Klam, Duhamel, Ben Hamed, & Graf, 2002) and the parieto-insular vestibular cortex (PIVC; e.g. Chen, DeAngelis, & Angelaki, 2010). In the human brain, the vestibular network has been posited to incorporate a number of brain regions including the posterior and anterior insula, superior temporal gyrus, inferior parietal lobule, temporoparietal junction which are known to have connections to sensory cortices, including somatosensory and visual systems (e.g. Lopez, Blanke, & Mast, 2012; Taylor-Clarke, Kennett, & Haggard, 2002). Thus there is mounting evidence to suggest that brain areas involved in postural control, locomotion and spatial cognition depend on interactions across multiple senses.

Cognitive resources such as attention and executive function are also necessary for balance control (Woollacott & Shumway-Cook, 2002; Yogev-Seligmann, Hausdorff, & Giladi, 2008). An inability to maintain postural stability while standing or under other conditions that challenge balance and require active cognitive input, such as when avoiding obstacles (Lord, Sherrington, & Menz, 2001), or updating spatial representations during navigation (Barrett et al., 2013), has been associated with a higher occurrence of falling. While a growing body of research is now addressing the impact of cognitive resources on balance control (e.g. Mirelman et al., 2012), very little is understood about the integration of information from multiple senses and the contribution thereof to falls risk in older adults.

Recent findings suggest that the integration of information across the senses can often lead to better or more robust perceptual performance and that sensory integration may be particularly advantageous for perception in the older population when sensory acuity declines (Laurienti, Perrault, Stanford, Wallace, & Stein, 2005). In particular, when stimuli from different modalities are congruent (temporally or spatially), then the relative benefit of multisensory over unisensory inputs on perception is greater in older than in younger adults (Laurienti, Burdette, Maldjian, & Wallace, 2006; Peiffer, Mozolic, Hugenschmidt, & Laurienti, 2007). However, Poliakoff, Ashworth, Lowe, and Spence (2006) reported that when spatially incongruent inputs from different modalities are presented to older adults, then this can result in distractibility and inefficient processing of the target stimulus. More specifically, previous studies have reported that in comparison to healthy older adults, fall-prone older adults are less successful at integrating (Mahoney, Holtzer, & Verghese, 2014; Setti, Burke, Kenny, & Newell, 2011) or re-weighting (Jeka, Allison, & Kiemel, 2010) the relative reliability of information from visual, vestibular and proprioceptive inputs in response to changes in the environment. This inefficient re-weighting across sensory inputs may, in turn, affect postural stability.

It has been argued that this relative inefficiency at integrating multiple sensory inputs may be mediated by a larger temporal window of integration of sensory information in older than in younger adults (Diederich, Colonius, & Schomburg, 2008). For older adults, perceptual outcomes can be affected by a combination of auditory and visual information even when the delay between these two cross-modal stimuli is large. To investigate whether falling in older adults may be affected by a large window of temporal integration, Setti et al. (2011) compared the effect of multisensory inputs on perception in two groups of older adults, those with and without a history of falls, by measuring their susceptibility to the sound-induced flash illusion or SIFI (Shams, Kamitani, & Shimojo, 2000). The illusion is experienced when participants report seeing two visual stimuli in a situation in which only one visual stimulus (a 'flash') is presented with two auditory 'beeps'. Setti et al. reported sustained susceptibility to this illusion over relatively large temporal delays between the auditory beeps in older relative to younger adults. Moreover, susceptibility to the SIFI was particularly pronounced for the fall-prone older adults, although both older adult groups were matched in cognitive abilities and sensory acuity. Setti et al. argued that this result provides evidence for relatively inefficient multisensory integration with increasing age (see also Stevenson, Zemtsov, & Wallace, 2012) but also that that impaired audiovisual integration may be linked to poor postural and balance control. Indeed, Stapleton, Setti, Doheny, Kenny, and Newell (2014) recently reported greater susceptibility to the SIFI illusion in older adults with a history of falls when they were in a standing (i.e. when balance control was required) than when in a seated position. Taken together, these findings strongly suggest that there is an important association between multisensory integration and a risk of falls in older adults. Moreover, given the known interactions between the main sensory systems and vestibular function (e.g. Lopez et al., 2012), as well as the efficiency by which sensory information is combined in the older brain (Diederich et al., 2008; Setti et al., 2011) these findings suggest the possibility that improving balance control in older adults may also affect multisensory function in general, possibly leading to a reduced risk of falling. The aim of the current study was to assess the impact of improved balance control, and therefore vestibular functioning, on the integration of information across two sensory systems which are important for spatial cognition, namely vision and audition, as measured by susceptibility to the SIFI.

Many balance training interventions have been devised in order to reduce the risk of falls in older adults. A recent Cochrane review outlined a number of interventions involving the combination of physiotherapist-lead balance training and exercise with other risk reduction approaches, such as education or calcium and vitamin D administration (Gillespie et al., 2012). Given that physical therapy treatment can be quite expensive (e.g. Robertson, Devlin, Gardner, & Campbell, 2001), more cost effective means of delivering balance training have recently been developed (e.g. Bateni, 2012). For example, the use of balance platforms in a training setting allows the individual to become more aware of their body position, and has proved an effective way to improve balance control (Lajoie, 2004; Sihvonen, Sipilä, & Era, 2004; Wolf, Barnhart, Ellison, & Coogler, 1997). The provision of visual feedback on body position appears to be a critical factor in successful balance therapy (Szturm, Betker, Moussavi, Desai, & Goodman, 2011). Sihvonen et al. reported that the use of visual feedback during the balance training programme was associated with both an increase in motivation and high compliance rates (i.e. 97.5%) relative to programmes which did not include feedback.

The use of such balance platforms, however, requires specialist administration and subsequent data analyses which limits the scalability of such balance training interventions. More recent balance training interventions have been developed using existing off the shelf technology such as the Nintendo 'Wii Balance Board' or 'Wii Fit' (e.g. Pigford & Williams Andrews, 2010). However, many commercially available games may not be designed with the older adult in mind (Hanneton & Varenne, 2009), particularly those involving dynamic, physical exercises, and may be particularly unsuitable for older adults at risk of falling. Therefore it is necessary to develop balance training interventions or games matched to the capabilities of the older cohorts and targeting the specific deficits they present.

To address this need, Young, Ferguson, Brault, and Craig (2011) developed a computerised game, based on the Nintendo 'Wii Balance Board' which was developed specifically to improve balance control in the older population, particularly those with a history of or fear of falling. This game specifically targets movements known to be problematic in balance control, such as a reduced range of movement (in both anterior-posterior and medio-lateral planes) and it also aims to train fast reactive movements. Moreover, their interface allows the user to determine their balance by viewing visual feedback on a screen which directly relates to their centre of pressure (COP). Furthermore, this visual feedback is incorporated into a virtual environment display, which depicts a game scenario. As such, the game can be controlled directly by the displacement of the participant's COP and contains real-time graphical feedback that reinforces how the person is moving to control their balance (Young et al., 2011). Young and colleagues later developed this game to introduce different levels of difficulty. Critically, the initial levels of game play are designed to be sympathetic to the balance capabilities of each older participant by calibrating the performance to movements which may involve small displacements of the participant's COP. The difficulty of the game is then progressively increased in line with the participant's rate of improvement which, in turn, forces larger and faster displacements of the COP. By progressing through increasing levels of difficulty, the participant will thus challenge their action capabilities and increase postural stability through their engagement with the game, and as a result improve balance function. Thus successful implementation of this balance training intervention in a laboratory setting would then provide a useful tool that could be potentially used independently by older adults in the future.

