Audiovisual Deficits in Older Adults with Hearing Loss: Biological Evidence

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Objective: To examine the impact of hearing loss (HL) on audiovisual (AV) processing in the aging population. We hypothesized that age-related HL would have a pervasive effect on sensory processing, extending beyond the auditory domain. Specifically, we predicted that decreased auditory input to the neural system, in the form of HL over time, would have deleterious effects on multisensory mechanisms.

Design: This study compared AV processing between older adults with normal hearing (N = 12) and older adults with mild to moderate sensorineural HL (N = 12). To do this, we recorded cortical evoked potentials that were elicited by watching and listening to recordings of a speaker saying the syllable "bi." Stimuli were presented in three conditions: when hearing the syllable "bi" (auditory), when viewing a person say "bi" (visual), and when seeing and hearing the syllables simultaneously (AV). Presentation level of the auditory stimulus was set to +30 dB SL for each listener to equalize auditory input across groups.

Results: In the AV condition, the normal-hearing group showed a clear and consistent decrease in P1 and N1 latencies as well as a reduction in P1 amplitude compared with the sum of the unimodal components (auditory + visual). These integration effects were absent or less consistent in HL participants.

Conclusions: Despite controlling for auditory sensation level, visual influence on auditory processing was significantly less pronounced in HL individuals compared with controls, indicating diminished AV integration in this population. These results demonstrate that HL has a deleterious effect on how older adults combine what they see and hear. Although auditory amplification vastly improves the communication abilities in most HLs, the associated atrophy of multisensory mechanisms may contribute to a patient's difficulty in everyday settings. Our findings and related studies emphasize the potential value of multimodal tasks and stimuli in the assessment and rehabilitation of hearing impairments.

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INTRODUCTION

Approximately 30% of Americans older than 65 years report a hearing loss (HL) that causes trouble in everyday communication (Gallulet Research Institute analysis of National Health Interview Survey data, 1997–2003) and has the potential to greatly impact their quality of life (Dalton et al. 2003). HL results primarily in a decline in auditory speech perception (Humes & Roberts 1990); however, changes in visual perceptual abilities indicate that adaptation to HL is not limited to the auditory modality. On the one hand, younger adults with early-onset hearing impairment are better at lip-reading sentences than controls (Auer et al. 2007), but even in normal-hearing (NH) people, this ability declines with age (Cienkowski & Carney 2002; Hay-McCutcheon et al. 2005; Sommers et al. 2005). Although investigations of unimodal perception in isolation help us understand how HL in older adults affects auditory and visual abilities, everyday perception for most people involves the combination of these inputs.

Surprisingly, little is known about whether hearing-impaired older adults combine, or integrate, auditory and visual information in the same way as their NH counterparts. A recent study by Tye-Murray et al. (2007) showed that older adults with mild HL could achieve levels of accuracy equal to those of NH controls for audiovisual (AV) speech perception in noise. Although this study is well founded and much needed, additional studies are needed to determine the variance and replicability of these results, especially in more typical listening environments. The scarcity of literature on this topic and the provocative implication that 30% of older adults could benefit from assessing multimodal faculties underscore the importance of finding out how HL impacts multisensory processing in this population. The current study is a step in this direction and investigates the neural mechanisms of AV integration in older adults with mild HL compared to those in the same age range with more normal hearing thresholds.

Studies on the neural mechanisms of AV integration in NH young adults provide the foundation for our experimental aims and predictions in the older and HL population. This topic has been investigated with many methods, such as evoked potentials, functional Magnetic Resonance Imaging, and intracranial local-field potentials. Evoked-potential data resolve the temporal scale of neural response with excellent fidelity and enable us to see when visual stimuli impact auditory processing. From this literature, we know that seeing lip movements while listening to speech speeds the latency of peaks as early as 10 msec poststimulation in human auditory brain stem responses (Musacchia et al. 2006) and from 40 to 200 msec poststimulation in cortical EPs (Mottonen et al. 2002; van Wassenhove et al. 2005). Recent cortical data also show smaller N1 peak amplitudes at approximately 120 to 140 msec to AV speech (Besle et al. 2004) and nonspeech stimuli (Stekelenburg & Vroomen 2007). This evidence may seem contrary to the prevalence of AV "super-additivity" in the fMRI (Calvert et al. 2001) and single-unit literature (Stein & Meredith 1993; Stanford et al. 2005), where the response to simultaneous flashes and tones exceeds the linear summation of the unimodal parts (AV > auditory [A] + visual [V]). However, more recent multisensory studies and those testing a broader range of stimulus parameters indicate that superadditivity is one of the multisensory response patterns, including subadditivity (AV < A + V) and direct linear summation (AV = A + V) (Perrault et al. 2005). Whether subadditive integration recorded by cortical EPs reflects the activity of speech-specific neurons or a more general neural mechanism that is cued by visual motion remains to be tested definitively. It seems likely that speech-specific mechanisms are involved when speech stimuli are used; however, they may not be solely responsible for the observed effects. Whatever the underlying mechanism of

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subadditive integration may be, we expected the cortical EP responses of the NH group to follow the pattern of integration observed in the study of Besle et al. (e.g., AV responses faster and lower than A + V).

In this study, we aimed to determine (1) what effect visual information had on the auditory responses of older adults with NH and (2) whether these effects, or the extent of effects, were different in a group of hearing-impaired adults in the same age range. To do this, we recorded cortical evoked potentials in three conditions: (1) when subjects heard only the acoustic speech (A), (2) when they saw a video projection of a speaker articulating only (V), and (3) when they saw and heard these tokens paired synchronously (AV). To tease the effects of age and HL apart, we controlled for age by recruiting age-matched participants and controlled for audibility in the HL population by presenting sounds at +30 dB SL for each individual. In this way, we were able to determine whether HL older adults show more or less AV interaction than their NH counterparts with equalized auditory input. Therefore, our baseline assumption was that no difference would exist between groups on measurements of the unimodal auditory response.

