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RESEARCH ARTICLE

Is inefficient multisensory processing associated with falls in older people?

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Abstract Although falling is a significant problem for older persons, little is understood about its underlying causes. Spatial cognition and balance maintenance rely on the efficient integration of information across the main senses. We investigated general multisensory efficiency in older persons with a history of falls compared to age- and sensory acuity-matched controls and younger adults using a sound-induced flash illusion. Older fallers were as susceptible to the illusion as age-matched, non-fallers or younger adults at a short delay of 70 ms between the auditory and visual stimuli. Both older adult groups were more susceptible to the illusion at longer SOAs than younger adults. However, with increasing delays between the visual and auditory stimuli, older fallers did not show a decline in the frequency at which the illusion was experienced even with delays of up to 270 ms. We argue that this relatively higher susceptibility to the illusion reflects inefficient audio–visual processing in the central nervous system and has important implications for the diagnosis and rehabilitation of falling in older persons.

Keywords Ageing · Falls · Older persons · Cross-modal · Perception · Multisensory · Integration · Temporal window · Balance

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We are continuously exposed to stimulation across our senses; some of which is relevant to the task at hand but most of which is not. The ability to isolate and process appropriate sensory stimulation whilst inhibiting irrelevant stimulation is essential in order to achieve our goals in a timely and efficient manner. However, as we age, it is thought that the inhibition of irrelevant information becomes more difficult (Hasher and Zacks 1988) such that available sensory information is processed more extensively (Poliakoff et al. 2006a). In the following study, we assessed the efficiency with which multisensory integration occurs as a function of ageing and investigated the role of multisensory integration in a particularly debilitating problem common in older people, namely, falling. In particular, we investigated the efficiency of sensory integration across vision and audition, in older adult groups with and without a history of falling.

Epidemiological studies show that falls are a common problem in the older population: 30% of community dwelling older people over the age of 65 years fall each year with 12% of these experiencing recurrent falls (Blake et al. 1988) and the incidence of falls increases with age. Falls are the leading cause of mortality due to injury in people aged over 75 years (O'Loughlin et al. 1993). Falls have been attributed to a decline in function within sensory systems, particularly the vestibular and visual systems, or in other physiological changes associated with ageing such as carotid sinus hypersensitivity and orthostatic hypotension (see e.g. Davies and Kenny 1996). None of these causal factors are exclusive, rather a complex interaction between some, if not all, of them is thought to underpin falls. In particular, the integration of information from across the peripheral senses is important for perceptual tasks in the real world and may be linked to falls (Horak et al. 1989). However, it is perhaps surprising to note that little is understood about the role of multisensory processing in the central nervous system in the context of falls.

Recent studies have shown that the brain is organised to process and combine inputs from multiple senses in a much more extensive way than previously thought (e.g. Driver and Spence 2000; Calvert et al. 2004; Ghazanfar and Schroeder 2006). Combining redundant information across the senses can often lead to better or more robust perceptual performance (Ernst and Bülthoff 2004). Some studies suggest that when stimuli from different modalities are congruent, then the benefit of multisensory inputs to perception is greater in older than younger adults (Laurienti et al. 2006; Peiffer et al. 2007). However, when incongruent inputs from different modalities are combined, then this can result in distractibility and inefficient processing of the relevant stimulus in older adults (Poliakoff et al. 2006a) possibly rendering older adults more accident prone. Very little is known, however, about what contributes to changes in multisensory efficiency as we age.

It is well established that there is a degradation in sensory acuity and unisensory perceptual performance as a consequence of ageing (Willott 1991; Ivy et al. 1992; Fozard and Gordon-Salant 2001; Scialfa 2002; Gordon-Salant 2005; Schieber 2006). Moreover, such deficits are thought to be associated with an increase in susceptibility to a loss of balance and falls (Tromp et al. 2001; Lord 2006; Kulmala et al. 2009; Viljanen et al. 2009) which, in turn, are a frequent cause of permanent injuries or death (Tinetti and Williams 1998). For example, balance maintenance becomes more difficult with ageing (Horak et al. 1989; Tinetti et al. 1988; Allison and Jeka 2004) and impaired vision affects the ability to maintain balance under challenging environmental conditions, such as standing on an unstable surface (Lord et al. 1991; Lord and Menz 2000). Furthermore, older persons who are prone to falls lose their stability more often than older persons without a history of falling (Piirtola and Era 2006; Pajala et al. 2008) particularly when one sensory modality, especially vision, is impaired (Abdelhafiz and Austin 2003).

