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Visual-Somatosensory Integration and Balance: Evidence for Psychophysical Integrative Differences in Aging

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Abstract

Research detailing multisensory integration (MSI) processes in aging and their association with clinically relevant outcomes is virtually non-existent. To our knowledge, the relationship between MSI and balance has not been well-established in aging. Given known alterations in unisensory processing with increasing age, the aims of the current study were to determine differential behavioral patterns of MSI in aging and investigate whether MSI was significantly associated with balance and fall-risk. Seventy healthy older adults ($M = 75$ years; 58% female) participated in the current study. Participants were instructed to make speeded responses to visual, somatosensory, and visual-somatosensory (VS) stimuli. Based on reaction times (RTs) to all stimuli, participants were classified into one of two groups (MSI or NO MSI), depending on their MSI RT benefit. Static balance was assessed using mean unipedal stance time. Overall, results revealed that RTs to VS stimuli were significantly shorter than those elicited to constituent unisensory conditions. Further, the current experimental design afforded differential patterns of multisensory processing, with 75% of the elderly sample demonstrating multisensory enhancements. Interestingly, 25% of older adults did not demonstrate multisensory RT facilitation; a finding that was attributed to extremely fast RTs overall and specifically in response to somatosensory inputs. Individuals in the NO MSI group maintained significantly better unipedal stance times and reported less falls, compared to elders in the MSI group. This study reveals the existence of differential patterns of multisensory processing in aging, while describing the clinical translational value of MSI enhancements in predicting balance and falls risk.

Keywords

Multisensory integration; sensory processing; aging; balance; falls

1. Introduction

Integrative processing of simultaneous sensory information has gained increasing attention over the past few decades. Much of the current research in the field focuses on investigating the complexities of processing simultaneous sensory information given that individuals are

constantly required to integrate information across multiple sensory domains. Multisensory researchers argue that our senses are specifically designed to process simultaneous sensory inputs across multiple modalities in a concerted manner in order for information to be identified correctly and responded to appropriately (Calvert, 2004). Efficient integration of visual, somatosensory, and auditory information would appear to be critical for functional independence and successful completion of activities of daily living in our multisensory world. Yet, research delineating the clinical utility of integrative effects across the lifespan is quite scarce.

To date, the majority of human multisensory integration (MSI) investigations have been conducted on healthy young adults (Fort *et al.*, 2002; Foxe *et al.*, 2002; Giard and Peronnet, 1999; Molholm *et al.*, 2002, 2004; Murray *et al.*, 2005; Schurmann *et al.*, 2002; Senkowski *et al.*, 2006). Empirical studies examining multisensory differences between old and young adults are limited, but there is evidence for increased multisensory integrative processing in older adults (see Freiherr *et al.*, 2013 for review). Specifically, using a forced-choice discrimination task, Laurienti *et al.* (2006) revealed RT facilitation to multi-sensory audio-visual stimuli compared to unisensory stimuli in both young and old adults, where multisensory integration effects were significantly greater in old relative to young adults, even after adjusting for age-related differences in speed of processing (Salthouse, 1985, 1996). Peiffer *et al.* (2007) similarly investigated AV integration effects in both young and old adults using a simple reaction time task and revealed significantly greater multisensory integration effects for old compared to young adults. However, results from our investigation examining the differential effects of audio-visual (AV), audio-somatosensory (AS) and visual-somatosensory (VS) multisensory processing revealed that older adults exhibited the greatest multisensory RT facilitation when presented with concurrent VS information (Mahoney *et al.*, 2011).

While greater multisensory RT enhancements for old relative to young adults have been reported, the behavioral or clinical implications behind such increased integrative effects have yet to be identified. Research detailing the clinical relevance of multisensory processing has just recently begun to emerge (Meyer and Noppeney, 2011; Wallace, 2012); however, many of these investigations have been conducted in patients with disorders or syndromes where sensory processing is typically affected (Brett-Green *et al.*, 2010; Cascio *et al.*, 2012; Foxe *et al.*, 2012; Russo *et al.*, 2010). While these studies discuss discrepancies in multisensory processing compared to healthy controls, little effort has been expended investigating the clinical consequences of differential multisensory processes and how such integrative processes differ with increasing age. Therefore, many important questions remain unanswered including: do older adults integrate simultaneous information similarly, are greater multisensory effects actually beneficial to older adults, and is MSI associated with everyday physical activities important for functional independence, including but not limited to balance? While the translational value of MSI with physical activities in aging is understudied, we and others have linked MSI to cognitive activities including attentional cueing in older adults (Hugenschmidt *et al.*, 2009; Mahoney *et al.*, 2012).

With normal aging comes a decline in sensory processing. Unisensory impairments in visual or somatosensory processing have been linked to various adverse health behaviors including

slower gait speed (Kaye *et al.*, 1994), functional decline (Laforge *et al.*, 1992), increased risks of falls (Camicioli *et al.*, 1997; Judge *et al.*, 1995; Lord and Ward, 1994; Lord *et al.*, 1999), and worse quality of life in aging (Carabellese *et al.*, 1993). Declines in mobility, including gait speed and gait adaptation, ultimately lead to increased falls and are common in older adults (Holtzer *et al.*, 2006; Verghese *et al.*, 2002, 2009a, b, 2011; Verghese and Xue, 2010). Findings from the Berlin Aging study demonstrate that declines in sensory, cognition and motor functioning are increasingly correlated in old adulthood and suggest that a common underlying neural mechanism (i.e., ‘common cause’) is likely responsible for such age-related differences (Baltes and Lindenberger, 1997; Lindenberger and Baltes, 1994).

