NEUROBIOLOGY OF AGING

Neurobiology of Aging 27 (2006) 1155–1163

www.elsevier.com/locate/neuaging

Enhanced multisensory integration in older adults

Paul J. Laurienti [a,*], Jonathan H. Burdette [a], Joseph A. Maldjian [a], Mark T. Wallace [b]

[a] Department of Radiology, Wake Forest University School of Medicine, Medical Center Boulevard, Winston-Salem, NC 27157, USA
[b] Department of Neurobiology and Anatomy, Wake Forest University School of Medicine, Medical Center Boulevard, Winston-Salem, NC 27157, USA

Received 13 January 2005; received in revised form 13 May 2005; accepted 23 May 2005
Available online 20 July 2005

Abstract

Information from the different senses is seamlessly integrated by the brain in order to modify our behaviors and enrich our perceptions. It is only through the appropriate binding and integration of information from the different senses that a meaningful and accurate perceptual gestalt can be generated. Although a great deal is known about how such cross-modal interactions influence behavior and perception in the adult, there is little knowledge as to the impact of aging on these multisensory processes. In the current study, we examined the speed of discrimination responses of aged and young individuals to the presentation of visual, auditory or combined visual–auditory stimuli. Although the presentation of multisensory stimuli speeded response times in both groups, the performance gain was significantly greater in the aged. Most strikingly, multisensory stimuli restored response times in the aged to those seen in young subjects to the faster of the two unisensory stimuli (i.e., visual). The current results suggest that despite the decline in sensory processing that accompanies aging, the use of multiple sensory channels may represent an effective compensatory strategy to overcome these unisensory deficits.

Keywords: Multisensory; Cross-modal; Visual; Auditory; Aging; Geriatric; Redundant-target

1. Introduction

Numerous examples serve to illustrate the profound influence that combining cues from the different senses can have on our perceptions [57]. The ventriloquist's act highlights how visual cues (i.e., the sight of the dummy's lip and head movements) can alter our ability to locate a sound source (i.e., the voice of the ventriloquist) [28]. Multisensory stimuli can also change the content of information. In the McGurk effect, when the sound of the phrase "ba-ba" is paired with the sight of a speaker making the articulatory movements for the phrase "ga-ga", the typical report is "da-da", a novel percept reflecting the synthesis of the two sensory channels [37]. Although these illusions are dramatic examples of perceptually based multisensory interactions, the combination of information across the senses can also play an important facilitatory role for simple behaviors. Most straightforward is the speeding of reaction times when visual and auditory stimuli are combined, which results in responses that are significantly faster than would be predicted based on the responses to the unisensory stimuli [18–20,27,31,34,39,43].

There now exists a substantial literature detailing how multisensory interactions shape behavior and perception in humans [5,57]. Thus, and because they are likely to be derived from the same event, multisensory stimuli that are spatially and temporally coincident and carry congruent information typically result in behavioral and/or perceptual enhancements [18–20,24,25,34,36,55,56,58]. Furthermore, and most germane to the current study, the greatest multisensory-mediated benefits are generally seen when the individual stimuli are weak in eliciting a response on their own [24,57,63]. This makes intuitive sense in that information from multiple sensory channels is likely to be most useful when the signal is ambiguous. Although there is substantial consensus that there is a deterioration of sensory processes in the aged [13,22,32,35,48], surprisingly little data exists on how multisensory interactions change as a function of age. Those studies that have looked at this issue have examined complex multisensory processes that are likely to index both sensory

* Corresponding author. Tel.: +1 336 716 3261; fax: +1 336 716 2870.
E-mail address: plaurien@wfubmc.edu (P.J. Laurienti).

0197-4580/$ – see front matter © 2005 Elsevier Inc. All rights reserved.
doi:10.1016/j.neurobiolaging.2005.05.024

and cognitive processes and have yielded conflicting results [9,26,59,60].

Perhaps one likely explanation for the conflicting reports is the use of different multisensory test paradigms and data analysis techniques. Testing paradigms that have been used have typically compared a multisensory condition to a single unisensory condition [26,59,60] or have utilized multisensory illusions that occur in response to incongruent sensory stimulation [9,60]. To determine the magnitude of multisensory gain than can be achieved by combining redundant multisensory information, the responses to combined stimulation should be compared to a combination of the unisensory responses. Reaction time tasks are unique in that responses can be collected to each unisensory condition and to the multisensory condition, and benefits associated with multisensory stimulation can be compared to a predicted model (the race model) that is based on responses to the unisensory conditions [38,49]. To date, no study has compared multisensory enhancement between young and elderly using the race model.

Another possible explanation for the conflicting results relates to the effectiveness of the individual stimuli. It has been clearly demonstrated that as the effectiveness of unisensory stimuli is decreased the multisensory gain is increased [24,57,63], a phenomenon referred to as inverse effectiveness. For a given stimulus intensity, age-related declines in sensory processing could result in the stimulus effectiveness differing between the elderly and young populations. Thus, based on the principle of inverse effectiveness, a given stimulus combination could result in different multisensory enhancement magnitudes in young and elderly populations.

The current study was designed to evaluate multisensory integration in the elderly using reaction time measures in a redundant-target discrimination task. Cumulative probability distributions were used to compare response times across conditions to allow for the comparison of multisensory responses to the summed probability of the unisensory responses (i.e. race model [38,49]). A task was designed where all subjects performed with a high accuracy but the elderly population was significantly slower than the young population for the unisensory discriminations. It was hypothesized that the elderly would exhibit a greater speeding of response from the multisensory combination compared to the young population, a prediction based on the idea that multisensory stimuli may offer a preferential performance benefit due to the deleterious impact of aging on individual sensory systems.

2. Methods

2.1. Subjects

Subjects were recruited from the general community in response to local flyers, community seminars and health fairs, and word-of-mouth. Subject populations that were specifically recruited were young adults aged 18–38 years old and elderly adults aged 65–90 years old. Over 100 people were screened during an initial telephone interview to eliminate individuals with a history of epilepsy, stroke, Parkinson's disease, Alzheimer's disease, attention deficit-hyperactivity disorder, serious vision problems (other than refractive errors or astigmatism), uncorrected hearing problems, head injury with loss of consciousness, brain surgery, psychiatric disorders other than treated depression, or diabetes. Of the respondents screened, 32 young adults and 35 elderly adults were presumed to qualify and were asked to attend a formal screening session.