Maintaining balance does not just dependent on high sensory acuity, however, but may also rely on the efficient integration of information from across multiple senses in the brain such as vision, audition, touch, kinaesthesia and proprioception (Allison et al. 2006). As Peiffer et al. (2007) suggested, if multisensory integration is relatively compromised in older persons with a history of falling, such that task-irrelevant information becomes integrated into the percept, this could provoke distractibility and contribute to an increase in falls. In other words, the integration of sensory information which is not directly related to postural control may have an impact on falls. There is evidence to suggest that multisensory integration affects balance maintenance in fallers, although this is not consistent. For example, the ability to prioritise the respective contribution of vision, vestibular inputs and proprioception which are important for posture stability (Peterka, 2002), known as multisensory reweighting, is thought to decline as a consequence of ageing (Horak et al. 1989) and could be particularly poor in older persons who are prone to falling (Woollacott 2000; Allison et al. 2006). However, Allison and Jeka (2004) found that older people prone to falls showed no sensory reweighting deficit in maintaining balance in a study which involved a manipulation of either the tactile or visual inputs. It is therefore unclear whether sensory acuity alone or multisensory processing per se contributes more to the maintenance of balance.

Several other studies have found evidence that the general processing of events across the different senses is affected by ageing (see De Sanctis et al. 2008 for a review). For example, some studies suggest that healthy older adults combine information from different sensory modalities more than their younger counterparts (Laurienti et al. 2006; Peiffer et al. 2007) which can lead to a decline in perceptual performance when information from different senses is incongruent (Poliakoff et al. 2006a). However, greater reliance on cross-modal interactions can constitute an advantage for older adults when the inputs from different modalities are congruent or redundant (Laurienti et al. 2006; Peiffer et al. 2007; Diederich et al. 2008).

In the present study, we investigated whether the incidence of falling in older adults might be related to a general impairment in multisensory processing. In particular, we assessed whether compromised audio–visual integration, rather than a difference in sensory acuity, characterises fall-prone older adults relative to older adults with no history of falling. To that end, we used a simple audio–visual illusion, known as the sound-induced flash illusion (Shams et al. 2000), to assess audio–visual integration abilities across the three groups of fall-prone, non-fall-prone older adults and young adults. Specifically, this illusion is induced when two auditory stimuli (beeps) presented with a single brief visual stimulus (flash) results in the perception of two visual 'flashes'. It occurs when the two sensory inputs are integrated due to their temporal proximity (Shams et al. 2002) but is unaffected by their spatial proximity (Innes-Brown and Crewther 2009) and it is thought to occur early in the processing stream (Shams et al. 2001; Watkins et al. 2006; Mishra et al. 2008).

This paradigm allowed us to investigate efficient audio–visual integration in conditions that were not challenging for balance maintenance and therefore did not induce inefficient cross-sensory integration due to the higher attentional demands of the task (see Teasdale and Simoneau 2001). This is an important point as our aim was to assess whether fall-prone older adults may suffer from perceptual deficits that could be related to, but are not a consequence of, impaired vestibular-proprioceptive functioning. Moreover, previous findings on age-related effects on multisensory processing (e.g. Poliakoff et al. 2006a), and research on impaired reweighting of multiple sensory inputs (e.g. Woollacott 2000; Jeka et al. 2010) raise the question as to whether multisensory processing per se is affected by ageing and is particularly compromised in individuals with a history of falling.

We therefore compared susceptibility to the sound-induced flash illusion in older fallers, non-fallers and young controls. If balance maintenance and the related incidence of falls are associated with a general impairment in the integration of information across the senses, then we expected less efficient audio–visual integration in fall-prone older adults, i.e. greater susceptibility to the illusion, relative to the healthy or younger adult groups. We manipulated the temporal onset (i.e. stimulus onset asynchrony, SOA) between the auditory beeps (Shams et al. 2002) and measured susceptibility to the illusion in the three groups of participants across different SOAs. By manipulating the SOA, we could indirectly measure differences in the temporal window of integration across the groups. According to previous studies, the temporal window of integration is thought to be larger in older relative to younger adults (Diederich et al. 2008). If multisensory integration is further compromised in older adults who are prone to falling, then we may also expect that a larger temporal window of integration would be evident between these older groups. In other words, we expected that fall-prone older adults would be more susceptible to the sound-induced flash illusion across longer delays between the auditory beeps than either younger or healthy older adults.