To our knowledge, only a few studies have reported associations of inefficient MSI with history of falls (Setti *et al.*, 2011) and balance (Stapleton *et al.*, 2014) in older adults. In the former, fall prone older adults were more susceptible to an AV illusion task, while in the latter fall-prone older adults with inefficient AV integration demonstrated marked body sway compared to healthy age-matched adults. Collectively, these findings as well as findings from the Berlin Aging study (Baltes and Lindenberger, 1997; Lindenberger and Baltes, 1994), highlight the critical link between sensory integration processes and balance control in older adults. However, we argue that successful integration between visual and somatosensory systems is likely more essential for behaviors like balance maintenance, as supported by evidence from early multisensory training studies of balance in older adults (Hu and Woollacott, 1994a, b). Given known age-related declines in both sensory and balance systems, and the overlap between neural systems responsible for MSI and balance maintenance, the overarching goal of the current experiment was twofold. Here, we aimed to (1) examine whether differential integrative processes exist in older adults by comparing RT facilitation effects of individuals in the lowest quartile (i.e., those with lowest or no integration effect) to RT facilitation effects from the rest of the sample and (2) develop the clinical translational value of MSI enhancements in balance maintenance and risk of falls.

2. Material and Methods

2.1. Participants

Seventy older adults (mean age 75.09 ± 6.29 years; 57% female) recruited from the Central Control of Mobility in Aging (CCMA) study at the Albert Einstein College of Medicine in Bronx, NY, participated in the current study. CCMA study procedures have been previously described (see Holtzer *et al.*, 2014, in press). Of the 70 participants, 64 were right-handed as assessed by the Edinburgh handedness inventory (Oldfield, 1971). Potential participants were identified from a population list of lower Westchester county, NY, and were first contacted *via* mail and then by telephone inviting them to participate. A structured telephone screening interview was administered to all potential participants to assess for study eligibility. Briefly, eligibility criteria required that participants be 65 years of age and older, reside in lower Westchester county, and speak English. Participants were required to see, hear, and feel all sensory stimuli at appropriate levels (see Section 2.3 below). Exclusion criteria included inability to independently ambulate, presence of dementia, significant loss of vision and/or hearing, current or history of neurological or psychiatric disorders, recent or

anticipated medical procedures that would affect mobility, and/or receiving current hemodialysis therapy. Given known alterations in unisensory processing with increasing age, the aim was to determine differential patterns of MSI in older adults, thus no healthy young control group was recruited for the present study. All participants provided written informed consent to the experimental procedures, which were approved by the institutional review board of the Albert Einstein College of Medicine.

2.2. Cognitive and Disease Status

All study participants took part in an initial telephone screening session where medical and psychological history was acquired by a research assistant to ensure appropriateness for the study. Presence of dementia was excluded using reliable cut scores from the AD8 Dementia Screening Interview (cutoff score = 2; Galvin *et al.*, 2005, 2006) and the Memory Impairment Screen (MIS; cutoff score < 5; Buschke *et al.*, 1999) and later confirmed using consensus clinical case conference procedures (see Holtzer *et al.*, 2008a). Standardized tests included in our clinical neuropsychology battery have been validated in previous studies of this aged population (Holtzer *et al.*, 2006, 2007, 2008b; Masur *et al.*, 1994; Sliwinski *et al.*, 1997). Additionally, we assessed global cognitive status using the Repeatable Battery for Assessment of Neuropsychological Status (RBANS). The RBANS is a brief cognitive test with alternate forms that measures immediate and delayed memory, attention, language, and visuo-spatial abilities, and also provides a total index score (Duff *et al.*, 2008).

Global disease summary scores (range 0–10) were obtained from dichotomous rating (presence or absence) of diabetes, chronic heart failure, arthritis, hypertension, depression, stroke, Parkinson's disease, chronic obstructive pulmonary disease, angina, and myocardial infarction (see also Holtzer *et al.*, 2006, 2008b; Mahoney *et al.*, 2010, 2011; Verghese *et al.*, 2007).

2.3. Sensory Screening Procedures and Neurological Examination

All participants were required to successfully complete a sensory screening exam, where visual, auditory, and somatosensory acuity were formally tested to ensure appropriateness for the study. All participants had visual acuity that was better or equal to 20/70 as measured by the Snellen eye chart. A computerized tone-emitting otoscope that delivered lateral and bilateral 20, 25, and 40 dB tones at 500, 1000, 2000, and 4000 Hz using E-prime 2.0 software (PST Psychology Software Tools, Inc., Pittsburgh, PA, USA) was employed to assess hearing loss; where individuals that were unable to hear a 2000 Hz tone at 25 dB in both ears were not included in the study. In terms of the somatosensory screening, participants received a pulse of 30 V that was gradually increased in voltage by 5 V in order to determine each individual's minimal bilateral threshold of sensory detection; this threshold was operationally defined as the minimum level of voltage necessary for each participant to feel equal stimulation in their left and right fingers at a level that was not painful (see Mahoney *et al.*, 2011, 2012).

All study participants received a comprehensive neurological exam as part of the CCMA study. For the present study, assessment of neuropathy and history of falls data were included. Presence and absence of neuropathy in hands was collected *via* self-report from

the study clinician; however, participants were only included in the study if results from the neurological exam confirmed absence of significant neuropathy in hands. Data for presence or absence of falls was also collected *via* self-report as participants were asked 'Have you fallen in the past year?'. If the participant endorsed a fall, further information regarding the number of falls and whether an injury was sustained from each fall was collected.