During the screening session an extensive medical history and multiple screening tests were performed to ensure appropriateness for this study and verify absence of the above-mentioned exclusion criteria. A medication review was performed to exclude participants on medications associated with the disorders of exclusion noted above. The alcohol use disorders identification test (AUDIT) was performed to exclude individuals at high risk for alcoholism (no participants were excluded). The modified mini-mental state examination was performed to assess cognitive function, and those performing at less than 2 standard deviations from the mean for their age and education were excluded [14]. An auditory test was used to ensure that subjects could hear the stimuli used in sensory tests. Subjects were required to be able to hear 1000–2000 Hz at an intensity of 40 dB using an audioscope (Welch Allyn, Skaneateles Falls, NY) or at an intensity of 55 dB using a Digital Audiometer (Digital Recordings, Halifax, Nova Scotia). A modified Snell visual acuity examination was performed for each eye (with corrective lenses if necessary), and each subject had to perform at 20/40 or better. Color blindness was tested using the Concise Edition of Ishihara's Test for Colour-Blindness (Kanehara and Co., Tokyo, Japan). A score of ≤ 7 was used as an exclusion criterion. Based on these criteria, five elderly males were excluded: one for vision deficit, three for hearing deficits, and one for a low mini-mental status score. None of the young subjects were excluded using these criteria.

Of the 32 young adult study participants, one was removed due to poor compliance and lack of responses on experimental tests. Of the 30 elderly adult study participants, three were removed (all male) due to poor compliance. The final subject cohorts whose data are reported are 31 young adults (average age = 28 ± 5.6 years) and 27 elderly adults (average age = 71 ± 5.0 years). Scores from screening tests and demographic details can be found in Table 1. All individuals gave written informed consent to participate, were compensated for their time, and were naive to the study design and the experimental tasks.

2.2. Behavior paradigms

The subjects performed a two-alternative forced-choice discrimination task that has been previously described [34]. During each trial, the subjects were presented with either

Table 1
Study population demographics

	Age	Years of education	MMSE	African-Americans	Handedness	Number of females
Young ($N = 31$)	28.1 (5.6)	14.2 (1.5)	28.9 (1.1)	11	28 right	16
Elderly ($N = 27$)	70.9 (5.1)	14.4 (2.3)	27.7 (1.5)	4	26 right	16

Handedness was based on scores from the Edinburgh Handedness survey. Positive scores were judged as right handed and negative scores as left handed. One young subject scored a 0 which is indicative of no hand preference (MMSE: mini-mental state exam score).

a visual stimulus alone, an auditory stimulus alone, or a combined visual/auditory (multisensory) stimulus. Stimulus conditions (visual, auditory, or multisensory) were presented in pseudo-random order to limit stimulus order effects. The task required the subjects to discriminate between the colors red and blue presented as visual (colored discs on the computer screen), auditory (verbalizations of the word for the color), or multisensory stimuli (simultaneously presented auditory and visual stimuli). The visual stimulus was either a red or blue-filled circle that subtended 7.7° of visual angle presented on a black background, and each visual stimulus was 250 ms in duration. The auditory stimuli were verbalizations of either the word *red* or the word *blue,* and were 350 ms in duration. During the multisensory condition, the visual and auditory stimulus onsets were simultaneous. Each trial was begun with a 1 s fixation period followed by the test stimulus. After the test stimulus the screen was cleared during the response period. A new trial was not presented until a response was made to the preceding stimulus. However, if the subject did not respond within 8 s, the experiment continued with the next trial.

The subjects were instructed that if they either saw the blue circle (visual) or heard the word *blue* (auditory), they were to press the response button under their index finger. Conversely, the subjects were instructed to press the response button under their middle finger if either the red circle or the word *red* was presented. Subjects were instructed to "respond as rapidly and accurately as possible." The visual alone, auditory alone, and multisensory conditions were each presented a total of 43 times. In addition to the task-relevant red and blue visual and auditory stimuli, task-irrelevant green stimuli were presented and subjects were instructed to ignore this color stimulus. Data on responses to these task-irrelevant stimuli are not presented in the current manuscript.

In addition to the multisensory paradigm, a redundant target visual discrimination task was also performed by each subject and has been described previously [34]. The order of the multisensory and redundant visual tasks was randomized across subjects. Briefly, stimulus timing was identical to the multisensory task, and subjects were again instructed to discriminate between the color (red or blue) of the sensory stimulus. One visual stimulus was a color-filled circle exactly as was used in the multisensory task. The other visual stimulus was a printed form of the color word that replaced the spoken word in the multisensory task. The printed word was presented in the center of the computer display when presented alone and in the center of the color-filled circle on the redundant stimulus trials. For both tasks subjects were instructed to "respond as rapidly and accurately as possible." As with the multisensory paradigm, visual stimuli were 250 ms in duration and were presented in pseudo-random order. Each trial was begun with a 1 s fixation period followed by the test stimulus. After the test stimulus the screen was cleared during the response period and the experiment continued with the next trial if the subject did not respond within 8 s.

2.3. Experimental setup

E-prime software (Physiology Software Tools, Pittsburgh, PA, USA) and Serial Response Box were used to record the subject's response time and accuracy and to control visual and auditory stimulus delivery. All experiments were carried out in a light and sound-attenuating testing booth (Whisper Room, Morristown, TN, USA). Subjects were seated comfortably, and their chin was positioned in a chin rest such that they were positioned 24 in. in front of the computer monitor that was used to display the visual stimuli. The auditory stimuli were presented through speakers located on both sides of the computer monitor. The volume of the stimuli was adjusted to a comfortable and easily discriminable level for each subject (typically ∼75 dB).