We used this improved version of the game developed by Young et al. (2011) to investigate specifically if improved balance function, as a consequence of a balance training intervention, was associated with improved multisensory function in older adults. The recent report by Stapleton et al. (2014) supports the suggestion of a direct link between balance control and temporal multisensory perceptual function (e.g. Jeka et al., 2010). However, it is unclear whether incremental changes in balance function may also be associated with an older adult's ability to efficiently perceive multisensory inputs. In order to elucidate the link between balance maintenance and multisensory integration we utilised a similar protocol to that previously reported (Setti et al., 2011; Stapleton et al., 2014) and measured the susceptibility of healthy and fall-prone older adults to the sound-induced flash illusion prior to and following a five week balance training intervention. Participants assigned to the Intervention group were required to perform two 30-min sessions of balance training per week. The Control group was required to keep a diary of daily physical activities. Since previous studies have reported less efficient multisensory perception in older adults with a history of falling, we were particularly interested in whether improved balance control in this older cohort group was linked to changes in multisensory function relative to a healthy, age-matched cohort.

2. Method and materials

2.1. Participants

A total of 104 participants volunteered to take part in the study. Twenty-eight volunteers did not complete the study: 8 due to ill health and 20 withdrew from the study for a variety of other reasons. Thus, the final sample included a total of 76 participants (16 male, 60 female)

Participants were recruited by advertising through local ageing organisations and local media in Dublin and Belfast. Most of the older adults were community dwelling (59 participants) and some were residing in sheltered accommodation for retired persons (17 participants). The criteria for participation included that the participant was 60 years of age or older, reported normal or corrected-to-normal vision and hearing, had no evidence of cognitive impairment and was able to follow instructions for testing and training. Seven of the participants reported the use of a hearing aid, which was switched on during all testing.

Recruitment targeted both healthy older adults and those with a history of falls. Within the final sample of 34 fall-prone older adults, 23 participants reported a history of recurrent falls during the previous five years, 7 experienced an unexplained fall within the last year prior to testing, and 4 persons had had a severe fall at least once within the 2–5 years prior to testing. The other 42 participants were healthy with no history of unexplained falls in the last five years (11 reported having one accidental fall within the year prior to testing which was due to environmental hazard, such as slipping on ice, but these individuals were not considered fall-prone according to clinical categorisation; Todd & Skelton, 2004).

Participants were assigned to either the 'Intervention' group or the 'Control' group in a pseudo-random order, based on their falls status and on their availability and willingness to commit to the balance training protocol. Accordingly, 38 participants were allocated to the Control group (15 male, 23 female) and 38 to the Intervention group (1 male, 37 female). Participants allocated to the Control group included 17 older adults with a history of falls and 21 healthy older adults while participants allocated to the Intervention group included 17 older adults with a history of falls and 21 healthy older adults. The intervention and control protocols took place over a series of 5 weeks. Participants assigned to the Intervention group were required to perform two, 30-min sessions of balance training per week. The Control group was required to keep a diary of daily light, medium and heavy physical activities.

The experiment was approved by the School of Psychology Research Ethics Committee, Trinity College Dublin and the School Research Ethics Committee, Queen's University Belfast and conformed to the Declaration of Helsinki. All participants provided informed, written consent prior to taking part in the experiment.

2.2. Stimuli and apparatus

Participants were tested in dedicated testing rooms which were located either on-site (i.e. in the sheltered accommodation site) in Belfast, or in a room located in a community centre in Dublin or in a testing laboratory at Trinity College Dublin.

The protocol comprised of three sets of assessments; baseline measures; pre- and post-intervention measures and the intervention itself. First, baseline measures including self-reported sensory acuity and cognitive function which was acquired using the Mini Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975) were recorded. We noted that all participants in our study scored higher than 24, which is consistent with the MMSE threshold of 24 marking evidence of cognitive impairment, suggesting that none had any cognitive impairments (Lezak, Howieson, & Loring, 2004). An account of falls history was also taken from each participant. This provided us with important background information with regards to history of falling and allowed us to classify each older adult as either 'fall-prone' or healthy according to previous definitions. That is, fall-prone older adults experienced one or more severe falls within the preceding 2–5 years or reported a history of recurrent falls within the preceding year. Healthy older adults reported no falls or one incidental fall within the year prior to testing.

2.2.1. Assessment measures (pre- and post-intervention/control sessions)

Both prior to and after the intervention, balance function was measured in each of the participants based on a number of standardised tests, as well as custom-designed objective measures of balance and postural control. First, balance and balance confidence was assessed using the Berg Balance Scale (BBS; Berg, Wood-Dauphinee, Williams, & Gayton, 1989) and the Activities-specific Balance Confidence scale (ABC; Powell & Myers, 1995) respectively. High scores on the BBS indicated greater functional balance control. High scores on the ABC indicated greater balance confidence. The Falls Efficacy Scale (FES; Tinetti, Richman, & Powell, 1990) was used as a measure of fear of falling. Higher scores indicated a greater fear of falling.

To provide an objective measure of balance control a number of custom-built balance tests, measuring both static and dynamic balance, were developed by Young et al. (2011). Static balance is the ability to maintain a position with minimal movement, while dynamic balance involves the ability to adapt to changes during movement (Winter, Patla, & Frank, 1990). The apparatus included a Nintendo 'Wii Balance Board' (WBB; Nintendo, Kyoto, Japan) which was interfaced with a laptop computer via Bluetooth. The WBB contains multiple sensors located at each corner of the platform which allows for the acquisition of pressure changes associated with changes in balance. The custom-designed static and dynamic balance tests were run either on a Dell Latitude E4300 laptop (Dublin cohort) or a Dell Alienware M15x laptop (Belfast group) and both laptops had a refresh rate of 60 Hz.[1] For each of these tasks visual stimuli were projected onto a white screen/background using a standard projector. The static balance test required the participant to shift their COP in order to move the location of a red dot on the visual scene, a visual representation of their centre of pressure, until it was collocated with a target square in the scene. They were then required to maintain that position for 10 s over three trials at a number of target locations (centre, anterior, right, posterior, and left, presented in the same order for each participant). For example, a participant who spent 1 s of the total 10 s trial period in the target region would receive a score of 10% time spent on target. As 3 trials were administered for each target zone, an average score was automatically calculated. For the dynamic balance test the participant was required to shift their COP until the visual representation of their COP was positioned over a series of visual targets which were presented in a number of different but fixed locations (posterior-centre, anterior-left, posterior-centre, anterior-centre, posterior-centre, and anterior-right). The participant was required to reach as many of these targets as possible within 60 s. Each target remained onscreen until the participant successfully reached it by shifting their balance.

The WBB was positioned in front of the projector screen at a distance of approximately 2 m. Participants were required to stand on the WBB during these balance assessments (and also during the balance training games described in Section 2.2.2). For safety and comfort, the WBB was embedded into a compliant surface mat which was flush with the platform floor. In addition, we included a waist-high frame which surrounded the participant on three sides, and onto which they could hold whenever they felt necessary during testing. Participants who utilised the frame during various trials at the pre-assessment were required to utilise the frame during the same trials at post-assessment.

