Published in final edited form as:

Brain Res. 2011 December 2; 1426: 43–53. doi:10.1016/j.brainres.2011.09.017.

Multisensory integration across the senses in young and old adults

Jeannette R. Mahoney^{1,2}, Po Ching Clara Li², Mooyeon Oh-Park¹, Joe Verghese¹, and Roe Holtzer^{1,2,*}

¹Ferkauf Graduate School of Psychology, Albert Einstein College of Medicine, Bronx, New York, USA

²The Department of Neurology, Division of Cognitive & Motor Aging, Albert Einstein College of Medicine, Bronx, New York, USA

Abstract

Stimuli are processed concurrently and across multiple sensory inputs. Here we directly compared the effect of multisensory integration (MSI) on reaction time across three paired sensory inputs in eighteen young (M=19.17 yrs) and eighteen old (M=76.44 yrs) individuals. Participants were determined to be non-demented and without any medical or psychiatric conditions that would affect their performance. Participants responded to randomly presented unisensory (auditory, visual, somatosensory) stimuli and three paired sensory inputs consisting of auditory-somatosensory (AS) auditory-visual (AV) and visual-somatosensory (VS) stimuli. Results revealed that reaction time (RT) to all multisensory pairings was significantly faster than those elicited to the constituent unisensory conditions across age groups; findings that could not be accounted for by simple probability summation. Both young and old participants responded the fastest to multisensory pairings containing somatosensory input. Compared to younger adults, older adults demonstrated a significantly greater RT benefit when processing concurrent **VS** information. In terms of co-activation, older adults demonstrated a significant increase in the magnitude of visual-somatosensory co-activation (i.e., multisensory integration), while younger adults demonstrated a significant increase in the magnitude of auditory-visual and auditory-somatosensory co-activation. This study provides first evidence in support of the facilitative effect of pairing somatosensory with visual stimuli in older adults.

Keywords

Multisensory Integration; Cross-Modal; Sensory Processing; Aging

1. Introduction

In everyday life, individuals are constantly inundated with stimulation across multiple sensory modalities, making our perception of the world naturally multisensory. Research shows that multisensory information is processed simultaneously, such that the probability

© 2011 Elsevier B.V. All rights reserved.

*Corresponding Author: Roe Holtzer, Ph.D., Albert Einstein College of Medicine, Yeshiva University, 1165 Morris Park Avenue, Room 306, Bronx, New York 10461, T#: 718-430-3962, F#: 718-430-3829, Roe.Holtzer@einstein.yu.edu.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

that objects and events are detected rapidly, identified correctly, and responded to appropriately is enhanced (Calvert et al., 2004). Much of the seminal work examining multisensory integration (MSI) was conducted by Stein, Meredith, Wallace, and colleagues who in a comprehensive set of experiments examining single cells in the superior colliculus (SC) of cats and primates, detailed a basic set of principles for multisensory integration (see Meredith et al., 1987; Meredith & Stein, 1986; 1996; Stein et al., 1975; 1988; Stein & Meredith, 1993; Stein & Wallace, 1996; Wallace et al., 1996). They showed that MSI in SC was the greatest when: 1) inputs were presented simultaneously or in close temporal alignment (“temporal rule”), 2) inputs were presented from the same spatial location (“spatial rule”), and 3) when inputs near a cell’s threshold of detection were presented close to simultaneously (“inverse-effectiveness rule”), such that the integrated stimuli elicited a dramatically larger response. Psychophysical and electrophysiological MSI studies conducted over the past several decades have systematically examined the properties of Stein & Meredith’s “rules,” as well as the fundamentals of integrative sensory processing, in healthy young participants. In these studies, MSI has been, typically, explored in pairings of three major sensory modalities (i.e., visual, auditory, and somatosensory systems) which are often referred to as auditory-visual (**AV**), auditory-somatosensory (**AS**), and visual-somatosensory (**VS**) pairs. Findings indicate multisensory facilitation with shorter reaction time for multisensory pairings as compared to reaction time of the constituent unisensory conditions for **AV** (Harrington & Peck, 1998; Molholm et al., 2002; Teder-Salejarvi et al., 2002), **AS** (Murray et al., 2005) and **VS** (Pavani et al., 2000) pairings. Spence and colleagues provide substantial evidence for the effect of multisensory cueing and crossmodal exogenous spatial attention across multisensory pairs (for a detailed review see Spence, 2010; Spence & Santangelo, 2009). Additionally, Diederich & Colonius (2004) examined multisensory interaction effects in a small sample of young adults and report that responses to trimodal stimuli were faster than responses to bimodal stimuli.

Electrophysiological studies examining event-related potentials in response to various unisensory and multisensory stimuli in young adults have revealed multisensory effects of short latency (i.e., ≤ 150 ms post-stimulation) which are thought to be reflective of basic sensory processing (bottom-up) for **AV** (Fort et al., 2002; Giard & Peronnet, 1999; Molholm et al., 2002; Teder-Salejarvi et al., 2005) **AS** (Foxe et al., 2000; Murray et al., 2005) and **VS** (Schurmann et al., 2002) combinations. Effects of longer latency (i.e., > 150 ms post-stimulation) which reflect higher-order (top-down) cognitive processing have also been identified (see Schroger & Widmann, 1998; Stekelenburg, et al., 2004; Stekelenburg & Vroomen, 2005). Despite the abundance of behavioral and electrophysiological evidence for MSI in young adults, most studies typically assessed the effect of only one multisensory pairing at a time.

There is a paucity of research simultaneously examining multisensory integration across auditory, visual, and somatosensory pairings in both young and old adults. Studies examining MSI in the elderly have predominately been limited to auditory-visual investigations. Laurienti et al. (2006) used a forced-choice discrimination task to compare speed of discrimination responses across auditory, visual, and multisensory **AV** inputs in young and old adults. Findings revealed RT facilitation (i.e., shorter reaction time) to multisensory compared to unisensory conditions in both age groups. Further, multisensory interactions were significantly greater in old relative to young adults, even after adjusting for age-related differences in speed of processing (Salthouse, 2000; 1996; 1985). Such results indicate that regardless of known unisensory processing deficits (i.e., hearing and vision loss) older adults benefited more from receiving redundant information across multiple sensory channels, which was interpreted as a form of sensory compensation. Peiffer et al. (2007) similarly investigated **AV** integration in both young and old adults using a simple reaction time (SRT) task. Participants were presented with visual, auditory, and **AV**

multisensory stimuli and were asked to respond to all sensory stimuli as soon as they detected any stimulation. Consistent with findings from Laurienti et al. (2006), results revealed RT facilitation to multisensory compared to unisensory conditions that was again significantly greater in old compared to young adults. It was argued that the facilitating effect of shorter RTs to **AV** stimuli was attributed to basic changes in multisensory processing during the aging process. Specifically, Peiffer et al. (2007) speculated that decreased low-level unisensory processing could ultimately result in increased feed-forward multisensory processing in older adults (see also Foxe & Schroeder, 2005).