2.4. Data analysis

The mean accuracy was computed for each subject under each condition and group comparisons were made with a 2 (group) × 3 (condition) analysis of variance (ANOVA) for repeated measures. Response time (RT) data were first analyzed to remove outlying data points (incorrect responses were not eliminated), which were defined as responses occurring faster than 250 ms or slower than 2 standard deviations from the mean response time for each subject. Mean values are used as a measure of central tendency because comparisons of median values across distributions with different amounts of skew and different sample sizes can result in significant bias [40]. Comparison of multisensory mean RTs to the fastest unisensory (visual) mean RTs effectively identifies speeding of responses during the multisensory condition. However, it does not account for the redundant nature of the multisensory stimulus and, therefore, is not the most appropriate analysis to compare multisensory gains between the populations. Nevertheless, central tendency gain was evaluated using a repeated measures 2 × 2 ANOVA comparing visual RTs to multisensory RTs in the young and elderly population. In addition, central tendency difference magnitudes were calculated by subtracting the multisensory response time from the fastest unisensory (visual) response time. Comparisons of the multisensory gain were performed using a linear regression analysis of co-variance (ANCOVA) model that included accuracy difference scores (multisensory accuracy − visual accuracy) as a covariate of no interest. Finally, a separate analysis was performed using log-transformed RTs to account for general slowing that is observed in the elderly [6,12,53]. This analysis also used a 2 × 2 ANOVA to compare log-transformed visual and multisensory RTs and a paired *t*-test to compare the multisensory gain magnitudes (log-transformed visual RT − log-transformed multisensory RT).

To control for the redundant nature of the multisensory condition, response times were analyzed using cumulative distribution functions (CDFs), and the multisensory data were compared to statistical facilitation using a CDF of the summed probability of the visual and auditory responses. This model is often referred to as the independent race model [38,39]. This model allows for the comparison of the multisensory condition to the joint probability of the unisensory conditions ((pA + pV) − (pA × pV)). If the probability of response to the multisensory stimulus is significantly greater than that predicted by the summed probability of the unisensory stimuli, it is said to violate the race model, a result that likely suggests the neural integration of the two unisensory inputs [38,39,49]. To perform this analysis, each subject's data were processed to generate subject-specific CDFs for each condition using 10 ms time bins. The CDFs from all subjects in each group were then averaged to generate group CDFs. This analysis procedure ensured that the results reflect a group pattern and are not skewed by one or a few outlying subjects. As was done for each of the sensory conditions, the race model CDF was generated for each subject and averaged at each time bin to generate a group CDF.

Significant deviations from the race model were determined by subtracting the predicted summed probability (race model) from the multisensory probability at each time bin for each subject, thereby creating a difference curve for each subject. A one-sample *t*-test was performed at each time bin within each group (young adults and elderly adults) to compare this difference curve to zero, and significant ($p \leq 0.05$) deviations were identified. A two-sample *t*-test was then performed comparing the difference curves (multisensory minus race model) of the two groups (young and elderly adults) to identify significant ($p \leq 0.05$) group differences.

3. Results

Although the multisensory discrimination task was designed to focus upon response times in order to measure behavioral enhancement, accuracy scores were also evaluated. For both the young and elderly subjects, mean performance accuracy was greater than 94% for the visual, auditory and multisensory conditions (see Table 2). Comparisons made using analysis of variance (ANOVA) did not reveal a significant group difference ($F_{2,56} = 3.53$, $p = 0.065$), although there was a trend for significance. A significant group by condition interaction was present ($F_{2,112} = 4.456$, $p = 0.014$), and post-hoc two-sample *t*-tests revealed a significant group difference for visual discrimination accuracy ($p = 0.017$), with young subjects being more accurate, but there were no group differences for auditory or multisensory discrimination.

Mean RTs for all conditions are presented in Table 2. Analyses of the mean response times and log-transformed RTs (Table 3) focused on comparisons between the multisensory and the fastest unisensory condition (visual). For mean RTs,

Table 2
Mean response time (ms) and mean accuracy (%) with standard deviations for multisensory and visual redundant target discrimination tasks

	Auditory	Visual	Multisensory
Multisensory			
Elderly			
RT	714 (127)	614 (111)	527 (89)
Accuracy	99.4 (1.2)	95 (4.2)	97.7 (4.0)
Young			
RT	623 (128)	538 (117)	485 (93)
Accuracy	99.0 (1.4)	97.4 (3.0)	98.4 (2.9)
	Visual 1	Visual 2	Dual visual
Dual visual			
Elderly			
RT	629 (107)	597 (111)	587 (114)
Accuracy	95.3 (5.1)	94.9(6.5)	96.2 (5.1)
Young			
RT	535 (91)	526 (89)	514 (101)
Accuracy	96.4 (5.6)	96.6 (4.7)	96.5 (4.1)

For the multisensory task the auditory stimulus was the spoken color word and the visual stimulus was a color-filled circle. For the redundant visual task, visual stimulus 1 was the written form of the color word and visual stimulus 2 was again the color-filled circle.

Table 3
Log-transformed response times with standard deviations for multisensory and visual redundant target discrimination tasks

	Auditory	Visual	Multisensory
Multisensory			
Elderly			
log RT	2.84 (0.077)	2.78 (0.084)	2.72 (0.079)
Young			
log RT	2.79 (0.078)	2.72 (0.084)	2.68 (0.079)
	Visual 1	Visual 2	Dual visual
Dual visual			
Elderly			
log RT	2.79 (0.071)	2.77 (0.078)	2.76 (0.083)
Young			
log RT	2.72 (0.073)	2.72 (0.073)	2.70 (0.083)

For the multisensory task the auditory stimulus was the spoken color word and the visual stimulus was a color-filled circle. For the redundant visual task, visual stimulus 1 was the written form of the color word and visual stimulus 2 was again the color-filled circle.

