

Auditory and tactile gap discrimination by observers with normal and impaired hearing

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Temporal processing ability for the senses of hearing and touch was examined through the measurement of gap-duration discrimination thresholds (GDDTs) employing the same low-frequency sinusoidal stimuli in both modalities. GDDTs were measured in three groups of observers (normal-hearing, hearing-impaired, and normal-hearing with simulated hearing loss) covering an age range of 21–69 yr. GDDTs for a baseline gap of 6 ms were measured for four different combinations of 100-ms leading and trailing markers (250–250, 250–400, 400–250, and 400–400 Hz). Auditory measurements were obtained for monaural presentation over headphones and tactile measurements were obtained using sinusoidal vibrations presented to the left middle finger. The auditory GDDTs of the hearing-impaired listeners, which were larger than those of the normal-hearing observers, were well-reproduced in the listeners with simulated loss. The magnitude of the GDDT was generally independent of modality and showed effects of age in both modalities. The use of different-frequency compared to same-frequency markers led to a greater deterioration in auditory GDDTs compared to tactile GDDTs and may reflect differences in bandwidth properties between the two sensory systems. © 2014 Acoustical Society of America. [<http://dx.doi.org/10.1121/1.4861246>]

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I. INTRODUCTION

Previous research suggests that temporal-processing ability is similar across different senses for some tasks but not for others. For example, it is well established that the stimulus-onset asynchrony required to discriminate the temporal order of two pulsatile signals is roughly independent of modality (e.g., [Hirsh and Sherrick, 1961](#); [Spence et al., 2001](#); [Zampini et al., 2005](#)) but that judgments of fusion or simultaneity are different across the senses ([Gescheider, 1966, 1967](#)). Such results have led to the hypothesis that modality-dependent tasks are mediated at the level of the sensory periphery whereas modality-independent tasks are mediated by higher-level cortical processing ([Wittman, 1999](#)).

In the current study, temporal processing ability was examined for the auditory and tactile senses. Such a comparison is of interest due to a variety of similarities and interactions between these two senses. For example, over certain frequency and intensity ranges, the same acoustic/vibratory stimuli can be experienced by both senses, and [von Békésy \(1959\)](#) suggested that these similarities may arise from evolution of the basilar membrane from an area of skin which became increasingly sensitive to vibration. Furthermore, recent research has revealed a variety of interactions between the senses of hearing and touch in the neuroanatomical ([Zhou and Shore, 2004](#)), neurophysiological ([Schroeder et al., 2001](#); [Song et al., 2011](#)), and perceptual domains ([Yau et al., 2009](#); [Wilson et al., 2009, 2010a,b](#)). For example, recent discoveries have shown that regions of the central nervous system traditionally thought to receive auditory-only inputs may also

receive inputs from the somatosensory system ([Zhou and Shore, 2004](#)). In the primary auditory cortex, there is evidence of both multi-sensory enhancement and suppression at the cellular level for combined auditory-tactile stimulation compared to responses in either sense alone ([Schroeder et al., 2001](#)). Additionally, at the perceptual level, both interference and integration effects have been observed for detection ([Wilson et al., 2009, 2010a](#)), discrimination ([Yau et al., 2009](#)), and loudness-matching ([Wilson et al., 2010b](#)) tasks when comparing performance for simultaneous auditory-tactile versus unisensory stimulation.

The frequency range to which the tactual sense is most sensitive (roughly 60–700 Hz) overlaps with the lower end of the frequency range responded to by the auditory system. Absolute detection thresholds for the vibrotactile presentation of sinusoidal signals are most sensitive in the vicinity of 250 Hz and increase systematically for frequencies above and below 250 Hz ([Bolanowski et al., 1988](#)). Absolute thresholds for the auditory detection of sinusoidal signals decrease systemically with frequency over the same range of 60–700 Hz reach a minimum value in the range of 1000–4000 Hz, and then increase steeply at higher frequencies ([Dadson and King, 1952](#); [Yeowart et al., 1967](#); [Green et al., 1987](#)). Frequency specificity is well established in the auditory domain through perceptual studies showing critical-band filtering ([Zwicker, 1961](#)) as well as through neurophysiological and imaging studies that demonstrate tonotopic mapping from the brainstem to the auditory cortex (e.g., [Talavage et al., 2004](#)). Psychophysical studies also provide some evidence for critical-band filtering in the tactile system (e.g., [Bensmaia et al., 2005](#)); however, these tactile filters may be less sharply defined than auditory filters (see [Wilson et al., 2010a,b](#)).

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The current study examined the relation between gap duration discrimination thresholds in the auditory and tactile modalities with the goal of assessing various properties of temporal and spectral processing. Gap-duration discrimination thresholds (GDDTs) were measured for observers with normal and impaired hearing as well as for observers with simulated hearing loss. The experiments used low-frequency sinusoidal signals (250 and 400 Hz) which are mediated by the Pacinian system in touch (Bolanowski *et al.*, 1988) and are within the spectral range to which both touch and audition are sensitive. The leading and trailing markers that defined the temporal gap to be discriminated took on either the same frequency (250 or 400 Hz) or different frequency values (250 Hz leading and 400 Hz trailing, and vice versa).

Studies in audition have found that the magnitude of the temporal-gap threshold increases with spectral disparity between the leading and trailing markers used to define the gap. Gap-detection and discrimination thresholds are lowest when the markers on both sides of the gap are equal in frequency and increase systematically up to frequency separations between the markers of roughly one-half to one-octave (e.g., Formby and Forrest, 1991; Oxenham, 2000; Phillips and Smith, 2004; Lister *et al.*, 2002, 2011). This effect has been related to auditory critical-band processing (Formby *et al.*, 1996). The temporal-gap threshold is hypothesized to increase systematically with an increase in spectral disparity for leading and trailing markers that lie within the same critical band and thus exhibit overlapping patterns of excitation. Once the spacing between the frequencies of the two markers is sufficiently large that they occupy separate critical bands, the gap threshold is maximized and is then independent of further increases in spectral disparity. This effect is assumed to arise as a consequence of greater difficulty in temporally relating signals from different auditory channels. Thus, a comparison of the spectral-disparity effects within audition and touch will provide some insight into the spectral processing and filtering within each of these senses.

Formby *et al.* (1992) investigated auditory and vibrotactile gap-detection ability using a leading marker of 250 Hz and trailing markers in the range of 250–375 Hz. Tactile gap-detection thresholds were independent of trailing-marker frequency and averaged roughly 35 ms across conditions. Auditory GDTs, however, increased systematically with an increase in trailing-marker frequency over the range of 250 to 300 Hz (from roughly 7 to 50 ms) but showed no further increase for trailers greater than 300 Hz. Formby *et al.* interpreted their results as indicative of the relative absence of tactile filtering, compared to auditory filtering, at 250 Hz. By comparing leading and trailing markers at 250 and 400 Hz, the current study provides a further exploration into auditory and tactile filtering in this frequency region.

Humes *et al.* (2009) examined performance on a temporal gap detection task as a function of age (for 179 subjects ranging in age from 18 to 88 yr) for stimuli presented through audition, touch, and vision. Auditory stimuli were 1000-Hz bands of noise centered at 1000 Hz or 3500 Hz, tactile stimuli were two 30-Hz bands of noise centered at 30 Hz or 250 Hz, and visual stimuli were created through a red light-emitting diode display. Within each modality, the

standard stimulus was always 400 ms in duration and comparison stimuli were created by inserting gaps into the center of the stimulus. Tactile stimuli were presented at a level of 25 dB sensation level (SL), auditory stimuli at a level of 91 dB sound pressure level (SPL), and visual stimuli at a mean luminance of 127.5 cd/m². Gap-detection thresholds (GDTs) were measured using a two-alternative forced-choice procedure that adapted the temporal-gap duration to estimate 75%-correct performance. GDTs, which were significantly higher for older compared to younger subjects, showed a strong effect of modality. For the young-adult group, GDTs were roughly 8 ms for hearing, 17 ms for vision, and 60 ms for touch. These values were significantly lower than those observed for the older-adult group, which were roughly 12 ms for hearing, 24 ms for vision, and 70 ms for touch. Weak correlations were observed between the magnitude of the auditory (both center frequencies) and visual thresholds as well as between auditory (3500-Hz center frequency) and tactile (250-Hz center frequency) thresholds. Such weak correlations of temporal thresholds between the different senses are not supportive of the hypothesis that gap-detection performance is independent of sensory modality.