Method

Participants

Sixteen young and 32 older participants took part in the experiment. The younger adults (mean age = 24.4, SD = 4, 7 male) were undergraduate and postgraduate students from Trinity College who participated for nominal pay or course credit. All reported normal or corrected-to-normal vision and normal hearing. Older adults were recruited through the Technology Research for Independent Living (TRIL) centre, and all were living independently in the community. The characteristics of this sample have been described in (Romero-Ortuno et al. 2010) and summarised in Table 1. In brief, the TRIL cohort is a convenient sample of self-referred or clinician-referred persons over 60 years of age. All participants underwent a detailed clinical assessment including risk of falls (based on AGS guidelines). Falls risk assessment included a number of events which measured posture control, i.e. Berg balance scale and Timed Up and Go test (TUG); sensory acuity including visual acuity (LogMar test), contrast sensitivity (Pelli-Robson contrast sensitivity chart) and hearing (Hughson Westlake test, Kamplex BA 25 screening audiometer); other measures of frailty including cardiovascular instability (Delta SBP) and grip strength (measured using a hand held dynamometer); medical usage (polypharmacy, 4 or more medications); and cognitive assessment (Mini Mental State Exam, MMSE). None of the participants had history of psychiatric or neurological illness.

We subdivided our older adult participants into two different groups: fallers and non-fallers. Amongst the

Table 1 Characteristics of the older participants in fall-prone and non-fall-prone groups (including standard deviations in parenthesis)

Characteristics of the older sample	Fall-prone older adults ($N = 16$)	Healthy older adults ($N = 16$)	*t* test
Age	72.4 (7.2)	68.7 (5.4)	$P = 0.1$
Vision			
Acuity (logMAR)	0.05 (0.1)	0.05 (0.09)	$P = 0.8$
Contrast sensitivity	1.74 (0.13)	1.73 (0.13)	$P = 0.7$
Hearing range			
Global	Normal	Normal	$P = 0.8$
Frequencies 1,000–2,000–3,000 Hz	18 (10)	17 (13)	
MMSE score	29.1 (1.26)	28.2 (1.18)	$P = 0.06$
Grip strength	44.5 (26.7)	50 (20.1)	$P = 0.5$
Cardiovascular instability			$P = 0.8$
Orthostatic hypotension	$N = 0$	$N = 0$	
Delta SBP	35.2 (17)	36.7 (19.7)	
Polypharmacy	$N = 9$	$N = 6$	$P = 0.4$
Berg Balance test	53.7 (2.46)	55.2 (1.34)	$P = 0.04$
TUG	8.5 (1.74)	7.3 (1.68)	$P = 0.06$

fallers, 7 persons had fallen within 1 year of the testing date, 3 persons were recurrent fallers, 4 had recent falls which were unexplained and 2 had fallen between 2 and 5 years before testing and all required medical attention. Older healthy adults had no history of falls within the past 5 years. Accordingly, we had 16 fall-prone (12 female) and 16 healthy adults (7 female) in the older adult group.

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

Stimuli and apparatus

A visual stimulus consisted of a white disc with a diameter subtending a visual angle of 1.5° and a luminance of 31.54 fl. This disc was projected against a black background and appeared 5° below fixation. The visual stimulus was briefly flashed for 12 ms. An auditory stimulus consisted of a brief burst of 3500 Hz presented for 10 ms (with 1 ms ramp) at 79 dB. Auditory stimuli were delivered through loudspeakers positioned on each side of the monitor at the same height as the fixation cross.

The experiment was conducted on a Dell PC with a Dell Monitor of 21″ CRT and with a refresh rate of 85 Hz. The experiment was programmed and run using shareware software called DMDX (see http://www.u.arizona.edu/~kforster/dmdx/dmdx.htm for further details).

Design

The experiment was based on a 3 × 7 mixed design with participant group (younger, healthy older and fall-prone older adults) and SOA (±30, 70, 110, 150, 190, 230 or 270 ms) as factors. Unisensory and audio–visual congruent conditions were also introduced as control conditions.