the ANOVA revealed significant main effects for both group ($F_{1,56} = 5.1$, $p = 0.027$) and modality ($F_{1,56} = 82$, $p < 0.001$) and a group by condition interaction ($F_{1,56} = 4.8$, $p = 0.03$). A difference between the multisensory and fastest unisensory (i.e. visual) condition does give an estimate of the multisensory gain (note that the most appropriate analyses using cumulative response time distributions are presented below). Mean RT difference data revealed that the elderly group (87.5 ms) exhibited a greater gain compared to the young group (53.2 ms) using an ANCOVA analysis ($F_{2,55} = 4.8$, $p = 0.033$) with accuracy as a covariate. To account for age-related generalized slowing log-transformed data were also evaluated. An ANOVA comparing the multisensory condition to visual condition replicated the findings from the mean RT analysis. Specifically, significant main effects of group ($F_{1,56} = 5.9$, $p = 0.018$) and modality ($F_{1,56} = 106$, $p < 0.001$), and a group by modality interaction ($F_{1,56} = 4.0$, $p = 0.049$) were observed. A paired t-test comparing the log-transformed RT difference between young (0.043 ± 0.03) and elderly (0.067 ± 0.05) as a metric for multisensory enhancement was also significant ($t = 2.2$, $p = 0.032$). RT data were also evaluated with Levene's test for equality of variance between groups, which revealed no variability differences for visual ($p = 0.67$), auditory ($p = 0.14$), or multisensory ($p = 0.97$) conditions, indicating that the age-related differences were not secondary to differential changes in variability between conditions.

The race model [38,39,49] was used to analyze RTs to determine if the observed multisensory behavioral enhancements were beyond that predicted by statistical summation for the unisensory visual and auditory conditions. This analysis is able to determine if the multisensory response is faster than predicted by statistical facilitation associated with redundant sensory stimuli. This analysis also considers differential speeds in each of the unisensory conditions by utilizing the individual subject's response time distributions for the visual and auditory conditions. In agreement with the results of a previous study using the same task [34], a significant speeding of responses was seen for multisensory stimuli compared to either unisensory condition in the young subjects (Fig. 1a). Furthermore, multisensory performance exceeded that predicted by the race model. This multisensory-mediated behavioral facilitation in young subjects was significant ($p \leq 0.05$) over a broad temporal interval (340–550 ms following stimulus onset), and at its peak resulted in an 8.3% performance benefit at 450 ms (Fig. 1b).

As in the young subjects, the elderly experienced a speeding of responses to the multisensory stimuli when compared with visual and auditory performance (Fig. 2a), and these responses exceeded those predicted by the race model. When examined for the temporal window in which this benefit was significant, it was seen from 330 to 690 and 730 to 740 ms following stimulus onset. The gain did not reach significance in the 700–720 ms window. The maximum gain in performance for the elderly under multisensory conditions was 13.5% at 520 ms (Fig. 2b).

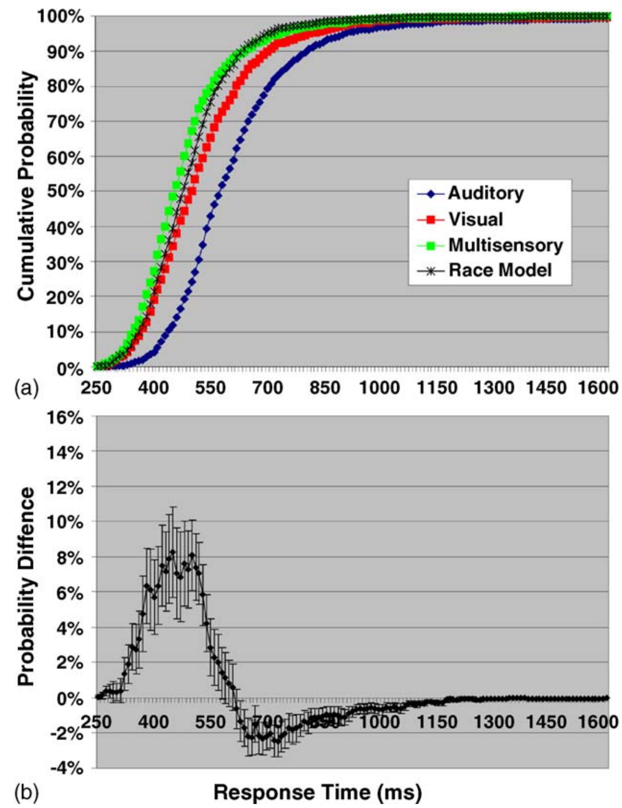

Fig. 1. Distributions of response times for target discrimination in young subjects. (a) Cumulative distribution functions (CDFs) for discrimination response times to auditory (blue curve), visual (red curve), and multisensory (green curve) stimuli. The summed probability for the visual and auditory responses is depicted by the race model curve (black curve). Note that multisensory responses are typically faster than the race model prediction. (b) The cumulative probability difference curve illustrates the substantial behavioral enhancements under multisensory conditions when compared to the race model prediction.

Direct comparisons between the younger and older adults revealed two striking differences in their multisensory performance (Fig. 3). First, the time window over which the multisensory benefit was achieved was considerably larger in the elderly (Fig. 3a). Whereas the temporal interval during which multisensory performance exceeded probability summation was approximately 200 ms in the young, this same window was twice as long (i.e., 410 ms) in the elderly subjects. Second, the magnitude of enhancement in the elderly was significantly ($p < 0.05$) greater than in the young subjects (Fig. 3b) from 530 to 760 ms. Although the maximal enhancement occurred at different absolute response times for the two populations, this peak enhancement occurred at approximately the same portion of the cumulative distribution curve. For the elderly subjects the peak enhancement occurred at 520 ms which is at the 60% probability for the multisensory response and 39% for the fastest unisensory (visual) response. For the young subjects the peak was at 450 ms which was at the 48% and 34% probability for multisensory and visual conditions, respectively. Although not at the exact same point on the CDFs, the enhancements were

