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The effect of multisensory cues on attention in aging

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Abstract

The attention network test (ANT) assesses the effect of alerting and orienting cues on a visual flanker task measuring executive attention. Previous findings revealed that older adults demonstrate greater reaction times (RT) benefits when provided with visual orienting cues that offer both spatial and temporal information of an ensuing target. Given the overlap of neural substrates and networks involved in multisensory processing and cueing (i.e., alerting and orienting), an investigation of multisensory cueing effects on RT was warranted. The current study was designed to determine whether participants, both old and young, benefited from receiving multisensory alerting and orienting cues. Eighteen young ($M = 19.17$ years; 45% female) and eighteen old ($M = 76.44$ years; 61% female) individuals that were determined to be non-demented and without any medical or psychiatric conditions that would affect their performance were included. Results revealed main effects for the executive attention and orienting networks, but not for the alerting network. In terms of orienting, both old and young adults demonstrated significant orienting effects for auditory-somatosensory (AS), auditory-visual (AV), and visual-somatosensory (VS) cues. RT benefits of multisensory compared to unisensory orienting effects differed by cue type and age group; younger adults demonstrated greater RT benefits for AS orienting cues whereas older adults demonstrated greater RT benefits for AV orienting cues. Both groups, however, demonstrated significant RT benefits for multisensory VS orienting cues. These findings provide evidence for the facilitative effect of multisensory orienting cues, and not multisensory alerting cues, in old and young adults.

Keywords

Multisensory integration; Alerting; Orienting; Executive attention; Aging

1. Introduction

On a daily basis, individuals receive a wealth of sensory information that is either processed or ignored depending upon various stimulus characteristics. While much of the irrelevant information is filtered, research suggests that salient sensory information, especially salient information that pops-out in a stimulation stream (Talsma et al., 2010), is processed

simultaneously across various sensory modalities such that objects and events are detected rapidly and responded to correctly (Calvert et al., 2004). Integration of sensory information has been linked to both (1) basic stimulus properties including time, space, and magnitude (Meredith and Stein, 1986, 1996; Meredith et al., 1987; Stein et al., 1988; Stein and Meredith, 1990, 1993; Wallace et al., 1996) and (2) higher-order cognitive functions including attention (Alsius et al., 2005, 2007; Hugenschmidt et al., 2009; Mozolic et al., 2008; Talsma and Woldorff, 2005; Talsma et al., 2007, 2010). These integrative effects typically vary depending upon the stimuli employed and the nature of the experimental task.

To date, many studies have reported the facilitative RT benefit of responding to simultaneous multisensory events (**AS**, **AV**, and **VS**) over unisensory events using simple reaction time (RT) tests in both young (Harrington and Peck, 1998; Molholm et al., 2002; Murray et al., 2005; Pavani et al., 2000; Teder-Salejarvi et al., 2002, 2005) and old adults (Mahoney et al., 2011; Peiffer et al., 2007). Furthermore, Diederich and Colonius (2004) revealed significantly faster RTs to trimodal over bimodal simultaneous sensory events in young adults. Collectively, these simple reaction time studies provide evidence for basic multisensory processing in old and young adults.

In terms of higher order multisensory processing, Spence and colleagues provide a framework for the facilitative effects of crossmodal selective attention and crossmodal spatial attention in young adults (Spence et al., 2000a, 2000b, 2002; Spence and Santangelo, 2009; Spence, 2010). While there is some evidence for increased difficulty on selective attention tasks in older adults (Diaz and Amenedo, 1998; Valeriani et al., 2003), the majority of these investigations have typically employed unimodal stimuli. Only a few studies to date have examined the effect of age on crossmodal selective attention mechanisms. For example, Poliakoff et al. (2006) used a selective attention paradigm where participants were asked to make elevation judgments for vibrotactile stimuli, while ignoring concurrent visual distractor stimuli that were spatially congruent or incongruent. Results from this study revealed impaired cross-modal selective attention for older adults, as they demonstrated increased difficulty responding to somatosensory stimuli when asked to simultaneously ignore visual distractor stimuli.

Despite limited evidence for increased multisensory integration in older adults for **AV** (Laurienti et al., 2006; Peiffer et al., 2007) and **VS** (Mahoney et al., 2011) combinations using simple-reaction time or forced-choice paradigms, there is a paucity of studies examining the direct effect of multisensory cues on visual attention tasks. Hugenschmidt et al. (2009) investigated the effect of **AV** multisensory cues and modality-specific attention cues (e.g., attend auditory or attend visual) on performance in old and young adults. Results from this study revealed that relative to young adults, older adults demonstrated increased multisensory integration benefits, for both selective and divided attention conditions, with the greatest integration demonstrated for divided attention cues. Reductions in multisensory integration were present for both age groups when provided with selective attention over divided attention cues.