However, the larger gap-detection thresholds obtained by Humes *et al.* (2009) for touch compared to audition may perhaps be related to the use of signals with different center frequencies and bandwidths across the two senses. Previous studies of auditory gap-detection and gap-duration discrimination performance have observed a decrease in threshold with an increase in stimulus frequency for normal-hearing listeners (e.g., Abel *et al.*, 1990; Moore *et al.*, 1993; Phillips and Smith, 2004). In particular, Moore *et al.* (1993) found a large increase in the auditory gap-detection threshold at 200 and 100 Hz compared to that obtained at higher frequencies. Thus, the smaller auditory gap-detection thresholds could arise from the use of higher-frequency auditory signals (bands of noise centered at 1000 or 3500 Hz) compared to the lower center-frequencies of the noise bands employed for tactile testing (i.e., 35 and 250 Hz). In the current study, GDDTs were measured using 250- and 400-Hz sinusoidal signals for auditory or vibrotactile presentation to allow for a more direct comparison of the effects of modality.

Gap-detection ability is also known to be dependent on stimulus level for both the auditory and tactile modalities. For normal-hearing listeners, the auditory gap-detection threshold has been shown to decrease with signal level and to remain relatively invariant at levels greater than 55–60 dB SPL (e.g., Florentine and Buus, 1984; Moore *et al.*, 1993). For the auditory experiments conducted in the current study, the stimulus markers were presented at a level of 70 dB SPL for listeners with normal hearing and for hearing-impaired listeners for whom this level represented at least 10 dB SL. For listeners with larger amounts of hearing impairment, the stimuli were presented at 10 dB above auditory detection threshold for the 250 Hz and 400 Hz signals. Listeners with simulated hearing impairment received the stimuli at the same level in dB SPL as their age-matched hearing-impaired counterparts. Equivalence between the simulated and real hearing impairments in terms of sensation and loudness

levels, which depends to some degree on the particular hearing loss, is discussed further in Sec. II B of Methods.

For tactile stimulation, Gescheider *et al.* (2003) observed that GDTs decreased with stimulus level and remained constant at levels of 25 dB SL and greater. For our tactile experiments, stimuli were presented at 25 dB SL relative to the absolute detection thresholds for the 250 and 400 Hz vibratory signals presented to the left middle finger. For young adults, absolute detection thresholds for vibrotactile signals presented through the tactile device used here are -29 dB re 1 micron at 250 Hz and -18 dB re 1 micron at 400 Hz (Wilson *et al.*, 2010b). When presented at a level of 25 dB SL, 250- and 400-Hz signals are closely matched in loudness (Verrillo *et al.*, 1969; Wilson *et al.*, 2010b). Absolute detection thresholds can be expected to increase with age (Verrillo, 1979), but the level at which the temporal thresholds were obtained was always set at 25 dB above the measured tactile threshold for each individual subject.

In the auditory modality, gap-duration discrimination thresholds were measured for listeners with normal hearing as well as for listeners with real and simulated cochlear hearing loss. An audibility-based simulation of cochlear hearing loss was applied to normal-hearing listeners who were matched roughly in age to the individual hearing-impaired listeners. The hearing-loss simulation employed here was designed to reproduce effects associated with a reduction in audibility, including threshold elevation, reduced dynamic range, and loudness recruitment (Desloge *et al.*, 2010, 2011a,b, 2012). This component of the research addressed the additional question of how the auditory gap-duration discrimination ability of listeners with cochlear hearing impairment compares to that of normal-hearing listeners and whether the performance of the hearing-impaired listeners can be reproduced by an audibility-based simulation of hearing loss. In the tactile modality, the gap-duration discrimination experiments were repeated for these same groups of observers using the same signals presented through the sense of touch. This component of the research permitted the comparison of auditory and tactile performance on individual observers from the three groups. In both modalities, performance was also examined as a function of the relatively limited age range of the observers (19 to 69 yr).

In summary, the goals of the study were to compare within-subject gap-duration discrimination thresholds for auditory versus tactual presentation of the same low-frequency sinusoidal signals. The effect of age on the ability to perform this task was examined in both modalities. In addition, the study examined the effects of hearing-impairment and hearing-loss simulation on performance in the auditory modality.

II. METHODS

A. Participants

The experimental protocol for testing human subjects was approved by the internal review board of the Massachusetts Institute of Technology. All testing was conducted in compliance with regulations and ethical guidelines on experimentation with human subjects. All observers

provided informed consent and were paid for their participation in the experiments.

1. Participants with hearing impairment

Nine observers with bilateral sensorineural hearing loss who were native speakers of American English participated in the study. These nine observers, HI-1, HI-2, HI-3, HI-4, HI-6, HI-7, HI-8, HI-9, and HI-10, also participated in experiments reported by Desloge *et al.* (2010, 2011a,b, 2012) and are labeled consistently across all studies. Cochlear origin of hearing loss was confirmed through a clinical audiological examination (within one year of entry into the laboratory study) on the basis of air- and bone-conduction audiometry, tympanometry, speech-reception thresholds, and word-discrimination scores. The participants (who ranged in age from 21 to 69 yr) were selected to have bilateral losses that were roughly symmetrical. Information about these participants is provided in Table I, which lists sex, audiometric thresholds in the test ear, and age. The test ear was typically the ear with better average thresholds across test frequencies.

Hearing losses ranged from mild/moderate to severe/profound across participants. The audiometric configurations observed across the hearing losses of these listeners included: (1) sloping high-frequency loss (HI-1, HI-2, HI-3, HI-4); (2) relatively flat loss with no more than a 20-dB difference between adjacent audiometric frequencies (HI-6, HI-7, HI-8); (3) severe low-frequency loss advancing to profound high-frequency loss (HI-9); and (4) inverted cookie-bite loss characterized by near-normal thresholds in the mid-frequency range and moderate loss at low and high frequencies (HI-10).

2. Participants with normal hearing

Twenty-seven NH observers who were native speakers of English were recruited to participate in the hearing-loss simulation component of the study. The hearing loss of each of the nine HI listeners was simulated in a different group of three NH listeners who were matched roughly in age to the HI listener. A clinical audiogram was obtained to screen for normal hearing in at least one ear, defined as 25 dB hearing level (HL) or better at frequencies in the range of 250 to 4000 Hz and 30 dB HL at 8000 Hz. These criteria were chosen to be representative of normal hearing for listeners across the age range of 18 to 70 yr who were selected as age-matched controls to each of the nine HI listeners (see Dubno *et al.*, 2002). These listeners' ages were in the range of plus or minus 9 yr relative to that of the given HI listener to whom they were assigned. The mean ages of the three age-matched listeners with hearing-loss simulation (AM-SIM) associated with HI-1 through HI-10 are provided in Table I. (For HI-7, only two of the three AM-SIM listeners completed the task.) For each NH listener, a test ear was selected for conducting the experiment based on a comparison of audiometric thresholds between the two ears. If audiometric thresholds were similar for both ears, then the same ear was selected as for the HI listener whose loss was being simulated. If thresholds of one ear were consistently higher than

TABLE I. Description of hearing-impaired subjects in terms of sex, audiometric thresholds in dB HL for the test ear at 6 frequencies, and age in years. Also provided are the mean ages of the age-matched, simulated-loss (AM-SIM) group and the method used to simulate the hearing loss (threshold noise, TN, or threshold noise plus multi-band expansion, TN/MBE) with the α factor (in dB) indicated for the TN/MBE simulations.