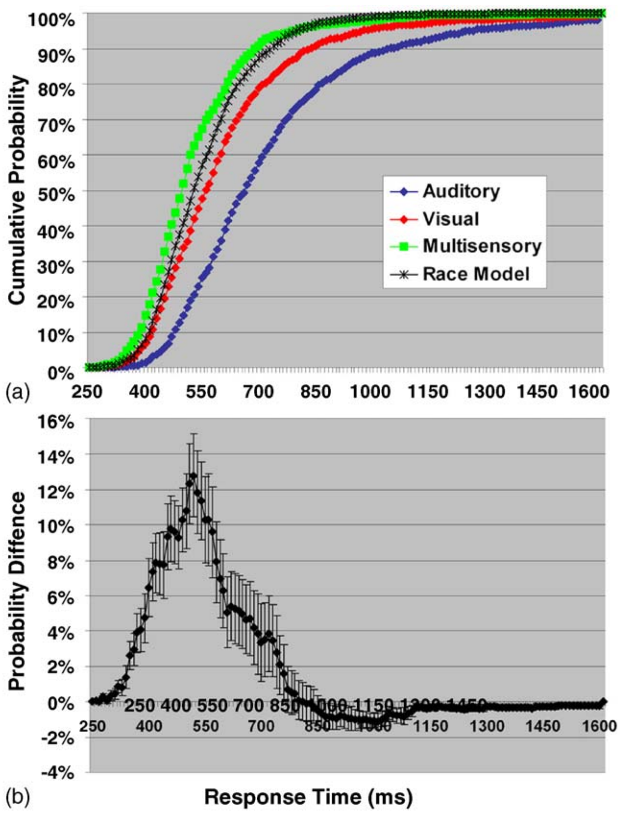

Fig. 2. Distributions of response times for target discrimination in elderly subjects. (a) Cumulative distribution functions (CDFs) for discrimination response times to auditory (blue curve), visual (red curve), and multisensory (green curve) stimuli. The summed probability for the visual and auditory responses is depicted by the race model curve (black curve). Note that multisensory responses are typically faster than the race model prediction. (b) The cumulative probability difference curve illustrates the substantial behavioral enhancements under multisensory conditions when compared to the race model prediction.

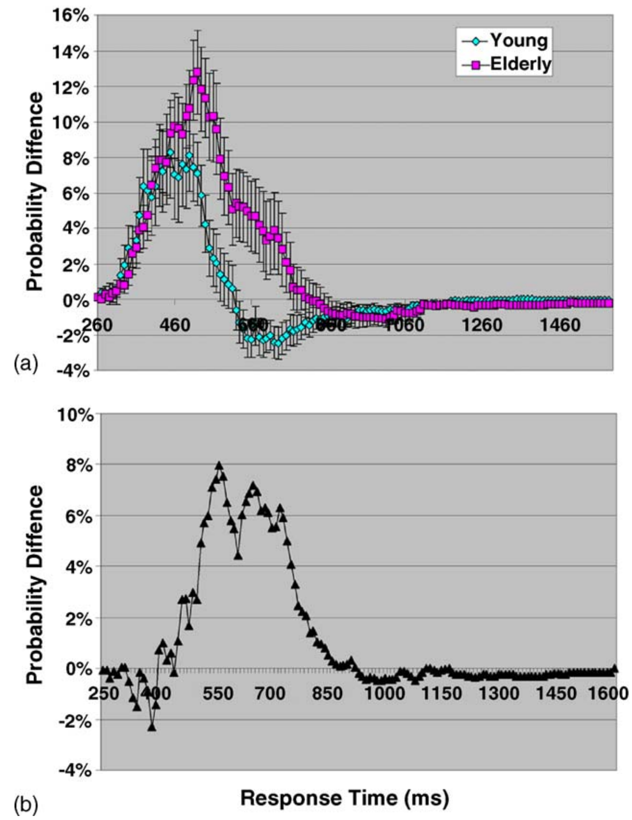

Fig. 3. A direct comparison of multisensory-mediated gains in performance relative to the race model between the young and elderly subjects. (a) A replotting of the CDF difference curves for the young (cyan; from Fig. 1b) and elderly (magenta; from Fig. 2b) highlights the difference in multisensory performance between the groups. (b) Subtraction of the CDF difference curve for the young subjects from the CDF difference curve for the elderly subjects directly illustrates both the magnitude and time window of the enhancement in the elderly relative to the young.

along the linear portion of the curves for both groups, not along the saturating curve tails associated with minimal or maximal response times.

In order to determine whether the observed performance enhancements were specific to the multisensory nature of the stimuli employed, or whether they simply reflected the addition of more sensory information, responses from a dual-visual redundant target task were analyzed (Table 1). An ANOVA performed on the mean RTs from the dual-visual redundant target task revealed that elderly subjects were slower than the younger subjects ($F_{2,56} = 9.45$, $p = 0.003$). This analysis also revealed that there was a significant main effect of stimulus condition ($F_{2,112} = 15.3$, $p < 0.001$), but a group by condition interaction did not reach significance ($F_{2,56} = 2.48$, $p = 0.088$). CDF analyses and comparisons to the race model (Fig. 4) did reveal that the young population experienced an enhanced response to the redundant visual condition, but this enhancement was relatively small, not exceeding 2% and limited to three time points (290, 320, and 330 ms). In contrast, the elderly failed to show any enhancements relative to the race model.

4. Discussion

The data presented here are the first to demonstrate that older adults can benefit more than younger adults from the combination of information from multiple sensory modalities. Differences in response times between young and elderly subjects can result from several factors that are independent of multisensory integration. Although much debate remains centered around the idea of generalized slowing that is thought to be associated with aging and how to analyze RT data [7,8,17,46,50,51,62], generalized slowing could result in misinterpretation of the findings presented here as enhanced multisensory integration. Specifically, statistical facilitation associated with redundant targets can result in greater gains in the elderly secondary to generalized slowing [21]. To account for generalized slowing mean RTs were evaluated after log-transformation [6,12,53]. This analysis continued to identify enhanced multisensory gains when compared to the visual modality. Furthermore, the race model analysis utilizes each subject's unisensory RT distributions to generate a model for comparison with the multisensory RT distribution. The race