In an effort to tease apart aspects of a complex construct that we call attention, Posner and colleagues developed a visual experimental paradigm referred to as the attention network test (ANT) that simultaneously investigates the effects of alerting, orienting, and executive attention, as well as their possible interactions (Fan et al., 2002, 2003, 2005; Fan and Posner, 2004; Posner and Petersen, 1990; Posner et al., 2006; Posner and Rothbart, 2007; Raz and Buhle, 2006). These attention networks vary in terms of their neuroanatomical substrates (Fan et al., 2002, 2005, 2007; Konrad et al., 2005; Niogi et al., 2010; Posner and Petersen, 1990) and associations with genetic polymorphisms (Fan et al., 2003; Fossella et al., 2002). The visual ANT is a reliable paradigm that has been implemented in many different clinical

populations, across the lifespan (see Mahoney et al., 2010 for review). Unlike selective attention paradigms, the ANT requires participants to attend to the visual cues and use the temporal and spatial information provided by the cues to respond to the ensuing target stimulus. The executive attention task necessitates integrative involvement of various brain regions as it requires successful online monitoring, stimulus detection, conflict resolution, as well as the production of accurate behavioral responses.

Age effects on visual attention networks have been examined using other experimental manipulations than the ANT. Tales et al. (2002) used a reaction time task with visual alerting cues and reported comparable benefits of alerting in both young and old groups. Similarly, intact phasic alerting in healthy aging and in Alzheimer's disease (AD) patients was found using a choice RT task with alerting cues (Nebes and Brady, 1993). Experiments using peripheral spatial cueing paradigms revealed comparable exogenous orienting in young and old adults (Folk and Hoyer, 1992; Hartley et al., 1990; Lincourt et al., 1997). Using the covert orienting of visual attention task to measure inhibition of return or reorienting, preserved exogenous orienting in aging was also reported (Danckert et al., 1998; Hartley and Kieley, 1995). Thus, there is clear evidence to suggest relatively intact visual alerting and visual orienting in older adults; however, the effects and interactions of alerting, orienting, and executive attention using multisensory cues in non-demented older adults and young adults has yet to be reported.

Therefore, using a modified multisensory ANT paradigm (see Section 4.4), the current study was specifically designed to test the hypothesis that multisensory orienting cues that provide preparatory spatial and/or temporal information would lead to greater RT facilitation on a visual flanker task than multisensory alerting cues that only provide spatial information. Given the well-documented RT benefit demonstrated from both visual orienting cues and from various multisensory cue combinations, we predicted that both old and young adults would benefit from receiving multisensory orienting cues over alerting cues, and that such facilitative orienting effects would vary as a function of age and sensory combination.

2. Results

2.1. Demographics

Eighteen old individuals (mean age of 76.44, ± 7.91 years; 61% female) and eighteen young individuals (mean age of 19.17, ± 2.66 years; 45% female) participated in the current study. All participants were considered to be non-demented as determined by their mini-mental status examination (MMSE) scores and relatively healthy as determined by their global health status (GDS; see Table 1). Table 1 also delineates mean education level (in years), overall reaction time (RT; in ms), overall accuracy, Beck anxiety inventory (BAI) scores, and hearing handicap inventory for the elderly (HHIE) scores, and mean values for somatosensory 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, overall accuracy and sensory screening levels. Table 2 depicts the mean RTs and standard deviations (in parentheses) to target stimuli preceded by each sensory cue type for unisensory averaged (*U*) and multisensory combined (*M*) conditions for both old and young adults. Additionally, the shaded columns in Table 2 represent the calculated attention network effects (in milliseconds) for each sensory cue type for old and young adults.

2.2. Descriptive and linear mixed effects model (LMEM) results

ANT performance accuracy was high for old adults (88%), but was significantly higher for young adults (98%). Nevertheless, high accuracy scores indicated that the participants

understood the instructions and were able to reliably determine the direction of the target stimulus. As expected, younger adults performed significantly faster ($M = 719.7$, $SD = 66.25$ ms,) than older adults ($M = 1001.60$, $SD = 125.48$ ms) on the visual flanker task.