Listener	Sex	Audiometric Thresholds in Test Ear (dB HL) Test Frequency in kHz						Age	AM-SIM Group Age	Simulation Method
		0.25	0.5	1	2	4	8			
HI-1	M	15	20	25	35	40	35	24	23.0	TN
HI-2	M	25	30	45	50	55	60	21	20.3	TN
HI-3	M	25	35	30	30	40	75	64	61.7	TN/MBE ($\alpha = 4$)
HI-4	F	10	30	45	60	60	80	59	53.0	TN/MBE ($\alpha = 7$)
HI-6	F	40	50	55	55	60	45	55	55.3	TN
HI-7	M	60	60	75	70	70	85	69	61.3	TN/MBE ($\alpha = 13$)
HI-8	M	60	65	65	70	80	70	68	64.0	TN/MBE ($\alpha = 10$)
HI-9	F	50	65	75	75	100	95	21	22.0	TN/MBE ($\alpha = 30$)
HI-10	F	50	35	30	20	15	95	43	44.7	TN/MBE ($\alpha = 26$)

those in the other ear, or if one ear met the screening criteria and the other ear did not, then the ear with better hearing was used in the experiments.

The experiments were also conducted on two groups of three normal-hearing observers without the use of hearing-loss simulation: A younger group of three observers ranging in age from 20 to 23 yr (mean age of 21.3 yr) and an older group of three observers (two of whom also participated as AM-SIM listeners) ranging in age from 42 to 62 yr (mean age 49 yr).

B. Hearing loss simulation

The current study simulated hearing loss using one of two techniques: Either with additive threshold-elevating noise (TN) or with additive threshold-elevating noise combined with multi-band amplitude expansion (TN/MBE). Additive threshold-elevating noise and multiband expansion have both been previously used to simulate threshold elevation, reduction in dynamic range, and loudness recruitment observed in sensorineural hearing loss (e.g., Villchur, 1974; Zurek and Delhome, 1987; Florentine *et al.*, 1988; Dubno and Schaefer, 1992; Moore and Glasberg, 1993; Duchnowski and Zurek, 1995; Lum and Braida, 1997). For brevity, this section provides only a short summary of these two simulation techniques. For a more complete description, please consult Desloge *et al.* (2010).

For the TN hearing-loss simulation technique, the desired frequency-dependent threshold shifts were used together with the corresponding critical ratio values (Hawkins and Stevens, 1950) to generate spectrally shaped additive TN that elevated the detection thresholds of NH listeners so that they matched those of HI listeners over the frequency range of 80 Hz to 12.5 kHz. This noise was then added to the stimulus signal to yield the hearing-loss-simulated presentation signal. This simulation technique had the advantage that the test stimuli were presented to HI and simulated-loss NH listeners at the same SPL and sensation level (SL). In order to avoid excessive levels of additive noise, however, the maximum permissible level of noise was limited to 80 dB SPL, which had the effect of limiting the maximum attainable threshold shift to approximately 60 dB.

For threshold shifts that required additive threshold noise levels in excess of 80 dB SPL, TN was combined with multi-band expansion (MBE) to yield a TN/MBE hearing-loss simulation. Specifically, in these cases, the TN was attenuated by a factor of α dB to yield a scaled threshold noise with a level of exactly 80 dB SPL. This scaled TN yielded a partial threshold shift of up to α dB lower than the desired threshold shift. MBE was then used to process the input signal dynamically in order to recover the “lost” threshold shift so that the complete threshold shift was realized when the scaled TN was added to the MBE-processed signal. MBE processing was based upon the work of Moore and Glasberg (1993) and consisted of the following steps: (1) bandpass filtering the input signal into 13 frequency bands with center frequencies in the range of 100 to 5837 Hz and corresponding bandwidths in the range of 106.5 to 1964 Hz; (2) monitoring the input signal levels within each band; (3) dynamically attenuating each band signal based upon the corresponding input level to achieve the desired threshold shift and recruitment characteristic; and (4) combining the attenuated band signals to yield the MBE-processed stimulus. Like the TN simulation, the TN/MBE simulation presented test stimuli to both the HI and simulated-loss NH listeners at the same sensation level (SL). However, due to the dynamic attenuation, stimuli were presented to simulated-loss NH listeners at SPLs that were up to α dB lower.

Table I states the hearing-loss simulation technique (TN or TN/MBE) used to simulate each HI listener’s loss. For losses simulated using TN/MBE, the α term is also specified.

C. Gap duration discrimination testing

The stimuli employed in the auditory and tactile gap-duration discrimination experiments were 250-Hz and 400-Hz pure tones that were generated digitally in MATLAB and played through the sound card (LynxOne by LynxStudios) of a desktop PC with 24-bit precision using the SoundMex toolbox for MATLAB.

1. Auditory modality

The digitized sine waves were passed through channel 1 of the sound card to a Tucker-Davis (TDT) PA4

programmable attenuator and then to a TDT HB6 headphone buffer. The resulting signal was presented either to the left or right ear of the subject via a pair of Sennheiser HD580 headphones. The level of the markers was based on detection thresholds for 500-ms signals at 250 Hz and 400 Hz, with the 400-Hz threshold being interpolated from measured thresholds at 250 and 500 Hz. Detection thresholds were measured using the adaptive, forced-choice procedure described in [Desloge *et al.* \(2010\)](#). If the detection threshold for a given marker frequency was less than or equal to 60 dB SPL, then the marker level was set to 70 dB SPL. If the marker-frequency threshold exceeded 60 dB SPL, then the marker level was set at 10 dB SL. For simulated-hearing loss conditions, the auditory stimuli were processed using either the TN or TN/MBE procedure described above prior to presentation to the subject.

2. Tactile modality

The digitized sine waves were passed through channel 2 of the sound card to a programmable attenuator (TDT PA4) and an amplifier (Crown D-75) before being delivered to an electromagnetic vibrator (Alpha-M Corporation model A V-6). The vibrator, whose contactor diameter was 0.9 cm, was housed in a wooden box to eliminate visual cues. The subject placed the distal pad of the left middle finger in contact with the vibrator and wore foam earplugs as well as headphones over which a broadband masking noise was presented at a level of 80 dB SPL. This combination of earplugs and masking noise was sufficient to mask air-conducted sounds arising from the vibrator itself and to eliminate any bone-conducted sounds at the stimulation levels employed here. This masking noise was generated digitally on channel 1 of the sound card and passed through a programmable attenuator (TDT PA4) at which point the signal was split and passed through both channels of a TDT HB6 stereo headphone buffer and presented to the listener diotically over a pair of Sennheiser HD580 headphones.

The marker levels for the tactile signals were set at 25 dB SL relative to absolute-detection thresholds for the 250-Hz and 400-Hz signals measured for each subject just prior to the gap-duration discrimination tests using an analogous procedure to that used for auditory thresholds ([Desloge *et al.*, 2010](#)).

3. Measurement procedures

Gap-duration discrimination thresholds (GDDTs) were measured using leading and trailing sinusoidal markers of 250 and 400 Hz in four pairings: (A) 250–250, (B) 250–400, (C) 400–250, and (D) 400–400. Marker duration was random and uniformly distributed between 80 and 120 ms. This randomization was introduced to reduce the possible use of overall stimulus duration as a cue in performing the gap duration discrimination threshold task. Each marker was ramped on and off with a 5-ms Hanning window. The baseline condition consisted of the two markers abutting one another, which yielded a reference gap (G) of 6.36 ms based on the -3 dB points between the ramps.