Participants were presented with visual-only, auditory-only and audio–visual trials in a randomised order. The visual-only trials consisted of either 1 or 2 flash stimuli. In the auditory-only condition, 2 beeps were presented in succession with an SOA of either 30, 70, 110, 150, 190, 230 or 270 ms. In the audio–visual trials (whether ‘congruent’ or ‘illusory’), an auditory beep was always delivered simultaneously with the (first) visual flash. In the illusory trials, the onset of the second auditory beep could either precede or follow it with a SOA of either 30, 70, 110, 150, 190, 230 or 270 ms. The congruent trials consisted of either 1 flash and 1 beep presented synchronously, or 2 flashes and 2 beeps (same SOA as illusory trials). The illusory or incongruent trials always consisted of 1 flash paired with 2 beeps. Each trial was repeated 4 times, yielding a total of 152 trials.

Procedure

Participants were seated in front of the computer screen with their chin comfortably positioned on a chin rest placed 57 cm from the screen. 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 be presented with brief flashes and beeps and were instructed to report to the experimenter the number of flashes they saw on the screen. If they perceived no flashes (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 flashes. At the end of each trial, the fixation cross disappeared and the participant was instructed to press a response key to initiate the next trial.

The experiment was preceded by a training phase in which participants could repeat the presentation of 10 practice trials 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 entire experiment was self-paced with no emphasis made on the speed of responses. The number of flashes (or beeps) reported was recorded by the experimenter.

Results

In order to ensure that the fall-prone and healthy older adult groups were matched in sensory acuity and cognitive functions, we compared performance across groups in the following variables using unpaired t test analyses: visual acuity, contrast sensitivity, grip strength and MMSE score. These results are summarised in Table 1. We found no difference across the older groups on any of these performance measures. Furthermore, the two groups did not differ in terms of hearing range. Polypharmaceutical medication also did not differ between fall-prone and healthy older adults, and none of the participants had cardiovascular instability. We did, however, find a significant difference on the Berg balance test (Berg et al. 1992) which was as expected: fall-prone older adults performed more poorly than non-fallers (unpaired t test, $P < 0.05$). Furthermore, fall-prone older adults were slower at the TUG test (Podsiadlo and Richardson 1991) than healthy older adults although this difference failed to reach significance (unpaired t test, $P = 0.06$).

For the main experiment, we calculated the mean percentage of correct trials across conditions for each participant, and the averages per participant group are summarised in Table 2. Note that in conditions when 2 or more stimuli were presented (e.g. 2 beeps or 2 flashes or 2 flashes/2 beeps), a correct response was one in which the participant indicated 2 or more flashes (or beeps when flashes were not present) occurred. This coding of responses is consistent with the previous literature (see Andersen et al. 2004).

We first analysed the number of correct responses made to the unisensory auditory-only and visual-only conditions. The mean percentage of correct responses in the auditory-only trials (i.e. 2 beeps) across the different SOAs and in the visual-only conditions are reported in Table 2. Using a mixed, 3 (group) × 7 (SOA) ANOVA on auditory-only trials, we found main effects of group [$F(2.45) = 5.36$, $P < 0.01$] and SOA [$F(6.270) = 60.15$, $P < 0.001$]. On the group effect, a LSD post hoc analysis revealed that younger adults were more accurate than both fallers and non-fall-prone older adults ($P < 0.05$) but older fallers did not differ from non-fallers ($P = 0.28$). On the SOA effect, a LSD post hoc analysis revealed that participants were less correct when the SOA between the beeps was 30 ms than all other SOAs ($P < 0.01$). We also found a significant interaction between group and SOA [$F(12,270) = 6.55$, $P < 0.001$] and a post hoc LSD analysis indicated that younger participants were more accurate than both fallers and healthy older groups, at the shorter SOA only (30 ms) but not at any of the longer SOAs. There was no significant difference between fallers and non-fallers for any of the SOAs.

For the visual-only conditions, separate one-way between-participants ANOVAs revealed no difference in accuracy performance across the groups for the ‘1 flash’ condition [$F(2,45) = 0.7$, $P = 0.5$] but an effect of group for the ‘2 flashes’ condition [$F(2,45) = 7.51$, $P < 0.01$]. Post hoc LSD analyses revealed that performance in the younger adults was more accurate than both older adult groups (Ps < 0.01); there was no difference in performance between the fall-prone and healthy older adult groups ($P = 0.41$). In summary, performance in the unisensory conditions was best in the younger adult group; however, we found no difference in unisensory performance across the two older adult groups.