We hypothesized that HL in older adults would have a deleterious effect on integration effects. Several lines of animal research show that multisensory mechanisms (such as the integration of sight and sound) depend on the integrity of each unimodal input. For instance, when subjects are deprived of one modality, the response to multisensory stimuli is often degraded relative to counterparts with normally functioning inputs (Heil et al. 1991; Korte & Rauschecker 1993; Rauschecker & Korte 1993; Wallace et al. 2004). HL can be considered a type of auditory deprivation because HL people receive less auditory input than NHs in normal listening conditions. From the above data, we hypothesized that adaptation to auditory deprivation impairs the HL multisensory system as well. This hypothesis is also partially based on the knowledge that auditory expertise, in the form of musical training, has positive consequences on early, and even subcortical, multisensory processing (Hairston et al. 2006; Musacchia et al. 2007). If our hypothesis were true, enhanced multisensory processing in auditory experts would logically contrast with poorer integration in the impaired auditory system. An alternative hypothesis is that HL in humans promotes compensation mechanisms that either have no effect on or serve to strengthen multisensory mechanisms.

Our findings show that the HL group fails to show the normal pattern of AV integration, especially at peaks P1 and N1. Overall, the extent of AV integration correlated with auditory threshold in both groups such that lower thresholds were associated with more AV integration. These data illustrate that HL has deleterious effects on neural mechanisms of multisensory function and emphasize the importance of assessing multimodal skills in hearing-impaired populations.

SUBJECTS AND METHODS

Subjects

Twelve older adults (mean = 70.8 yr, SD = 4.5 yr) with near NH thresholds and 12 older adults with mild to moderate HL (mean = 72.2 yr, SD = 3.7 yr) were recruited from visitors, staff, and continuing education attendants of the Northwestern University campus and the Buehler Center on Aging research registry. All subjects were native English speakers. Subjects who had worn hearing aids in the past 5 years, had a history of neurological disorders (e.g., seizures, cerebral palsy, spina bifida, or any syndrome associated with central or peripheral nervous system), and exhibited below-normal cognitive function were excluded. Testing required a 3.5 hr session, which most participants completed in 1 day. Each participant signed an informed consent form before the commencement of the experiment in accordance with the Institutional Review Board procedures at Northwestern University and was compensated for his or her participation.

Cognitive function was assessed with the Wechsler Abbreviated Scale of Intelligence Full-4 to measure verbal, nonverbal, and general cognitive functions. Mean intelligence quotient scores were calculated for each individual. Groups did not differ significantly on any measure of cognitive function (Table 1).

Subjects whose normal or corrected-to-normal visual acuity, as assessed with a Snellen 10-foot eye chart, exceeded 10/15 were excluded. Because visual acuity was controlled for in this way, we did not anticipate unimodal visual differences. The audiologic assessment included pure-tone air conduction and bone conduction thresholds, as well as binaural speech audiometry. Hearing sensitivity was established at 250, 500, 1000, 2000, 4000, and 8000 Hz in each ear using the GSI 61 Audiometer (Grason-Stadler) in a sound-treated room and with sound delivered through insert earphones (Etymotic Research, ER-3A) (Table 2). Bone conduction testing was performed to differentiate between sensorineural and conductive HL. Subjects with a conductive HL were excluded from the study. Speech testing consisted of a binaural word recognition test presented at a subjectively determined most comfortable level (around 30 to 40 dB SL above pure-tone average). A binaural speech awareness threshold was determined using the same auditory stimulus used for the neurophysiological recordings ("bi"). The participants were instructed to say "yes" when the syllable became audible and distinct.

Subjects with either normal or a symmetric sloping sensorineural HL no greater than a moderately severe degree (<80 dB HL) in the speech frequencies (500 to 4000 Hz) were selected for this study. HL was defined as pure-tone thresholds that exceeded the normative sensitivity values in at least two or more frequencies set forth by the ISO Standard on hearing by age and sex (ISO 7029:2000 Acoustics). Larger standard deviations in the HL group are caused by the sloping configurations of their HL. A feature of the NH group is elevated thresholds at 8 kHz relative to typical normal thresholds for young adults. Because most adults in this age range do not have entirely normal thresholds especially in the higher frequencies, we thought that this was an acceptable and representative range of HL for this group. As can be seen in Table 2, despite the elevated thresholds for 8 kHz in the NH group, a significant difference was still observed between NHs and HLs.

Stimuli and Presentation Sequence

The acoustic stimulus consisted of a five-formant, 430 msec, synthetic speech syllable, "bi," created with a DH Klatt synthesizer. The visual stimulus was a digital recording of a male speaker saying the "bi" syllable in a clear speaking style (Fig. 1).

TABLE 1. Age and cognitive measures for older adults with normal hearing thresholds (NH) and mild hearing loss (HL)

Group	Subject	Age (yr)	WASI verbal (percentile)	WASI nonverbal (percentile)	WASI full (percentile)
NH	1	74	98	99	99
	2	72	86	86	88
	3	67	82	70	81
	4	68	91	88	93
	5	73	47	47	50
	6	75	66	100	95
	7	65	88	99.5	98
	8	72	96	99.8	99.6
	9	64	90	90	93
	10	77	79	97	94
	11	66	87	82	87
	12	76	91	97	96
Mean		70.8	83.4	87.9	89.5
SD		4.5	14.2	15.8	13.6
HL	1	72	90	90	93
	2	75	79	92	90
	3	71	70	99	94
	4	70	45	73	63
	5	75	86	99	97
	6	67	73	61	70
	7	74	82	75	82
	8	72	19	70	42
	9	70	77	99	95
	10	75	96	95	97
	11	79	73	32	53
	12	66	68	88	81
Mean		72.2	71.5	81.1	79.8
SD		3.7	21.0	20.1	18.7
Independent *t* test					
t		0.84	1.63	0.93	1.46
p		0.410	0.117	0.363	0.159

NH, normal hearing; AV, audiovisual; HL, hearing loss; WASI, Wechsler Abbreviated Scale of Intelligence. Bold values indicate significance levels of $p < 0.05$.