GDDTs were measured separately for audition and for touch using a three-interval, three-alternative adaptive forced-choice procedure with trial-by-trial correct-answer feedback. Each interval contained a leading marker and a trailing marker that were separated by a temporal gap. Two of the intervals contained the reference gap G (6.36 ms) and the third interval (selected at random on each trial) had a gap duration of $G+E$, where E was an additional value added to the baseline gap. The subject's task was to identify the interval that contained the larger gap duration. The duration of E was adjusted adaptively using a one-up two-down rule to estimate the gap-duration increment that could be discriminated from the baseline gap at a performance level of 70.7% correct. The starting value of the variable gap was 20 ms and the initial adaptive step size was 10 ms. The step size was halved following each of the first three reversals until reaching the final step size of 1.25 ms which was used in the measurement phase consisting of the next eight reversals. The GDDT was obtained by averaging the values of E over the final eight reversals. Within each modality, two threshold measurements were obtained at each of the four experimental conditions presented twice in random order.

The experiments were controlled by a desktop PC using the AFC Software Package for MATLAB (provided by Stephan Ewert and developed at the University of Oldenburg, Germany) to generate and adaptively modify the experimental stimuli. Testing was conducted in a sound-treated booth which contained a monitor, keyboard, and mouse for interaction with the control PC. Each stimulus interval was visually cued on the monitor; at the end of each trial subjects responded by selecting the observation interval (using a mouse or keyboard) which contained the larger-gap stimulus; and visual correct-answer feedback was provided after the subject's response on each trial.

Due to the range of GDDT thresholds observed across subjects and conditions, we have plotted these thresholds using a logarithmic scale in all the figures describing the results of the experiments. In addition, the analyses of variance and correlation analyses reported below were always conducted using a logarithmic conversion of the GDDT threshold values.

III. RESULTS

A. Auditory gap-duration discrimination thresholds

Absolute detection thresholds of HI listeners at 250 Hz and 500 Hz are provided in Table II as are the thresholds of the AM-SIM groups in the presence of the hearing-loss simulation. The HI-listener data are the average of two measurements, while the AM-SIM data represent the average of six measurements (two measurements for each of the three listeners within a group). Also shown are linearly interpolated (in the log-frequency vs dB SPL domain) thresholds at 400 Hz. Averaged across all HI listeners the RMS differences between HI-listeners and corresponding AM-SIM groups were 1.9, 1.2, and 1.6 dB at 250, 400, and 500 Hz with an across frequency RMS difference of 1.6 dB.

Auditory gap-duration discrimination thresholds (AGDDTs) for the younger and older NH groups are shown

TABLE II. Hearing thresholds for HI and average AM-SIM listeners measured at 250 and 500 Hz and linearly interpolated at 400 Hz.

Listener	HI / AM-SIM Threshold (dB SPL)		
	250 Hz	400 Hz	500 Hz
HI-1	25.5 / 24.9	21.9 / 20.6	20.2 / 18.6
HI-2	33.2 / 32.5	31.4 / 30.2	30.5 / 29.2
HI-3	38.8 / 37.9	35.9 / 33.8	34.5 / 31.9
HI-4	21.2 / 26.2	25.8 / 27.5	28.0 / 28.2
HI-6	60.2 / 60.8	58.9 / 58.0	58.3 / 56.7
HI-7	61.0 / 60.3	58.1 / 57.8	56.7 / 56.7
HI-8	76.9 / 76.0	73.0 / 72.7	71.2 / 71.2
HI-9	72.2 / 72.8	71.9 / 72.2	71.8 / 71.9
HI-10	62.8 / 61.3	48.0 / 49.8	41.0 / 44.3

in the two left panels of Fig. 1 for each of the four pairs of leading-trailing markers. Average standard deviations for each listener ranged from 0.80 to 2.3 ms with an across-listener average of 1.3 ms. Although performance was similar for the two groups with the same-frequency markers (in the range of 9 to 13 ms), the AGDDTs of the older NH group were substantially higher than those of the younger group with the different-frequency markers (mean of 60 ms for older listeners versus 16 ms for younger listeners). A two-way analysis of variance (ANOVA) indicated significant main effects of group [$F(1,16) = 15.1, p = 0.001$] and marker type [$F(3,16) = 17.43, p < 0.0001$] as well as a significant interaction effect [$F(3,16) = 4.99, p = 0.012$]. *Post hoc* Scheffe tests indicated that AGDDTs for the 400–250 Hz condition were significantly higher than for the other three marker types (which were equivalent) and that the AGDDTs of the older group at 400–250 Hz were substantially higher than the AGDDTs at every other combination of group and marker type.

AGDDTs for individual HI listeners and their associated AM-SIM groups are shown in Fig. 1 for each of the four pairs of leading-trailing markers. Average standard deviations for each HI listener ranged from 0.78 to 3.0 ms with an across-listener average of 1.5 ms. Average standard deviations for each AM-SIM listener ranged from 0.87 to 3.1 ms with an across-listener average of 1.5 ms. As previously

stated, the stimulus level was set to the maximum of 70 dB SPL or 10 dB SL. When stimulus levels greater than 70 dB SPL were used, these levels are provided in the individual panels for each observer. For 8 of 9 HI listeners and AM-SIM groups (with the exception of HI-4), AGDDTs were lower for the two same-frequency conditions compared to the different-frequency conditions. Mean AGDDTs across the HI listeners and across the AM-SIM groups were 28.3 ms (range of 4–96 ms) and 23.4 ms (range of 12–43 ms), respectively, for the 250–250 Hz condition and 27.9 ms (range of 7–91 ms) and 19.2 ms (range of 6–39 ms), respectively, for the 400–400 Hz condition. For the different-marker conditions, mean AGDDTs were 56.7 ms (range of 30–112 ms) and 60.8 ms (range of 29–101 ms), respectively, for the 250–400 Hz condition and 66.6 ms (range of 28–137 ms) and 75.2 ms (range of 40–115 ms), respectively, for the 400–250 Hz condition. A two-way ANOVA conducted on main effects of group (HI versus AM-SIM) and marker type indicated a significant effect of marker type [$F(3,64) = 21.5, p < 0.0001$] but not group [$F(1,64) = 0.06, p = 0.81$] or the interaction of group and marker type [$F(3,64) = 0.6, p = 0.62$]. A *post hoc* Scheffe test on the marker-type effect indicated that AGDDTs for the two same-frequency conditions were equivalent and significantly lower than those for the two different-frequency conditions (which in turn were equivalent to each other).

The AGDDTs are replotted in Fig. 2 which shows the threshold for each marker type for a given HI listener versus that of the associated AM-SIM group. The data are labeled by marker type in the upper panel of the plot and by HI listener in the lower panel. A significant correlation, with the effects of age partialled out, was observed between the AGDDTs of the HI and AM-SIM listeners ($r = 0.618$ and $p < 0.0001$). Thus, the lack of significance for the group effect in the ANOVA and the correlation between the HI and AM-SIM data indicate that the hearing-loss simulation was effective in reproducing the AGDDTs of the HI listeners.

It has been shown that age and signal presentation level may influence performance on temporal gap tasks (Florentine and Buus, 1984; Moore *et al.*, 1993; Humes *et al.*, 2009). The dependence of the AGDDT on age, signal presentation level in dB SPL, and signal presentation level

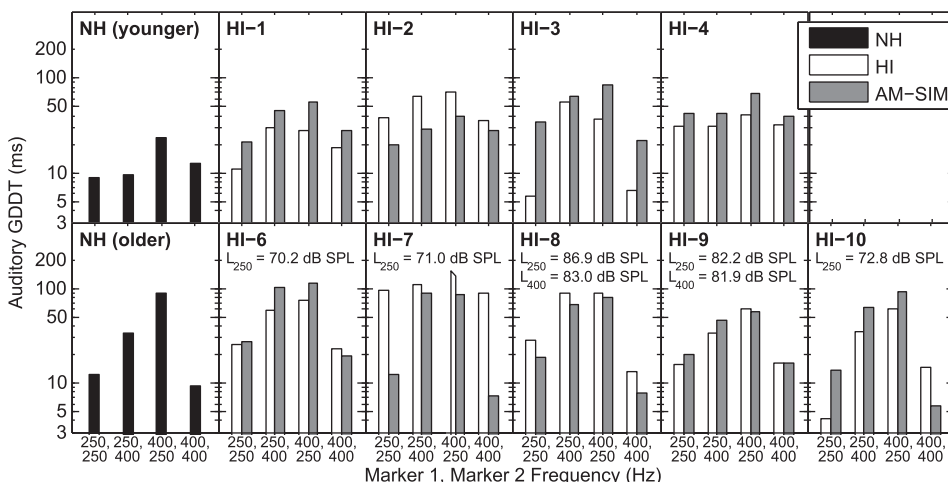


FIG. 1. Auditory gap-duration discrimination thresholds (AGDDTs) for each of four leading-trailing marker conditions: 250–250 Hz, 250–400 Hz, 400–250 Hz, and 400–400 Hz. The leftmost panels in the top and bottom rows show mean AGDDTs across the younger normal-hearing (NH) group and the older NH group, respectively. The remaining panels provide mean data for each of the nine hearing-impaired (HI) listeners and their associated age-matched simulation (AM-SIM) groups. The 250-Hz and 400-Hz marker stimuli were presented at a level of 70 dB SPL except where noted.