Multisensory perceptual function in all participants was measured in a separate session using the sound-induced flash illusion (Shams et al., 2000). The test included both visual and auditory stimuli and was presented on a laptop (described earlier). Participants were required to sit in front of the laptop in order to perform the task. The laptop was positioned on a table in front of each participant at an approximate distance of 57 cm. The visual stimulus consisted of a white disc with a diameter subtending a visual angle of approximately 1.5° and a luminance of 31.54 fl. This was projected against a black background on the laptop screen and appeared approximately 5° below fixation. The visual stimulus was briefly flashed for 12 ms. The auditory stimulus consisted of a brief burst of 3500 Hz presented for 10 ms. at 79 dB, which had the subjective experience of a 'beep'. Auditory stimuli were delivered through speakers which were integrated into the laptop. The SIFI experiment was programmed, and participants' responses were recorded, using Presentation software (http://www.neurobs.com).

2.2.2. Balance training intervention

For the purpose of training balance control, two custom-designed games were developed in Queen's University Belfast (Young et al., 2011) with the aim of improving balance function in older adults. The games were based on virtual environments which were created using Virtools 4.0 (Dassault Systems) software. The WBB was used as the interface device to record balance data from the WBB sensors. There were two games, each designed to improve medio-lateral body movements or both medio-lateral and anterior-posterior body movements respectively. The first game comprised of visual scene of an apple tree from which apples would fall to the ground from any position on the tree. The participant was required to shift their balance on the WBB in order to control the position of a virtual basket located on the ground to catch apples falling from the tree. The second game was comprised of a dynamic, virtual 'sea-scape' in which participants were required to shift their balance to move the position of a character in the scene so that the character could burst rising bubbles which could appear in any position. Each game became incrementally more difficult as the participant's performance improved. Data representing the participant's COP positions were acquired relative to the start and end of each trial (which were time-stamped) and automatically saved in a text file for later analysis. Further details of the balance games and performance measures are provided in Whyatt, Merriman, Newell, and Craig (2012).

2.3. Design

The overall experimental design was based on mixed, factorial design with participant group (Intervention or Control) and the falls status of the participant (fall-prone or healthy) as between group factors. The within group factor included the assessment measures (pre- and post-intervention) for any of the specific tasks. For the static balance test, performance was measured by calculating the average amount of time a participant spent in each of the different target positions (i.e. centre, anterior, right, posterior, and left) across 3 trials. For the purpose of this analysis, performance was collapsed across position to give an overall measure

[1] As two different laptops were used to run the sound-induced flash illusion paradigm across sites, a multivariate analysis was performed to ensure there was no difference in performance on the balance task across testing sites. The main effect of testing site did not reach significance [$F(16,59) = 1.45$, $p = 0.15$].

of static balance performance. During the dynamic balance test performance was measured as the number of targets successfully hit within the 60s time limit. The target positions were presented onscreen in a fixed order (posterior-centre, anterior-left, posterior-centre, anterior-centre, posterior-centre, and anterior-right) and were repeated in this order during the trial.

The multisensory function test was based on performance on the sound-induced flash illusion (SIFI; Shams et al., 2000). The design of the SIFI test was based on mixed design with group (Control and Intervention) and falls status (fall-prone or healthy older adults) as between-subject measures and assessment (pre- and post-session) and stimulus onset asynchrony (SOA; −70, −150, −230, 70, 150, or 230 ms) as within-subject factors. The dependent variable included the mean percentage of correct responses across assessments (i.e. before and after the intervention/control period) for each participant. There were three different trial types: unisensory (audio or visual), audiovisual congruent or audiovisual incongruent (i.e. illusory) trials. All trials were presented in a random order across participants. The audiovisual 'illusory' trials always consisted of 1 flash paired with 2 beeps in the following manner: one of the auditory 'beeps' was always delivered simultaneously with a visual flash and the onset of the second auditory beep could either precede or lag behind the other 'beep' with a stimulus onset asynchrony (SOA) of either 70, 150, or 270 ms, yielding six trials. The unisensory, auditory-only condition consisted of four trials of either 1 beep or 2 beeps (with an SOA of 70, 150, or 230 ms). The unisensory visual-only condition consisted of two trials of either 1 or 2 'flash' stimuli. The 2 flash stimuli were presented in quick succession with an SOA of 70 ms. The congruent audiovisual trials consisted of either 1 flash synchronously presented with 1 beep, or 2 flashes synchronously presented with 2 beeps. In the case of the 2 beeps and 2 flashes, the same SOA delays were presented between the beep and flash stimuli as in the illusory trials. Each trial was repeated 4 times, producing a total of 64 trials.

Depending on the group to which they were allocated, participants embarked on either the intervention or the control protocols. Both of these procedures involved the same assessment tasks which were administered before and after the 5-week intervention or control period and which measured static balance, dynamic balance (as assessed using the WBB), as well as performance on standardised tests including the BBS, ABC and FES questionnaires and multisensory function (as assessed using the SIFI). The order of assessments was counterbalanced across participants.

2.4. Procedure

All participants first completed the baseline assessments as described in Section 2.2.1. They then completed the initial set of assessments prior to embarking on the balance training or control condition.

2.4.1. Assessment measures (pre- and post-intervention)

The measures of balance confidence (ABC and FES), balance control (BBS, static and dynamic balance tests), and multisensory function (SIFI) were carried out in either a single session which took no longer than 1 h and 30 min or (at the participant's discretion) over two sessions lasting no longer than 45 min each. During the static and dynamic balance tests the participant was required to stand on the WBB apparatus, and shift their body weight in order to follow the visual targets which were presented on the screen. Thus, the participant was required to move their COP (utilising visual feedback) into the target area depicted on screen by shifting their weight on the WBB and then to maintain that position (static balance) or to move their COP to the location of a series of fixed order visual targets (dynamic balance), as outlined in Section 2.2.1.

During the SIFI test, participants were seated in front of the laptop which was positioned on a table at approximately 57 cm from the participant. A fixation cross appeared at the centre of the screen and remained on display throughout the trial. Participants were instructed to maintain fixation throughout each trial. They were informed that they would see brief visual flashes on the screen and that they would hear short sound 'beeps'. They were instructed to verbally report the number of flashes they saw on the screen in any one trial. If no flashes were shown (such as in the auditory-only trials), then they were instructed to report perceiving no flashes and to report the number of auditory beeps instead. However, it was emphasised that the task required participants to report the number of visual flashes in all other cases. At the end of each trial, the experimenter recorded the participants' response on the keyboard. At the end of each trial the fixation cross disappeared from the screen and the experimenter pressed a key on the keyboard to initiate the next trial. The experiment was preceded by a training phase in which participants were presented with 10 practice trials, which they could repeat until they felt comfortable with the task (practice included trials with 1 or 2 unimodal flashes; 1 flash with 1 beep; 1 flash with 2 beeps across different SOAs). The SIFI experiment was self-paced and no emphasis was made on the speed of responses.

2.4.2. Balance training intervention and control phase

To play the balance training games, participants were first required to stand on the WBB apparatus. They were instructed that they had to shift their body weight on the WBB in order to control the game. All participants allocated to the intervention played both games (i.e. static and dynamic balance training) at levels of increasing difficulty over a 30-min session. Participants were required to complete training sessions twice a week over a 5-week period, with a minimum of one day between sessions to allow for sufficient levels of rest and recovery.