We then compared performance across groups to the incongruent trials. Based on a comparison between performance to the 1 flash with 1 beep (AV congruent) and 1 flash with 2 beeps (AV incongruent) conditions, we determined that all participants experienced the illusion in that they failed to correctly report the number of visual flash stimuli present in a trial when more auditory beep stimuli were also presented. Accuracy was greater in the audio–visual congruent trials than the incongruent trials for

Table 2 Percentage (%) of correct responses in younger, non-fall-prone and fall-prone adult groups across each of the unisensory and multisensory conditions in the experiment (including standard deviations in parenthesis)

Experimental conditions	Younger (%)	Non-fallers (%)	Fallers (%)
Unisensory conditions			
Visual (1 flash)	98 (6)	92 (21)	92 (19)
Visual (2 flashes)	92 (17)	60 (33)	50 (41)
Auditory (2 beeps) per SOA *(in ms)*			
30	81 (32)	31 (42)	25 (36)
70	100	78 (35)	90 (25)
110	100	86 (30)	98 (6)
150	100	92 (25)	96 (8)
190	100	95 (18)	98 (6)
230	100	90 (25)	97 (8)
270	100	92 (25)	98 (6)
Multisensory conditions			
Congruent (1 flash, 1 beep)	100	98 (6)	100
Congruent (2 flashes, 2 beeps)	83 (16)	68 (29)	80 (17)
Incongruent (1 flash, 2 beeps) per SOA *(in ms)*			
30	66 (36)	81 (33)	77 (38)
70	54 (29)	55 (40)	37 (39)
110	77 (29)	56 (42)	25 (36)
150	82 (19)	57 (45)	27 (36)
190	88 (27)	63 (44)	26 (39)
230	91 (17)	60 (44)	26 (42)
270	96 (9)	62 (42)	30 (43)

the young adults [$t = 5.93$, $P < 0.001$], healthy older [$t = 4.13$, $P < 0.001$] and fall-prone [$t = 7.62$, $P < 0.001$] older adults.

We assessed whether the three groups of participants differed in the amount of illusions experienced across both the negative SOAs (i.e. when one of the auditory stimuli occurred before the simultaneous auditory–visual event) and the positive SOAs (i.e. when one of the auditory stimuli occurred after the simultaneous auditory–visual event). The proportion of correct responses across all SOAs and participant groups is shown in Fig. 1. We conducted a $3 \times 2 \times 7$ mixed ANOVA on the average proportion of correct responses with Group (young, healthy older and fall-prone older adults), sequence of stimuli (A/V–A; V–A/A) and SOA (30 ms; 70 ms; 110 ms; 150 ms; 190 ms; 230 ms; 270 ms) as factors. We found main effects of Group [$F(2,45) = 8.59$, $P < 0.001$] and SOA [$F(1,6) = 8.31$, $P < 0.001$], but no effect of the sequence of stimuli [$F(1,45) = 0.39$, $P = 0.53$]. The only significant interaction was between the Group and SOA factors [$F(6,270) = 8.47$, $P < 0.001$]. There were no interactions between any of the factors and the sequence of stimuli.

Post hoc analyses (LSD tests) on the main effect of Group revealed that fall-prone older adults provided fewer correct responses, (i.e. more illusory responses), than the younger ($P < 0.001$) or healthy older adult ($P = 0.02$) groups. The difference between the overall number of correct responses made by the younger adults and healthy older adults was not significant ($P = 0.11$). A post hoc analysis (LSD test) on the main effect of SOA revealed that more accurate responses (i.e. a higher number of correct '1 flash' responses) were provided when the SOA was 30 ms than when the SOA was longer. Furthermore, responses were more accurate at the SOA of 70 ms than 190 ms or longer (all Ps < 0.01). The relatively high proportion of correct responses when the SOA was 30 ms was probably due to the difficulty in discriminating the two beeps with such a short delay especially in older adults; therefore, it appears not to be due to a lack of audio–visual integration but to an inability to perceive a distinction between the beeps.