2.4. Stimuli and Task Procedures

Participants were seated comfortably in a well-lit room and required to look at a fixation point (a black cross measuring 0.5×0.5 cm) visible on the center of the display (see Fig. 1a). The viewing distance was set at 57 cm and the stimulus field was 38×30.5 degrees of visual angle. The background field luminance was 105 cd/m^2 . Participants' arms were rested on a table and their hands were about 60 cm apart, symmetrical about the vertical meridian. Reaction time and accuracy were collected as participants performed a simple RT task by pressing a foot pedal located under their right foot as quickly as possible in response to all stimuli, regardless of sensory condition.

Participants responded to three different sensory conditions (unisensory visual (V), unisensory somatosensory (S) and multisensory VS; see Fig. 1b) that were presented in random order with equal frequency using E-prime 2.0 software. Stimuli were presented in three blocks of 45 trials (15 trials per condition type), yielding a total of 45 trials per condition (see Fig. 1c). The inter-stimulus interval (ISI) varied randomly from 1.0 to 3.0 s to avoid anticipatory effects. The V stimuli were bilateral black asterisks presented for 100 ms on a 17" computer monitor, which were 0.64 cm in diameter and had a luminosity of 253.99 cd/m^2 . Bilateral unisensory S pulses were produced from a constant voltage linear isolated programmable stimulator (Biopac Systems, Inc., www.biopac.com) that delivered 100 ms pulses at a custom voltage (individually adjusted to a comfortable level for each participant) to electrodes placed symmetrically on both the left and right index or middle fingers (depending upon any pre-existing nerve or skin damage at time of testing).

2.5. Distinguishing Differential MSI Effects

Since a gold standard for defining MSI effects is currently lacking, we discuss main MSI effect approaches below and then describe the rationale and method used to investigate MSI in the current study. Stein and Meredith assessed multisensory interactions or MSI effects by measuring the magnitude of differences in neuronal activation between summed unisensory conditions and simultaneous conditions (Meredith and Stein, 1986). Foxe and others asserted that this methodology will not be sensitive to areas of purely multisensory convergence wherein responses to two sensory modalities might occur, but would sum linearly (Engel *et al.*, 2012; Foxe *et al.*, 2002; Senkowski *et al.*, 2008). Others have employed a magnitude of response estimate to measure MSI, where the response to the maximal unimodal response (M) is subtracted from the combined multisensory response (C), divided by M , and multiplied by 100 ($[(C - M)/M * 100]$; see Meredith and Stein, 1986). This approach has been validated and is well received in measuring differences between uni- and multisensory neural activation (Engel *et al.*, 2012; Lim *et al.*, 2011; Meredith *et al.*, 2012; Perrault *et al.*, 2005; Wallace *et al.*, 2006).

In the case of psychophysical data, MSI researchers prefer to test for integrative processes using cumulative probability (CP) models. That is, when two sources of sensory information (e.g., a visual cue and somatosensory pulse) are presented concurrently, they offer redundant signals that give rise to faster detection responses. This phenomenon is referred to as a redundant signals effect (RSE; Kinchla, 1974). Two very distinct models can be implemented to explain a RSE: race models and co-activation models (Miller, 1982). In race models, when two information sources are presented concurrently (e.g., a multisensory stimulus), the signal from the information source that is processed the fastest is the signal that produces the response (i.e., the ‘winner’ of the race). However, co-activation models are supported when reaction times (RTs) to multisensory stimuli are faster than would be predicted by race models. In the latter case, the RT facilitation is accounted for by interactions that allow signals from redundant information sources to integrate or combine non-linearly. Nonetheless, tests developed to assess race model violations are inherently controversial (Eriksen *et al.*, 1989; Mordkoff and Yantis, 1991) as they have been referred to by some as conservative (Gondan *et al.*, 2004; Miller, 1986) and have inherent limitations like assumptions about independence between unisensory processes (Colonius and Diederich, 2006; see also Mahoney *et al.*, 2011).

To circumvent these various limitations, a more conventional test of the race model as outlined by Colonius and Diederich (2006) was employed in the current study: $R_{XY} = P(RT_{XY} - t) - \min[P(RT_X - t) + P(RT_Y - t), 1]$. For any latency, the race model holds when the CP value of the multisensory condition (*actual* CP) is less than or equal to the sum of the CP values from each of the unisensory stimuli or the *predicted* CP. The model places an upper limit of one on the *predicted* CP of reaction time (RT) for the constituent unisensory stimuli. When the *actual* CP value is greater than the *predicted* CP value, the result of this inequality is a positive value which is indicative of a violation of the race model.

We and other researchers have also investigated behavioral MSI effects in older adults by comparing RTs to simultaneous multisensory conditions to averaged unisensory RTs (Mahoney *et al.*, 2011, 2012; see also Mozolic *et al.*, 2012; Peiffer *et al.*, 2007). However, this methodology is likely not sensitive to individual differences in integrative processes. In the current study, we aimed to identify whether differential patterns of multisensory processing exist in older adults using RT data. Here, we examined mean RT to unisensory V and unisensory S conditions and compared the shorter of the two unisensory RTs to the multisensory VS condition on an individual basis. RT facilitation effects were computed by subtracting RT to the VS condition from the shorter of the two unisensory RTs. Each of the seventy participants was classified into one of two groups; those that demonstrated a RT benefit to multisensory stimulation (MSI group) and those that did not (NO MSI group). Specifically, we compared RT facilitation effects of individuals in the lowest quartile (i.e., those with no or very low integration) to RT facilitation effects from the rest of the sample. The cutoff for the lowest quartile was equal to 8.1 ms. Of the 18 individuals in the NO MSI group, 10 individuals demonstrated negative RT facilitation effects where RTs to S stimuli were faster than RTs to VS stimuli, whereas the other eight individuals had positive RT facilitation effects where RTs to VS stimuli were not materially different from RTs to S stimuli (range 3–8 ms shorter). If however, the participant demonstrated a RT facilitation

greater than 8.1 ms, the person was said to exhibit a MSI effect. Individuals in the MSI group were further sub-classified into either a MSI: Soma or MSI: Visual subgroup, based on the shorter of the two unisensory RTs. Actual and predicted cumulative probability distribution waveforms were subsequently plotted by MSI classification to further corroborate existence of differential MSI patterns in this elderly sample.