Results from the linear mixed effects model (LMEM; see Table 3), which adjusted for speed of processing, gender, education and global health status revealed a main effect of flanker type (Table 3, #1; $p < .01$). The flanker $\times$ age group interaction was significant ($p < 0.01$), revealing that regardless of cue type, the ability to resolve conflict differed by chronological age. That is, younger adults ($M = 126.54$, $SD = 39.11$) demonstrated significantly better ability to resolve conflict than older adults ($M = 151.94$, $SD = 42.52$). With regard to the cues, there was no significant effect for multisensory alerting cues (Table 3, #1; $p = .15$) and the interaction between alerting $\times$ age group was not significant. These findings suggest that relative to no cues, neither **AS**, **AV**, nor **VS** multisensory or unisensory-averaged alerting cues enhanced performance in old compared to young adults (see Table 2 for descriptive data). Thus, no further analyses were conducted using alerting cues¹.

There was a main effect of multisensory orienting cues (Table 3, 1; $p < .01$). Further, the interaction of orienting $\times$ age group was significant and revealed that relative to the bilateral multisensory and unisensory-averaged alerting cues, orienting cues enhanced performance significantly greater in young adults as compared to old adults across **all three** sensory combinations (see Table 2 for descriptive data and network effects and Table 3, 2). Given the significant age $\times$ orienting interaction, stratified analyses were also conducted to determine differences between orienting sensory cue types within each age group. Results revealed significant orienting network effects across all three sensory conditions ($p < .01$) for both old (Table 3, 3) and young adults (Table 3, 4).

Within the same LMEM, further comparisons were necessary to determine potential multisensory cueing benefits within old and young adults. These effects are listed in Table 3 for each sensory condition (**AS**, **AV**, or **VS**) and are called *Orienting: Mult vs. Uni Average* for each combination. First, the interaction of orienting $\times$ multisensory combination $\times$ age group was investigated across each of the three sensory combinations (Table 3, 2). Results suggest that the difference in multisensory vs. unisensory-averaged **AS** orienting networks was significantly greater in young adults as compared to old adults ($p = .04$); these results are visually depicted in Fig. 1. This three-way interaction was not significant for the **AV** ($p = .75$) nor **VS** ($p = .58$) condition. Stratified analyses by age group revealed that relative to alerting cues, multisensory orienting cues enhanced performance greater than unisensory combined orienting cues differentially by age group. That is, old adults demonstrated significant multisensory orienting effects for **AV** and **VS** conditions (see Table 3, 3), while young adults demonstrated significant multisensory orienting effects for **AS** and **VS** conditions (see Table 3, 4).

2.3. Summary of results

Overall, older adults demonstrated slower RTs and poorer ability to resolve conflict as compared to younger adults. Neither old nor young adults demonstrated significant overall alerting cue benefits; however the young adults did specifically benefit from receiving **AV** alerting cues. In terms of orienting cues, both old and young adults demonstrated significant orienting effects across all three sensory combinations. However, old adults demonstrated significant multisensory orienting effects for sensory combinations that included visual information (i.e., **AV** and **VS**), whereas young adults demonstrated significant multisensory

¹Table 3 depicts a stratified analyses for old (see 3) and young (see 4) individuals. The **AV** alerting effect (**AV** alert cues vs. no cues) was only significant ($p = .04$) for young adults; all other alerting effects were not statistically significant.

orienting effects for sensory combinations that included somatosensory information (i.e., **AS** and **VS**). Taken together, these results provide evidence for differential facilitative effects of multisensory orienting and not alerting cues across sensory combination and age group.

3. Discussion

3.1. Summary of findings

As expected, participants were significantly faster at responding to congruent compared to incongruent flankers, regardless of sensory cue combination; thus revealing significant executive attention network effects for both old and young adults. The executive attention network differed by age group, with young adults demonstrating significantly better ability to resolve conflict compared to older adults, regardless of cue type. Significant orienting network effects were also found across all three multisensory combinations in old and young adults after adjusting for overall speed of processing, gender, education and global health status. However, regardless of multisensory combination, younger adults demonstrated significantly greater orienting benefits than older adults. Further comparisons were required to determine potential benefits of multisensory cueing between old and young adults. These results revealed that the difference in the multisensory vs. unisensory-averaged **AS** orienting network was significantly greater for younger adults as compared to older adults; multisensory orienting effects that were not apparent for the **AV** or **VS** conditions. Stratified analyses within each age group revealed that relative to alerting cues, multisensory orienting cues enhanced performance greater than unisensory combined orienting differentially for old and young adults. That is, old adults demonstrated the greatest RT benefit when they received multisensory **AV** or **VS** orienting cues while young adults demonstrated the greatest RT benefit when they received multisensory **AS** or **VS** orienting cues. These results suggest equal multisensory **VS** orienting benefits for both old and young adults (see Section 3.2.2).