We then examined the interaction between participant group and SOA more closely. Planned comparisons showed that fallers were significantly less correct (i.e. more susceptible to the illusion) than non-fallers, at SOAs of 110 ms [$P = 0.01$], 150 ms [$P = 0.02$], 190 ms [$P = 0.007$], 230 ms [$P = 0.01$], and 270 ms [$P = 0.01$]. At the SOAs of 30 and 70 ms, the difference in performance between faller and non-faller groups was not significant [$P = 0.7$ and $P = 0.1$ for the respective SOAs] nor was the difference significant between the faller and younger groups [$P = 0.2$]. The performance of the faller group was significantly worse than that of the younger adult groups at the longer SOAs of 110 ms, [$P < 0.001$], 150 ms [$P < 0.001$], 190 ms [$P < 0.001$], 230 ms [$P < 0.001$] and 270 ms [$P < 0.001$]. Moreover, healthy older adults were significantly less accurate (i.e. more susceptible to the illusion) than younger adults at SOAs of 150 ms [$P < 0.05$], a trend at 190 ms [$P = 0.06$], 230 ms [$P = 0.02$], and 270 ms [$P = 0.009$] but not at SOAs of either 30 ms [$P = 0.2$] or 70 ms [$P = 0.9$].

Finally, we compared performance across the participant groups to the audio–visual congruent trials incorporating single cross-modal or double cross-modal stimuli (see Table 2). When a single visual flash was presented

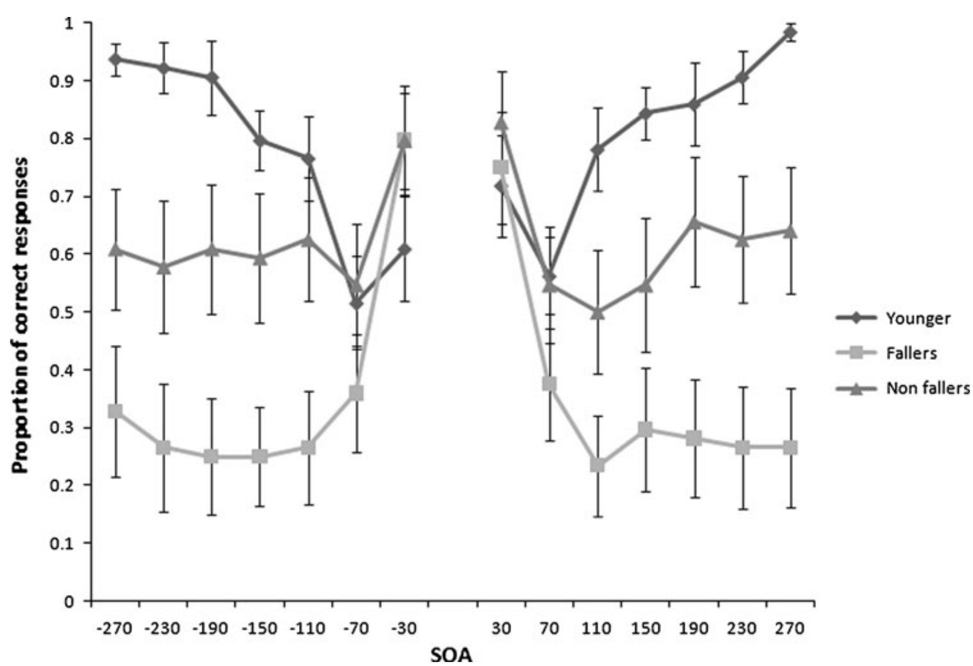

Fig. 1 Proportion of correct responses across the different SOAs for each of the three participant groups: younger, older non-fall-prone and older fall-prone in the incongruent conditions. Negative SOAs indicate a sequence of stimuli A–V/A, positive SOAs indicate V/A–A. *Error bars* indicate ± 1 standard error of the mean. A high score indicates that participants responded correctly, i.e. they perceived 1 flash even when presented with 2 beeps. A low score indicates that participants experienced a high amount of illusions

with a single auditory beep (1 flash, 1 beep), the accuracy across the young, healthy older and fall-prone older adults was not significantly different [$F(2,45) = 1$, $P = 0.4$]. When two visual flashes were presented with two auditory beeps, the difference in accuracy found across groups was also not significant [$F(2,45) = 2.13$, $P = 0.13$].[1]