2.6. Static Balance

Static balance was assessed using unipedal stance time, a measure of balance that requires individuals to balance their body weight with one foot on the ground for a maximum of 30 s (Hurvitz *et al.*, 2000, 2001). Unipedal stance time is a widely used clinical test of balance; poor scores on this test have been associated with presence of neuropathy (Hurvitz *et al.*, 2001) and predicts falls (Hurvitz *et al.*, 2000) in the elderly. This test was administered twice and the mean unipedal stance time in seconds served as the outcome measure.

2.7. Statistical Approach

2.7.1. Differential MSI Patterns—Mean RTs to unisensory visual, somatosensory, and multisensory VS conditions were group averaged. As previously mentioned (see Section 2.5), each individual was classified into a MSI or NO MSI group based on their individual RT profiles. Participants in the MSI group were further subdivided based on their most efficient unisensory performance (e.g., either somatosensory or visual).

Individual RTs were recorded for each trial and only accurately detected trials were analyzed. Trials with RT responses that exceeded ± 2 standard deviations from the individual mean of each participant were excluded as outliers. As in our previous studies, trials with RTs < 100 ms were also excluded from the analysis as they were not considered to be physiologically plausible responses (Mahoney *et al.*, 2011, 2012). The mean percentage of excluded trials was less than 5% across all three sensory conditions.

Repeated-measures ANOVA examined whether significant differences in RTs existed across the three sensory conditions in the overall sample. Huynh–Feldt corrections were used when appropriate. Simple contrast analyses were used to determine the differential effects of multisensory stimulus processing by comparing the RT of the multisensory condition to the RTs of the constituent unisensory conditions (i.e., V and S conditions) across all participants.

Two additional repeated-measures ANOVAs were implemented to assess the integrity of the differential MSI processing patterns across the elderly sample. As a confirmatory analysis, a second ANOVA was implemented to test for significant differences in RT between MSI classifications (NO MSI vs. MSI) with a within-subject factor VS stimulation type (V, S, or VS). A third ANOVA tested for significant differences in RT between the two MSI sub-classifications (MSI: Soma vs. MSI: Visual) with a within-subject factor VS stimulation type (V, S, or VS). Again, simple contrast analyses were used to determine the differential effects of multisensory stimulus processing and Huynh–Feldt corrections were used when appropriate.

2.7.2. Test of the Race Model—RTs were sorted in ascending order by stimulus condition and then averaged on an individual basis. For each participant, the RT range within the valid RTs was calculated across the three stimulus conditions and quantized into twenty bins from the fastest RT (or zero percentile) to the slowest RT (hundredth percentile) in 5% increments (0%, 5%, ..., 95%, 100%). Differences between *actual* CP distributions [$P(RT_{XY} - t)$] and *predicted* CP distributions [$\min[P(RT_X - t) + P(RT_Y - t)]$] were calculated across each time bin across all participants (see also Colonius and Diederich, 2006; Mahoney *et al.*, 2011); where values greater than zero are indicative of race model violation, providing support for multisensory integrative processes. Differences between *actual* CP distributions and *predicted* CP distributions were plotted for each MSI group and sub-classification.

2.7.3. MSI and Balance—One-way ANOVAs were used to examine differences in unipedal stance time by MSI classification (NO MSI *vs.* MSI). Significant differences were further examined using linear regression analysis. Hierarchical regression analyses were performed with unipedal stance time as the dependent variable, and the MSI sub-classification as the independent variables in Step 1 (unadjusted model). Additional covariates were entered in a stepwise manner. In Step 2, age, gender, and ethnicity were added as independent variables. In Step 3, voltage, neuropathy, visual acuity, and global health status were added as independent variables. All data analyses were run using IBM's Statistical Package for the Social Sciences (SPSS), Version 20.0 (2011). Additionally, a chi-square analysis was conducted to determine whether older individuals within MSI classifications exhibited differential fall risks.

3. Results

3.1. Demographics

Seventy older individuals (mean age 75 ± 6.09 years; 40 female) participated in the current experiment. None of the participants met criteria for dementia using established clinical consensus case-conference procedures (Holtzer *et al.*, 2008b). All participants were deemed relatively healthy as determined by their global health status (Holtzer *et al.*, 2006; see Holtzer *et al.*, 2008b; Mahoney *et al.*, 2010; Verghese *et al.*, 2007). Table 1 delineates other demographic information including but not limited to mean education level (in years), Global Health Score, RBANS total score, Geriatric Depression Scale (GDS; Yesavage *et al.*, 1982) score, Beck Anxiety Inventory (BAI; Beck *et al.*, 1988) score, mean voltage of somatosensory probe, overall RT in milliseconds (ms), and mean unipedal stance time (s).

3.2. MSI Results by Classification

The current task required participants to quickly press a foot-pedal in response to both unisensory and multisensory stimulation (see Section 2.4 and Fig. 1 for details). In total, participants received 135 randomly presented trials and their RT per trial was recorded in milliseconds (ms). Overall, participants maintained 85% accuracy for the somatosensory trials, 87% accuracy for the visual trials, and 90% accuracy for the VS trials. Individuals in the NO MSI ($n = 18$) group maintained 88% accuracy for the somatosensory trials, 89% accuracy for the visual trials, and 90% accuracy for the VS trials, while individuals in the

MSI group ($n = 52$) maintained 84% accuracy for the somatosensory trials, 87% accuracy for the visual trials, and 91% accuracy for the VS trials. Nonetheless, performance accuracy between individuals in the NO MSI vs. VS MSI group were not materially different for somatosensory trials ($p = 0.16$), visual trials ($p = 0.45$), or multisensory VS trials ($p = 0.76$) when examined using simple t -tests. In terms of RTs, mean values (with SEM bars) to the multisensory VS condition are displayed next to the constituent unisensory conditions for convenience in Fig. 2.