For the participants allocated to the Control group, they were asked to keep a diary of daily activities by recording their activities according to the following three categories; light (e.g. light housework), medium (e.g. walking, gardening), or heavy (dancing, swimming). There were no further instructions provided to this group.

3. Results

3.1. Assessment of baseline differences between groups

We analysed participants' data on the baseline measures to ensure that the fall-prone and healthy groups were matched in age and cognitive ability as well as in the pre-assessment measures of perceived balance confidence, balance control and in performance on the sound-induced flash illusion. First, because of different numbers of participants across groups, we used independent t-tests[2] to compare age and cognitive performance across the fall-prone and healthy within each of the Control and Intervention groups. These data and results of the comparisons are presented in Table 1. No significant differences were found in age between test groups, nor between fall-prone and healthy older adults. Similarly, there was no difference found in the mean MMSE scores between test groups, nor between fall-prone and healthy older adults.

3.2. Training effect on balance function and balance confidence

To establish whether the balance training intervention was effective, we compared performance on the balance function tests

[2] The lack of differences between the groups was also confirmed using a 2×2 ANOVA on each of the age and MMSE measures: $F < 1$ for all comparisons.

Table 1
Mean age profile and cognitive characteristics of the fall-prone and healthy older adults within each of the Control and Intervention groups (standard deviations in parentheses).

	Control group				Intervention group			
	Fall-prone	Healthy	*t*-test	*p* value	Fall-prone	Healthy	*t*-test	*p* value
Age	73.41 (7.00)	74.33 (11.09)	$t(36) < 1$	0.76	74.06 (6.66)	74.90 (8.97)	$t(36)<1$	0.75
MMSE	28.47 (1.66)	28.19 (1.57)	$t(36) < 1$	0.6	28.12 (1.69)	28.67 (1.43)	$t(36) = 1.09$	0.29

Table 2
Summary of participants' mean performance on all assessment tasks taken prior to and after the intervention or control sessions for each of the fall-prone and healthy older adult groups (standard deviations in parentheses).

Test	Pre-assessment				Post-assessment			
	Control group		Intervention group		Control group		Intervention group	
	Fall-prone	Healthy	Fall-prone	Healthy	Fall-prone	Healthy	Fall-prone	Healthy
Berg balance scale	47.88 (11.82)	49.62 (8.37)	51.47 (4.68)	49.24 (7.75)	48.24 (11.87)	49.95 (8.13)	53.59 (3.24)	52.29 (5.20)
ABC	75.04 (21.90)	75.92 (25.97)	71.92 (19.20)	74.12 (19.17)	78.69 (18.12)	78.45 (18.31)	78.24 (17.80)	84.10 (13.36)
FES	31.00 (28.92)	22.33 (19.97)	20.59 (8.49)	21.62 (13.61)	27.65 (22.14)	18.95 (12.51)	20.06 (9.92)	15.00 (6.92)
Static balance test	50.92 (21.41)	56.04 (14.61)	51.42 (20.25)	54.63 (14.32)	63.18 (16.82)	61.37 (19.19)	73.69 (13.99)	77.56 (13.49)
Dynamic balance test	8.24 (7.50)	12.48 (8.41)	9.12 (10.09)	6.57 (5.99)	14.59 (13.13)	13.71 (10.93)	27.65 (9.19)	29.57 (16.59)

such as the Berg Balance Scale, ABC, FES, and the custom-built balance tests which measured static and dynamic balance. A summary of the mean results can be found in Table 2. We expected that the Intervention group would improve across assessments on the balance measures whereas we did not expect any such improvement for the Control group. Separate 3-way, mixed ANOVAs were conducted on each of the balance measures with test group (Intervention or Control) and fall-status (fall-prone or healthy older adults) as between-subject measures and assessment (pre- or post- the intervention or control period) as the within-subjects factor.

First, for the Berg balance scores we found a main effect of assessment [$F(1, 72) = 13.08$, $p < 0.01$], with an overall improvement in the Berg score observed from pre- ($M = 49.54$, $SD = 8.4$) to post-assessment ($M = 51.03$, $SD = 7.82$). Importantly the interaction between assessment and test group was significant [$F(1, 72) = 7.66$, $p < 0.01$], as shown in Fig. 1. Post-hoc comparisons using the Tukey HSD test indicated that Berg score for the Intervention group significantly improved from pre- ($p < 0.001$; $M = 50.24$, $SD = 6.57$) to post-assessment ($M = 52.87$, $SD = 4.42$) whereas the same score for the Control group did not ($p = 0.93$; $M = 48.84$, $SD = 9.95$; $M = 49.18$, $SD = 9.87$). Furthermore, there was no difference in performance across groups in the assessment prior to the intervention or control sessions ($p = 0.87$). The interaction between assessment and fall status failed to reach significance [$F(1, 72)<1$]. There was no effect of test group [$F(1, 72) = 2.2$, $p = 0.14$], or of fall status [$F(1, 72) < 1$], nor was there an interaction between these factors [$F(1, 72) < 1$]. No other significant interactions were found.

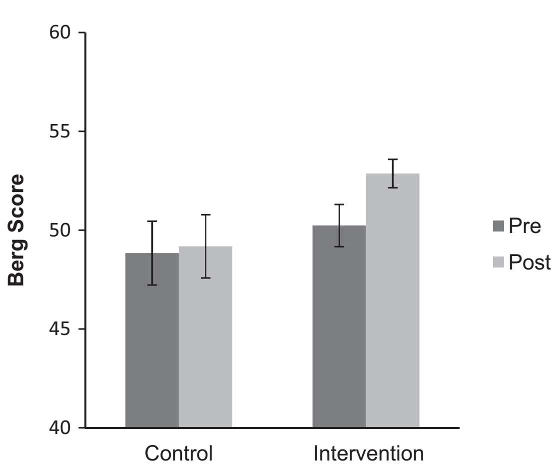

Fig. 1. Plot showing the two-way interaction between test group (Intervention and Control groups) and assessment (pre- and post-the intervention/control sessions) on the mean scores in the Berg Balance test. Error bars indicate ± 1 standard error of the mean.

For performance on the Activities-specific Balance Confidence Scale (ABC) a main effect of assessment [$F(1, 72) = 12.08$, $p < 0.001$] was found, with improvement in ABC score observed from the pre ($M = 74.44$, $SD = 21.59$) to post-assessment ($M = 80.04$, $SD = 16.75$). We failed to find evidence for an interaction between assessment and test group [$F(1, 72) = 2.35$, $p = 0.13$], or between assessment and falls status [$F(1, 72) < 1$]. There was no effect of test group [$F(1, 72) < 1$], or of falls status [$F(1, 72) < 1$], nor any interaction between these factors [$F(1, 72) < 1$]. No other interactions were significant.

An analysis of performance on the Falls Efficacy Scale (FES) revealed no effect of test group [$F(1, 72) = 2.92$, $p = 0.092$] or of falls status [$F(1, 72) = 2.16$, $p = 0.15$]. The main effect of assessment failed to reach significance [$F(1, 72) = 3.47$, $p = 0.067$] although there was a trend for improvement across assessments (i.e. a reduction in the mean score from 23.88 to 20.41 across assessments). All interactions failed to reach significance.