Discussion

In the present study, we compared three groups of participants, fall-prone and healthy older adults and young adults, on the susceptibility to a sound-induced flash illusion (Shams et al. 2000). We found that, in accordance with the findings of Shams et al. (2002), susceptibility to the illusion was maximal at 70 ms SOA for young participants and decreased with an increase in the onset delay between auditory beeps from an SOA of 110 ms such that they were no longer susceptible to the illusion at a SOA of 270 ms. In contrast, healthy older adults did not show as much of a decrease in the frequency at which the illusion was experienced as the young participants from 70 to 270 ms, although the two groups overall did not statistically differ in the amount of illusion experienced. Importantly, the number of illusions experienced by fall-prone older adults was greater than for healthy older and young adults, and the number of illusions they experienced was unaffected by the onset delay between the auditory beeps from 70 to 270 ms.

These findings suggest that the temporal window of audio–visual integration for fall-prone older adults is wider than that of healthy older or younger participants. In contrast to young adults who experienced the illusion more often with an SOA of 70 ms than with longer SOAs, the pattern of illusions experienced by fall-prone older adults was not associated with a systematic decrease with longer SOAs. Fall-prone older adults were least susceptible to the illusion at 30 ms SOA but susceptibility increased from 70 ms over longer delays between the onset of the auditory beeps. Notably, the number of illusions experienced by fall-prone older adults for SOAs between 110 and 270 ms was significantly greater than the number experienced by their healthy counterparts.

Although the results of previous studies suggest that deficiencies in parsing information from across different senses (Peiffer et al. 2007; Hugenschmidt et al. 2009), or in the reweighting of information across sensory information linked to posture control, could lead to distractibility and contribute to an increase in the risk of falls (Woollacott 2000), a deficit in audio–visual integration in older persons who are fall-prone had not hitherto been shown, particularly not in situations where balance control was not involved. Our findings that fall-prone older persons are more susceptible to an AV illusion than healthy age-matched and young adults suggest that they may have a general deficit in the duration of the temporal window of integration, which may be linked to a risk of falls in older adults.

Previous studies have suggested that poor vision and auditory deficits may be linked with the incidence of falls (Tromp et al. 2001; Lord 2006; Kulmala et al. 2009; Viljanen et al. 2009). We therefore selected a sample of participants with relatively good hearing and vision for their age in order to be able to assess inefficiency in multisensory integration which was unrelated to the relative differences in the reliability of the sensory input. Since our older adult groups were matched on sensory acuity (see Table 1), we would argue that the higher susceptibility to the illusion in fall-prone compared to healthy older adults cannot be accounted for by a difference in unisensory acuity in the peripheral nervous system across the two older groups. It may, however, be reasonable to assume that the difference between the number of illusions experienced by older adults in general, relative to younger adults, may be related to changes in sensory acuity that can decline as a function of ageing (e.g. Fozard and Gordon-Salant 2001). This sensory decline in older adults may then result in weaker or noisier sensory input which may, in turn, increase the number of perceptual illusions. This may occur as a consequence of what is known as the law of inverse effectiveness (Stein and Meredith 1993) in which multisensory integration is enhanced when unisensory information is relatively noisy or unreliable. Moreover, given that the difference between the older groups is on multisensory rather than unisensory processing, it suggests that these differences reside in the processing of information across the senses within the central nervous system and not the peripheral system.

The causes behind inefficient multisensory processing as a consequence of ageing are not well established (Laurienti et al. 2006). We suggest that older participants may rely more on multisensory integration for everyday perceptual tasks because of the (putatively ‘superadditive’) gain to perception from integrating across multisensory events when unisensory information is noisy (Stein and Meredith 1993). Since cross-sensory inputs are usually associated with redundant information in the real world, i.e. cross-sensory information originating from the same object or event source, the perceptual system may increasingly rely on multisensory integration for robust perception as unisensory information becomes more degraded (e.g. Ernst and Bülthoff 2004). It may be the case that, as older people

[1] Interestingly, in line with previous research [e.g. Laurienti et al. 2006] we found a benefit for congruent multisensory over uni-sensory stimulation on performance in the older fall-prone adults only [$F(2.45) = 5.08$, $P < 0.05$].

increasingly rely more on multisensory processing for robust perception, the limits of the spatial and temporal window of integration become less fixed. As a consequence, irrelevant information can become integrated leading to inefficient perception when cross-sensory inputs are from discrete sources in the environment.