Knowledge of VS integration in aging is limited. Using a subjective visual straight ahead task, Strupp et al. (1999) reported age-related increase in the integration of somatosensory information into the multisensory representation of body orientation. Poliakoff et al. (2006) examined the effects of ageing on crossmodal selective attention and concluded that relative to young adults, old adults demonstrate impaired visual-somatosensory selective attention. Somatosensory impairment in older adults has been linked to functional decline (Kaye et al., 1994), increased risks of falls (Lord et al., 1999; Camicoli et al., 1997; Judge et al., 1995, Lord & Ward, 1994), and slower gait speed (Kaye et al., 1994). It is noteworthy that visual and auditory impairments (Yeuh et al., 2003, Appollonio et al., 1996; & Carabellese et al., 1993; Laforge et al., 1992) are common in older adults and have been linked to poor functional outcomes in older adults as well. MSI across AV, AS, and VS pairings appears to have differential effects on performance that may also vary as a function of age. Examining MSI effects across these paired sensory inputs in young and old individuals may provide clues as to how the brain compensates for age-related sensory impairments. Therefore, the current study was designed to directly compare the effect of MSI across three multisensory pairings and determine whether MSI varied as a function of age.

2. Results

2.1. Demographics

Eighteen old individuals (mean age of 76.44 ($\pm$ 7.91 years)) and eighteen young individuals (19.17 ($\pm$ 2.66 years)) participated in the current study. All participants were considered to be non-demented as determined by their MMSE scores (Folstein et al., 1975) and relatively healthy as determined by their global health status (see Holtzer et al., 2006; Holtzer et al., 2008; Mahoney et al., 2010; Verghese et al., 2007). Table 1 also delineates mean education level (in years), Geriatric Depression Scale (GDS; Yesavage et al., 1983) score, Beck Anxiety Inventory (BAI; Beck et al., 1988) score, and mean value and range of the unisensory probes for both old and young adults. Old and young adults did not differ in terms of education, depression, or anxiety level (see Table 1). However, as expected, there were significant age differences in MMSE score, global health status, overall RT, and three sensory screening levels.

2.2. Descriptive & ANOVA Results

The current task required participants to quickly and accurately press a foot-pedal in response to unisensory and multisensory stimulation (refer to section 4.4 and Figure 4 for details). In total, participants received 108 randomly presented trials (18 trials per condition) and their reaction time per trial was recorded in milliseconds (ms) using E-prime 2.0 software. Individual mean RT values were calculated. Trials that exceeded $\pm$ 2 standard deviations from the mean and that were $\leq$ 100 ms were excluded from the analysis to avoid the influence of outliers; this outlier resulted in a mean exclusion of 5.14% of trials for old adults and 6.20% of trials for young adults. The percentage of excluded trials was comparable across both age groups and trial type ($p \geq 0.05$). The mean RT of each multisensory condition was significantly faster than the mean RT of the constituent

unisensory conditions for both young and old adults. The mean RTs (with SEM bars) to each sensory condition for the old group (panel a) and young group (panel b) are illustrated in Figure 1.

A 2 (age group: old vs. young) $\times$ 2 (sensory condition: unisensory vs. multisensory) $\times$ 3 (sensory modality: auditory, visual or somatosensory) repeated-measures analysis of variance (ANOVA) was performed to examine the effect of MSI, age, and their interaction on RT. Helmert contrasts were used to determine the differential effects of **AV**, **AS**, and **VS** multisensory processing relative to constituent unisensory processing in old and young participants (i.e., **AV** condition vs. auditory and visual conditions; **AS** condition vs. auditory and somatosensory conditions; & **VS** condition vs. visual and somatosensory conditions). Simple contrasts were used to determine differences between the 3-level sensory modality variable. RT distributions were examined descriptively and graphically, and Huynh-Feldt corrections were used when appropriate.

Results from the repeated-measures ANOVA revealed significant main effects for sensory condition ($F(1,34) = 363.04, p < .01$), sensory modality ($F(2,68) = 39.29, p < .01$), and group ($F(1,34) = 7.85, p < .01$). The two-level interactions of sensory condition $\times$ group ($F(1,34) = 8.89, p < 0.01$) and sensory condition $\times$ sensory modality ($F(2,68) = 4.94, p < .05$) were significant. The sensory modality $\times$ group interaction was not significant ($F(2,68) = .59, p = .54$).

Helmert contrast analyses were used to further understand the significant main effect of sensory condition (unisensory vs. multisensory), as well as its significant interaction with age. Comparing multisensory **VS** stimuli to the combined effect of visual and somatosensory stimuli when presented alone revealed a significant MSI effect ($F(1,34) = 204.38, p < .01$; also see Figure 1) and an interaction with age group ($F(1, 34) = 7.14, p = .01$, see Figure 1). This interaction indicated that older adults demonstrated greater visual-somatosensory RT facilitation (i.e., multisensory integration) than young adults. Comparing multisensory **AV** stimuli to the combined effect of auditory and visual stimuli when presented alone revealed a significant MSI effect ($F(1, 34) = 131.40, p < .01$) and no interaction between sensory condition and age group ($F(1, 34) = 1.75, p = .20$). Similarly, comparing multisensory **AS** stimuli to the combined effect of auditory and somatosensory stimuli when presented alone revealed a significant MSI effect ($F(1, 34) = 92.86, p < .01$) and no interaction between condition and age group ($F(1, 34) = 2.21, p = .15$).

We were also interested to directly compare the effects of the three multisensory conditions. Simple contrast analyses revealed that both age groups were significantly faster at detecting **AS** ($F(1,34) = 25.90, p < .01$) and **VS** stimuli ($F(1,34) = 14.33, p < .01$) compared to **AV** stimuli; no significant difference in RT was found between **AS** and **VS** stimuli ($F(1,34) = 1.39, p = .25$). In terms of unisensory conditions, both groups were significantly faster at detecting auditory ($F(1,34) = 45.47, p < .01$) and somatosensory stimuli ($F(1,34) = 49.18, p < .01$) compared to visual stimuli. There was no significant difference in RT between auditory and somatosensory stimuli ($F(1,34) = 1.52, p = .23$). The interactions of group with sensory modality for multisensory ($F(1,34) = 0.12, p = .88$) and unisensory ($F(1,34) = 0.61, p = .52$) conditions were not significant.