The first ANOVA tested for the overall MSI effect across all 70 participants. The within-subject factor was sensory condition (unisensory V, unisensory S, and multisensory VS). Results indicated a main effect of sensory condition ($F(2, 68) = 147.47, p < 0.001$). Simple contrast analyses were used to further understand the significant main effect and revealed that mean RTs to multisensory VS stimuli were significantly shorter than mean RTs to visual ($F(1, 69) = 629.34, p < 0.001$) and somatosensory ($F(1, 69) = 66.87, p < 0.001$) stimuli; also see Fig. 2, first set of bars.

Results from the second repeated-measures ANOVA, a test run as a confirmatory analysis to determine whether MSI groups were indeed performing differently, revealed a significant main effect for sensory condition ($F(2, 68) = 161.12, p < 0.001$) and MSI classification ($F(1, 68) = 18.79, p < 0.001$). Additionally, the interaction of sensory condition $\times$ MSI classification was also significant ($F(2, 68) = 21.15, p < 0.001$). Simple contrast analyses revealed a robust MSI effect, where mean RT to VS stimuli was significantly shorter than mean RTs to visual ($F(1, 68) = 502.26, p < 0.001$) and somatosensory ($F(1, 68) = 34.47, p < 0.001$) stimuli; however, this difference varied based on MSI classification. That is, participants in the MSI group had significantly shorter mean RTs to VS stimuli than to visual ($F(1, 51) = 434.76, p < 0.001$) and somatosensory ($F(1, 51) = 110.29, p < 0.001$) stimuli, whereas participants in the NO MSI group demonstrated mean RTs to somatosensory stimuli that were not materially different than the mean RTs to the multisensory VS stimuli ($F(1, 17) = 1.17, p = 0.29$; see Fig. 2, second set of bars).

A third ANOVA aimed to examine the integrity of the MSI effect based on most efficient unisensory performance. Results revealed a main effect for sensory condition ($F(2, 50) = 160.09, p < 0.001$) and for MSI sub-classification ($F(1, 49) = 18.95, p < 0.001$); where participants in the MSI: Soma group demonstrated significantly more robust MSI effects than those in the MSI: Visual group. Additionally, the interaction of sensory condition $\times$ MSI sub-classification was significant ($F(2, 50) = 55.01, p < 0.001$). Simple contrast analyses further revealed a robust MSI effect, where mean RT to VS stimuli was significantly shorter than mean RT to visual ($p < 0.001$) and somatosensory ($p < 0.001$) stimuli, with the shortest unisensory RT varying by sub-classification (see Fig. 2, panel b).

3.3. Race Model Results

Cumulative probability (CP) distributions across all time bins are plotted in Fig. 3 for *actual* CP [$P(RT_{XY} < t)$] (dashed lines) and *predicted* CP distributions [$\min[P(RT_X < t) + P(RT_Y < t)]$] (solid lines), with the top tier depicting the actual and predicted CP values for the overall sample ($n = 70$). The second tier illustrates the actual and predicted CP values for individuals in the NO MSI group ($n = 18$, left panel) and individuals in the MSI group ($n =$

52, right panel). Note the clear waveform differences in these two MSI classifications, where in the case of the NO MSI group the predicted CP values are always greater than the actual CP values, whereas in the case of the MSI group the actual CP values are mainly greater than the predicted CP values. The third tier illustrates the actual and predicted CP values for individuals in the NO MSI group ($n = 18$, left panel: purposefully duplicated), the MSI: Soma group ($n = 40$, middle panel), and the MSI: Visual group ($n = 12$, right panel). Here, the main difference lies between the MSI sub-classifications, with individuals benefiting the most from visual inputs demonstrating larger differences between actual and predicted CP values. The difference waveforms between actual and predicted CP distributions are depicted in Fig. 4 by MSI classification and sub-classification. Here, positive values represent a violation in the race model (i.e., support for multisensory integrative processing).

Behavioral results from this study indicate that the race model was indeed violated for the overall sample (Fig. 4 — gray dashed line). In order to determine the reliability of each violation, one-way ANOVAs were conducted for each of the first five time bins after 0 (i.e., first 25% of all RTs) and Bonferroni corrections were applied to adjust for multiple comparisons. Significant race model violation was obtained for the MSI group (see Fig. 2). A trend for statistical significance ($p = 0.06$) was obtained for the overall group. However, any violation of the race model (value greater than zero) is indicative of the existence of coactivation.

In terms of the MSI classifications, individuals in the NO MSI group did not demonstrate a violation of the race model (Fig. 4 — black line). Here, negative values support the race model, suggesting that the response to the multisensory event was merely triggered by the fastest unisensory RT which the reader will recall was in response to the somatosensory input. However, individuals in the MSI group (gray line), including MSI: Soma (black dashed line) and MSI: Visual (black dotted line) sub-classifications, reliably violated the race model over the first 30% of all RTs at the $p < 0.05$ level.