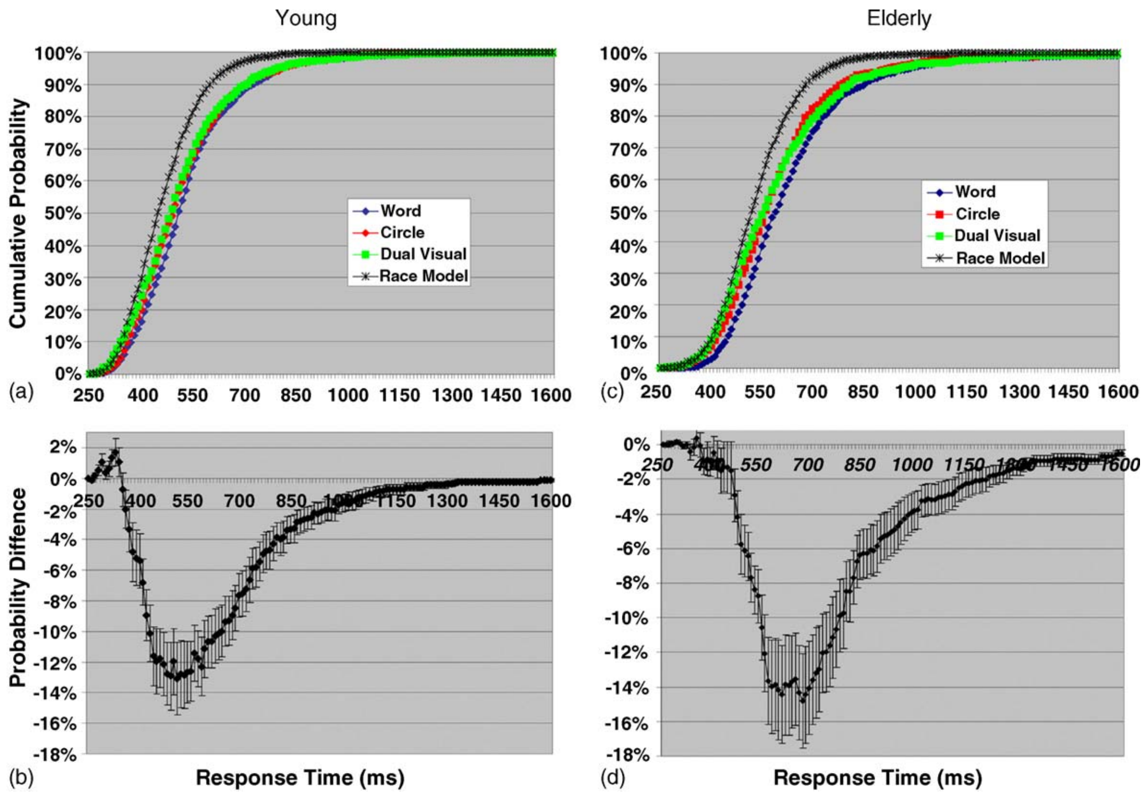

Fig. 4. Distributions of response times for the visual redundant-target task. (a) Cumulative distribution functions (CDFs) in young subjects for discrimination response times to the printed word (word—blue curve), the color-filled circle (circle—red curve), and the redundant visual (simultaneous presentation of word and circle—green curve) stimuli. The summed response probability for the two single sensory conditions is depicted by the race model (black curve). Note that the predicted race model responses are typically faster than the dual-visual responses. (b) The cumulative probability difference curve for young subjects illustrates enhanced response probability under dual-visual condition at 290, 320, and 330 ms when compared to the race model prediction. For all other time points there is no behavioral enhancement associated with the redundant visual cue beyond that predicted by the race task. (c) Cumulative distribution functions (CDFs) for elderly subjects demonstrate that the predicted race model responses are faster than the dual-visual responses. (d) The cumulative probability difference curve for elderly subjects illustrates no enhanced response probability under dual-visual condition when compared to the race model prediction.

model analysis also identified enhanced multisensory integration in the elderly even with the multisensory gain normalized to unisensory RTs.

A second factor that must be considered is an age-related difference in speed-accuracy tradeoff. It may be that the elderly are gaining more on the multisensory condition at the expense of accuracy. If the findings were the result of a differential speed-accuracy tradeoff between young and older adults, it would be expected that greater improvements in RT performance in the elderly would be associated with accuracy decrements for the multisensory condition. The fact that the elderly exhibited a significant improvement in performance when multisensory was compared to visual suggests that the current findings are not the result of speed-accuracy tradeoffs [64]. The ANCOVA analysis that compared mean RT gains with accuracy as a covariate provides further support for a true difference in multisensory gain between populations. Despite the strong support for differences in RT gains between the young and elderly, it is not possible to rule out some form of a speed-accuracy tradeoff in the current experiment.

To identify multisensory enhancements it is necessary to compare the multisensory RTs with a mathematical combination of the unisensory RTs. This comparison ensures that speeding of response is an integrative effect rather than a simple statistical facilitation due to the fact that the multisensory condition contains redundant stimulus components. The use of cumulative distributions to evaluate the race model also ensures that multisensory enhancement is identified using the entire response time distribution rather than a single central tendency score (mean or median), which are more susceptible to bias associated with small sample sizes and skewed distributions [40,41]. In the present data, comparisons with the race model revealed that older adults exhibited a greater peak and a broader temporal window of multisensory enhancement. The peak benefit for both young and older populations was near the 50% probability of response. Therefore, differences in the peak enhancement are not likely to be the result of response saturation on the cumulative distribution curves. The broadened window of integration observed in the elderly is most likely secondary to their overall slowing of response. The elderly population exhibited slower responses to the unisensory stimuli resulting in a broader window over which multisensory benefits could occur.

Although the mechanisms underlying the enhanced multisensory performance in the elderly population remain unknown, the fact that elderly individuals experience declines in each of the unisensory modalities is a likely factor. It is well established at both the neural and behavioral levels that the major benefit of multisensory integration is seen when unisensory performance levels are low, and that as individual stimuli become increasingly more effective on their own, the benefit from combining them declines [24,57,63]. Although such an interpretation makes intuitive sense and can be used to predict performance in a variety of different tasks and settings, its generalizability awaits future work designed to evaluate the full spectrum of multisensory capabilities in the elderly.