2.3. Race Model Results

Multisensory studies typically test for race model violations using cumulative probability (CP) models which investigate behavioral multisensory integrative processes by comparing actual CP distributions to predicted CP distributions using Miller's Inequality (1982; refer to section 4.5.2). These models are conservative (Miller 1986; Gondan et al., 2004) and controversial (Eriksen et al., 1989; Mordkoff & Yantis, 1991). Due to inherent limitations of

Miller's inequality, a more stringent test of race model as outlined by Colonius & Diederich (2006) was used to examine MSI effects on the three paired sensory inputs in each group. CP at each quintile was group-averaged separately for each multisensory condition (**actual**) to form a distribution that maintained the shape of the individuals' data and was then compared to the model (**predicted**; see Figure 2) for both old and young adults across all three multisensory pairings. Here, differences between **actual** CP distributions $\{P(RT_{XY} \leq t)\}$ and **predicted** CP distributions $\{\min [P(RT_X \leq t) + P(RT_Y \leq t), 1]\}$ were calculated for each multisensory pairing and group over the first quartile (0 – 25%) of RT responses to avoid multiple tests. Figure 3 represents the difference wave of actual minus predicted values for the AS, AV, and VS combinations for both young and old adults. Evidence of co-activation (i.e., values greater than zero) was observed in all multisensory conditions within the fastest 25% of the grouped RT distribution for both old and young adults and is highlighted in the gray boxes of Figure 3. It should be noted that any violation of the race model, regardless of whether the magnitude is significant, is indicative of the existence of a co-activation (Colonius et al., 2006). These findings are consistent with the main effect of sensory modality of the ANOVA and the significant effect of MSI across all three multisensory pairings as revealed in the Helmert contrast analyses.

To further assess the magnitude of the race model violation or co-activation within each group, paired T-tests comparing actual and predicted cumulative probability values were conducted using a single numerical index (responses over the fastest quartile (0–25% of RTs) as outlined by Colonius et al. (2006) for each multisensory condition. Results show a significant increase in the magnitude of co-activation for the VS pairing in old adults ($p=0.01$) and a significant increase in the magnitude of co-activation for the AS ($p=0.03$) and AV pairings ($p=0.01$) in young adults. The results from the test of the magnitude of co-activation, albeit not exactly the same, are consistent with the ANOVA described earlier (see Discussion Section 3.2).

3. Discussion

3.1. Summary of Multisensory Findings

To our knowledge, this is the first study to report on the effect of MSI using simultaneously presented somatosensory, auditory, and visual cross-modal pairings in both young and old adults. Results from both the ANOVA and test of the race model confirm that regardless of age, participants were significantly faster at responding to multisensory compared to unisensory stimuli, providing evidence for a redundant signals effect (RSE; Kinchla, 1974) across **AS**, **AV**, and **VS** pairings. These findings are consistent with findings from other single multisensory pairing studies examining young (**AV**: Harrington & Peck, 1998; Molholm et al., 2002; Teder-Salejarvi et al., 2002; **AS**: Murray et al., 2005; **VS**: Pavani, Spence, & Driver, 2000) and old adults (**AV**: Laurienti et al., 2006; Peiffer et al., 2007). Simple contrasts revealed that for each multisensory pairing, RTs were significantly shorter than that of the two constituent unisensory modalities; indicating successful neuronal integration of information across sensory systems in both old and young adults.

While RT enhancement occurred across all multisensory pairings relative to constituent unisensory conditions, both young and old adults demonstrated significantly faster RT to multisensory events where redundant auditory or visual information was simultaneously received with somatosensory information (i.e., **AS** and **VS** conditions; see Figure 1). This advantage may be attributed, in part, to the fact that somatosensory inputs were individually optimized. It is noteworthy that this study provides first evidence in support of the facilitative MSI effect in older adults when pairing somatosensory input with visual and auditory stimulation.

3.2. Differential Multisensory Effects & Relation to Aging Models

Further results from the Helmert contrasts revealed that age influenced the effect of **VS** integration on RT. Relative to young adults, older adults demonstrated a nearly 50% RT benefit when processing concurrent visual-somatosensory information. This finding is also consistent, with the results of the race model revealing that old but not young participants demonstrated increased magnitude of co-activation when visual and somatosensory inputs were combined (see Figure 3 – **VS** condition). However, the latter finding should be interpreted with caution given that it was based on stratified analyses and not on direct comparisons between the two age groups (see also Nieuwenhuis et al., 2011). Results from a power analysis (analysis not shown) revealed that the current study was underpowered to detect the difference between the actual and predicted MSI values (i.e., co-activation analysis) when comparing old and young participants directly. While the mechanism underlying the advantage of combining visual and somatosensory inputs in older adults remains to be evaluated, the possible implications of these findings are discussed elsewhere in the discussion (see section 3.3).

Young adults demonstrated significant increase in the magnitude of co-activation for the **AS** and **AV** pairings, a finding that was not significant in the ANOVA. The discrepancy of the ANOVA and the test of the magnitude of race model violation in this case may be, in part, related to the fact that the ANOVA approach takes the mean of RT responses over the entire distribution, whereas the race model test is limited to the cumulative probability of the fastest 25% of RT responses. In the current study, the interaction of group by **AV** modality was not significant. This result is in contrast to findings from Peiffer et al. (2007) where older adults demonstrated greater **AV** multisensory enhancements than younger adults. This difference can be attributed to several methodological differences between the two studies including actual auditory and visual stimuli, stimulus presentation duration, differences in response pads (mouse vs. foot pedal), and differences in number of trials per condition.

Age did not interact with sensory modality type within the multisensory or the unisensory conditions, suggesting similar sensory processing across both age groups. At present, it is unclear whether such stability of sensory processing across age groups could be attributed to the recruitment of additional neural resources by older individuals to compensate for age-related changes in brain architecture to maintain performance (Stern et al. 2005; 2000).

RT to all sensory conditions was significantly slower for old as compared to young adults. Given the nature of the simple reaction time task and the fact that simple stimulus detection occurs at relatively early processing stages, generalized cognitive slowing cannot account for differences in multisensory integration between age groups (see also Yordanova et al., 2004). Here, differences in multisensory relative to unisensory processing across groups, is likely indicative of differences in sensory processing at the synaptic level between old and young adults.