Interestingly, the orienting network has been linked to activation in brain regions including but not limited to the superior parietal lobes, superior colliculus, and thalamus (Corbetta et al., 2000; Corbetta and Shulman, 2002)—brain regions that all contain multisensory neurons (see Calvert et al., 2004; Meredith and Stein, 1986; Molholm et al., 2006; Stein et al., 2009; Stein and Meredith, 1993). Although admittedly speculative, the robust RT benefit observed in **VS** orienting cues may be attributed to shared neural networks sub-serving both multisensory and spatial information. Further investigation is clearly warranted.

3.2. Differential multisensory cueing effects

3.2.1. Alerting—As predicted, multisensory alerting cues that provide warning prompts to prepare for ensuing target stimuli were not facilitative overall with regard to a visual conflict resolution task across both age groups; although young adults did benefit from receiving specific **AV** alerting cues. Overall, when presented with more than one pair of bilateral sensory inputs (e.g., somatosensory pulses with concurrent visual asterisks), both age groups demonstrated multisensory alerting effects that were not facilitative and not comparable to those previously described using unisensory visual alerting cues (Fernandez-Duque and Black, 2006; Mahoney et al., 2010; Tales et al., 2002). Interestingly, this phenomenon occurred regardless of chronological age, implying that the effect cannot solely be explained by healthy aging. Thus, it appears as though multisensory temporal cues alone do not provide ample information to aid in conflict resolution; a finding that is not novel. Work from Laurienti et al. (2004) and Mozolic et al. (2008) has revealed that in addition to temporal or spatial information, semantic content of a multisensory event is necessary as it provides critical information regarding how to effectively combine sensory information which subsequently enhances behavioral performance. Taken together, our results

demonstrate that participants did not benefit from receiving two concurrent sets of bilateral sensory cues that offer spatially non-specific preparatory information. In fact, multisensory alerting cues were actually distractive to our participants, regardless of age.

3.2.2. Orienting—Contrary to the effects of the alerting network, the orienting network was significant for both old and young adults. While young adults demonstrated greater orienting effects than old adults, the difference between the alerting and orienting cues was significant for both age groups. Results from this study reveal that in order for multisensory cues to be effective on a visual conflict resolution task, they must concurrently prompt the individual about the occurrence of a target, while also providing the exact spatial location of the target.

Given the similar **VS** orienting benefits across young and old adults and the fact that older adults benefit the most from orienting cues that contain visual information (i.e., **VS** and **AV** orienting cues), the following two questions arise: (1) why is multisensory **VS** orienting beneficial across the lifespan and (2) why do older results rely more heavily on visual cues, while younger adults rely on somatosensory cues? One plausible explanation could be related to the notion that sensory processing varies across age groups due to the necessary recruitment of additional neural resources by older individuals to compensate for age-related changes in brain architecture in order to maintain performance (Stern et al., 2000, 2005); but such an account does not explain the benefit of multisensory **VS** orienting found here or the fact that older adults demonstrate the greatest multisensory benefit when responding directly to **VS** inputs (Mahoney et al., 2011). Given the concordance of these two findings in aging, it is clear that the combination of visual-somatosensory inputs is beneficial to older adults for both basic and higher-order multisensory processing. Such a finding in non-demented older adults further supports claims made by Talsma and colleagues (2010) in a detailed review emphasizing the role of a “multifaceted interplay” between multisensory integration and attention. Future studies should focus on identifying the neurobiological substrates of visual-somatosensory integration in aging in an effort to provide greater insight to the underlying structural and functional substrates that sub-serve age-related **VS** multisensory enhancement.

3.3. Conclusions

In summary, the current study provides initial evidence for the differential facilitative effect of multisensory orienting across sensory combination and age group. Younger adults demonstrated greater RT benefits for **AS** and **VS** orienting cues whereas older adults demonstrated greater RT benefits for **AV** and **VS** orienting cues. Given the overlap of neural correlates involved in multisensory processing and orienting, especially in the superior colliculus, thalamus, superior temporal and parietal regions, such multisensory orienting effects across the lifespan are perhaps not surprising. However, the fact that multisensory alerting cues were distracting, and not facilitative, across age groups suggests that too much non-specific information can confuse participants, regardless of their age. Taken together, the current study provides initial evidence for differential facilitative effects of multisensory orienting cues by sensory combination and age group.