For the static balance test, we found a main effect of assessment [$F(1, 72) = 69.43$, $p < 0.001$], with an overall improvement across assessments from pre- ($M = 53.47$, $SD = 17.36$) to post-intervention/control ($M = 69.0$, $SD = 17.27$). The effect of test group was marginal but failed to reach significance [$F(1, 72) = 3.6$, $p = 0.062$], and there was no effect of falls status [$F(1, 72) < 1$]. There was a significant interaction between test group and assessment [$F(1, 72) = 13.44$, $p < 0.001$], which is shown in Fig. 2a. Post-hoc comparisons using the Tukey HSD test indicated that the static balance score for the Intervention group significantly improved from pre- ($p < 0.001$; $M = 53.19$, $SD = 17.05$) to post-assessment ($M = 75.83$, $SD = 13.67$) as it did for the Control group ($p = 0.01$; $M = 53.75$, $SD = 17.90$; $M = 62.18$, $SD = 17.95$). There was no difference in performance between the groups in the initial assessment ($p = 0.99$). However, following the intervention/control period, the Intervention group performed significantly better than the Control group ($p = 0.003$). All other interactions failed to reach significance [all $F(1, 72) < 1$].

For performance on the dynamic balance test, we found a main effect of assessment [$F(1, 72) = 87.19$, $p < 0.001$], with an overall improvement observed following the intervention/control period. A main effect was found for test group [$F(1, 72) = 8.06$, $p < 0.01$]

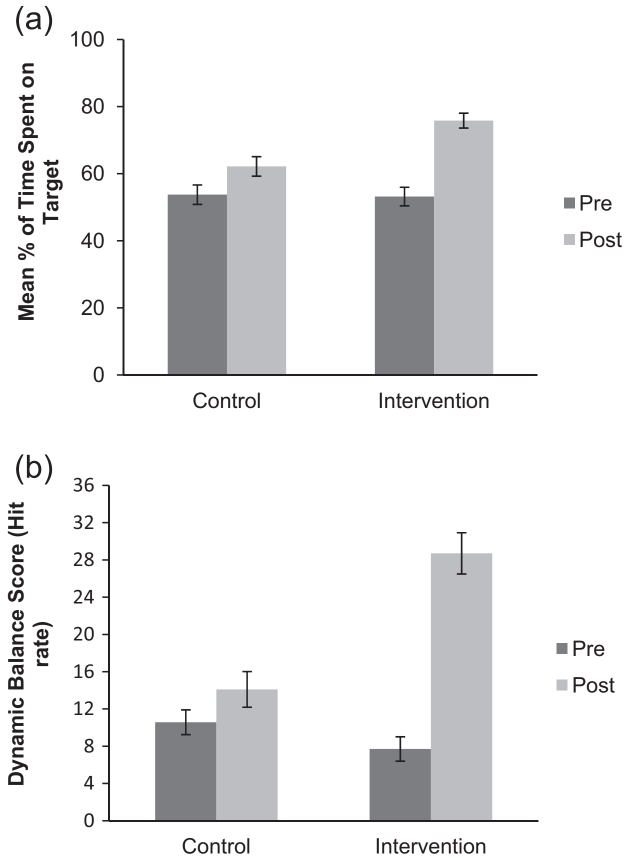

Fig. 2. Plots showing the two-way interaction between test group (Intervention and Control groups) and assessment (pre- and post-the intervention/control sessions) on the mean performance scores for the (a) static and (b) dynamic balance tests. Error bars indicate ± 1 standard error of the mean.

with the Intervention group out-performing the Control group. There was a significant interaction between assessment and test group [$F(1, 72) = 41.62$, $p < 0.001$] which is shown in Fig. 2b. Post-hoc comparisons using the Tukey HSD test indicated that the dynamic balance scores for the Intervention group significantly improved from pre- ($p < 0.001$; $M = 7.71$, $SD = 8.07$) to post-assessment ($M = 28.71$, $SD = 13.65$) whereas the scores for the Control group did not improve ($p = 0.23$; $M = 10.58$, $SD = 8.19$; $M = 14.11$, $SD = 11.80$). There was no difference in performance across groups in the initial balance test ($p = 0.65$), i.e. prior to the intervention/control sessions. However, the Intervention group outperformed the Control group ($p < 0.001$) following the intervention. The 3-way interaction between assessment, test group and falls status failed to reach significance [$F(1, 72) = 3.32$, $p = 0.073$] and all other interactions failed to reach significance [all $F(1, 72) < 1$].

3.3. Assessment of multisensory perception between groups

In our final set of analyses, we wished to assess whether there was any differences across the test groups or the fall-prone and healthy older adults on their susceptibility to the sound-induced flash illusion (Setti et al., 2011; Shams et al., 2000). Note that, consistent with previous literature (see Andersen, Tiippana, & Sams, 2004), when 2 or more stimuli were presented in a trial (i.e. unisensory 2 beeps or 2 flashes, or multisensory 2 flashes/2 beeps) a response indicating ‘2 or more flashes’ (or beeps) was correct. The mean percentage of correct responses across assessments for participants in each group is shown in the supplementary Table A. In order to ensure that the Intervention and Control groups, as well as the fall-prone and healthy older adults, were matched on perceptual function prior to the intervention, we compared the number of correct responses made across groups to the unisensory trials only, (i.e. the auditory-only 1 ‘beep’ or visual-only ‘1 flash’ or ‘2 flashes trials) in the initial assessment phase only. We conducted separate, 2-way between-group ANOVAs with test group and fall status on performance to each of these trial conditions. For the visual-only ‘1 flash’ condition, we found no effect of test group [$F(1, 72) < 1$], or of falls status [$F(1, 72) < 1$] nor any interaction between these factors [$F(1, 72) < 1$]. For performance on the ‘2 flash’ condition, there was no effect of test group [$F(1, 72) < 1$] or of falls status [$F(1, 72) < 1$] .There was a significant interaction between test group and falls status [$F(1, 72) = 6.62$, $p = 0.012$]. However post-hoc comparisons using the Tukey Unequal N HSD test failed to reveal any significant differences in performance between possible pairwise comparisons (all $ps > 0.05$) although there was a trend for fall-prone older adults to perform better than healthy older adults in the Intervention group only ($p = 0.06$). For performance in the auditory-only ‘1 beep’ trials we found no effect of test group [$F(1, 72) < 1$], or of falls status [$F(1, 72) = 1.22$, $p = 0.27$], nor any interaction between these factors [$F(1, 72) < 1$]. A 3-way, mixed ANOVA with test group and fall status as between subject factors and SOA (70 ms, 150 ms and 230 ms) as a within subject factor was performed on performance to the ‘2 beep’ auditory-only trials. Again, we found no main of test group [$F(3, 70) < 1$], nor of falls status [$F(3, 70) < 1$], nor an interaction between test group and faller status [$F(3, 70) = 1.4$, $p = 0.25$]. Taken together, the findings from the unisensory conditions suggest that there were no underlying perceptual differences across the groups, either Intervention or Control, or between the fall-prone or healthy older adults, prior to the intervention/control period.