3.3. Implication of Neural Substrates in Aging

The basic circuitry of the sensory systems involves a series of interactive neuronal loops (both feedback and feedforward) between the thalamus and the neocortex in order to effectively process sensory and higher-order cognitive information. The thalamus plays a very important role in cortico-cortical communication and integration of sensory information (Sherman, 2005; Sherman & Guillery, 1996). Research suggests that these loops are compromised with age, resulting in impaired information processing in the aging brain that has been variously attributed to dedifferentiation (Dustman et al., 1981); inhibition (Dustman et al., 1996); prefrontal cortico-cortico facilitation (Chao & Knight, 1998; Knight et al., 1999); prefronto-thalamo-cortical gating (Knight et al., 1999; Zikopoulos & Barbas,

2006); general slowing (Salthouse, 1985;1996;2000); compensatory reallocation (Cabeza, 2002a; 2002b); or neural compensation (Stern et al., 2005; cf. Holtzer et al., 2009 for comments on other relevant models). While RT to unisensory conditions were longer for old adults, Laurienti et al. (2006) conveyed that decline in unisensory performance could be directly attributed to enhanced multisensory performance as old adults benefited more than young adults from receiving redundant information across multiple sensory channels. Laurienti et al. (2006) furthered that such enhanced multisensory gain is likely the result of compensatory mechanisms which aid in successful multisensory information processing across auditory and visual systems. It is likely that multisensory gain in the current study is also the result of compensatory mechanisms across all three sensory modalities; however, this was not empirically tested here.

3.4. Importance of Somatosensory Stimulation

At present, it is unclear whether observed somatosensory RT facilitation in young and old adults was attributed to individual optimization of somatosensory inputs ensuring that each individual could feel the stimulation at a level that was not painful. As expected, older adults required higher voltage to feel the somatosensory stimuli (Verrillo et al, 2002). This is consistent with the reduced number of sensory receptors on hairless skin (e.g, finger tips) in aging which has been associated with declines in vibration perception or touch thresholds (see Shaffer & Harrison, 2007). However, noteworthy is the fact that both old and young adults respond the fastest to stimuli containing somatosensory information, and this effect is greatly enhanced in older adults when visual and somatosensory stimuli are paired.

Findings from earlier visual-somatosensory studies examining vision and balance provide clues for the importance of intact proprioception or somatosensation. Judge et al. (1995) investigated a large cohort of older adults using a sensory organization test (SOT) and revealed that proprioceptive errors negatively affected balance to a greater degree than visual errors, with the oldest participants demonstrating the greatest difficulty in conditions where proprioception was reduced. Camicioli et al. (1997) investigated healthy young-old and old-old participants using a SOT and reported a significant difference in the adaptive ability of the old-old participants (≥ 80 years of age and older) when proprioceptive input was disrupted. The oldest participants required accurate proprioception to maintain balance, while the young-old participants (< 80 years of age) were better able to adapt to proprioceptive errors by using visual cues. These results clearly indicate the importance of additional concurrent visual information to compensate for somatosensory deficits.

It is well-known that declines in sensory and perceptual functions are omnipresent in aging humans which have been linked to poor functional outcomes in older adults (Yeuh et al, 2003, Appollonio et al., 1996; & Carabellese et al, 1993; Laforge et al; 1992). Such declines, especially in auditory and visual modalities, have been linked to neural (e.g., reduction in nerve cell quantity) and non-neural (e.g., opacity of the visual lens or epithelial atrophy to organ of Corti) modifications over time (Corso et al., 1971). Research by Erber et al. (1972) delineated the ability of older adults to compensate for auditory impairments by relying on visual cues. However, recent work from Tye-Murray et al. (2007) and Musacchia et al. (2009) indicates that regardless of visual compensation, people with auditory (i.e., hearing) sensory impairments do not benefit from increased AV integration and such hearing loss actually impacts the efficiency of neural mechanisms involved with AV integration. However, Tye-Murray et al. (2010) argue that “the integration of audiovisual speech stimuli differs in some fundamental way from the integration of other bimodal stimuli.” Given the above reported facilitative findings of somatosensory processing and the enhanced RT benefits in older adults for simultaneous VS information processing, it will be interesting for future studies to determine whether both auditory and visual information can compensate for

somatosensory deficits (as indicated by Camicoli et al., 1997 in balance studies) or whether somatosensory information can compensate for auditory and visual deficits.

3.5. Limitations & Future Directions

As previously stated the current study was underpowered to directly compare group differences in the magnitude of co-activation using the transformed race model data. Larger sample sizes would be required to reliably determine age-related differences in the magnitude of co-activation between young and old adults. Additionally, identifying the neural substrates underlying such age-related differences in MSI would be of major scientific value to the field.

Clearly multisensory integration is an integral aspect of functioning and mobility in the real world. The finding that older adults demonstrated a facilitative benefit when processing concurrent visual-somatosensory information has major public health implications. Specifically, this finding can be utilized to help identify opportunities to introduce cognitive and physical remediation programs incorporating VS enhancement strategies to older adults in an effort to improve disability and maintain functional independence.

4. Experimental Procedure

4.1. Participants

Eighteen (11 female) young and eighteen (11 female) old adults participated in the current study. The young participants were recruited from the Albert Einstein College of Medicine campus in Bronx, New York. The old participants were recruited from a local independent senior living facility located on the United Hebrew senior living campus in New Rochelle, New York. Fifteen young participants and eighteen old participants were right-handed as assessed by the Edinburgh handedness inventory (Oldfield, 1971). Eligibility criteria required that old participants be 65 years of age or older and young participants be 16 years of age or older, and all participants were required to speak English. Participants were also required to be able to hear, see, and feel all stimulation (see 4.3 *Sensory Screening Procedures* section below). Exclusion criteria for all participants included severe auditory disturbances (see below) that would interfere with completion of neuropsychological tests, significant loss of vision (acuity less than 20/40), inability to ambulate even with a walking aid or in a wheelchair, and institutionalization. All participants provided written informed consent to the experimental procedures, which were approved by the Committee on Clinical Investigation (CCI; the institutional review board of the Albert Einstein College of Medicine).

4.2. Cognitive & Disease Status

All study participants participated in an initial screening session where extensive medical and psychological history was acquired by the study psychologist to ensure appropriateness for this study. Participants were determined to be cognitively normal using the Mini Mental Status Exam (MMSE; best score: 30 and worst possible score: 0; Folstein et al., 1975). MMSE is the most commonly used screening test for assessing cognitive impairment and a cut score of 27 was found to have an “optimal balance” of sensitivity (0.89) and specificity (0.91) for correctly identifying cognitive impairment in older populations of higher educated individuals (O’Bryant et al., 2008). Participants were also screened for depression (Geriatric Depression Scale (GDS) – 30 item; Yesavage et al., 1983) and anxiety (Beck Anxiety Inventory (BAI; Beck et al., 1988).