4. Experimental procedure

4.1. Participants

Eighteen (8 female) young and eighteen (11 female) old adults participated in the current study and most of these participants were also enrolled in our recent multisensory simple reaction time study (see Mahoney et al., 2011 for results). 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. All participants were required to speak English. Exclusion criteria for all participants included severe auditory disturbances 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 in accordance with the *Declaration of Helsinki* and approved by the Committee on Clinical Investigation (CCI; the institutional review board of the Albert Einstein College of Medicine).

4.2. Cognitive and 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 be optimal for correctly identifying cognitive impairment in older populations of higher educated individuals (O'Bryant et al., 2008). Participants were also screened for depression using the 30 item geriatric depression scale (GDS; Yesavage et al., 1982) and for anxiety using the 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, 2008; Mahoney et al., 2010, 2011; 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, 2000, and 4000 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) questionnaire which is specifically designed to measure the degree of social and emotional handicap from hearing loss (Ventry and Weinstein, 1983; Weinstein, 1986). Scores on the HHIE questionnaire range from 0 (no handicap) to 40 (maximum handicap).

As in our previous study (Mahoney et al., 2011), each individual received an initial somatosensory screener test where a pulse of 30 V was gradually increased by 5 V in an effort 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 at a level 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 V) higher for old as compared to young adults; a finding that is in keeping with findings 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 and task procedures

The stimuli employed in Posner and colleagues' visual ANT were rows of five black lines with arrowheads that pointed leftward or rightward, and appeared directly above or below a central fixation cross (Fan et al., 2002; Fan and Posner, 2004; Fan et al., 2005; Posner et al., 2006). The target stimulus was the central arrow, and was always surrounded by two flanker arrows on each side that provided either no (two dashes on each side of the central arrow), congruent (two arrows on each side that point in the same direction as the central target stimulus), or incongruent (two arrows on each side that point in the opposite direction of the central target stimulus) information regarding the target stimulus. In the case of the incongruent flanker condition, the conflicting information typically causes an interference that results in an increase in the time required to respond to the target relative to the congruent flanker condition.

The traditional warning cues that precede each target trial included: no cue, center cue, double cue, and orient cues. Alerting cues indicated that the target stimulus was about to appear, thus providing only temporal information. The orienting cues, however, provided both temporal and spatial information with respect to the ensuing target stimulus. The actual warning cue was an asterisk (*) that was presented in the center of the screen for center cue conditions, above and below central fixation for double cue conditions, and either above or below central fixation for the spatial cue conditions. In the case of the no cue condition, the fixation point (+) remained visible until the target stimuli was displayed. The no cue condition served as the control, whereas the double and center cue conditions measured alerting, and the spatial cues (either above or below fixation) measured orienting. The stimuli that followed the no, central, and double cue conditions were centrally presented; however, the stimuli that followed the spatial cue conditions were presented 1.06° above or below central fixation depending upon the location of the orienting cue. This visual angle of 1.06° above and below fixation also corresponded to the placement of the asterisks for the double and spatial cue conditions.

The current study employed a modified version of the traditional ANT where various unisensory and multisensory alerting and orienting cues preceded the visual target stimulus. All visual stimuli were presented on a 17" computer monitor and participants sat at a fixed distance of 75 cm away from the visual display (see Fig. 2). As in the traditional visual ANT, the central "target" arrow was surrounded by two flanker arrows on either side that pointed in the same (congruent trials) or opposite direction (incongruent trials). The height of the arrows was 0.64 cm, the width of the arrows was 4.41 cm, and the luminosity of the arrows was 253.99 cd/m² for both congruent and incongruent flanker conditions. All target stimuli were presented laterally (3.64° to the left or right of the fixation cross).

The chief modification in this ANT paradigm was the addition of unisensory auditory (**A**) and unisensory somatosensory (**S**) cues to the original visual (**V**) cues. Additionally, three multisensory combination cues (**AS**: auditory-somatosensory; **AV**: auditory-visual; and **VS**: visual-somatosensory) were added to the current paradigm. Taken together, there were a total of six sensory alerting cues and six sensory orienting cues. Additionally, the no cue, or control condition, was included and during this condition the central fixation point (+) was visible until the target was displayed. While the unisensory cues were examined independently to investigate the effects of unisensory cueing, the express purpose of this experiment was to examine the effects of multisensory cueing by comparing each multisensory combination to the average of the respective unisensory cues (e.g., **AS**_alert vs. (**A+S**)/2_alert); see Section 4.5 below for more information).