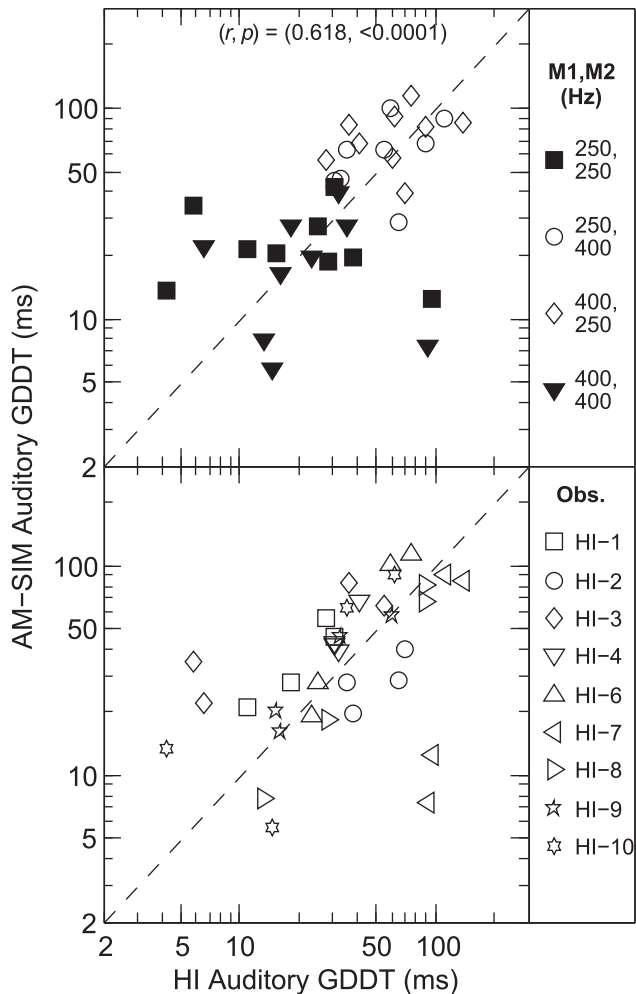


FIG. 2. Auditory gap-duration discrimination thresholds (GDDTs) of hearing-impaired (HI) listeners (abscissa) plotted versus those of their associated age-matched simulation (AM-SIM) groups (ordinate). Upper panel labels data on the basis of the four leading and trailing marker pairs and lower panel labels data on the basis of individual HI listeners. The correlation between HI and AM-SIM GDDT, with the effect of age partialled out, is shown.

in dB SL was examined using partial correlations. The correlation between AGDDT and each of these variables was calculated with the effects of the remaining two partialled out of the analysis. Figure 3 considers the relation between AGDDT and age for each of the four marker combinations across all three listener groups. The partial correlations shown on each panel indicate that there is little effect of age on AGDDT for same-frequency markers but that the AGDDT shows a significant increase with age for both the 250–400 Hz condition ($r=0.45$ and $p=0.0085$) and the 400–250 Hz condition ($r=0.51$, $p=0.0025$). A similar analysis with presentation level in dB SPL as the main variable indicated no significant partial correlation with AGDDT for any of the marker conditions. When presentation level in dB SL was considered as the main variable, a partial significant correlation was observed with AGDDT for the 250–400 Hz condition ($r=-0.60$ and $p=0.0002$) and 400–250 Hz conditions ($r=-0.374$, $p=0.03$). The negative correlation indicates a decrease in AGDDT with an increase in SL.

B. Tactile gap-duration discrimination thresholds

The tactile gap-duration discrimination thresholds (TGDDTs) for the younger and older NH groups are shown in the two left panels of Fig. 4. Average standard deviations for each subject ranged from 0.83 to 2.4 ms with an across-listener average of 1.4 ms. Results were similar for both groups of observers in terms of magnitude of the TGDDT and effect of marker type. The results of a two-way ANOVA indicated that the main effect of marker type [$F(3,16)=4.45$, $p=0.02$] was significant but not the effect of group [$F(1,16)=0.003$, $p=0.96$] or the interaction of group and marker type [$F(3,16)=0.28$, $p=0.84$]. Regarding the main effect of marker type, none of the pairwise comparisons reached significance in *post hoc* Scheffe tests, even though a tendency was observed for larger TGDDTs for the two different-frequency markers (means of 41.7 ms for the 250–400 Hz condition and 38.5 ms for the 400–250 Hz condition) compared to the two same-frequency markers (means of 21.0 ms for the 250–250 Hz condition and 23.9 ms for the 400–400 Hz condition).

The TGDDTs are shown in Fig. 4 for each HI observer and for the AM-SIM groups (where the hearing-loss simulation was not activated during the tactile testing). Average standard deviations for each HI listener ranged from 0.99 to 2.5 ms with an across-listener average of 1.7 ms. Average standard deviations for each AM-SIM listener ranged from 0.83 to 2.4 ms with an across-listener average of 1.4 ms. Mean TGDDTs for the HI and AM-SIM subjects were 24.0 (range of 9–39 ms) and 28.7 ms (range of 16–47 ms), respectively, for the 250–250 Hz condition, 48.4 ms (range of 11–160 ms) and 32.2 ms (range 18–58 ms), respectively, for the 400–400 Hz condition, 76.9 ms (range of 20–179 ms) and 50.5 ms (range 26–85 ms), respectively, for the 250–400 Hz condition, and 50.3 ms (range 18–113 ms) and 47.2 (range 25–76 ms), respectively, for the 400–250 Hz condition. A two-way ANOVA indicated a significant effect of marker type [$F(3,64)=6.64$, $p=0.0006$] but not for group [$F(1,64)=0.12$, $p=0.73$] or for the interaction between the two main variables [$F(3,64)=0.65$, $p=0.58$]. A *post hoc* Scheffe test of the marker-type effect indicated a significant difference only between the 250–250 Hz condition and the 250–400 Hz and 400–250 Hz conditions; all other pairs of marker types were equivalent. This result differs from that observed in the auditory conditions where AGDDTs for both of the two same-frequency markers were significantly lower than for the two different-frequency conditions. The TGDDTs of the HI observers are plotted versus those of the associated AM-SIM group in Fig. 5 where data points are coded by marker type (top panel) or observer (bottom panel). A partial correlation controlling for the effects of age revealed a mild correlation with marginal significance ($r=0.365$, $p=0.034$).