3.4. Balance and MSI Classification

Mean unipedal stance time for the overall sample, as well as stance time by MSI classification and sub-classification, is listed in the last row of Table 1. A one-way ANOVA revealed significant differences in mean unipedal stance time between MSI classification (NO MSI vs. MSI; $F(1, 69) = 9.51, p < 0.01$). Results from the hierarchical regression are presented in Table 2. Mean unipedal stance time for individuals in the NO MSI group was 22 s (± 11), while mean unipedal stance time for individuals in the MSI group was 13 s (± 11). In the unadjusted model (1), MSI classification was a significant predictor of mean unipedal stance time ($\beta = 0.35, p < 0.01$). The MSI classification remained a significant predictor of mean unipedal stance time, even after controlling for age, gender, ethnicity, voltage level, visual acuity, neuropathy, and global health score in models 2 and 3 ($\beta = 0.29, p < 0.01$).

3.5. Fall History and MSI Classification

Given the finding that older adults in the NO MSI group manifested longer unipedal stance times compared to older adults in the MSI group, we wanted to further explore the relationship of MSI classification with fall history. A chi-square analysis was conducted to determine whether older individuals in the NO MSI group exhibited less falls than older adults in the MSI group. Results revealed that only 3 of the 18 (17%) older adults in the NO MSI group had reported a fall, whereas 22 of the 52 (42%) older adults in the MSI group had reported a fall. This difference was significant ($\chi^2 = 3.83$; $p = 0.05$).

4. Discussion

Results from the current experiment reveal that overall, older adults were significantly faster at responding to the VS multisensory conditions compared to the constituent unisensory stimuli. These results are consistent with other multisensory behavioral findings for young (Harrington and Peck, 1998; Molholm *et al.*, 2002; Murray *et al.*, 2005; Pavani *et al.*, 2000) and old adults (Laurienti *et al.*, 2006; Mahoney *et al.*, 2011; Peiffer *et al.*, 2007). The significant redundant signals effect subsequently violated the race model, confirming that the effect could not be accounted for by simple probability summation. Collectively, these results reveal a significant VS RT facilitation effect for simultaneously presented visual and somatosensory stimulation in a well characterized sample of non-demented older adults.

4.1. MSI in Aging

Multisensory research in young adults has shown clearly that sensory information is simultaneously gathered in the brain and integrated in a parallel, not serial, manner (Harrington and Peck, 1998; Molholm *et al.*, 2002; Murray *et al.*, 2005; Pavani *et al.*, 2000). To date, however, much of the research examining multisensory processing in aging remains under-developed. Nonetheless, studies have reported that older adults demonstrate multisensory enhancement effects across various sensory pairings that are greater than their younger counterparts (Diederich *et al.*, 2008; Hugenschmidt *et al.*, 2009; Laurienti *et al.*, 2006; Mahoney *et al.*, 2011; Peiffer *et al.*, 2007; Stephen *et al.*, 2010). As previously reported, Laurienti and colleagues reported greater AV RT facilitation effects in old compared to young adults using AV stimuli (Laurienti *et al.*, 2006; Peiffer *et al.*, 2007). Results from our recent investigation (Mahoney *et al.*, 2011) examining the differential effect of AV, AS and VS multisensory processing in young and old adults also revealed that older adults exhibit greater RT facilitation effects than young adults across three multisensory pairings. Moreover, results also revealed that the greatest multisensory RT benefit for older adults occurred when concurrent VS information was presented. Yet, the notion of whether greater RT facilitation (i.e., MSI) effects are actually beneficial is not known, as it could be the case that older adults simply require increased RT facilitation to maintain adequate sensory functioning.

In the limited extant of multisensory experiments conducted on older adults, the effect of MSI has been attributed to basic degenerative changes in neuronal architecture during the aging process. However, this speculative interpretation has yet to be empirically tested in older adults. Given that compensatory models of aging suggest that alternate brain networks

are recruited to help older adults compensate for age-related differences (Stern *et al.*, 2005), it could be argued that increased multisensory RT facilitation in older adults might be a compensatory process used to overcome age-related physiological declines in unisensory processing; however, such a notion needs to be tested empirically in future studies.

4.2. MSI Effects and Classifications

In the current experiment, we argue that comparing RTs to simultaneous multisensory VS conditions to averaged RTs to V and S conditions (see Mahoney *et al.*, 2011, 2012; Mozolic *et al.*, 2012; Peiffer *et al.*, 2007) would be insensitive in identifying individual differences in integrative processes since the averaged RT likely represents an inflated unisensory RT. Here, rather than manipulating the unisensory RT data and then subsequently subtracting the RTs to the multisensory data to create an ‘MSI proxy’ term, we implement a data-driven classification procedure to identify differential MSI processing patterns. Inspection of the individual datasets revealed the presence of three MSI patterns, which included: (1) NO MSI pattern ($n = 18$) — where RTs to somatosensory stimuli were not materially different from RTs to VS stimuli; (2) MSI pattern based on somatosensory stimulation ($n = 40$) — where RTs to visual stimuli were longer than RTs to somatosensory stimuli, which were both longer than RTs to VS stimuli; and (3) MSI pattern based on visual stimulation ($n = 12$) — where RTs to somatosensory stimuli were longer than RTs to visual stimuli, which were both longer than RTs to VS stimuli. Given known alterations in unisensory processing with increasing age, the existence of differential patterns of multisensory processing based on the individual’s most resilient unisensory system was not surprising.