Global disease status 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; Holtzer et al., 2008; Mahoney et al., 2010; Verghese et al., 2007).

4.3. Sensory Screening procedures

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 normal or corrected to normal visual acuity as measured by a Snellen eye chart (better or equal to 20/40). A computerized tone-emitting otoscope that delivered lateral and bilateral 20, 25, and 40 dB tones at 500, 1000, 2,000, and 4,000 Hz using E-prime 2.0 software (Psychology Software Tools, Inc., (PST), Pittsburgh, PA, USA) was employed to assess hearing loss. This was also accompanied with the validated self-administered Hearing Handicap Inventory for the elderly (HHIE-S) questionnaire which is specifically designed to measure the degree of social and emotional handicap from hearing loss (Ventry & Weinstein, 1983; Weinstein, 1986). Scores on the HHIE-S questionnaire range from 0 (no handicap) to 40 (maximum handicap). In terms of the somatosensory screening, each individual received a somatosensory pulse of 30 volts which was gradually increased by 5 volts in order to determine each individual's minimal threshold of 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 that was not painful. While the range of visual and auditory thresholds were within the normal range for both old and young participants, somatosensory thresholds were noticeably (on average over 25 volts) higher for old as compared to young adults. This finding is in keeping with work from Verrillo et al. (2002) who reported that older adults required higher frequency vibrations to achieve the same sensation-perceived magnitude as younger adults.

4.4. Stimuli & Task procedures

Participants received a total of six stimulus conditions (three unisensory and three multisensory; see Figure 4a). The unisensory conditions included lateral and bilateral visual (V), auditory (A), and somatosensory (S) stimuli. The visual stimuli were 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/m². The auditory stimuli were 1000 Hz tones (100 ms duration, 75 dB, 5ms rise/fall times) that were presented via headphones. The somatosensory 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 the left and right index or middle fingers (depending upon pre-existing nerve or skin damage at time of testing).

The multisensory conditions included simultaneous auditory-visual (AV), auditory-somatosensory (AS) or visual-somatosensory (VS) stimulation presented either bilaterally or to the same lateral location (left or right); participants did not receive concurrent sensory stimulation that was presented to two different locations (e.g., right visual and left somatosensory stimulation). Using E-prime 2.0, the six stimulus conditions were presented in random order with equal frequency over 108 trials. The inter-stimulus interval (ISI) varied randomly from 1.0 to 3.0 second to avoid anticipatory effects. [Insert Figure 4 Here]

Reaction time was collected as participants performed a simple reaction time task in response to all unisensory and multisensory stimuli by depressing a foot pedal located under their right foot as quickly as possible for each stimulus event (see Figure 4b). Participants' arms were rested on a table and their hands were 60 cm apart, symmetrical about the vertical

meridian. Participants were required to fixate a central fixation point (a black cross) visible on the center of the computer monitor.

4.5. Behavioral Data Analysis

4.5.1. 2x2x3 ANOVA—A 2 (age group: old vs. young) $\times$ 2 (condition: unisensory vs. multisensory) $\times$ 3 (modality: auditory, visual or somatosensory) repeated-measures ANOVA examined whether significant differences in RTs existed between age groups and across sensory condition and modalities. Huynh-Feldt corrections were used when appropriate. Helmert 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., **AV** condition vs. **A** and **V** conditions) in old versus young participants. Simple contrast analyses were used to determine differences between the 3-level factor of modality.

4.5.2. Test of the Race Model—Behavioral data allows for a direct measurement of multisensory integrative processes through reaction times because when two sources of information (e.g., a simultaneous light and a vibro-tactile stimulus) are presented at the same time, they offer redundant signals that give rise to faster detection responses. This phenomenon is often 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, 1986; 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 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.

Tests developed to assess race model violations are inherently controversial because they contain assumptions about independence between unisensory processes. In fact, whether or not the test of the race model is “overly severe” or “too conservative” (Eriksen et al., 1989; Mordkoff & Yantis, 1991) is still under debate. Nevertheless, a majority of multisensory studies report violations of the race model using the method employed by Miller (1982) which compares the actual multisensory cumulative probability (CP(t)) distribution to the predicted cumulative probability distribution ((CP(t) unisensory 1 + CP(t) unisensory 2) – (CP(t) unisensory 1 $\times$ CP(t) unisensory 2) at any given latency (t) (see Molholm et al., 2002; Murray et al., 2005; Laurienti et al., 2006; Peiffer et al., 2007). In Miller’s inequality (1982), the predicted CP is calculated by subtracting the product of the unisensory CP distributions from the sum of the unisensory CP distributions; a method that can lead to an overestimation of the degree of race model violation or inflation of Type I error. Studies that employ Miller’s inequality typically further assess the magnitude of race model violation by conducting multiple t-tests for various time or percentile bins without applying corrections for multiple tests.

To circumvent these various limitations, a more conservative test of the race model as outlined by Colonius & Diederich (2006) was used to establish whether or not a co-activation model could explain the data: $R_{XY} = P(RT_{XY} \leq t) - \min [P(RT_X \leq t) + P(RT_Y \leq t), 1]$. 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 1 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.

Here, individual RTs were recorded for each trial. Reaction times were sorted in ascending order by stimulus condition and then averaged. Trials with RT responses that exceeded ± 2 standard deviations from the individual mean of each participant were considered outliers and were excluded. Trials with RTs < 100 ms were also excluded from the analysis as they were not considered to be physiologically plausible responses. For each participant, the RT range within the valid RTs was calculated across the six 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 $\{P(RT_{XY} \leq t)\}$ and **predicted** CP distributions $\{\min [P(RT_X \leq t) + P(RT_Y \leq t), 1]\}$ were calculated for each multisensory pairing and group over the fastest quartile (0 – 25%) of RT responses). To alleviate the need for applying multiple t-tests across various bins, the information contained in R_{XY} is reduced to a single numerical index over the fastest quartile of RT responses (0–25%) (see Colonius & Deiderich, 2006). Paired samples t-tests comparing actual and predicted values were used to assess the magnitude of the violation within each age group.

Acknowledgments

Research was supported by funding from the Albert Einstein College of Medicine's Resnick Gerontology Center Pilot Grant awarded to Dr. Mahoney. Dr. Holtzer is supported by the National Institute on Aging Paul B. Beeson Award K23 AG030857. The authors would like to thank Dr. Vance Zemon for his statistical assistance.