An additional (and possibly interrelated) possibility is that the elderly are better able to exploit the redundant nature of the cues regardless of the sensory modality. Such a benefit may be a secondary effect resulting from increased levels of noise in sensory systems, or may be due to changes in sensory attention [1,2]. Gains associated with redundant unisensory targets in normal subjects can be accounted for by statistical facilitation alone [3,10,11,38,44,45] or can exceed statistical facilitation, but such gains are typically much smaller than those observed for multisensory redundant targets and require bilateral presentations [11,31,47,54]. However, in certain populations such as split-brain patients [10,11,52] or dyslexics individuals [3] the unisensory redundant target effect can be quite large, approaching the gain magnitudes observed in the current study. The magnitude of the within modality redundant target gains observed in the young population in the present study (<2%) was considerably less than the multisensory gains (>8%) and are consistent with previous findings [34,42,54]. Arguing against a simple redundant target explanation, and highlighting a multisensory specificity for the effect seen in the current study, is the fact that a visual redundant-target did not result in behavioral facilitation in the elderly population. Although within-modality redundant target facilitations have been reported in the elderly [1,2], these studies did not use a race model, and, therefore, enhancements could have been the result of statistical facilitation.

Perhaps more exciting than the differences in multisensory performance seen here in the elderly is the potential that such information might be used in a practical way to improve quality of life in older adults. Thus, rather than there being a simple acceptance that there is an inevitable decline in sensory function with aging [4,13,48], methods to make greater use of multisensory cues can be developed. For example, declines in auditory discrimination performance may be ameliorated by the addition of a simple visual cue. In fact, the data demonstrated that multisensory responses in the elderly (mean response time = 537 ms) were speeded such that they were as fast as the fastest unisensory (visual) responses in the young population (mean response time = 538 ms). Thus, the benefit provided by multisensory stimuli was substantial enough to restore performance in the aged to levels comparable to those seen for the fastest unisensory channel (i.e., vision) in young individuals. Relating these findings to a real-world situation, the use of video telephones could provide redundant visual and auditory cues resulting in amplification of the perceived volume of the speaker [61] and increased listener comprehension [15,16,23]. The results from the present study also support the idea that multisensory training strategies may hold great potential for improving age-related functional decline. For example, there is evidence that multisensory training programs can improve balance and posture in the elderly [29,30]; the wide-spread implementation of such programs could reduce the incidence of falls. Future studies directed at evaluating the clinical efficacy of multisensory interventions and training programs could have considerable impact on health care and the quality of life in the elderly.

Acknowledgements

This work was supported by NIH grant NS 42568 (PJL). We would like to thank Ms. Debra Hege for her assistance with data collection and analyses.

References

[1] Allen PA, Groth KE, Weber TA, Madden DJ. Influence of response selection and noise similarity on age differences in the redundancy gain. J Gerontol 1993;48:P189–98.
[2] Allen PA, Madden DJ, Groth KE, Crozier LC. Impact of age, redundancy, and perceptual noise on visual search. J Gerontol 1992;47:P69–74.
[3] Badzakova-Trajkov G, Hamm JP, Waldie KE. The effects of redundant stimuli on visuospatial processing in developmental dyslexia. Neuropsychologia 2005;43:473–8.
[4] Bozian MW, Clark HM. Counteracting sensory changes in the aging. Am J Nurs 1980;80:473–6.
[5] Calvert GA, Spence C, Stein BE, editors. The handbook of multisensory processes. Cambridge, MA: MIT Press; 2004.
[6] Cerella J. Information processing rates in the elderly. Psychol Bull 1985;98:67–83.
[7] Cerella J. Age effects may be global, not local: comment on fisk and rogers. Exp Psychol Gen 1991;120:215–23.
[8] Cerella J. Generalized slowing in brinley plots. J Gerontol 1994;49:P65–71.
[9] Cienkowski KM, Carney AE. Auditory–visual speech perception and aging. Ear Hear 2002;23:439–49.
[10] Corballis MC. Interhemispheric neural summation in the absence of the corpus callosum. Brain 1998;121(Pt 9):1795–807.
[11] Corballis MC, Hamm JP, Barnett KJ, Corballis PM. Paradoxical interhemispheric summation in the split brain. J Cogn Neurosci 2002;14:1151–7.
[12] Cornelissen FW, Kooijman AC. Does age change the distribution of visual attention? A comment on mccalley, bouwhuis, and juola. J Gerontol B: Psychol Sci Soc Sci 2000;55:P187–90.
[13] Corso JF. Sensory processes and age effects in normal adults. J Gerontol 1971;26:90–105.
[14] Crum RM, Anthony JC, Bassett SS, Folstein MF. Population-based norms for the mini-mental state examination by age and educational level. JAMA 1993;269:2386–91.
[15] Erber NP. Auditory, visual, and auditory–visual recognition of consonants by children with normal and impaired hearing. J Speech Hear Res 1972;15:413–22.