The articulation was contained within 37 frames that began and ended at the same neutral resting position. The total trial time from frame 1 to frame 37 of the visual stimulus was 1.3 sec. Frames 16 to 18 depicted the release of the consonant, which coincided with auditory onset at 570 msec. Hence, time 0 will be referenced to acoustic onset. The visual stimuli were projected 1.8 m in front of the subject, with a visual angle of 38°, and the auditory stimulus, "bi," was presented bilaterally through insert earphones (Etymotic Research, ER-3A). Delivery of the audio and visual stimuli was controlled by Presentation software (Neurobehavioral Systems, Inc., CA). Stimuli were presented in the A, AV, and V conditions randomly throughout the testing session. The auditory stimulus was presented at 30 dB SL above the speech awareness threshold determined during the hearing evaluation. Presentation at a fixed sensation level was used to ensure equal audibility across all participants. To control for attention, participants were asked to count the number of catch trials silently. Catch trials consisted of sporadic visual projections of a red asterisk and were interspersed randomly (15%) throughout the presentation sequence. No difference was seen in catch trial percent error across groups ($M_{NH} = 17.5$, SD = 10.76; $M_{HL} = 13.16$, SD = 5.98; $t = 1.219$, $p = 0.236$). Eighteen blocks of 75 stimulus repetitions were presented to each subject, with a short break between each block. A long break was provided midway through the testing session that usually lasted approximately 45 min. In all, 450 responses were recorded in each of the three conditions.

Recording Parameters and Off-line Processing

Neurophysiological recordings were conducted in a sound-attenuated booth. Cortical responses were acquired with Neuroscan 4.3 (Compumedics, El Paso, TX) using Ag–AgCl electrodes (impedance <5 kΩ). Reference, ground, and eye blink monitor electrodes were placed on the nose, forehead, and superior vertical electrooculogram and outer horizontal electrooculogram canthus of the left eye, respectively. Five active electrodes were positioned according to the 10–20 International system at Fz, F3, F4, Cz, and Pz. Continuous Electroencephalogram was recorded with a band-pass filter from 0.5 to 30 Hz at a sampling rate of 1000 Hz. Off-line processing included dividing continuous Electroencephalogram into epochs from −150 to 1000 msec postacoustic onset. An artifact criterion was applied to horizontal electrooculogram and vertical electrooculogram channels to reject those epochs that contained myogenic and eye-blink artifacts. Any epoch with a voltage exceeding ±65 μV was omitted from the average. The artifact-free epochs (mean = 418 sweeps, SD = 14, per condition) were then averaged according to stimulus type and baseline corrected to the preauditory-stimulus period.

TABLE 2. Audiometric thresholds for older adults with normal hearing thresholds (NH) and mild hearing loss (HL)

		Left ear pure tone thresholds (dB)						Right ear pure tone thresholds (dB)					
Group	Subject	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
NH	1	5	5	5	15	30	55	5	10	10	15	20	50
	2	25	20	10	25	35	50	25	20	20	15	35	20
	3	15	10	15	15	35	35	15	10	15	10	20	40
	4	25	15	5	5	10	20	20	15	5	5	10	20
	5	10	10	10	0	10	30	5	5	5	0	10	40
	6	15	15	20	20	35	45	15	15	20	25	25	45
	7	25	15	10	10	15	40	10	10	10	10	5	45
	8	5	15	5	10	15	35	15	10	10	15	15	5
	9	40	25	20	15	15	30	15	20	10	15	15	25
	10	25	25	15	20	35	65	25	25	15	20	40	65
	11	5	10	5	10	10	25	10	10	5	10	10	45
	12	25	10	20	10	25	75	20	5	20	15	25	45
Mean		18.3	14.6	11.7	12.9	22.5	42.1	15.0	12.9	12.1	12.9	19.2	37.1
SD		10.9	6.2	6.2	6.9	11.0	16.6	6.7	6.2	5.8	6.6	10.6	16.4
HL	1	50	40	25	35	50	75	40	35	30	35	50	70
	2	30	35	50	50	55	70	25	25	50	50	50	65
	3	45	40	35	50	60	70	40	40	30	40	55	65
	4	35	20	15	30	40	50	30	30	15	25	40	40
	5	35	20	15	40	60	65	40	15	10	30	65	65
	6	20	25	30	50	55	15	20	25	30	40	55	25
	7	25	30	35	35	45	40	30	35	30	40	45	50
	8	40	35	15	10	50	60	40	25	15	5	30	45
	9	15	25	30	35	55	75	10	15	20	35	35	75
	10	20	20	15	35	40	50	15	25	10	45	50	60
	11	15	15	20	45	80	90	20	20	20	70	80	95
	12	25	20	20	35	55	65	20	15	20	50	55	70
Mean		29.6	27.1	25.4	37.5	53.8	60.4	27.5	25.4	23.3	38.8	50.8	60.4
SD		11.6	8.7	11.0	11.2	10.7	19.6	10.8	8.4	11.4	15.7	13.3	18.3
Independent *t* test													
t		2.45	4.07	3.79	6.48	7.07	2.47	3.41	4.15	3.06	5.26	6.45	3.29
p		0.023	0.001	0.001	0.000	0.000	0.022	0.003	0.000	0.006	0.000	0.000	0.003

NH, normal hearing; HL, hearing loss. Bold values indicate significance levels of $p < 0.05$.