Non-Standard Abbreviations

MSI	multisensory integration
CP	cumulative probability
AS	auditory-somatosensory
AV	auditory-visual
VS	visual-somatosensory

References

- Appollonio I, Carabellese C, Frattola L, et al. Effects of sensory aids on the quality of life and mortality of elderly people: A multivariate analysis. *Age Ageing*. 1996; 25:89–96. [PubMed: 8670534]
- Beck AT, Epstein N, Brown G, Steer RA. An inventory for measuring clinical anxiety: Psychometric properties. *J Consult Clin Psychol*. 1988; 56:893–897. [PubMed: 3204199]
- Biopac Systems Inc. [accessed September 20, 2010] Retrieved from <http://www.biopac.com>
- Calvert, GA.; Spence, C.; Stein, BE. *The Handbook of Multisensory Processes*. The MIT Press; Cambridge: 2004.
- Cabeza R. Hemispheric asymmetry reduction in older adults: the HAROLD model. *Psychol Aging*. 2002a; 17(1):85–100. [PubMed: 11931290]
- Cabeza R, Anderson ND, Locantore JK, McIntosh AR. Aging gracefully: compensatory brain activity in high-performing older adults. *Neuroimage*. 2002b; 17(3):1394–1402. [PubMed: 12414279]
- Camicoli R, Panzer VP, Kaye J. Balance in the healthy elderly. *Arch Neurol*. 1997; 54:976–981. [PubMed: 9267972]
- Carabellese C, Appollonio I, Rozzini R, et al. Sensory impairment and quality of life in a community elderly population. *J Am Geriatr Soc*. 1993; 41:401–407. [PubMed: 8463527]

- Chao LL, Knight RT. Contribution of human prefrontal cortex to delay performance. *J Cogn Neurosci*. 1998; 10:167–177. [PubMed: 9555105]
- Corso JF. Sensory processes and age effects in normal adults. *J Gerontol*. 1971; 26:90–105. [PubMed: 4926474]
- Colonius H, Diederich A. The race model inequality: Interpreting a geometric measure of the amount of violation. *Psychol Rev*. 2006; 113:148–154. [PubMed: 16478305]
- Diederich A, Colonius H. Bimodal and trimodal multisensory enhancement: Effects of stimulus onset and intensity on reaction time. *Percept Psychophys*. 2004; 66:1388–1404. [PubMed: 15813202]
- Dustman RE, Emmerson RY, Shearer DE. Life span changes in electrophysiological measures of inhibition. *Brain Cogn*. 1996; 30:109–126. [PubMed: 8811986]
- Dustman RE, Snyder EW. Life-span change in visually evoked potentials at central scalp. *Neurobiol Aging*. 1981; 2:303–308. [PubMed: 7335148]
- Erber N. Auditory, visual, and auditory-visual recognition of consonants by children with normal and impaired hearing. *J Speech Hear Res*. 1972; 15:413–422. [PubMed: 5047880]
- Eriksen CW, Goettl B, StJames JD, Fournier LR. Processing redundant signals: co-activation, divided attention, or what? *Percept & Psychophys*. 1989; 45:356–370.
- Folstein MF, Folstein SE, McHugh PR. “Mini-mental state”: a practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res*. 1975; 12:189–198. [PubMed: 1202204]
- Fort A, Delpuech C, Pernier J, Giard MH. Early auditory-visual interactions in human cortex during nonredundant target identification. *Brain Res Cogn Brain Res*. 2002; 14:20–30. [PubMed: 12063127]
- Foxe JJ, Morocz IA, Murray MM, Higgins BA, Javitt DC, Schroeder CE. Multisensory auditory-somatosensory interactions in early cortical processing revealed by high-density electrical mapping. *Brain Res Cogn Brain Res*. 2000; 10:77–83. [PubMed: 10978694]
- Foxe JJ, Schroeder CE. The case of feed-forward multisensory convergence during early cortical processing. *Neuroreport*. 2005; 16:419–423. [PubMed: 15770144]
- Giard MH, Peronnet F. Auditory-visual integration during multimodal object recognition in humans: a behavioral and electrophysiological study. *J Cogn Neurosci*. 1999; 11:473–490. [PubMed: 10511637]
- Gondan M, Lange K, Rosler F, Roder B. The redundant target effect is affected by modality switch costs. *Psychon Bull Rev*. 2004; 11:307–313. [PubMed: 15260198]
- Harrington LK, Peck CK. Spatial disparity affects visual-auditory interactions in human sensorimotor processing. *Exp Brain Res*. 1998; 122:247–252. [PubMed: 9776523]
- Holtzer R, Rakitin BC, Steffener J, Flynn J, Kumar A, Stern Y. Age effects on load-dependent brain activations in working memory for novel material. *Brain Res*. 2009; 1249:148–161. [PubMed: 18983833]
- Holtzer R, Verghese J, Wang C, Hall CB, Lipton RB. Within-person across-neuropsychological test variability and incident dementia. *JAMA*. 2008; 300:823–830. [PubMed: 18714062]
- Holtzer R, Verghese J, Xue X, Lipton RB. Cognitive processes related to gait velocity: results from the Einstein Aging Study. *Neuropsychology*. 2006; 20:215–223. [PubMed: 16594782]
- Judge JO, King MB, Whipple R, Clive J, Wolfson LI. Dynamic balance in older persons: effects of reduced visual and proprioceptive input. *J Gerontol A Biol Sci Med Sci*. 1995; 50A:M263–M270. [PubMed: 7671028]
- Kaye JA, Oken BS, Howieson DB, Howieson J, Holm LA, Dennison K. Neurologic evaluation of the optimally healthy oldest old. *Arch Neurol*. 1994; 51:1205–1211. [PubMed: 7986175]
- Kinchla R. Detecting target elements in multielement arrays: A confusability model. *Percept Psychophys*. 1974; 15:149–158.
- Knight RT, Staines WR, Swick D, Chao LL. Prefrontal cortex regulates inhibition and excitation in distributed neural networks. *Acta Psychol (Amst)*. 1999; 101:159–178. [PubMed: 10344184]
- LaForge RG, Spector WD, Sternberg J. The relationship of vision and hearing impairment to one-year mortality and functional decline. *J Aging Health*. 1992; 4:126–148.