[16] Erber NP. Auditory–visual perception of speech. J Speech Hear Disord 1975;40:481–92.
[17] Fisk AD, Fisher DL, Rogers WA. General slowing alone cannot explain age-related search effects: reply to cerella. J Exp Psychol Gen 1992;121:73–8.
[18] Forster B, Cavina-Pratesi C, Aglioti SM, Berlucchi G. Redundant target effect and intersensory facilitation from visual–tactile interactions in simple reaction time. Exp Brain Res 2002;143:480–7.
[19] Frens MA, Van Opstal AJ, Van der Willigen RF. Spatial and temporal factors determine auditory–visual interactions in human saccadic eye movements. Percept Psychophys 1995;57:802–16.
[20] Giard MH, Peronnet F. Auditory–visual integration during multimodal object recognition in humans: a behavioral and electrophysiological study. J Cogn Neurosci 1999;11:473–90.
[21] Gottlob LR. Aging and capacity in the same-different judgment. Aging Neurpsych Cog, in press.
[22] Habak C, Faubert J. Larger effect of aging on the perception of higher-order stimuli. Vision Res 2000;40:943–50.
[23] Hack ZC, Erber NP. Auditory, visual, and auditory–visual perception of vowels by hearing-impaired children. J Speech Hear Res 1982;25:100–7.
[24] Hairston WD, Laurienti PJ, Mishra G, Burdette JH, Wallace MT. Multisensory enhancement of localization under conditions of induced myopia. Exp Brain Res 2003.
[25] Harrington LK, Peck CK. Spatial disparity affects visual–auditory interactions in human sensorimotor processing. Exp Brain Res 1998;122:247–52.
[26] Helfer KS. Auditory and auditory–visual recognition of clear and conversational speech by older adults. J Am Acad Audiol 1998;9:234–42.
[27] Hershenson M. Reaction time as a measure of intersensory facilitation. J Exp Psychol 1962;63:289–93.
[28] Howard IP, Templeton WB. Human spatial orientation. London: Wiley; 1966.
[29] Hu MH, Woollacott MH. Multisensory training of standing balance in older adults. I. Postural stability and one-leg stance balance. J Gerontol 1994;49:M52–61.
[30] Hu MH, Woollacott MH. Multisensory training of standing balance in older adults. II. Kinematic and electromyographic postural responses. J Gerontol 1994;49:M62–71.
[31] Hughes HC, Reuter-Lorenz PA, Nozawa G, Fendrich R. Visual–auditory interactions in sensorimotor processing: saccades versus manual responses. J Exp Psychol Hum Percept Perform 1994;20:131–53.
[32] Keller BK, Morton JL, Thomas VS, Potter JF. The effect of visual and hearing impairments on functional status. J Am Geriatr Soc 1999;47:1319–25.
[34] Laurienti PJ, Kraft RA, Maldjian JA, Burdette JH, Wallace MT. Semantic congruence is a critical factor in multisensory behavioral performance. Exp Brain Res 2004;158:405–14.
[35] Lichtenstein MJ. Hearing and visual impairments. Clin Geriatr Med 1992;8:173–82.
[36] Lovelace CT, Stein BE, Wallace MT. An irrelevant light enhances auditory detection in humans: a psychophysical analysis of multisensory integration in stimulus detection. Brain Res Cogn Brain Res 2003;17:447–53.
[37] McGurk H, MacDonald J. Hearing lips and seeing voices. Nature 1976;264:746–8.
[38] Miller J. Divided attention: evidence for coactivation with redundant signals. Cognit Psychol 1982;14:247–79.
[39] Miller J. Timecourse of coactivation in bimodal divided attention. Percept Psychophys 1986;40:331–43.
[40] Miller J. A warning about median reaction time. J Exp Psychol Hum Percept Perform 1988;14:539–43.
[41] Miller J, Lopes A. Testing race models by estimating the smaller of two true mean or true median reaction times: an analysis of estimation bias. Percept Psychophys 1988;44:513–24.
[42] Miniussi C, Girelli M, Marzi CA. Neural site of the redundant target effect electrophysiological evidence. J Cogn Neurosci 1998;10:216–30.
[43] Molholm S, Ritter W, Javitt DC, Foxe JJ. Multisensory visual–auditory object recognition in humans: a high-density electrical mapping study. Cereb Cortex 2004;14:452–65.
[44] Mordkoff JT, Miller J. Redundancy gains and coactivation with two different targets: the problem of target preference and the effects of display frequency. Percept Psychophys 1993;53:527–35.
[45] Murray MM, Foxe JJ, Higgins BA, Javitt DC, Schroeder CE. Visuo-spatial neural response interactions in early cortical processing during a simple reaction time task: a high-density electrical mapping study. Neuropsychologia 2001;39:828–44.
[46] Myerson J, Adams DR, Hale S, Jenkins L. Analysis of group differences in processing speed: brinley plots, *q–q* plots, and other conspiracies. Psychon Bull Rev 2003;10:224–37.
[47] Nozawa G, Reuter-Lorenz PA, Hughes HC. Parallel and serial processes in the human oculomotor system: bimodal integration and express saccades. Biol Cybern 1994;72:19–34.
[48] Nusbaum NJ. Aging and sensory senescence. South Med J 1999;92:267–75.
[49] Raab DH. Statistical facilitation of simple reaction times. Trans NY Acad Sci 1962;24:574–90.
[50] Ratcliff R, Spieler D, McKoon G. Explicitly modeling the effects of aging on response time. Psychon Bull Rev 2000;7:1–25.
[51] Ratcliff R, Thapar A, McKoon G. The effects of aging on reaction time in a signal detection task. Psychol Aging 2001;16:323–41.
[52] Reuter-Lorenz PA, Nozawa G, Gazzaniga MS, Hughes HC. Fate of neglected targets: a chronometric analysis of redundant target effects in the bisected brain. J Exp Psychol Hum Percept Perform 1995;21:211–30.
[53] Salthouse TA. The complexity of age × complexity functions: comment on charness and campbell. J Exp Psychol: Gen 1988;117:425–8.
[54] Savazzi S, Marzi CA. Speeding up reaction time with invisible stimuli. Curr Biol 2002;12:403–7.
[55] Schroger E, Widmann A. Speeded responses to audiovisual signal changes result from bimodal integration. Psychophysiology 1998;35:755–9.
[56] Stein BE, Lagondon N, Wilkinson LK, Price DD. Enhancement of perceived visual intensity by auditory stimuli: a psychophysical analysis. J Cogn Neurosci 1996;8:497–506.
[57] Stein BE, Meredith MA. The merging of the senses. Cambridge, MA: MIT Press; 1993.
[58] Stein BE, Meredith MA, Huneycutt WS, McDade L. Behavioral indices of multisensory integration: orientation to visual cues is affected by auditory stimuli. J Cogn Neurosci 1989;1:12–24.
[59] Stine EA, Wingfield A, Myers SD. Age differences in processing information from television news: the effects of bisensory augmentation. J Gerontol 1990;45:P1–8.
[60] Strupp M, Arbusow V, Borges Pereira C, Dieterich M, Brandt T. Subjective straight-ahead during neck muscle vibration: effects of ageing. Neuroreport 1999;10:3191–4.
[61] Sumby WH, Pollack I. Visual contribution to speech intelligibility in noise. J Acoust Soc Am 1954;26:212–5.
[62] Verhaeghen P, Cerella J. Aging, executive control, and attention: a review of meta-analyses. Neurosci Biobehav Rev 2002;26:849–57.
[63] Wallace MT, Wilkinson LK, Stein BE. Representation and integration of multiple sensory inputs in primate superior colliculus. J Neurophysiol 1996;76:1246–66.
[64] Wickelgren WA. Speed-accuracy tradeoff and information processing dynamics. Acta Psychologica 1977;41:67–85.