A between-groups, 2-way ANOVA with test group and fall status as factors was conducted on performance to the ‘1 flash and 1 beep’ condition, which revealed no effects of test group [$F(1, 72) < 1$], or of falls status [$F(1, 72) = 2.24$, $p = 0.14$], nor any interaction between these factors [$F(1, 72) = 1.65$, $p = 0.2$]. A 3-way mixed ANOVA with SOA (70 ms, 150 ms and 230 ms) as a within-subjects factor on the ‘2 flashes, 2 beeps’ condition also revealed no effect of test group [$F(3, 70) = 1.62$, $p = 0.19$] or falls status [$F(3, 70) < 1$], nor was there any interaction between test group and falls status [$F(3, 70) < 1$]. The findings from the analysis of performance on the congruent multisensory conditions prior to the intervention/control sessions also confirmed that there were no underlying differences across the groups. The summary of results can be found in the supplementary Table A.

Prior to assessing whether participants’ susceptibility was affected by the balance training intervention, we first needed to determine that participants experienced the sound-induced flash illusion. If participants were susceptible to this illusion then we would expect more accurate performance to the multisensory congruent than incongruent (i.e. illusory) conditions. We compared performance to the illusory (1 flash with 2 beeps) with the multisensory congruent (2 flashes with 2 beeps) condition, using a mixed ANOVA with test group (Control or Intervention) and fall status (fall-prone or healthy) as between subject factors, and multisensory condition (congruent or incongruent) and SOAs (70 ms, 150 ms and 230 ms[3]) as within-subject factors. We found no effects of test group [$F(1, 72) < 1$], falls status [$F(1, 72) = 1.3$, $p = 0.26$], nor any interaction between test group and falls status [$F(1, 72) < 1$]. The main effect of multisensory condition was significant [$F(1, 72) = 23.17$, $p < 0.001$] with greater accuracy for the multisensory

[3] We found no difference in performance between the negative and positive SOA trials [$t(75) = -1.46$, $p = 0.15$] in the multisensory incongruent conditions, therefore, for all subsequent analyses, we decided to collapse across sequence for the SOA factor.

congruent ($M = 75.66$, $SD = 30.72$) than illusory conditions ($M = 43.38$, $SD = 34.85$). There was an effect of SOA [$F(2, 71) = 10.01$, $p < 0.001$] with better performance for SOA's of 150 ms and 230 ms compared to SOA of 70 ms ($ps < 0.05$) and no difference in performance between SOAs of 150 ms and 230 ms. There was a significant 2-way interaction between condition and SOA [$F(2, 71) = 8.39$, $p = 0.001$] and 3-way interaction between condition, SOA and test group [$F(2, 71) = 4.9$, $p = 0.01$] driven by better performance for the multisensory congruent trials at all SOAs when compared to the illusory trials ($ps < 0.05$). There was no difference, however, between the Intervention groups' performance at SOA 70 ms in the congruent and illusory conditions. All other interactions failed to reach significance. A similar analysis comparing performance to the illusory condition with performance to the congruent '1 flash with 1 beep' condition revealed similar effects but the main effect of multisensory condition was significant [$F(1, 72) = 113.62$, $p < 0.001$] with more accurate performance for the congruent than illusory conditions. Taken together, we were satisfied that participants in our study were susceptible to the SIFI illusion.

Finally, we found no evidence for a difference in susceptibility to the sound-induced flash illusion in the initial assessment phase only (i.e. multisensory incongruent trials). A mixed AVOVA with test group and fall status as between group factors and SOA (70 ms, 150 ms and 230 ms) as a within subject factor, revealed no effect of test group [$F(3, 70) = 1.79$, $p = 0.16$] or of fall status [$F(3, 70) < 1$], although fall-prone older adults ($M = 41.43$, $SD = 33.95$) were not as accurate in this condition than healthy older adults ($M = 44.64$, $SD = 35.95$). There was no interaction between test group and falls status [$F(3, 70) < 1$].

3.4. Training effect on multisensory processing

To assess whether the intervention affected performance in the unisensory conditions, we conducted a series of mixed, 3-way ANOVAs (test group, fall status and assessment) on the unisensory trials (auditory only, '1' or '2' beeps; or visual only, '1' flash or '2' flashes). We found no main effects or interactions on the performance to the '1 beep', '1 flash' or '2 flashes' conditions [all $ps > 0.05$]. Analysis of performance to the auditory only '2 beeps' condition revealed a main effect of assessment [$F(1, 72) = 7.11$, $p = 0.009$] with more accurate performance following ($M = 89.91$, $SD = 15.05$) than preceding ($M = 84.32$, $SD = 19.1$) the intervention/control session. There was no effect of test group [$F(1, 72) < 1$] or of falls status [$F(1, 72) < 1$] nor any interaction between test group and falls status found [$F(1, 72) = 3.31$, $p = 0.07$].

An analysis of the multisensory congruent '1 flash with 1 beep' condition revealed no main effects or interactions. A four-way mixed ANOVA (with test group (2) and falls status (2) as between group factors, and assessment (2) and SOA (3) as within group factors) was conducted on the performance to the multisensory congruent '2 flashes, 2 beeps' condition. This analysis revealed no main effects of test group [$F(1, 72) < 1$], falls status [$F(1, 72) = 2.13$, $p = 0.15$], assessment [$F(1, 72) = 1.61$, $p = 0.21$], nor any interaction between test group and falls status [$F(1, 72) < 1$]. There was an effect of SOA [$F(2, 71) = 24.5$, $p < 0.001$] and a significant interaction between SOA and test group [$F(2, 71) = 3.73$, $p = 0.03$]. Post hoc analyses using the Tukey HSD test revealed this interaction was driven by better performance in the Control group for the SOA of 230 ms compared to SOA of 70 ms. Similarly performance was better in the Intervention group for SOA of 150 ms and 230 ms compared to 70 ms. Performance at the SOA of 70 ms in the Intervention group was also worse when compared to performance in the Control group at SOAs of 150 ms and 230 ms (all $ps < 0.05$) (see Fig. 3).

We hypothesised that participants in the Intervention group would become less susceptible to the illusory conditions across

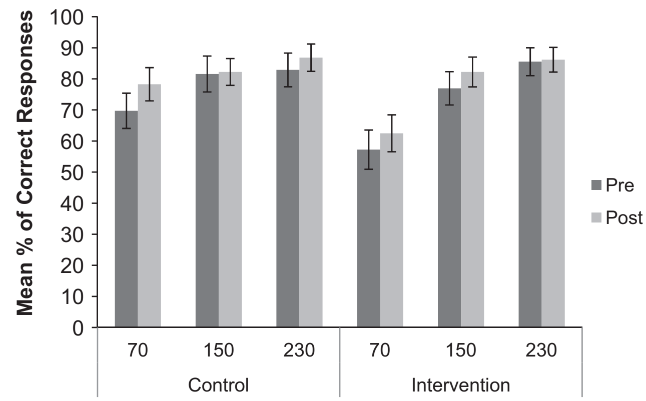

Fig. 3. Plot showing the 2-way interaction between the test group (Intervention and Control) and SOA (70 ms, 150 ms, & 230 ms) on the multisensory congruent '2 flashes with 2 beeps' condition assessments. Error bars indicate ± 1 standard error of the mean.