Here, the alerting cues were bilateral presentations of visual asterisks, auditory tones, individually optimized somatosensory pulses, or any combination of two unisensory cues presented for a total duration of 100 ms. 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, 5 ms 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; range 60–120 V) 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).

Fig. 2 panel a depicts the no cue and the six bilateral sensory alerting cue conditions. The orienting cues were presented 3.64° either to the left or to the right of the central fixation cross at the exact location of the subsequent target stimulus. This modification to the original ANT afforded lateralized cues across all sensory combinations, especially in the case of the somatosensory cues. Importantly, the constituents of the multisensory orienting cues were always presented to the same side. Given the high correlation between (1) the congruent and neutral flankers and (2) the double and central alert cues reported by Mahoney et al. (2010), the neutral flankers and the center cues were not included in the current experimental paradigm.

Psychophysical data (reaction time (RT) and accuracy) was collected as participants performed a forced-choice reaction time task. Participants received one practice block consisting of 24 trials and were required to attain 75 % or higher accuracy to proceed to the three experimental blocks consisting of 208 trials per block. Of the 208 stimuli, 104 target trials were surrounded by congruent flankers and 104 target trials were surrounded by incongruent flankers. Each of the 13 cue conditions equally preceded the congruent and incongruent flanker stimuli and all stimuli were presented in a random order across all three blocks. Fig. 2 panel b illustrates the time course of events in this modified ANT paradigm. Since the somatosensory electrodes were taped to the their fingers, the participants were required to make left or a right foot pedal presses in response to the direction of the central arrow (see Fig. 2 panel c). During the test, participants were required to fixate a central fixation point (a black cross) visible on the computer monitor and respond to each stimulus as quickly as possible without making errors. Participants were encouraged to take breaks as necessary between blocks to reduce fatigue effects and to facilitate performance. Consistent with previous studies, reaction times to accurate responses were only included in the statistical analyses (Fan et al., 2002, 2003; Mahoney et al., 2010).

4.5. Attention network analysis

As previously mentioned, the ANT paradigm implemented in the current study consisted of two flankers (congruent and incongruent), and thirteen cue conditions². Individual median values were calculated across trials for each condition to avoid the influence of outliers. Each attention network was calculated using simple subtractions to determine the influence of flankers (executive attention), alerting cues, and orienting cues on RTs (see Fan et al., 2002). For the **executive attention** network, the averaged mean RT of all *congruent trials* was subtracted from the averaged mean RT of all *incongruent trials*. For the **alerting** attention network, the averaged mean RT of trials containing *bilateral alerting cues* was subtracted from the averaged mean RT of trials containing *no cues*. The *bilateral alerting*

²The thirteen sensory cues were comprised of a no cue, six alerting sensory cues (three multisensory and three combined unisensory conditions) and six orienting sensory cues (three multisensory and three combined unisensory conditions).

cues were designed to enhance alertness by providing the subject with a temporal cue to prepare attentional resources for the ensuing target, whereas the *no cue* trials served as the control. The **orienting** attention network was obtained by subtracting the averaged mean RT of trials containing *orienting cues* from the averaged mean RT of trials containing *bilateral alerting cues*. The *orienting cues* provide both temporal and spatial information with respect to the appearance of the target stimulus. Therefore, the derivation of the orienting attention network represents the incremental effect of spatial cues as compared to temporal alerting cues on ANT performance. While larger alerting and orienting network scores are indicative of faster cue-related performance, larger executive attention network scores are indicative of worse performance (i.e., longer RTs required for conflict resolution). The attention networks were calculated across all cue types to determine overall effects of alerting, orienting and executive attention. Further comparisons were calculated to investigate the effects of age, cue type, sensory modality, and their interactions on RT performance.

Given that the current study was specifically designed to investigate potential benefits of multisensory cueing in aging, the three attention networks were individually calculated for each of the three multisensory combinations using mean RTs of averaged unisensory conditions vs. respective multisensory conditions for each flanker and cue type. For example, to examine combined unisensory cueing in the **AS** alerting network, the averaged mean RT of both auditory and somatosensory *alert cue trials* $(A+S)/2$ was compared to the mean RTs of the *no cue trials* across both age groups; thus yielding a unisensory-averaged **AS** alerting network (e.g., $[No\ cue - (A+S)/2_alert\ cues] = Uni\ Avg\ AS\ alerting\ network$). The multisensory **AS** alerting network was derived by comparing RTs to trials containing **AS alert cues** to the RTs of trials containing *no cues* across both age groups. Differences between unisensory-averaged attention networks and multisensory attention networks were examined for **AS**, **AV**, and **VS** combinations in an effort to understand potential benefits of multisensory alerting and orienting across age groups.