Statistical analyses conducted on the mean RTs to the V, S, and VS conditions within each of the three classifications revealed three independent and reliable MSI patterns in this well-characterized elderly sample. The intensity of the differential MSI patterns was best illustrated by their subsequent race model violations, or in the case of the NO MSI pattern—race model acceptance (see Fig. 4). In the NO MSI group, the response to the multisensory event was merely triggered by the fastest unisensory RT which was in response to somatosensory information, where the concurrent visual information was of little to no help in facilitating the multisensory response. Given the nature of the simple RT task and the fact that simple stimulus detection occurs at relatively early processing stages, generalized cognitive slowing cannot account for differences in multisensory integration here (Mahoney *et al.*, 2011; Peiffer *et al.*, 2007; Yordanova *et al.*, 2004). Nevertheless, two independent samples t -tests tested for significant differences in overall RT between (1) the NO MSI group and the MSI: Soma group and (2) the NO MSI group and the MSI: Visual group — where overall RT was equal to the average RT across all valid V, S, and VS stimuli. Results revealed that individuals in the NO MSI group demonstrated significantly shorter overall RTs than individuals in the MSI: Soma ($t = -3.40$; $p < 0.001$) and MSI: Visual ($t = -9.08$; $p < 0.001$) effect groups even after controlling for multiple comparisons (see Fig. 5).

In the current experiment, 25% of older adults did not benefit from receiving simultaneous 100 ms presentations of visual (bilateral asterisks presented on a computer screen) and somatosensory stimuli (bilateral electrical pulses on their index or middle fingers). It appears that individuals in this group were so sensitive and quick at responding to the tactile

stimulation, that there simply was not enough time for the coincident visual information to be processed and efficiently integrated with the somatosensory information, leaving little to no room for RT improvement from combined visual information. Thus, their RTs to the VS stimuli were equal to their RTs to the S stimuli.

Perhaps it is inaccurate to make a blanket statement that older adults in this group do not benefit from MSI; but rather more appropriate to posit that, 25% of older adults did not benefit from simultaneous VS stimulation using the current V and S stimulation. Given that the RT distribution to the S stimuli was equal to the RT distribution to the VS stimuli and more positively skewed than the RT distribution to the V stimuli, there was likely no overlap in unisensory RT distributions. Thus, visual information was clearly not beneficial in facilitating the behavioral response to the VS stimuli for the elders in this MSI classification.

4.3. MSI Classifications and Balance: Implications for Daily Functioning for Elders

Declines in sensory, cognitive and motor functioning are increasingly correlated in aging and suggest that a common underlying mechanism is likely responsible for these negative age-related differences (Baltes and Lindenberger, 1997; Lindenberger and Baltes, 1994). Given known age-related declines in both sensory and balance systems, we deemed it necessary to determine the translational value of MSI enhancements in predicting balance maintenance. Results from the current study revealed a significant association of MSI classification (NO MSI vs. MSI) with mean unipedal stance time even after controlling for many important covariates. Further, our results revealed a significant difference between fallers and non-fallers across MSI classifications; where only 17% of older adults in the NO MSI group reported a previous fall, and 42% of older adults in the MSI group reported a previous fall. Our results are in line with findings from Setti and colleagues where inefficient audio-visual MSI was associated with falls (Setti *et al.*, 2011) and balance (Stapleton *et al.*, 2014); however, note that our operational definition of inefficient MSI is different from that of Setti and colleagues. Here, we argue that larger differences in RTs between responses to multisensory VS and the fastest unisensory RT represent inefficient integration for older adults, where the former studies operationalize inefficient MSI based on increased susceptibility to an AV illusion. Nevertheless, given the reported link between sensory and motor processes, one possible explanation for the current finding is that participants with faster RTs, especially faster somatosensory RTs, are more sensitive and therefore quicker to respond to fluctuations in important balance signals, making them less likely to fall; however, further research is clearly warranted.

Taken together, these results indicate that those older adults that maintain very fast RTs, so fast where integrative processes are not able to actually be beneficial, also maintain better balance and are less vulnerable to falls. In fact, this subgroup of individuals with very short RTs maintains behavioral performance that is comparable to that reported in younger adults. It is already known that RT facilitation effects are reportedly less for young as compared to old adults (Laurienti *et al.*, 2006; Mahoney *et al.*, 2011; Mozolic *et al.*, 2012; Peiffer *et al.*, 2007) and that younger adults maintain better balance and less history of falls than older adults. Thus, perhaps it is not unreasonable that the older individuals in the NO MSI group demonstrate better balance and report less falls. Nonetheless, future studies should be

conducted across the adult lifespan to determine whether differential MSI patterns exist regardless of chronological age. Overall, our findings that increased MSI enhancements in older adults is associated with worse balance and increased risk of falls, clearly demonstrate the clinical utility of intact sensory processing mechanisms with everyday activities. Further, if MSI is indeed a compensatory mechanism, it could play a critical role in supporting existing functions that are comprised due to age-related declines.

4.4. Future Directions and Conclusions

We believe that multisensory integration is an integral aspect of functioning and mobility in the real world. Successful MSI requires intact cortico–cortico and cortico–thalamic connections (Schroeder and Foxe, 2004) that likely overlap with connections involved in successful motor functioning. The finding that older adults with less MSI enhancement maintain better balance and report less falls provides evidence for the clinical-translational utility of MSI in aging. Specifically, findings from the current study could be utilized to help identify opportunities to introduce MSI programs, incorporating simple RT enhancement strategies, to improve balance and reduce fall risk in older adults; however, future research is necessary to determine whether such transfer effects would be viable.

Further investigations are clearly warranted to better understand the biological basis of the aging process as it relates to VS RT facilitation. It will be important to determine whether there are protective factors that support appropriate MSI enhancement levels in the elderly, which could in turn ensure better clinical outcomes important for functional independence including, but not limited to gait and cognition. Hence, future studies are necessary to identify the psychophysical, as well as functional and anatomical correlates of differential MSI processing patterns in aging. Additionally, investigations that aim to determine the associations of MSI with other outcome measures in aging could potentially prove to be paramount from a public health perspective.