assessments due to the effect of the balance training on multisensory processing. To that end we conducted a mixed ANOVA on the percentage correct performance with test group (2) and fall status (2) as between-group factors and assessment (2) and SOA (3) as within group factors. Performance across the main conditions of test group, falls status and assessment is shown in Fig. 4. There were no main effects of test group, falls status or assessment found [all *F ratios were* $(1, 72) < 1$]. The main effect of SOA failed to reach significance [$F(2, 71) = 3.04$, $p = 0.054$], although accuracy was better to the 230 ms SOA than either 70 ms or 150ms SOAs. All interactions failed to reach significance. In summary, although we found no evidence for a direct benefit of the balance training intervention on performance in the SIFI, there was a trend for better performance for fall-prone older adults in the Intervention group as their accuracy improved from 36.79 to 52.21 from pre- to post-assessment. To clarify this difference further, we decided to investigate whether there might be any differences in susceptibility to the SIFI depending on whether older adults were living in specialised, sheltered accommodation or were living independently in the community. Although the number of older adults in each of the fall-prone and healthy groups was unmatched (31 fall-prone and 28 healthy living in the community; 3 and 14 respectively living in sheltered accommodation) we nevertheless observed a difference in the mean percentage accuracy to the SIFI between the fall-prone older adults. Performance on the SIFI by the fall-prone older adults from the sheltered accommodation cohort was less accurate ($M = 23.61$, $SD = 6.37$) than that of the fall-prone

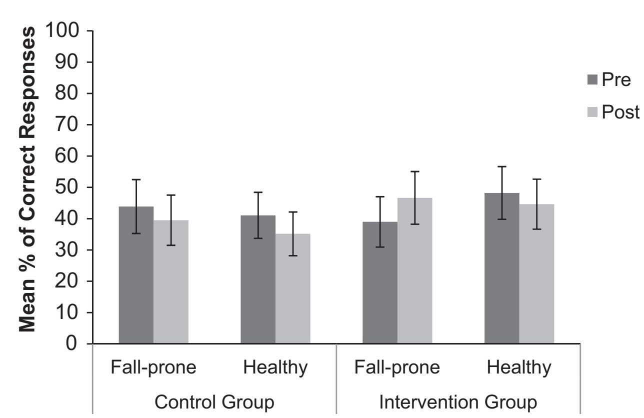

Fig. 4. Mean percentage accuracy in the illusory condition across assessments (pre and post) for each of the test groups according to whether they were fall-prone or healthy older adults. Error bars indicate ± 1 standard error of the mean.

community dwelling older adults (M = 43.16, SD = 35.07). Moreover, the fall-prone older adults performed worse on the SIFI than healthy older adults living in sheltered accommodation (M = 45.54, SD = 34.72), whereas the healthy older adults living in sheltered accommodation performed as accurately as their community dwelling counterparts (M = 44.20, SD = 37.16).

Although we failed to find evidence for a direct change in susceptibility to the SIFI following balance training in the Intervention group as a whole, we wished to ascertain whether there were any associations between the amount of improvement in performance in the balance tests following intervention and a change in susceptibility to the SIFI for any of the fall-prone or healthy participant groups. We therefore tested whether a change in functional balance from the initial to the final assessment, as measured by the standardised 'Berg Balance Scale', was associated with a change in susceptibility to the SIFI using Spearman's correlation. We conducted separate correlations for each of the fall-prone and healthy older adult groups assigned to either the Control or Intervention groups. For the Control group we found no evidence of a correlation between Berg balance score improvement and susceptibility to the SIFI for either the fall-prone [$r(15) = 1.4$, $p = 0.61$], or healthy older adults [$r(19) = -0.102$, $p = 0.66$]. However, for participants assigned to the Intervention group, we found a positive correlation between improved Berg score and improved accuracy to the SIFI in the fall-prone group only [$r(15) = 0.48$, $p < 0.05$]. In other words, this result suggests that as the Berg score improved for the fall-prone older adults following the balance intervention, their susceptibility to the SIFI was reduced (i.e. accuracy increased), and is shown in Fig. 5a. No such correlation was found between these variables for the healthy older adults in the Intervention group [$r(19) = -0.20$, $p = 0.38$], as shown in Fig. 5b. Finally we assessed whether an improvement on any of the other balance measures was correlated with a change in susceptibility to the SIFI for the fall-prone or healthy older adults. We found no evidence of an association between improved balance and SIFI susceptibility for any of the balance measures from the healthy older adults. In contrast, we found that the correlation between improved static balance performance and an increase in accurate performance to the SIFI trials (i.e. reduced susceptibility) for the fall-prone older adults approached significance [$r(32) = -0.33$ $p = 0.055$].

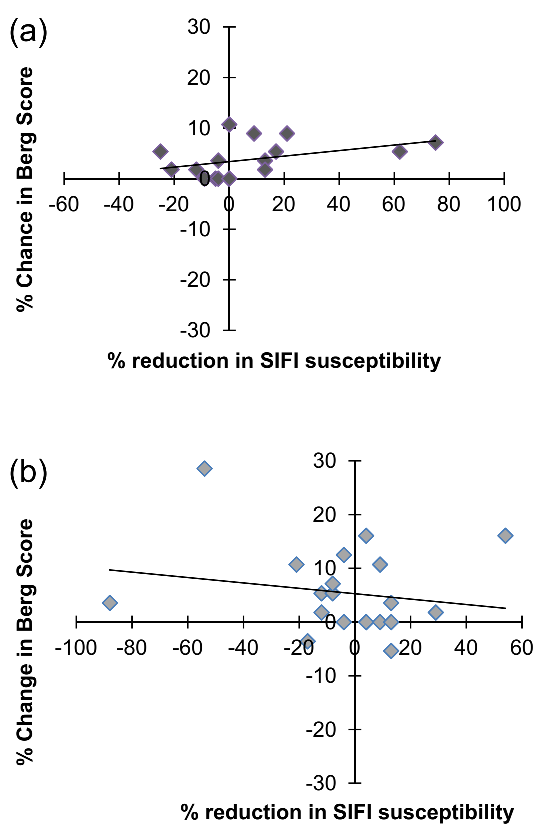

Fig. 5. Plots showing the correlation between the percentage improvement in balance control (i.e. Berg Balance Score) following the intervention and percentage increase in accurate performance (i.e. reduced susceptibility) to the SIFI trials for (a) fall-prone older adults but not for (b) the healthy older adults.

4. Discussion

The present study was designed to investigate whether balance training, based on an intervention using the Wii balance board with custom-built balance game, had an impact on multisensory function in fall-prone older adults. A second aim was to elucidate the relationship between improved performance in balance control and subsequent efficiency in multisensory integration. Firstly, we found that the balance training intervention was successful in improving balance control in older adults in general. Specifically, balance control performance improved based on a range of measurements taken such as the Berg Balance Scale (i.e. a standardised measure of balance function) as well as performance on two, custom-built, tests of static and dynamic balance control. This improvement in both static and dynamic balance control is of particular interest as both tasks are differentiated by the level of fine motor control required as well as the level of anticipation involved. For example, the static balance task relies on the use of fine but precise levels of COM–COP alignment to compensate for very slight, imperceptible changes in posture. In contrast, the dynamic balance task can accommodate higher velocity and more ballistic shifts in balance control. In terms of balance confidence, there were no differences between the test groups or between fall-prone and healthy older adults at either stage of assessment (pre or post the intervention). We noted, however, that most of the older adults scored highly on the balance confidence tasks prior to testing, suggesting that these subjective reports may not be sufficiently sensitive for assessing balance confidence. For example, neither of the fall-prone or healthy older adult groups reported a score of less than 67% on the Activities-specific Balance Confidence Scale, which is a score that is typically indicative of falls risk (Lajoie & Gallagher, 2004).