- Laurienti P, Burdette JH, Maldjian JA, Wallace MT. Enhanced multisensory integration in older adults. *Neurobiol Aging*. 2006; 27:1155–1163. [PubMed: 16039016]
- Lord SR, Rogers MW, Howland A, Fitzpatrick R. Lateral stability, sensorimotor function and falls in older people. *J Am Geriatr Soc*. 1999; 47:1077–1081. [PubMed: 10484249]
- Lord SR, Ward JA. Age-associated differences in sensori-motor function and balance in community dwelling women. *Age Ageing*. 1994; 23:452–460. [PubMed: 9231937]
- Mahoney JR, Verghese J, Goldin Y, Lipton R, Holtzer R. Alerting, orienting, and executive attention in older adults. *J Int Neuropsychol Soc*. 2010; 27:1–13.
- Meredith MA, Nemitz JW, Stein BE. Determinants of multisensory integration in superior colliculus neurons. I Temporal factors *J Neurosci*. 1987; 7:3215–3229.
- Meredith MA, Stein BE. Visual, auditory, and somatosensory convergence on cells in superior colliculus results in multisensory integration. *J Neurophysiol*. 1986; 56:640–662. [PubMed: 3537225]
- Meredith MA, Stein BE. Spatial determinants of multisensory integration in cat superior colliculus neurons. *J Neurophysiol*. 1996; 75:1843–1857. [PubMed: 8734584]
- Miller J. Divided attention: evidence for co-activation with redundant signals. *Cogn Psychol*. 1982; 14:247–279. [PubMed: 7083803]
- Miller J. Timecourse of coactivation in bimodal divided attention. *Percept Psychophys*. 1986; 40:331–343. [PubMed: 3786102]
- Molholm S, Ritter W, Murray MM, Javitt DC, Schroeder CE, Foxe JJ. Multisensory auditory-visual interactions during early sensory processing in humans: a high-density electrical mapping study. *Brain Res Cogn Brain Res*. 2002; 14:115–128. [PubMed: 12063135]
- Mordkoff JT, Yantis S. An interactive race model of divided attention. *J Exp Psychol Hum Percept Perform*. 1991; 17:520–538. [PubMed: 1830090]
- Murray MM, Molholm S, Michel CM, Heslenfeld DJ, Ritter W, Javitt DC, Schroeder CE, Foxe JJ. Grabbing your ear: rapid auditory-somatosensory multisensory interactions in low-level sensory cortices are not constrained by stimulus alignment. *Cereb Cortex*. 2005; 15:963–974. [PubMed: 15537674]
- Musacchia G, Aram L, Nicol T, Garstecki D, Kraus N. Audiovisual deficits in older adults with hearing loss: Biological evidence. *Ear Hear*. 2009; 30:505–514. [PubMed: 19546807]
- Nieuwenhuis S, Forstmann BU, Wagenmakers E. Erroneous analyses of interactions in neuroscience: a problem of significance. *Nat Neurosci*. 2011; 14:1105–1107. [PubMed: 21878926]
- O'Bryant SE, Humphreys JD, Smith GE, Ivnik RJ, Graff-Radford NR, Peterson RC, Lucas JA. Detecting Dementia with the Mini-Mental State Exam in Highly Educated Individuals. *Arch Neurol*. 2008; 65:963–967. [PubMed: 18625866]
- Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*. 1971; 9:97–113. [PubMed: 5146491]
- Pavani F, Spence C, Driver J. Visual capture of touch: out-of-the-body experiences with rubber gloves. *Psychol Sci*. 2000; 11:353–359. [PubMed: 11228904]
- Peiffer AM, Mozolic JL, Hugenschmidt CE, Laurienti PJ. Age-related multisensory enhancement in a simple audiovisual detection task. *Neuroreport*. 2007; 18:1077–1081. [PubMed: 17558300]
- Poliakoff E, Ashworth S, Lowe C, Spence C. Vision and touch in Ageing: Crossmodal selective attention and visuotactile spatial interactions. *Neuropsychologia*. 44:507–517. [PubMed: 16098997]
- Salthouse TA. Speed of behavior and its implication for cognition. In: Birren, JE.; Schaie, KW., editors. *Handbook of the Psychology of Aging*. 2. Van Nostrand Reinhold Company; New York: 1985. p. 400-426.
- Salthouse TA. The processing speed theory of adult age differences in cognition. *Psychol Rev*. 1996; 103:403–428. [PubMed: 8759042]
- Salthouse TA. Aging and measures of processing speed. *Biol Psychol*. 2000; 54:35–54. [PubMed: 11035219]
- Schroger E, Widmann A. Speeded responses to audiovisual signal changes result from bimodal integration. *Psychophysiology*. 1998; 35:755–759. [PubMed: 9844437]