4.6. Linear mixed effect model (LMEM)

The effects of attention networks, their interactions and the benefit of different multisensory cueing, flanker, and age group on RT were assessed using a linear mixed effect model (LMEM), adjusting for gender, education, global disease status and processing speed (Salthouse, 1985). All statistical analyses were run using SAS 9.2 (SAS Institute Inc., Cary, N.C) statistical software. A random intercept was included in the model to allow the entry point to vary across individuals. The model consisted of a two level flanker (congruent and incongruent) and a thirteen level cue defined by cue type and sensory combination (No, **AS**_alert, $(A+S)/2_alert$, **AV**_alert, $alert_ (A+V)/2$, alert_**VS**, $alert_ (V+S)/2$, orient_**AS**, $orient_ (A+S)/2$, orient_**AV**, $orient_ (A+V)/2$, orient_**VS**, and $orient_ (V+S)/2$). Inverse transformation for RT $(1/RT \times 1000)$ was applied to achieve normality and variance stabilization of differences in speed of processing between old and young participants. The advantage of the linear mixed effects model (LMEM) is that the heterogeneity and correlation of repeated measures under different conditions are taken into account (Laird and Ware, 1982).

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Abbreviations

MSI	Multisensory integration
ANT	Attention network test
AS	Auditory-somatosensory
AV	Auditory-visual
VS	Visual-somatosensory

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Fig. 1. Experimental Design

(a) A complete list of the six sensory cues where V = visual, A = auditory, S = somatosensory, AV = audio-visual, AS = audio-somatosensory, and VS = visual somatosensory. Note that alerting, or bilateral representations, are depicted in Panel a; however, orienting cues are represented by lateralized (left OR right placement) of the respective sensory cues. (b) Panel b represents the time course of events for the attention network test (also see Fan et al., 2002). (c) Participants sat comfortably on a stationary chair looking at a computer monitor with headphones on their ears and somatosensory stimulators on their index or middle fingers. Their task was to respond to the direction of the central arrow (left or right) for each target stimulus by pressing either the left or right foot pedal.

Fig. 2. Multisensory vs. unisensory orienting effects by sensory combination and age group
 Panel a illustrates orienting effects in old adults for unisensory averaged (dark green bars) and multisensory (light green bars) AS, AV, and VS conditions. Significant differences in RT benefit between unisensory averaged and multisensory AV and VS orienting cues are depicted. Note that there was no significant difference in RT benefit between unisensory-averaged and multisensory AS orienting cues for old adults. Panel b illustrates orienting effects in young adults for unisensory averaged (dark blue bars) and multisensory (light blue bars) AS, AV, and VS conditions. Significant differences in RT benefit between unisensory-averaged and multisensory AS and VS orienting cues are depicted. However, there was no significant difference in RT benefit between unisensory-averaged and multisensory AV

orienting cues for young adults. The difference in multisensory vs. unisensory-averaged AS orienting was significantly greater in young adults as compared to old adults. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1

Demographic information for old ($n = 18$; 11 female) and young ($n = 18$; 8 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	28.61 (1.42)	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	1001.60 (125.48)	810–1239	719.77 (66.25)	647–864	<0.01
Overall accuracy	0.88 (0.10)	0.67–0.99	0.98 (0.02)	0.93–1.00	<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 (V)	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

Summary of reaction times (SD) to unisensory-averaged (*U*) and multisensory (*M*) cues and concomitant attention networks for each of the three sensory combinations by age group.

Table 2

Sensory combination	Age group	Uni (<i>U</i>) or multi (<i>M</i>) sensory cue ^a	Cue type			Network		
			No	Alert	Orient	Alerting	Orienting	Executive attention
AS	Old	<i>U</i>	1005 (140)	1000 (121)	985 (120)	5	15	158
		<i>M</i>	1005 (140)	988 (116)	970 (156)	17	18	152
	Young	<i>U</i>	731 (53)	719 (63)	692 (72)	12	27	128
		<i>M</i>	731 (53)	725 (57)	670 (76)	6	55	126
AV	Old	<i>U</i>	1005 (140)	997 (128)	975 (130)	8	22	156
		<i>M</i>	1005 (140)	1002 (123)	948 (158)	3	53	143
	Young	<i>U</i>	731 (53)	714 (54)	662 (76)	17	52	126
		<i>M</i>	731 (53)	718 (52)	651 (73)	13	67	126
VS	Old	<i>U</i>	1005 (140)	1001 (122)	993 (138)	4	8	156
		<i>M</i>	1005 (140)	1009 (131)	967 (143)	-4	43	155
	Young	<i>U</i>	731 (53)	721 (54)	677 (74)	10	44	124
		<i>M</i>	731 (53)	718 (58)	652 (82)	13	66	132