Response Measurements

Signal to noise ratio was calculated by dividing the root mean square amplitude of the poststimulus period by the root mean square amplitude of the prestimulus period. Only responses with a signal to noise ratio >3 were used for data analysis. One subject from each group in the original subject pool was eliminated in this way to result in 12 NHs and 12 HLs.

For all included subjects ($N = 24$), individual averages for the unimodal auditory and unimodal visual were added together to create a summed A + V response. Subsequent comparisons were made between measurements of the summed (A + V) and the simultaneous (AV) responses. In the current study, "multisensory integration" is defined as any significant difference between the summed (A + V) and the simultaneous (AV) responses, without restriction to super- or subadditivity. The rationale for this comparison strategy is that (1) the responses to the unimodal auditory and visual stimuli reflect processing in unisensory structures, (2) when summed, the A + V response reflects the linear combination of synchronous activity in unisensory structures, and (3) activation of AV, or integrating, nuclei would result in a response that differs from the combined synchronous activity of unisensory structures. This methodology, which defines multisensory integration as a nonlinear combination of modality-specific information, has been the predominant litmus test for identifying integration by multisensory neurons for more than a decade. However, it must be noted that this model is completely insensitive to multisensory convergence involving the linear summation of unisensory responses. In fact, a recent study exploring a range of unimodal stimulus "effectiveness" (or perceptibility) showed that the majority of neurons approximated the linear summation of unimodal inputs for strongly effective stimuli (Stanford et al. 2005). Although we do use the AV versus A + V model here, we recognize its inability to capture different types of multisensory integration.

Peaks P1 and N1 for each individual's AV and A + V averages were picked by visual inspection of two raters who were "blinded" to group and condition. These marks were used to measure peak latency and amplitude. Inter-rater reliability for peaks P2 and N2 was low; therefore, measures from these two peaks were excluded from analysis. Measures of the visual stimulus alone were similarly excluded because inter-rater reliability was less than 50% for peaks picking. The slope between peaks P1 and N1 was computed to create a composite measure of early response strength. As in our previous publications (Russo et al. 2004; Musacchia et al. 2008), this measure is used to assess the synchrony of positive to negative deflection in successive cortical peaks.

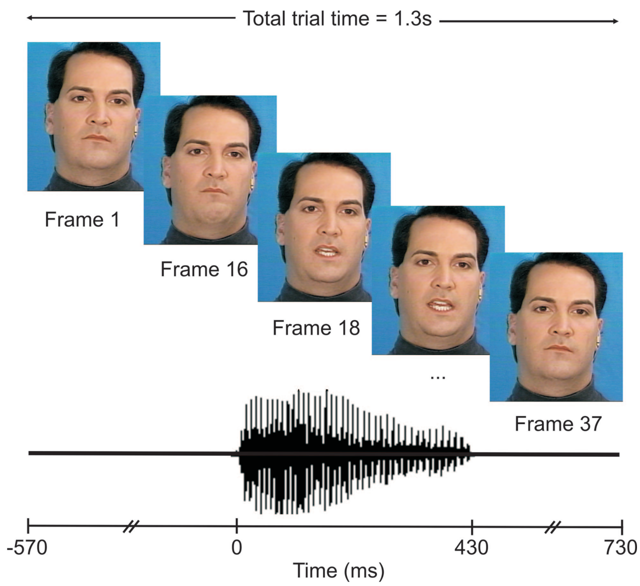

Fig. 1. Auditory and visual components of experimental stimuli. The waveforms of the acoustic stimulus (bottom) and visual articulation (top) are depicted. The visual component was digitized from a video of a speaker saying "bi." Acoustic onset occurred 570 msec after the first video frame and simultaneously with the release of consonant closure. Duration of the acoustic stimulus was 430 msec. Additional frames followed the end of the acoustic speech syllable to allow labial closure. The total trial time (and stimulus onset asynchrony) was 1.3 sec.

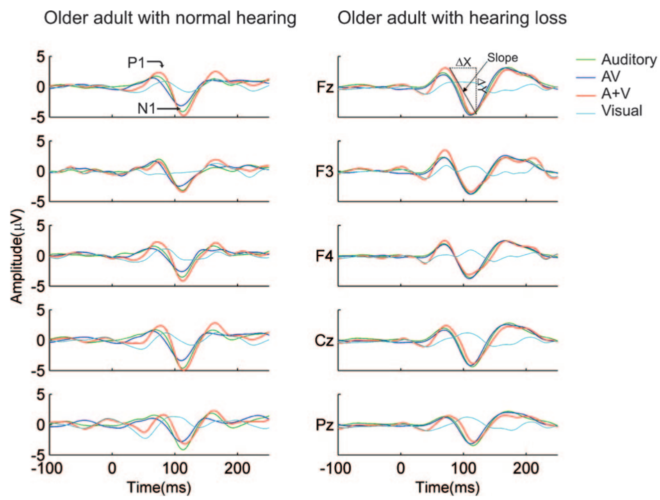

Fig. 2. Example averages from each group in the unimodal, bimodal, and summed conditions. Evoked-potential waveforms for one NH subject (left column) and one HL subject (right column) are shown for all five electrodes (top to bottom: Fz, F3, F4, Cz, and Pz). Unimodal auditory (green) and audiovisual (blue) responses to the speech syllable "bi" reliably elicited two sequential peaks of alternating positive and negative deflections labeled P1 and N1 in the top left column. Responses to unimodal visual stimuli (cyan) elicited a peak of response approximately 100 msec in most subjects, but the peaks could not be detected reliably. The linear summation of the unimodal stimuli, or A + V, is shown in red. The slope between P1 and N1 was calculated to assess the synchrony of positive to negative deflection in the early portion of the cortical response (shown in the top right column).