Tactile sensitivity has been shown to deteriorate with age on a variety of temporal-processing tasks (e.g., Van Doren *et al.*, 1990; Humes *et al.*, 2009; Craig *et al.*, 2010). The TGDDTs are plotted as a function of age in Fig. 6 for individual NH, HI, and AM-SIM observers for each of the four marker conditions. Although the correlation between age and TGDDT is weak for the 250–250 Hz condition, it is

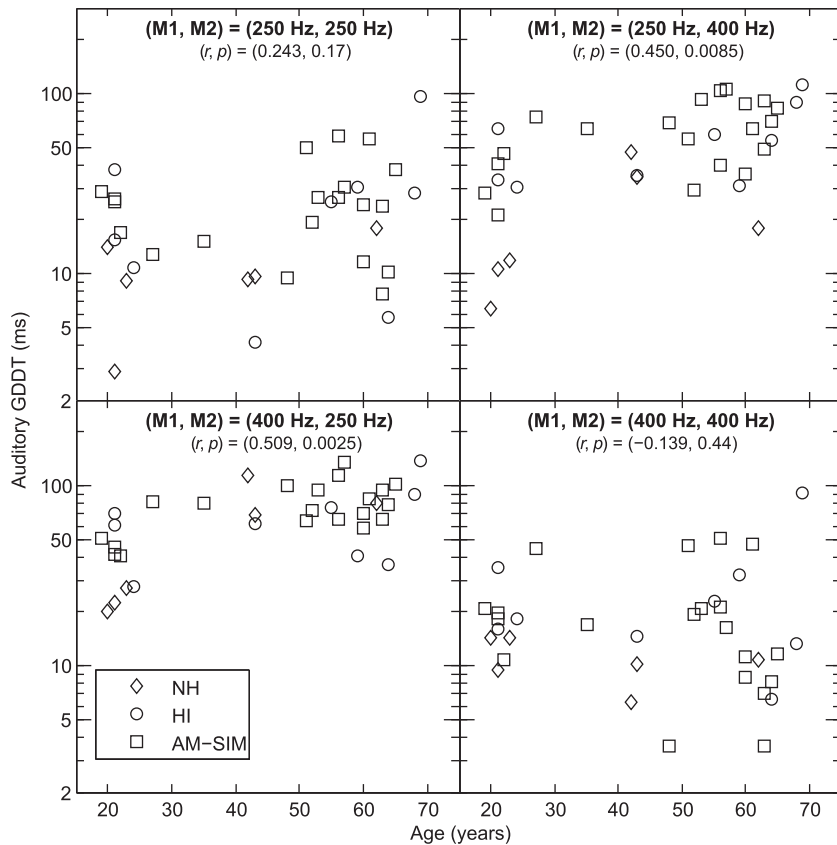


FIG. 3. Auditory gap-duration discrimination thresholds (GDDTs) plotted as a function of age. Different symbols identify observers within each of three groups: Normal-hearing (NH), hearing-impaired (HI), and age-matched simulation (AM-SIM). Each of the four panels shows results for one of the four leading-trailing marker combinations where Marker 1 (M1) and Marker 2 (M2) each take on values of 250 and 400 Hz. The correlation between age and GDDT is shown in each panel with effects of stimulus presentation level in SL and in dB SPL partialled out.

stronger and more highly significant for the three conditions involving at least one 400-Hz marker (see values of correlation coefficient and probability provided in Fig. 6). Van Doren *et al.* (1990) also found very little effect of age (over a range of 8 to 75 yr) on tactile gap-duration discrimination performance with a 250-Hz sinusoidal signal. A decline in tactile gap-detection performance with age was observed, however, for narrowband noise signals by both Van Doren *et al.* (1990) and Humes *et al.* (2009).

C. Relation between auditory and tactile gap-duration discrimination thresholds

The relation between auditory and tactile gap-duration discrimination thresholds across the four marker conditions

is shown in Fig. 7 for individual NH observers (leftmost panels), individual HI observers (center panels), and individual AM-SIM observers (rightmost panels). A moderate correlation of roughly 0.4 to 0.5 was observed for each group, with probability of significance of 0.049 for NH, 0.0021 for HI, and 0.0001 for AM-SIM. The correlation between GDDTs in the two modalities was also calculated as a function of marker pair combining GDDT measures across all observers. The strength of these correlations was generally weak within each marker pair but did achieve a modest level of significance for the 250–250 ($r = 0.38$, $p = 0.025$) and 250–400 Hz ($r = 0.35$, $p = 0.037$) pairs.

For each observer group, a two-way ANOVA was conducted to examine effects of modality and marker type. Marker type was significant in each of the analyses [NH:

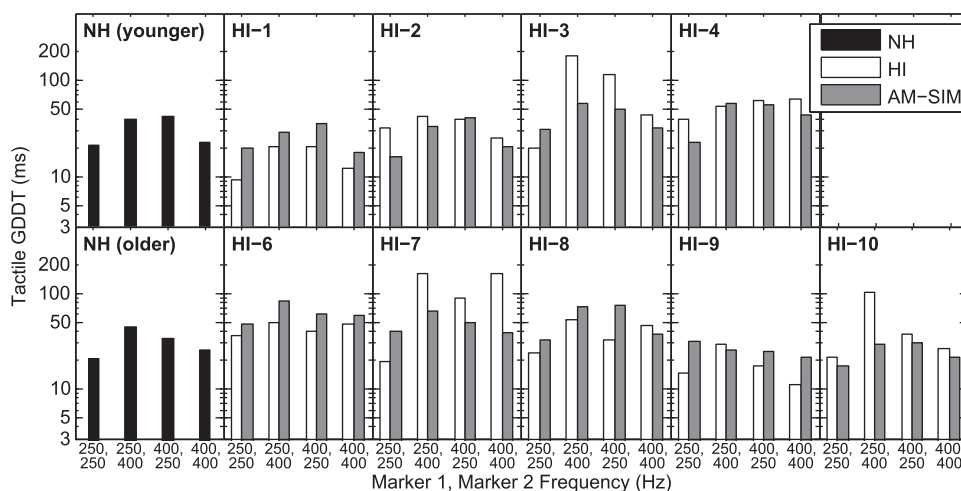


FIG. 4. Tactile gap-duration discrimination thresholds (GDDTs) for each of four leading-trailing marker conditions: 250–250 Hz, 250–400 Hz, 400–250 Hz, and 400–400 Hz. The leftmost panels in the top and bottom rows show mean GDDTs across the younger normal-hearing (NH) group and the older NH group, respectively. The remaining panels provide mean data for each of the nine hearing-impaired (HI) observers and their associated age-matched simulation (AM-SIM) groups.

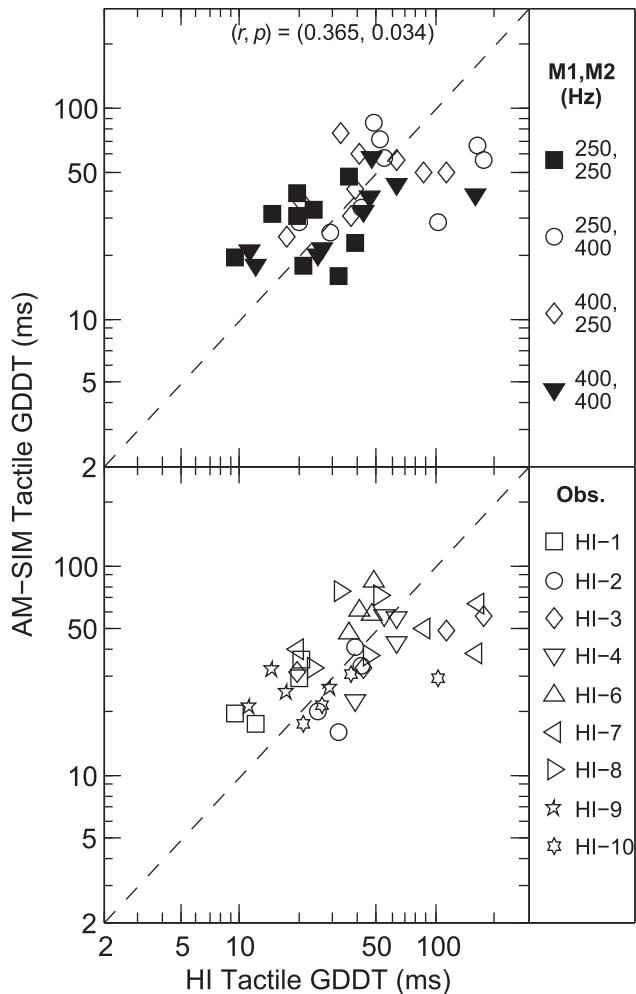


FIG. 5. Tactile gap-duration discrimination thresholds (GDDTs) of hearing-impaired (HI) observers (abscissa) plotted versus those of their associated age-matched simulation (AM-SIM) groups (ordinate). Upper panel labels data on the basis of the four leading and trailing marker pairs and lower panel labels data on the basis of individual HI observers. The correlation between HI and AM-SIM GDDT, with the effect of age partialled out, is shown.