According to our hypothesis, we expected a reduction in susceptibility to the sound-induced flash illusion in the older adults who successfully completed and improved on the balance training intervention. We found that the test groups did not differ in their performance on either the unisensory trials or multisensory congruent trials prior to the intervention or control sessions. Although performance was poor overall for the '2 flashes' unisensory trials, it is possible that the relatively short SOA between the two visual stimuli (70 ms) led to the perception of one visual flash in the older adults. However, with the exception of this '2 flashes' condition, the mean accuracy scores to the unisensory and audiovisual congruent trials were generally high (see supplemental Table A), suggesting that there was no overall impairment in perceiving multiple stimuli within each modality.

In contrast to our expectation, we found no difference across the control and intervention groups in their accuracy at responding to the SIFI trials at the post- assessment stage. At face value, this finding suggests that that the balance training intervention had no effect on susceptibility to the sound-induced flash illusion. Moreover, guided by previous findings (Setti et al., 2011; Stapleton et al., 2014) we expected that fall-prone older adults would be more susceptible to the illusion than older adults with no history of falling prior to our intervention. However, we found no overall group difference in susceptibility to the illusion across the fall-prone and healthy older adult groups. As previously mentioned, participants were recruited from two sample populations, namely either community dwelling or living in sheltered accommodation. As reported earlier, we observed a difference in susceptibility to the SIFI illusion between these two fall-prone older adult groups, with fall-prone older adults from the sheltered accommodation being more susceptible to the illusory SIFI trials than the fall-prone community dwelling older adults. Thus it would seem that fall-prone older adults who are at greater risk of a repeated fall (i.e. that live in sheltered accommodation) are more susceptible to the sound-induced flash illusion when compared to their community dwelling counterparts. This may suggest a possible benefit for multisensory integration when remaining active in the community in older age despite a history of falls. This observation may merit further research in future experiments.

Although it is unclear why we did not find an overall difference in susceptibility across the fall-prone and healthy older adult groups, there are some possibilities why this may be the case. First, ageing itself is associated with an increase in susceptibility to the sound-induced flash illusion and given that the participants in this study were relatively old (i.e. 74 years of age), the variability in performance with older adults may have concealed any group differences which may otherwise have been present. Moreover, the risk of falls increases with age, therefore it is possible that greater falls-risk, without the occurrence of a fall, may be related to increased susceptibility to the SIFI. Indeed, increased susceptibility to the SIFI is generally found for older adults with a history of falling in which balance function is particularly compromised (see Setti et al., 2011) and group differences are reduced when fall-prone older adults are more high-functioning (see e.g. Stapleton et al., 2014). Furthermore, although a self-reported falls history was recorded for each participant, the categorisation of 'fall-prone' or 'healthy' was conducted without clinical confirmation (although conformed to the clinical literature on fall-prone older adults). It is possible that a more comprehensive, clinical diagnosis of falls risk in each participant may have resulted in differences in the groups to which each participant was allocated. Finally, previous studies investigating susceptibility to the SIFI used a wider range of SOAs (see Setti et al., 2011) than those used in the present study which may have further reduced the possibility of detecting differences across the groups.

The more interesting finding in this study was the relationship between the change in Berg Balance score and change in susceptibility to the sound-induced flash illusion for fall-prone older adults who received balance training. Essentially, as their Berg score improved, their susceptibility to the illusory conditions decreased. This relationship was not observed either for fall-prone older adults assigned to the Control group, or for healthy older adults assigned to either the Control or Intervention groups. This is an important finding as it suggests a link between balance control and multisensory integration in older age, as well as a direct relationship between performance in balance control and the efficiency with which sensory information is integrated. Recent research has attempted to elucidate the relationship between multisensory integration and postural stability (Jeka et al., 2010; Setti et al., 2011; Stapleton et al., 2014). Setti et al. (2011) have demonstrated that fall-prone older are relatively more susceptible to the SIFI, suggesting that the integration of multisensory information from the environment may not be optimal in this particular cohort. This is in line with the findings from other studies on balance reweighting (e.g. Jeka et al., 2010) suggesting that an associated with impaired postural control in older adults which may lead to an increase in the risk of falling. Similarly, Stapleton et al. reported increased susceptibility to the SIFI (i.e. less efficient multisensory integration) in fall-prone older adults while standing relative to a sitting position. Morevoer, postural sway increased for fall-prone older adults when presented with incongruent (i.e. illusory) relative to congruent multisensory stimulation. Also, Mahoney et al. (2014) reported an association with inefficient multisensory integration and reduced unipedal stance time in fall-prone older adults. Taken together, these findings suggest that efficient postural control relies on the successful integration of multisensory inputs and, moreover, that inappropriate integrations of cross-modal information may reduce the ability to maintain postural control. As postural control depends on both the integration of internal cues, such as proprioception or kinaesthesis (e.g. Maurer, Mergner, & Peterka, 2006) and external signals from the environment (e.g. visual, auditory, tactile) the inefficient processing of these cues may lead to a less coherent percept of the environment. As a consequence, perceptual functions relating to balance control may be particularly affected which may, in turn, lead to disorientation and a fall. For example, Barrett et al. (2013) provided evidence to suggest that spatial cognition may be compromised in fall-prone older adults. They found that spatial updating was worse during a navigation tasks for fall-prone older adults, particularly when visual inputs were reduced. Recent studies have also provided growing evidence for the role of multiple sensory inputs into the vestibular system (e.g. Chang et al., 2012) on body awareness (Ferrè, Vagnoni, & Haggard, 2013), balance maintenance (Stapleton et al., 2014) and self-motion (deAngelis & Angelaki, 2012), as well as into the hippocampus for more higher-level tasks such as spatial navigation (see Wolbers & Hegarty, 2010 and Moffat, 2009, for reviews).

The results from the current study are promising as they suggest that an intervention aimed at improving functional balance may also be associated with improving multisensory perception in older adults with a history of falling. Although there is a consistent link between less efficient integration of audio-visual input and incidence of falls in older adults, the results of the present study are consistent with recent findings that postural control relies on the efficient integration of information across multiple sensory modalities. The specific direction of these interactions, and the role of each of the sensory systems on maintaining efficient multisensory integration in older age is not yet known. However, one possibility suggested from the current study, is that the refinement or fine-tuning of visuo-motor control during balance training may positively impact on the temporal dynamics underpinning the integration of information from different sensory systems.. Future research is necessary to elucidate this relationship further, but recent findings on the role of entrainment in neural oscillations (e.g. Henry, Herrmann, & Obleser, 2014) suggest a progression in a positive direction.

5. Conclusions

In sum, our findings suggest an interesting link between improvement of fall-prone older adults' functional balance and improved multisensory integration as measured by performance on the sound-induced flash illusion paradigm. The results suggest that balance training interventions lead to increased postural control as well as more efficient multisensory processing for fall-prone older adults. Further research on the link between balance maintenance and multisensory integration could focus on the design of a balance training intervention that specifically targets audiovisual processing as well as functional balance and may provide an effective intervention in reducing the number of falls in older adults.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.chb.2014.12.017.

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