Statistical Analysis

To test our baseline assumption of equalized auditory input in both groups, we compared the unimodal auditory responses between the NH and HL groups first by conducting independent *t* tests on the group grand averages (Fig. 3). For this analysis, averages were spline fit to 256 points, and successive *t* tests were performed at each time point. A Bonferroni correction for multiple comparisons was applied to the significant criterion ($t = 4.46$, df $= 22$, $p < 0.0002$). Independent *t* tests were also performed between group latency and amplitude measures of P1 and N1 peaks ($t = 1.72$, df $= 22$, $p < 0.05$). Although we were unable to pick peaks on the unimodal visual responses as a result of low inter-rater reliability, we did perform independent *t* tests on the unimodal visual group grand averages in the manner described above (Fig. 3). No significant differences were observed at any time point in the unimodal grand averages, and no peak differences were observed between groups in the auditory condition.

The degree of multisensory integration in NH and HL groups was established in a three-step statistical process. First, control patterns of AV integration were established by conducting Student's paired *t* tests between AV and A + V response measurements of latency and amplitude at each peak and electrode the NH group (criteria and df described below). In the second step, we tested whether the experimental group showed similar patterns of integration by conducting the same tests in HLs. Finally, 2 × 2 repeated-measure tests of group-by-condition analysis of variance comparisons were conducted for each measure, which showed a significant integration effect in the NH group. This enabled us to determine which integration effects were different in control and experimental groups. In addition, we assessed broad group differences in AV integration by comparing the AV − (A + V) difference wave grand averages across groups as described for the unimodal grand average comparisons above (Fig. 3).

To determine relationships between the severity of HL and AV integration, bivariate Pearson's *r* correlation tests were conducted between speech awareness threshold values and neurophysiological measures that showed integration effects.

RESULTS

In all subjects, A and AV stimuli elicited a prominent peak before 100 msec (P1) followed by a negative trough, N1 (Fig. 2). Peak latencies were similar to previously reported normative values (Hall 1992). Broad group differences were seen in the grand average difference over N1 (Fig. 3, left panel). In keeping with our underlying assumption, no group differences were observed between the auditory grand averages or between measures of peak latency or amplitude at any electrode (Fig. 3, middle panel). In addition, unimodal visual grand averages did not differ between groups (Fig. 3, right panel).

AV Integration in NH and HL Older Adults

AV integration was observed in the NH group at both P1 and N1 peaks (Tables 3 through 6). P1 latencies were earlier in the AV condition at Fz, F4, Fz, Cz, and Pz electrodes compared with A + V (Table 3). Integration effects were less pervasive with P1 amplitude measures because subadditivity was observed only at electrodes F3 and F4 (Table 4). N1 latencies were earlier in the AV condition compared with A + V at Fz, F4, and Pz for the NH group (Table 5), and subadditive

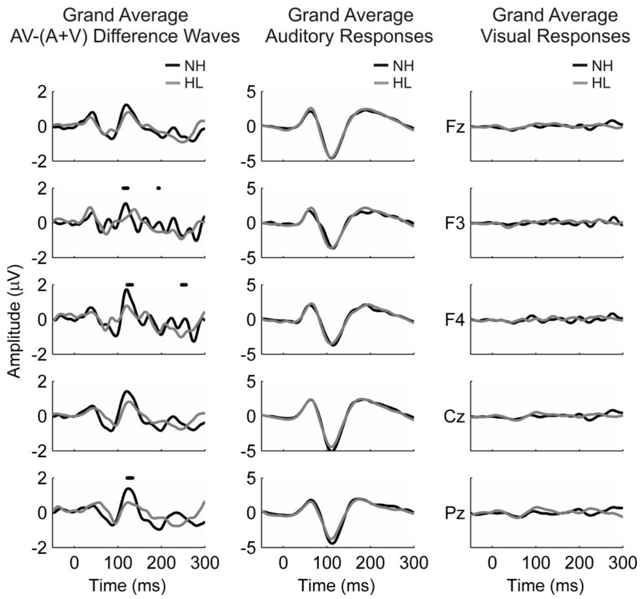

Fig. 3. Grand average difference and unimodal responses. Grand average difference waveforms [(AV − A + V)] from NH (black) and HL (grey) groups are overlaid in the leftmost panel. Independent t-tests were performed across time points. Time points that exceeded the alpha criterion after correction for multiple comparisons (t = 4.46, df = 22, p = 0.0002) are plotted above the waveforms in black. The middle panel shows overlaid grand average unimodal auditory responses from the NH (black) and HL (grey) groups. With independent t-tests repeated as above, no significant differences were observed. The right panel shows overlaid grand average unimodal visual waveforms from NH (black) and HL (grey) groups. No significant differences between waveforms were observed in this condition. This indicates, broadly, that NHs and HLs have different degrees of AV integration despite similar responses to unimodal stimuli.

amplitudes were observed at all electrodes for N1 measurements (Table 6).

Older adults with HL failed to show the integration effects for P1 latencies and P1 and N1 amplitudes that were observed in the NL group (Tables 3, 4, and 6, respectively). However, HLs did show a pattern of AV integration similar to controls with N1 peak latency measurements (Table 5). In the AV condition, HLs had earlier N1 peak latencies at electrodes Fz, F3, and Pz compared with A + V responses. Notably, the topography of integration effects was shifted to the right in the NH group (F4, but not F3 effects) but shifted to the left in the HL group (F3, but not F4 effects).