$F(3,40) = 11.13, p < 0.0001$; HI: $F(3,64) = 8.7, p = 0.0001$; AM-SIM: $F(3,64) = 23.04, p < 0.0001$. A significant effect of modality was observed only for the NH group [$F(1,40) = 13.36, p = 0.0007$]. The interaction effect was significant in the analysis of the NH [$F(3,40) = 2.88, p = 0.048$] and the AM-SIM results [$F(3,64) = 5.51, p = 0.002$]. The interaction effect arises from a more clear-cut effect of marker type in the auditory compared to the tactile modality: for both the NH and AM-SIM observers, there are more instances of significant pairwise differences as a function of marker pair in audition than in touch.

IV. DISCUSSION

The AGDDTs obtained for young NH listeners were consistent with those reported by Formby *et al.* (1992, 1998) using a 250-Hz leading marker and trailing markers in the range of 250 to 500 Hz. The data of Formby *et al.* (1992, 1998) for monaural 250-Hz conditions indicate an increase in the GDT from roughly 7 ms for their 250–250 Hz condition to roughly 25–30 ms for their 250–375 Hz condition,

consistent with our young NH results shown in Fig. 1. Our observation of an increase in the AGDDT with age for different-frequency markers but not for same-frequency markers is also consistent with previous studies that have shown that older participants are more affected by spectral disparity than younger listeners (e.g., Lister *et al.*, 2002).

The AGDDTs of the HI listeners were on average higher than those of the NH listeners for the same-frequency conditions but roughly comparable to those of the older NH listeners for the different-frequency conditions. The performance of the HI listeners was in general fairly well-matched by the audibility-based simulations carried out on age-matched NH listeners, although it must be noted that the comparatively small number (3) of simulated-loss subjects per HI subject makes this result somewhat inconclusive. Previous studies have also demonstrated that audibility-based hearing-loss simulations were capable of reproducing the GDTs of HI listeners in broadband (Florentine and Buus, 1984) or narrow-band (Buss *et al.*, 1998) noises. Moore *et al.* (1992) included low-frequency sinusoidal signals in their measurements of GDTs in elderly listeners with and without cochlear hearing loss. At frequencies of 200 and 400 Hz, the mean geometric thresholds of the two groups of elderly listeners were similar at a value of roughly 10 ms. However, similar to the data of the current study, individual outliers with large GDTs were observed in both groups of elderly observers whose mean GDTs were larger than those of young normal-hearing listeners. Our result of stronger age effects for different-frequency compared to same-frequency markers is consistent with the summary of a literature review conducted by Reed *et al.* (2009) which concluded that age effects on GDTs are stronger when measured in complex stimulus conditions including spectral asymmetries in leading and trailing markers.

For the NH observers, TGDDTs were significantly larger than AGDDTs for both same-frequency and different-frequency marker conditions but did show some effects of spectral disparity in the leading and trailing markers (as was also observed in audition). The mean TGDDT for the same-frequency conditions was roughly 20 ms compared to 40 ms for the two different-frequency conditions. This pattern of results differs from that reported by Formby *et al.* (1992) who found no spectral-disparity effect for vibrotactile stimulation. Their GDT remained constant at roughly 30 ms across conditions with a 250-Hz leading marker and trailing markers ranging from 250 to 375 Hz. This result contrasts with their auditory data where the GDT increased from roughly 7 to 60 ms over the same range of trailing-marker frequencies. Thus, while their data show no evidence of tactile frequency selectivity at 250 Hz, our results do suggest some evidence for tuning. Methodological differences that may account for the difference in results between our study and that of Formby *et al.* (1992) include our use of two same-frequency conditions (both 250–250 and 400–400 Hz) and spectrally disparate conditions in which the leading marker was either 250 or 400 Hz.

Tactile gap-discrimination ability for our same-frequency conditions was inferior to that reported by Van Doren *et al.* (1990) and Gescheider *et al.* (2003) for the detection of gaps in sinusoidal signals presented over a

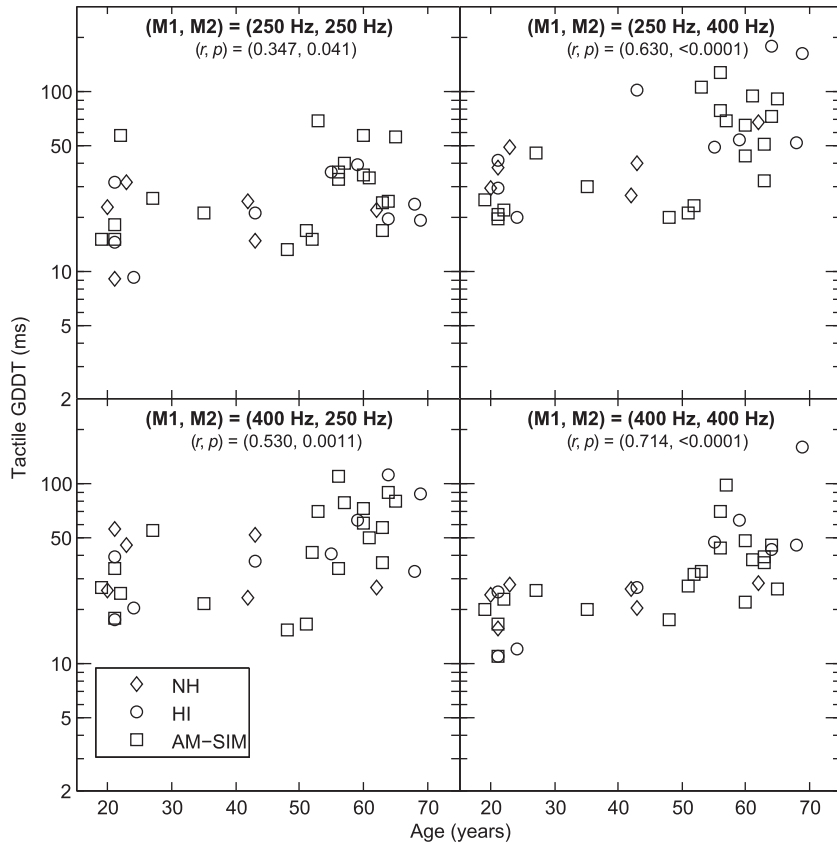


FIG. 6. Tactile gap-duration discrimination thresholds (GDDTs) plotted as a function of age. Different symbols identify observers within each of three groups: Normal-hearing (NH), hearing-impaired (HI), and age-matched simulation (AM-SIM). Each of the four panels shows results for one of the four leading-trailing marker combinations where Marker 1 (M1) and Marker 2 (M2) each take on values of 250 and 400 Hz. The correlation between age and GDDT is shown in each panel.

vibrator at the thenar eminence. In both of these previous studies GDTs of 8 ms were reported for sinusoids in the region of 250 Hz at a presentation level of 25 dB SL. The longer stimulus markers of 350 ms employed in these previous studies compared to the average 100 ms duration employed here may account in part for their lower GDTs. Gescheider *et al.* (2003) observed that the GDT did not vary with contactor size for a 250-Hz signal and was also the same for 62-Hz and 250-Hz sinusoids, indicating that gap-detection ability is similar for the Pacinian and non-Pacinian

channels. Both Van Doren *et al.* (1990) and Gescheider *et al.* (2003) observed an increase in the GDT for narrowband noise stimuli compared to sinusoids. Humes *et al.* (2009) employed narrowband noise stimuli centered around 35 Hz and 250 Hz and found mean tactile GDTs of roughly 50–60 ms for young adults.