It is not clear why fall-prone older adults seem to rely more on multisensory inputs than their healthy counterparts. Since there are no differences in unisensory perception across the groups, both could be said to have equivalent time resolution within each modality. Consequently, their deficit is likely to be specific to cross-modal temporal processing per se (see Andersen et al. 2004), rather than related to perception within each modality (Fitzgibbons and Gordon-Salant 1998; Ulbrich et al. 2009). For example, other research has found that older people in general are characterised by a larger window of integration across the senses (Diederich et al. 2008), have difficulties in cross-modal temporal discrimination (Poliakoff et al. 2006b) and have higher susceptibility to processing irrelevant (cross-sensory) background inputs (Hugenschmidt et al. 2009). These problems may be exacerbated in fall-prone individuals as shown in the present study.

We can speculate that there may be either an indirect or a direct effect of a wider temporal window of integration on balance maintenance and posture control. Indirectly, balance can be challenged by the processing of irrelevant sensory information due to the extended temporal window. A wide literature, namely on dual-tasking, shows that the balance system, despite relying on visual, proprioceptive and vestibular inputs, is permeable to other cognitive and perceptual variables that are not strictly part of the system (e.g. Lajoie et al. 1993; Woollacott and Shumway-Cook 2002; Hausdorff et al. 2008; Beauchet et al. 2009). If irrelevant stimuli are automatically processed by the central nervous system during balance control, this sensory confusion may detract the necessary attentional resources from the balance task. Some studies have shown that maintaining balance and walking are not independent from attentional demands (Woollacott and Shumway-Cook 2002). This hypothesis could be tested by assessing the susceptibility to the illusion in challenging balance conditions or whilst walking (see Dingwell et al. 2008).

Alternatively, balance could be directly impacted by a change in sensory reweighting over time. Sensory reweighting requires each source of sensory information to be assigned a certain weight. An extended window of integration may be related to a persistent reliance on an unreliable sensory input over time or a delayed response to the change in the sensory inputs (see Jeka et al. 2010). The assessment of such a relationship between the senses represents a challenge due to the temporal processing differences of the sensory modalities (Barnett-Cowan and Harris 2009).

In sum, in the present study, we found that older adults with a history of falling integrated audio–visual stimuli over a longer delay between the onset of cross-sensory stimulations than either older adults without a history of falling or younger adults. Specifically, fall-prone older adults experienced higher overall rates of the sound-induced flash illusion at longer SOAs (from 110 to 270 ms) than non-fallers. The older adult groups were not significantly different in age, sensory acuity and cognitive abilities; however, they were not sex matched which may constitute a limitation in our results. Although previous studies suggest sex differences in multisensory processing, these studies have a spatial component that is absent in our study (Kennedy et al. 1996; Darlington and Smith 1998; Viaud-Delmon et al. 1998; Barnett-Cowan et al. 2010; Cadieux et al. 2010). In a separate analysis, we found no evidence that performance differed across the sexes or that the sex of the participant interacted with their fall status; therefore, we have no reason to assume sex difference in temporal processing of audio–visual information in our task. Future work, involving larger participant numbers, will help confirm this point. Importantly, we used a task which did not challenge balance maintenance in that all participants were comfortably seated throughout the task; therefore, the deficit in multisensory integration that has been found here is unlikely to be ascribed to a deficit in functioning of the proprioceptive or vestibular systems. This is not to say that there is no relationship between a multisensory integration deficit (as assessed by the sound-induce flash illusion), and balance maintenance. As mentioned earlier, for example, it is possible that faulty allocation of attentional resources in early perceptual processing leads to less efficient multisensory perception which could, in turn, contribute to a loss of balance in older individuals. Further studies are needed to elucidate the association between poor multisensory, particularly audio–visual integration and balance maintenance.

Interestingly, we found no differences in performance across the participants in either unisensory processing or on the overall perception of congruent audio–visual events. Therefore, we suggest that the differences found in multisensory processing between the older adult groups reside in differences in processing in the central, not peripheral, nervous system. If these differences reside in the central nervous system, then this means that impaired multisensory integration should be amenable to rehabilitative training (Powers et al. 2009; Mozolic et al. 2009) as the older brain maintains some plasticity (Grady 2008). Furthermore, impaired audio–visual integration could constitute an early biomarker for a risk of falling and a modifiable risk factor for falls prevention in older persons.

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