Although 2 × 2 repeated-measure tests of group-by-condition analysis of variance comparisons showed a significant effect of condition for almost every measure, only P1 latency at Cz showed a significant group-by-condition interaction (F = 7.20, p = 0.013). The fact that the strongest difference between groups was seen at this electrode for this measure was not altogether surprising because P1 latency integration effects were largest and most significant for the NH group along the midline. Trends toward group-by-condition differences were also observed for N1 amplitudes at F3 (F = 4.12, p = 0.054) and Cz (F = 2.98, p = 0.098) electrodes.

Figure 4 shows a composite summary of the differences in AV integration between groups for P1 latency and N1 amplitude. Bars signify AV − (A + V) differences for each group, and asterisks denote significant AV versus A + V tests for the NH group. The HL group showed no significant differences for any of the measures in Figure 4.

Composite Measures and Relationships Between HL and AV Integration

To assess the interaction effects of timing and size together, the slope ($m = \Delta Y/\Delta X$) between peaks P1 and N1 was computed for each subject in the AV and A + V conditions. Paired t tests in each group showed that NHs had broader slopes in the AV condition than in the A + V at Fz (t = 3.74, p = 0.003) and Cz (t = 3.36, p = 0.006). The HL group showed no slope differences at any electrode. Repeated-measures analysis showed a significant group-by-condition interaction effect at Cz only (F = 7.70, p = 0.011).

Magnitude of integration effect for the two measures showing significant group-by-condition effects (P1 latency at Cz and P1–N1 slope at Cz) was computed by subtracting the A + V value from AV (AV − [A + V]). To determine whether auditory speech thresholds were related to the magnitude of AV integration, we correlated auditory thresholds for the stimulus syllable "bi" with our integration effect values. A significant correlation was observed between hearing thresholds for "bi" and P1–N1 slope integration effects (r = −0.465, p = 0.022). The nature of the relationship showed that elevated

TABLE 3. Mean P1 latency values and statistics for older adults with normal hearing thresholds (NH) and mild hearing loss (HL) in the AV and A + V conditions

P1 latency		Means (msec)		Paired differences			
Group	Electrode	AV	A + V	Mean	SD	t	p
NH	Fz	59.58	65.92	−6.33	4.70	−4.67	**0.001**
	F3	64.92	64.92	0.00	16.72	0.00	1.000
	F4	60.83	64.75	−3.92	4.50	−3.01	**0.012**
	Cz	59.75	65.67	−5.92	5.42	−3.78	**0.003**
	Pz	55.92	63.67	−7.75	11.43	−2.35	**0.039**
HL	Fz	63.92	65.58	−1.67	3.77	−1.53	0.154
	F3	64.50	67.25	−2.75	5.94	−1.60	0.137
	F4	64.42	66.83	−2.42	4.54	−1.84	0.092
	Cz	63.33	64.92	−1.58	4.74	−1.16	0.272
	Pz	63.33	63.75	−0.42	6.54	−0.22	0.829

NH, normal hearing; HL, hearing loss; AV, audiovisual; A, auditory; V, visual. Bold values indicate significance levels of p < 0.05.

TABLE 4. Mean P1 amplitude values and statistics for older adults with normal hearing thresholds (NH) and mild hearing loss (HL) in the AV and A + V conditions

P1 amplitude		Means (μV)		Paired differences			
Group	Electrode	AV	A + V	Mean	SD	t	p
NH	Fz	1.92	2.29	−0.37	0.88	−1.46	0.172
	F3	2.00	2.63	−0.63	0.94	−2.32	**0.041**
	F4	1.86	2.51	−0.65	0.54	−4.15	**0.002**
	Cz	1.92	2.34	−0.42	0.84	−1.74	0.109
	Pz	1.41	2.70	−0.36	1.01	−1.23	0.244
HL	Fz	2.36	2.70	−0.33	1.15	−1.01	0.335
	F3	2.24	2.49	−0.24	1.09	−0.78	0.453
	F4	2.37	2.71	−0.33	1.11	−1.04	0.321
	Cz	2.36	2.23	0.13	1.10	0.41	0.691
	Pz	1.77	1.48	0.29	1.09	0.92	0.379

NH, normal hearing; HL, hearing loss; A, auditory; V, visual. Bold values indicate significance levels of $p < 0.05$.

auditory thresholds for “bi” were associated with less AV integration (Fig. 5).

DISCUSSION

Many older adults with hearing impairment rely on visual cues to compensate for the degraded auditory signal (Erber 1972). However, recent data suggest that hearing impairment in older adults is not necessarily associated with better AV integration abilities (Tye-Murray et al. 2007). Here, we show degraded AV integration in older adults with HL relative to NHs in the same age group. Specifically, NH older adults consistently exhibited earlier peak latencies and subadditive amplitudes in the AV condition relative to the linear summation of unimodal responses (A + V). Similar trends were seen in the HL group, but differences did not reach statistical significance. Group differences were not observed in either unimodal auditory or visual conditions. This indicates that HLs may be using the same underlying neurophysiological mechanisms for integration of seen and heard speech, only to a lesser extent than more NH controls.

These findings indicate that HL in the aging population impacts neural mechanisms of AV integration. It has been suggested that auditory mechanisms of excitation and inhibition may be degraded in the aging system, especially when faced with fast time-varying acoustics (Tremblay et al. 2003). We show that older adults exhibit the same qualitative pattern of AV integration that has been previously observed in younger adults to auditory and visual speech (Besle et al. 2004). This suggests that aging alone may not alter mechanisms of AV integration, as opposed to unisensory auditory processing, but that HL in this population does have a deleterious effect on both auditory and AV mechanisms. Whether this degradation occurs immediately and whether behavioral adaptation to HL is related to improvement or deterioration in multisensory processing remain to be seen.