- Schurmann M, Kolev V, Menzel K, Yordanova J. Spatial coincidence modulates interaction between visual and somatosensory evoked potentials. *Neuroreport*. 2002; 13:779–783. [PubMed: 11997686]
- Shaffer SW, Harrison AL. Aging of the somatosensory system: A translational perspective. *Phys Therap*. 2007; 87:193–207. [PubMed: 17244695]
- Sherman SM. Thalamic relays and cortical functioning. *Prog Brain Res*. 2005; 149:107–126. [PubMed: 16226580]
- Sherman SM, Guillery RW. Functional organization of thalamo-cortical relays. *J Neurophysiol*. 1996; 76:1367–1395. [PubMed: 8890259]
- Spence C. Crossmodal spatial attention. *Ann N Y Acad Sci*. 2010; 1191:182–200. [PubMed: 20392281]
- Spence C, Santangelo V. Capturing spatial attention with multisensory cues: A review. *Hear Res*. 2009; 258(1–2):134–42. [PubMed: 19409472]
- Stein BE, Huneycutt WS, Meredith MA. Neurons and behavior: the same rules of multisensory integration apply. *Brain Res*. 1988; 448:355–358. [PubMed: 3378157]
- Stein BE, Magalhaes-Castro B, Kruger L. Superior colliculus: visuotopic-somatotopic overlap. *Science*. 1975; 189:224–226. [PubMed: 1094540]
- Stein, BE.; Meredith, MA. *The Merging of the Senses*. Cambridge, MA: MIT Press; 1993.
- Stein BE, Wallace MT. Comparisons of cross-modality integration in midbrain and cortex. *Prog Brain Res*. 1996; 112:289–299. [PubMed: 8979836]
- Stekelenburg JJ, Vroomen J. An event-related potential investigation of the time-course of temporal ventriloquism. *Neuroreport*. 2005; 16:641–644. [PubMed: 15812324]
- Stekelenburg JJ, Vroomen J, de Gelder B. Illusory sound shifts induced by the ventriloquist illusion evoke the mismatch negativity. *Neurosci Lett*. 2004; 357:163–166. [PubMed: 15003275]
- Stern Y, Habeck C, Moeller J, Scarmeas N, Anderson KE, Hilton HJ, Flynn J, Sackeim H, van Heertum R. Brain networks associated with cognitive reserve in healthy young and old adults. *Cereb Cortex*. 2005; 15(4):394–402. [PubMed: 15749983]
- Stern Y, Moeller JR, Anderson KE, Lubner B, Zubin NR, DiMauro AA, Park A, Campbell CE, Marder K, Bell K, Van Heertum R, Sackeim HA. Different brain networks mediate task performance in normal aging and AD: defining compensation. *Neurology*. 2000; 55:1291–1297. [PubMed: 11087770]
- Strupp M. Subjective straight ahead during neck muscle vibration: effects of ageing. *N Neuroreport*. 1999; 10:3191–3194.
- Teder-Salejari WA, Di Russo F, McDonald JJ, Hillyard SA. Effects of spatial congruity on audio-visual multimodal integration. *J Cogn Neurosci*. 2005; 17:1396–1409. [PubMed: 16197693]
- Teder-Salejari WA, McDonald JJ, Di Russo F, Hillyard SA. An analysis of audio-visual crossmodal integration by means of event-related potential (ERP) recordings. *Brain Res Cogn Brain Res*. 2002; 14:106–114. [PubMed: 12063134]
- Tye-Murray N, Sommers MS, Spehar B. Audiovisual integration and lipreading abilities of older adults with normal and impaired hearing. *Ear Hear*. 2007; 28:656–668. [PubMed: 17804980]
- Tye-Murray N, Sommers M, Spehar B, Myerson J, Hale S. Aging, audiovisual integration, and the principle of inverse effectiveness. *Ear Hear*. 2010; 31:636–644. [PubMed: 20473178]
- Ventry IM, Weinstein BE. Identification of elderly people with hearing problems. *ASHA*. 1983; 25:37–42. [PubMed: 6626295]
- Verghese J, Wang C, Lipton RB, Holtzer R, Xue X. Quantitative gait dysfunction and risk of cognitive decline and dementia. *J Neurol Neurosurg Psychiatry*. 2007; 78:929–935. [PubMed: 17237140]
- Verrillo RT, Bolanowski SJ, Gescheider GA. Effect of aging on the subjective magnitude of vibration. *Somatosens Mot Res*. 2002; 19:238–244. [PubMed: 12396581]
- Wallace MT, Wilkinson LK, Stein BE. Representation and integration of multiple sensory inputs in primate superior colliculus. *J Neurophysiol*. 1996; 76:1246–1266. [PubMed: 8871234]
- Weinstein BE. Validity of a screening protocol for identifying elderly people with hearing problems. *ASHA*. 1986; 28:41–45. [PubMed: 3718608]

- Yesavage JA, Brink TL, Rose TL, Um LO, Huang V, Adey M, Leirer VO. Development and validation of a geriatric depression rating scale: A preliminary report. *J Psych Res.* 1983; 17:37–49.
- Yueh B, Shapiro N, MacLean CH, et al. Screening and management of adult hearing loss in primary care: Scientific Review. *JAMA.* 2003; 289:1976–1985. [PubMed: 12697801]
- Yordanova J, Kolev V, Hohsbein J, Falkenstein M. Sensorimotor slowing with ageing is mediated by a functional dysregulation of motor-generation processes: Evidence from high-resolution event-related potentials. *Brain.* 2004; 127:351–362. [PubMed: 14607784]
- Zikopoulos B, Barbas H. Prefrontal projections to the thalamic reticular nucleus form a unique circuit for attentional mechanisms. *J Neurosci.* 2006; 26:7348–7361. [PubMed: 16837581]

Research Highlights

1. All participants were significantly faster at responding to multisensory stimuli compared to unisensory stimuli, regardless of sensory combination.
2. RT facilitation was significantly greater in multisensory conditions containing somatosensory stimulation (i.e., **AS** and **VS**).
3. Older adults exhibited greater reaction time facilitation as compared to younger adults in the multisensory **VS** condition.

a)

b)

Figure 1. Averaged RT data by modality and group

Mean values (with SEM bars) of each multisensory pairing placed directly next to the constituent unisensory mean values for (a) old and (b) young adults.

Cumulative Probability Models by Group and Modality

Figure 2. Cumulative Probability Model Results

Actual (black lines) and predicted (grey lines) cumulative probability for each of the three multisensory pairs for old (left column) and young (right column) adults over percentiles.

Test of the Race Model by Group and Sensory Modality

Figure 3. Test of the Race Model

These graphs depict the probability difference waves (actual minus predicted probability) for old adults (gray lines) and young adults (black lines) over percentiles for AS, AV, and VS multisensory pairs. The gray boxes delineate the first quartile of responses for each modality; values greater than zero indicate race model violation (i.e., co-activation).

Figure 4. Experimental Procedures

a) The first column is a complete listing of the six sensory conditions employed in the current study. **V**=visual, **A**=auditory, **S**=somatosensory, **AV**=audio-visual, **AS**=audio-somatosensory, and **VS**=visual somatosensory stimuli. The second column delineates the exact placement and duration of the various sensory stimuli. b) Participants sat comfortably on a chair looking a video monitor, with headphones on their ears and somatosensory stimulators on their index or middle finger. They responded to all stimulation by pressing the foot pedal under their right foot.

Table 1

Demographic Information for Old (n=18; 11 female) and Young (n=18; 11 female) Groups

	Old (M±SD)	Range	Young (M±SD)	Range	p value
Age (years)	76.44 (7.91)	63 – 89	19.17 (2.66)	17–28	<0.01
Education (years)	12.94 (2.13)	7 – 16	13.00 (1.68)	10 – 17	0.93
MMSE Score	28.67 (1.33)	27 – 30	29.67 (0.49)	29 – 30	<0.01
Global Health Status	1.11 (0.83)	0 – 3	0.00 (0.00)	0	<0.01
Overall RT	421.64 (119.01)	253 – 690	329.17 (73.82)	232 – 547	<0.01
BAI	3.61 (2.64)	0 – 9	2.39 (2.43)	0 – 6	0.16
GDS	4.67 (3.43)	0 – 11	3.11 (3.64)	0 – 16	0.20
Somatosensory (volts)	108.89 (22.79)	80 – 155	81.67 (16.18)	60 – 120	<0.01
Auditory (HHIE score)	3.33 (5.49)	0 – 18	0.00 (0.00)	0	<0.05