^aWhere multi (*M*) cue represents RT of target stimulus preceded by a simultaneous combination of sensory cues and uni (*U*) cue represents RT of target stimulus preceded by the average of the constituent unisensory cues.

Table 3

Linear mixed effect model results for: (1) Overall attention network effects across age groups; (2) Interactions of attention networks by age group and sensory combination; (3) Attention networks effects for old adults by sensory combination; (4) Attention networks effects for young adults by sensory combination; (5) Adjustments.

No.	Group/adjustment	Condition	Estimate	95 % confidence interval		SE	P value
				Lower	Upper		
(1)	Overall Attention Networks	Executive attention	0.21	0.20	0.22	0.00	<0.01
		Alerting	-0.01	-0.03	0.00	0.01	0.15
		Orienting	-0.07	-0.08	-0.06	0.01	<0.01
(2)	Attention Networks by group	Executive attention	0.11	0.09	0.12	0.01	<0.01
		AS alerting	0.01	-0.03	0.04	0.02	0.62
		AV alerting	0.02	-0.01	0.06	0.02	0.22
		VS alerting	0.03	-0.01	0.06	0.02	0.13
		AS orienting	0.07	0.05	0.10	0.01	<0.01
		AV orienting	0.10	0.07	0.12	0.01	<0.01
		VS orienting	0.10	0.07	0.13	0.01	<0.01
		AS orienting: Mult vs. Uni average	0.03	0.00	0.05	0.01	0.04
		AV orienting: Mult vs. Uni average	0.00	-0.03	0.02	0.01	0.75
		VS orienting: Mult vs. Uni average	0.01	-0.02	0.03	0.01	0.58
(3)	Cue effects in olds	Executive attention	-0.16	-0.17	0.15	0.01	<0.01
		AS alerting	-0.01	-0.03	0.01	0.01	0.38
		AV alerting	-0.01	-0.03	0.02	0.01	0.57
		VS alerting	0.00	-0.02	0.03	0.01	0.76
		AS orienting	-0.02	-0.04	0.00	0.01	0.01
		AV orienting	-0.04	-0.06	-0.02	0.01	<0.01
		VS orienting	-0.03	-0.04	-0.01	0.01	<0.01
		AS orienting: multi vs. Uni average	0.00	-0.02	0.01	0.01	0.60
		AV orienting: Multi vs. Uni average	-0.02	-0.04	0.00	0.01	0.02
		VS orienting: Multi vs. Uni average	-0.02	-0.04	0.00	0.01	0.02
(4)	Cue effects in youngs	Executive attention	-0.26	-0.27	0.25	0.01	<0.01
		AS alerting	-0.02	-0.05	0.01	0.01	0.19

No.	Group/adjustment	Condition	Estimate	95 % confidence interval		SE	P value
				Lower	Upper		
		AV alerting	-0.03	-0.06	0.00	0.01	0.04
		VS alerting	-0.02	-0.05	0.00	0.01	0.10
		AS orienting	-0.09	-0.11	-0.07	0.01	< 0.01
		AV orienting	-0.14	-0.16	-0.12	0.01	< 0.01
		VS orienting	-0.13	-0.15	-0.11	0.01	< 0.01
		AS orienting: Multi vs. Uni average	-0.03	-0.05	-0.01	0.01	< 0.01
		AV orienting: Multi vs. Uni average	-0.02	-0.04	0.01	0.01	0.15
		VS orienting: Multi vs. Uni average	-0.03	-0.05	-0.01	0.01	0.01
(5)	Adjustments	Gender	-0.03	-0.12	0.06	0.05	0.49
		Education	-0.01	-0.03	0.01	0.01	0.35
		Global health status	-0.03	-0.11	0.05	0.04	0.49

* This linear mixed effect model adjusted for processing speed by using the inverse transformation of reaction time (RT: 1/RT×1000) and also controlled for gender, education and global health status.