Animal studies on sensory deprivation give us a model for how HL might impact multisensory mechanisms. In these studies, profound unimodal degradation, in the form of total deprivation, changes the functional properties of neurons in multisensory regions and unisensory regions of the intact modality (Heil et al. 1991; Korte & Rauschecker 1993; Rauschecker & Korte 1993; Wallace et al. 2004). As older adults lose their hearing, the unimodal acoustic input becomes increasingly less audible or more degraded over time. Adapta-

TABLE 5. Mean N1 latency values and statistics for older adults with normal hearing thresholds (NH) and mild hearing loss (HL) in the AV and A + V conditions

N1 latency		Means (msec)		Paired differences			
Group	Electrode	AV	A + V	Mean	SD	t	p
Normal Hearing	Fz	105.83	113.83	−8.00	9.64	−2.88	**0.015**
	F3	107.42	109.33	−1.92	6.39	−1.04	0.321
	F4	109.33	113.00	−3.67	4.98	−2.55	**0.027**
	Cz	106.33	109.25	−2.92	4.93	−2.05	0.065
	Pz	107.42	112.67	−6.08	5.99	−3.52	**0.005**
Hearing Loss	Fz	108.92	112.67	−3.75	5.51	−2.36	**0.038**
	F3	108.25	112.50	−4.25	3.70	−3.98	**0.002**
	F4	108.92	109.50	−0.58	5.35	−0.38	0.713
	Cz	108.00	110.92	−2.92	6.37	−1.59	0.141
	Pz	108.50	113.92	−5.42	4.34	−4.33	**0.001**

NH, normal hearing; HL, hearing loss; AV, audiovisual; A, auditory; V, visual. Bold values indicate significance levels of $p < 0.05$.

TABLE 6. Mean N1 amplitude values and statistics for older adults with normal hearing thresholds (NH) and mild hearing loss (HL) in the AV and A + V conditions

N1 amplitude		Means (μV)		Paired differences			
Group	Electrode	AV	A + V	Mean	SD	t	p
Normal Hearing	Fz	−4.46	−5.52	1.06	1.10	3.35	**0.006**
	F3	−3.52	−4.59	1.08	0.88	4.22	**0.001**
	F4	−4.23	−5.13	0.90	0.80	3.90	**0.002**
	Cz	−3.62	−4.58	0.96	0.66	5.02	**0.000**
	Pz	−3.99	−4.77	0.77	1.16	2.31	**0.041**
Hearing Loss	Fz	−4.05	−4.39	0.33	0.97	1.19	0.258
	F3	−3.51	−4.31	0.81	1.34	2.08	0.061
	F4	−4.16	−4.57	0.41	0.73	1.93	0.080
	Cz	−3.56	−3.92	0.36	0.78	1.60	0.138
	Pz	−3.14	−3.45	0.32	1.03	1.06	0.312

NH, normal hearing; HL, hearing loss; AV, audiovisual; A, auditory; V, visual. Bold values indicate significance levels of $p < 0.05$.

tion to moderate HL may engender similar mechanisms of plasticity and likewise impact multisensory regions. One way to test this would be to compare AV integration effects with differing lengths of hearing impairment to determine whether AV integration can be improved with experience and directed training. Further studies are needed to determine the timeline of the deleterious plasticity in mechanisms of integration. Auditory experts, such as musicians, lie on the opposite end of the perceptual spectrum from individuals with HL. Lifelong music training has been given to enhance both auditory and AV processing (Zatorre 1998; Gaser & Schlaug 2003; Wong et al. 2007; Musacchia et al. 2007, 2008; Zatorre et al. 2007). In our previous study, auditory and AV speech tokens elicited larger and earlier P1 and N1 peaks in musicians than in nonmusician controls (Musacchia et al. 2008). Although a direct continuum cannot be drawn between the integration mechanisms of "auditory expertise" and hearing impairment, it is interesting to note that the musicians in our previous study and HLs in the current one show effects at the same peaks. One potential implication of these observations is to consider the use of multisensory and musical training in rehabilitation strategies for older adults with HL.

An alternative hypothesis is that attentional mechanisms may be excessively impacted by hearing impairment in older adults. The facial movements that precede acoustic onset cue a listener to focus his or her attention when the speaker releases the consonant. In this case, seeing a speaker prepare to say "bi" would increase expectation and hence attention to the auditory signal. If hearing impairment impedes a listener's ability to focus his or her attention, the visual motion may not serve its cuing purpose. This hypothesis is unlikely because attentional differences across groups would likely be reflected through differences in task accuracy, whereas no difference was seen in task accuracy between the NH and HL groups.

Because the high-frequency thresholds are most impaired in our HL group, our results could hypothetically reflect diminished input in the high-frequency hearing range. High-frequency information in consonant-vowel syllables is concentrated in the consonant portion of the sound (e.g., the "b" of "bi"), where visual articulation is most active. It is possible that HL subjects received less high-frequency information despite equalized presentation levels. In this case, abnormal AV interaction in HL subjects may still be related to less auditory input. However, AV integration has been shown to operate inversely to stimulus salience, so that lower unimodal salience results in larger integration effects (Stein & Meredith 1993). If AV integration were dependent purely on audibility, one would predict enhanced AV effects in the HL group because they received a less effective high-frequency stimulus. However, our findings consistently show smaller AV effects in the HL group. Thus, we conclude that despite possible differences in high-frequency input levels between the two groups, AV integration deficits in the HL group cannot be attributed solely to differences in high-frequency thresholds between the groups.