For the HI and AM-SIM observers, the GDDTs obtained in the auditory and tactile modalities were equivalent in magnitude. Using the same sinusoidal markers in both modalities, the results obtained in the current study suggest a

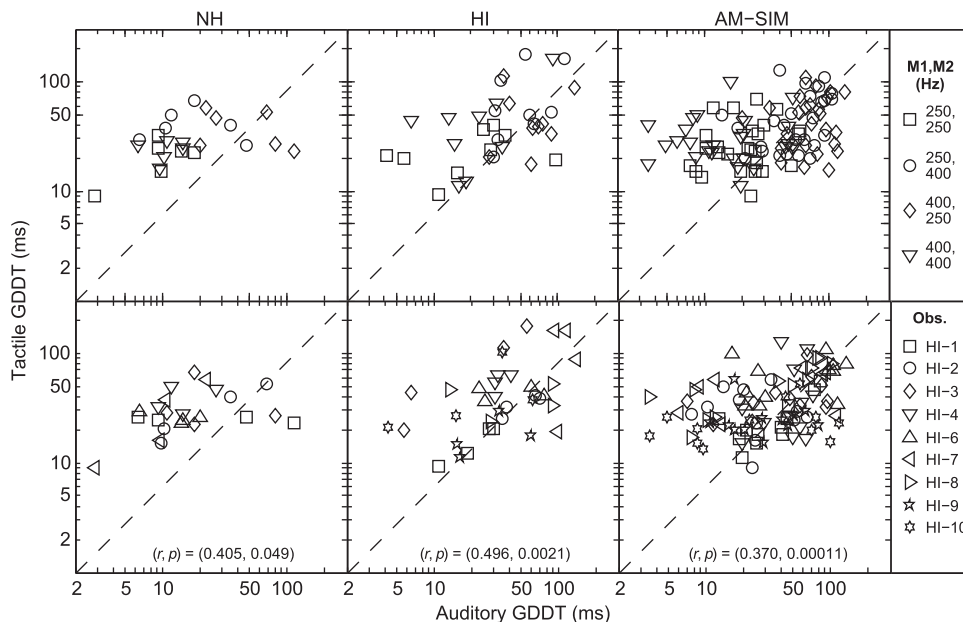


FIG. 7. Auditory gap-duration discrimination threshold (GDDT) plotted as a function of tactile GDDT for individual observers. The left panel shows data for individual normal-hearing (NH) observers, the middle panel for individual hearing-impaired (HI) observers, and the right panel for individual age-matched simulation (AM-SIM) observers.

possible cross-modality correspondence in gap-duration discrimination ability for these two groups of observers. Not only was a moderate but significant correlation observed between auditory and tactile GDDTs, but there was also no significant difference in the magnitude of the auditory and tactile GDDTs for the HI and AM-SIM observers. These results contrast with those of [Humes *et al.* \(2009\)](#) who found only a weak correlation between the auditory GDT obtained with a narrowband noise signal with a center frequency of 3500 Hz and the tactile GDT obtained with a narrowband noise signal with a center frequency of 250 Hz as well as substantially larger tactile than auditory GDTs. Their correlations, however, were derived from data on a much larger population of subjects ($N = 179$) than used in the current study.

One difference observed in the pattern of results obtained between the two modalities in the current data was a more pronounced effect of spectral asymmetry in the auditory compared to tactile modality (compare the filled versus open symbols in the upper panels of Figs. 2 and 5). Our results showing stronger effects of frequency disparity for markers of 250 and 400 Hz in the auditory compared to tactile modality suggest sharper auditory compared to tactile tuning. This observation is consistent with results obtained in earlier studies exploring frequency selectivity in audition and touch ([Formby *et al.*, 1992](#); [Wilson *et al.*, 2010a,b](#)). [Formby *et al.* \(1992\)](#) found no evidence for vibrotactile frequency selectivity in tasks involving temporal-modulation detection, gap detection, and rate discrimination for amplitude-modulated tones. [Wilson *et al.* \(2010a,b\)](#) found some evidence for critical-band filtering in the vibrotactile sense in studies exploring the perceptual integration of both threshold-level and supra-threshold auditory and tactile sinusoidal signals. The differences in detection associated with the frequency spacing of auditory and tactile tones ([Wilson *et al.*, 2010a](#)) have been mirrored in differences in the loudnesses of auditory-tactile complexes ([Wilson *et al.*, 2010b](#)). Furthermore, the results of both of these studies indicate that critical-band filtering is exhibited in both modalities but that the auditory filters are more sharply defined than the tactile filters.

Age-related effects on the magnitude of the GDDT were observed in both our auditory and tactile data and tended to be stronger for the different-frequency compared to same-frequency marker conditions. Performance on the different-frequency conditions may reflect not only effects of critical-band filtering but also greater cognitive difficulty in comparing signals across different critical bands. Recent results of [Humes *et al.* \(2013\)](#) strongly suggest that a decline in peripheral processing ability may lead to decreased cognitive function, rather than the reverse. [Humes *et al.*](#) amassed a database consisting of 40 measures of threshold and temporal sensory processing in three modalities (hearing, vision, and touch) and 15 measures of higher-level cognitive function on 245 adults ranging in age from 18 to 87 yr. The data were collapsed into a global sensory processing and a global cognitive processing function, both of which were correlated with age as well as with each other. Further analysis of partial correlations between pairs of these variables, however,

revealed that the correlation between age and cognitive function disappeared when controlled for sensory processing (while the other two partial correlations remained significant). The authors conclude that age-related changes in cognitive function may be triggered by a deterioration in performance at the sensory processing level. Thus, it is possible that in the tactile modality (where we controlled for stimulus sensation level) the increase in TGDDT with age may be related to peripheral loss (e.g., in terms of elevated absolute thresholds of detection, for which we did not control). In fact, [Verrillo \(1979\)](#) has shown that absolute-detection thresholds for vibrotactile stimuli in the range of 250–400 Hz indicate a loss of sensitivity with age caused by changes in the number and the structure of the Pacinian corpuscles. Our result in the tactile modality of an increase in TGDDTs for stimulus conditions with a 400-Hz marker (compared to the 250–250 Hz condition) may perhaps be related to poorer peripheral processing at 400 Hz.

V. CONCLUDING REMARKS

The current study was concerned with measuring gap-duration discrimination thresholds in audition and touch using the same sinusoidal signals within each modality. Age effects were examined in both modalities for observers in the range of 21–69 yr. Observers included groups with normal hearing and with cochlear hearing loss as well as normal-hearing listeners with simulated hearing loss.

The major results of the study may be summarized as follows:

- (1) In both the auditory and tactile modalities and for all observers, gap-duration discrimination thresholds tended to be more sensitive for same-frequency markers and to increase when leading and trailing markers assumed different frequencies.
- (2) The auditory gap-duration discrimination thresholds of the hearing-impaired listeners were generally larger than those of the normal-hearing listeners and were fairly well-reproduced by the audibility-based simulations of hearing loss conducted on age-matched normal-hearing individuals.
- (3) Effects of age on the magnitude of the gap-duration discrimination threshold were observed in both the auditory and tactile modality.
- (4) Moderate correlations were observed between the size of the auditory and tactile gap-duration discrimination thresholds which were significantly different only in the normal-hearing data and not for the hearing-impaired and simulated-loss results.
- (5) Peripheral processing within each sensory modality may play a role in gap-duration discrimination ability as evidenced by modality differences for spectrally disparate signals. The similarity of the results between the two modalities suggests that modality-independent cognitive processing may also play a role; however, the cognitive decline with age observed here may be related to a decline in peripheral processing as observed by [Humes *et al.* \(2013\)](#).

ACKNOWLEDGMENT

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