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a. Apparatus: **b. Sensory Conditions:** **c. Sequence of Events:** **Figure 1.**

Experimental procedures. (a) Apparatus: Participants rested hands comfortably on a table while maintaining fixation on the computer screen, and were required to make speeded responses to all stimuli, regardless of sensory modality, by pressing a foot pedal located under their right foot. (b) Sensory conditions: Participants received bilateral visual (V), bilateral somatosensory (S), and bilateral multisensory VS stimulus conditions. (c) Sequence of events: Three blocks of V, S, and multisensory VS stimuli (45 trials per block) were randomly presented with random inter-trial-intervals (ITIs) of 1–3 s.

Figure 2.

Averaged reaction time (RT) data by modality. (a) Mean RT values (with SEM bars) for V, S, and VS by multisensory integration (MSI) classification. The first set of bars demonstrates the mean RT values for the overall sample ($n = 70$), where RTs to the VS stimuli are significantly shorter compared to RTs of the constituent unisensory stimuli. The next set of bars depicts the mean RT values for the 18 participants that did not demonstrate an MSI effect (see Section 2.5); where there is no meaningful difference between the mean RT to somatosensory alone condition *versus* the mean RT to multisensory VS condition. The third set of bars illustrates the mean RT values for the 52 participants that demonstrated a MSI effect; overall there is a degradation of mean RT length, where RTs to visual stimuli were longer than RTs to somatosensory stimuli, which were both longer than RTs to multisensory VS conditions. (b) The last two sets of bars in the large dashed rectangle represent the mean RTs of the two MSI sub-classifications, where the first set of bars depicts mean RT values for the MSI: Soma group ($n = 39$) and the second set of bars depicts mean RT values for the MSI: Visual group ($n = 12$).

Cumulative Probability Models by MSI Classification

Figure 3.

Cumulative probability model results. Actual (dashed line) and predicted (solid line) cumulative probability values over percentiles by MSI classification and sub-classification. For convenience, results for the NO MSI classification are repeated on the third tier (dashed box).

Figure 4.

Results of Miller's test of the race model. The cumulative probability difference waves (actual minus predicted probability) over the trajectory of averaged responses for each MSI classification and sub-classification. The shaded grey box represents the fastest quartile of RTs (i.e., 25th percentile). Values greater than zero indicate violations of the race model.

Figure 5. Overall Reaction Time (RT) by MSI Classification. Mean RT in milliseconds (with SEM bars) for the NO MSI and MSI groups.

Table 1

Participant demographics

	Overall	NO MSI	MSI	MSI: Soma	MSI: Visual
Sample size	70	18	52	40	12
Age (years)	75.09 (6.29)	73.39 (6.05)	75.68 (6.32)	75.70 (6.29)	75.61 (6.69)
Education (years)	14.76 (3.42)	14.06 (2.39)	15.00 (3.71)	15.00 (3.62)	15.00 (4.15)
Global Health Scale Score (0–10)	1.06 (0.99)	1.06 (0.94)	1.06 (1.02)	1.13 (1.11)	0.83 (0.56)
% female	57	61	56	58	50
% Caucasian	86	89	85	88	75
% with neuropathy	14	22	12	13	8
% moderate visual impairment (Snellen of 20/70 or worse)	3	0	4	5	0
% right handed	92	95	89	93	83
RBANS total score (SS)	95.00 (12.40)	96.61 (10.39)	94.33 (13.07)	94.18 (13.15)	94.83 (13.38)
Geriatric Depression Scale — 30 item	4.71 (4.21)	5.44 (4.60)	4.77 (4.17)	4.68 (4.48)	4.75 (3.41)
Beck Anxiety Inventory — 21 item	4.59 (5.77)	5.17 (6.96)	4.33 (5.49)	4.50 (6.00)	3.75 (3.44)
Voltage (V)	78.00 (20.68)	80.28 (25.00)	77.31 (19.19)	79.00 (17.77)	71.67 (23.29)
Overall RT (ms)	336.26 (75.26)	277.68 (37.64)	356.53 (74.57)	335.63 (67.57)	426.20 (52.06)
Mean unipedal stance time (0–30 s)	15.32 (11.50)	21.42 (11.62)	13.21 (10.78)	13.84 (10.97)	11.08 (10.31)

Mean values ($\pm$ SD) unless otherwise noted.

Table 2

Summary of linear regression model for predicting mean unipedal stance time (s)

Model	Coefficients						
	Unstandardized coefficients			Standardized coefficients			Sig.
	B	Std. error	Beta				
1 MSI classification	-8.21	3.01	-0.31	-2.73	0.01	-14.21	-2.21
2 MSI classification	-6.43	2.75	-0.25	-2.34	0.02	-11.92	-0.93
Age	-0.83	0.19	-0.45	-4.27	0.00	-1.22	-0.44
Gender	0.15	2.43	0.01	0.06	0.95	-4.70	4.99
Ethnic	3.02	3.44	0.09	0.88	0.38	-3.85	9.89
3 MSI classification	-6.73	2.81	-0.26	-2.39	0.02	-12.36	-1.10
Age	-0.81	0.20	-0.44	-3.97	0.00	-1.22	-0.40
Gender	-0.45	2.43	-0.02	-0.19	0.85	-5.30	4.40
Ethnic	2.39	3.49	0.07	0.68	0.50	-4.59	9.36
Voltage	0.01	0.06	0.02	0.18	0.86	-0.10	0.12
Neuropathy	-8.03	3.48	-0.25	-2.31	0.02	-14.98	-1.08
Visual acuity	6.04	8.11	0.09	0.75	0.46	-10.16	22.25
GHS score	-0.49	1.28	-0.04	-0.38	0.70	-3.06	2.07