Implications for Rehabilitation and Research

The clinical implication of these findings is that integration mechanisms, in addition to unisensory ones, may be degraded in more than 30% of the aging population. It is well known that auditory and visual speech cues are essential to hearing-impaired populations, especially in noisy conditions. A remaining question is whether AV training can improve perception and processing in this population. Although AV training has not been investigated to date, auditory training has been shown to impact early cortical components of auditory-evoked potentials in young adults and language-impaired children. NH adults who were trained to discriminate small differences in syllable contrasts, such as voice onset times, showed training-related increases in P1 and N1 peak amplitudes and mismatch negativity components (Tremblay et al. 1997, 2001). A subsequent study suggested that the capacity for short-term training-related plasticity may be greatest in the right hemisphere (Tremblay & Kraus 2002). These data are particularly encouraging given that hemispheric differences were evident between the NL and HL groups at N1.

Currently, there are a handful of tests and training materials available for auditory-visual communication assessment and treatment. Tyler et al. (1983) developed the Iowa Consonant Confusion test, which measures auditory-visual perception of phonemes and everyday sentences. Plant (2001) created the

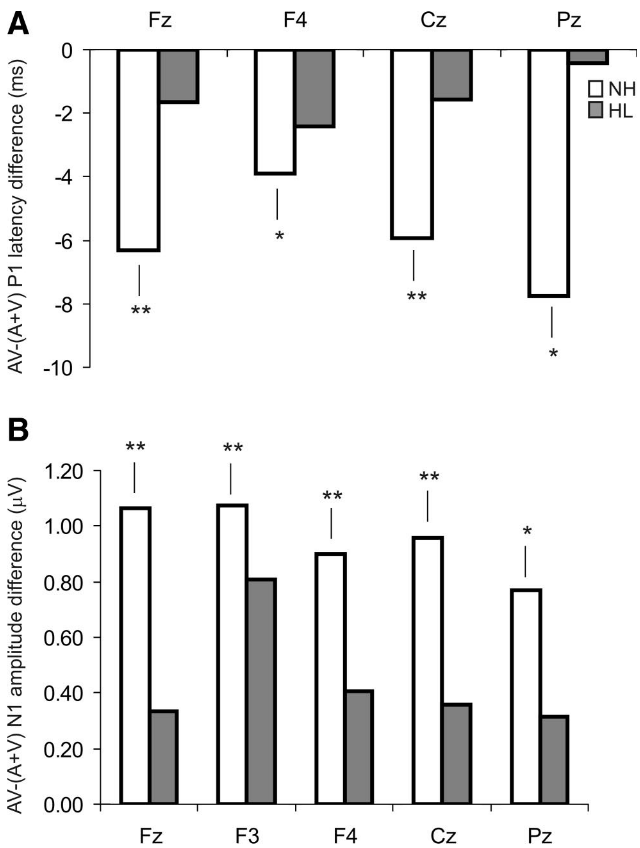

Fig. 4. Mean latency and amplitude differences between AV and A + V responses. (A) Bars show the mean difference between P1 latency in the AV and A + V condition (AV minus A + V). Negative values indicate that P1 latencies were earlier in the AV condition than in the linear summation of the two unimodal responses. AV vs. A + V paired t-tests showed that these differences were significant for the NH group (white bars) at FZ, F4, Cz and Pz, as denoted by the asterisks (** denotes $P < 0.01$, * denotes $p < 0.05$). No significant differences between AV and A + V were observed in the HI group. (B) Mean differences between AV and A+V N1 amplitudes for NH and HI groups. Bars show the mean difference between N1 amplitude in the AV and A+V condition (AV minus A + V). Positive values indicate that N1 amplitudes were smaller in the AV condition than in the linear summation of the two unimodal responses. AV vs. A + V paired t-tests showed that these differences were significant for the NH group (white bars) at all electrodes (** denotes $P < 0.01$, * denotes $p < 0.05$). No significant differences between AV and A + V were observed in the HL group.

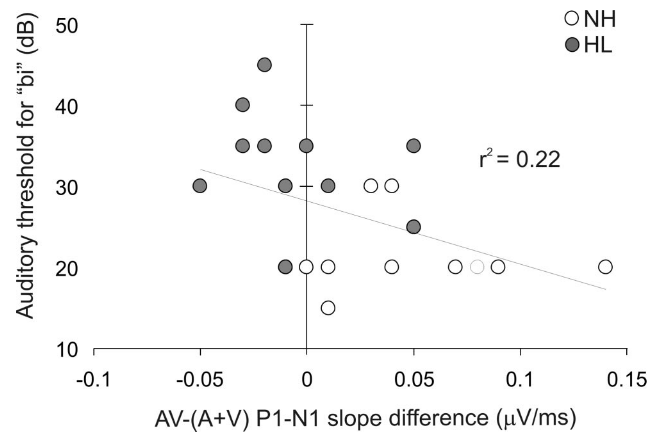

Fig. 5. Relationship between auditory thresholds for hearing speech and audiovisual integration in early cortical responses. The difference between P1–N1 slope in the AV and A + V conditions (AV − [A + V]) shows a composite measure of audiovisual integration in early cortical peaks. A positive value indicates that the P1–N1 slope was broader in the AV condition than in the linear summation of the two unimodal responses. The between-condition P1–N1 slope difference correlated negatively with speech hearing thresholds..

Auditrain program containing analytic and synthetic sentence materials for development of auditory-visual perception skills in cochlear implant users. Seeing and Hearing Speech (Sensimetrics Corporation, Somerville, MA) is a computerized home-study program that emphasizes combined auditory and visual cues of everyday communication in varied levels of background noise. Conversations Made Easy (Tye-Murray 2002), a computerized program distributed by the Central Institute for the Deaf (St. Louis, MO), presents sentences and everyday scenarios in closed-set format for training in an auditory-visual mode or a visual-alone mode. Further studies are needed to understand how such auditory-visual training programs, combined with auditory and AV cortical response measures, can help understand and assess multisensory training effects. In addition, this and related studies raise questions about how integration of other senses, such as touch and hearing, may function in the aging and hearing-impaired populations.

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