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Temporal processing deficits in the pre-senescent auditory system

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Abstract

This study tested the hypothesis that temporal processing deficits are evident in the pre-senescent (middle-aged) auditory system for listening tasks that involve brief stimuli, across-frequency-channel processing, and/or significant processing loads. A gap duration discrimination (GDD) task was employed that used either fixed-duration gap markers (experiment 1) or random-duration markers (experiment 2). Independent variables included standard gap duration (0, 35, and 250 ms), marker frequency (within- and across-frequency), and task complexity. A total of 18 young and 23 middle-aged listeners with normal hearing participated in the GDD experiments. Middle age was defined operationally as 40 – 55 years of age. The results indicated that middle-aged listeners performed more poorly than the young listeners in general, and that this deficit was sometimes, but not always, exacerbated by increases in task complexity. A third experiment employed a categorical perception task that measured the gap duration associated with a perceptual boundary. The results from 12 young and 12 middle-aged listeners with normal hearing indicated that the categorical boundary was associated with shorter gaps in the young listeners. The results of these experiments indicate that temporal processing deficits can be observed relatively early in the aging process, and are evident in middle age.

I. INTRODUCTION

Temporal processing declines with advanced age, and independently of hearing loss. In human studies, deficits of temporal processing in the senescent auditory system have been measured using gap detection and duration discrimination paradigms (Abel et al., 1990; Fitzgibbons and Gordon-Salant, 1994; Schneider et al., 1994; Fitzgibbons and Gordon-Salant, 1995; Snell, 1997; Schneider et al., 1998; Strouse et al., 1998; He et al., 1999; Schneider and Hamstra, 1999; Snell and Frisina, 2000; Lister and Tarver, 2004). Most of these studies have dealt with within-frequency-channel temporal processing where the acoustic markers of the gap, or the stimuli of varying duration, are spectrally similar. Two key findings can be highlighted from these studies of elderly listeners. First, the effects of advanced age become more pronounced as the durations of the markers bounding the gap are reduced (Muchnik et al., 1985; Schneider and Hamstra, 1999). Second, the decline in duration discrimination performance for suprathreshold gaps is particularly striking when the acoustic markers form part of a tone sequence (Fitzgibbons and Gordon-Salant, 1995; Gordon-Salant and Fitzgibbons, 1999; Fitzgibbons and Gordon-Salant, 2004). This enhanced effect is attributed to increased task complexity. Temporal processing in the senescent auditory system, therefore, appears to be particularly challenged by brief stimuli presented in complex contexts.

The present study examined the hypothesis that deficits in auditory temporal processing may actually begin in middle age. In the experiments conducted here, middle age is operationally

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defined as 40 – 55 years of age. From both an anatomical and physiological point of view, there is reason to expect compromised temporal performance in the middle-aged, or pre-senescent, auditory system. For example, neuropharmacological studies that have included psychoacoustic measures of gap detection/discrimination have suggested that acuity in the processing of brief auditory events is associated with the level of dopamine activity in the basal ganglia (Artieda et al., 1992; Rammsayer and Classen, 1997). In parallel, imaging studies have pointed to a decline in the dopamine receptors in this brain region throughout adult life (Kaasinen et al., 2000), with a particular acceleration in this decline beginning at about 36 years of age (Mozley et al., 1999). In terms of electrophysiological evidence for pre-senescent deficits in temporal processing, some differences between young and middle-aged listeners are apparent in the N1-P2 response elicited as a function of stimulus duration (Ostroff et al., 2003). Behavioral evidence on the question of a pre-senescent decline in auditory temporal processing is sparse. Abel et al. (1990) measured duration discrimination in several populations, including a group of young normal-hearing listeners (20–35 yrs) and a group of normal-hearing middle-aged listeners (40–60 yrs). They found that these two groups differed in their ability to discriminate the duration of brief (20-ms) stimuli. Early aging effects have also been noted in studies of gap detection and discrimination. Snell and Frisina (2000) found that, in a group of normal-hearing listeners aged 17 – 40 years, there was a significant correlation between age and detection threshold for a gap placed in a modulated low-pass noise. Muchnik et al. (1985) found that gap detection was poorer in middle-aged than in young listeners, particularly when the duration of the acoustic gap markers was brief (10 ms). Evidence for a pre-senescent age effect in across-frequency-channel temporal processing also exists. Grose et al. (2001) found that a limited sample of young listeners had consistently lower gap discrimination thresholds than middle-aged listeners for both within- and across-frequency-channel conditions. Lister et al. (2002) also measured the discrimination of gaps bounded by disparate marker frequencies in normal-hearing young and middle-aged listeners in a study that included elderly listeners. Although they highlighted the performance deficits in the elderly listeners, and did not identify a decline in performance in their middle-aged listeners, it is evident from their data that the middle-aged and young listeners diverged in performance for the widest (two-octave) marker frequency separation.[1]

In summary, a substantial body of work has established that temporal processing declines with advanced age, and independently of hearing loss, but there has been little focus on the emergence of these temporal deficits in the pre-senescent, or middle-aged, auditory system. The evidence to date suggests that such deficits may be identified in listening tasks that involve brief stimuli, particularly those that span disparate frequency channels. Furthermore, it is likely that any temporal processing deficits will be heightened when the listening tasks are complex. The purpose of this investigation, therefore, was to test the hypothesis that temporal processing deficits are evident in middle age for listening tasks that involve brief stimuli, across-frequency-channel processing, and/or significant processing loads. This hypothesis was tested in a series of three experiments.

II. EXPERIMENT 1. GAP DURATION DISCRIMINATION FOR FIXED-DURATION MARKERS

The purpose of this experiment was to measure the just-noticeable increment in the duration of a silent interval bounded by two brief acoustic markers in normal-hearing young and middle-

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[1] Submitting the data for only the young and middle-aged listeners from Lister et al. (2002) to a repeated-measures analysis of variance reveals no main effect of age group, but a significant interaction between the factors of age group and marker frequency separation ($F_{5,50} = 4.92$; $p = 0.001$). Bonferroni-corrected paired-comparisons indicate that for the widest marker frequency separation (2 octaves) the young and middle-aged listeners differed significantly ($t_{10} = 3.339$; $p = 0.008$).

aged listeners. The three main stimulus parameters manipulated were marker frequency, standard gap duration, and the acoustic context of the gap markers.

A. Method

1. Listeners—Across the various conditions of this experiment, a total of 18 young and 23 middle-aged listeners participated. The young listeners ranged in age from 18 – 27 years (mean = 21.6 years), and the middle-aged listeners ranged in age from 40 – 55 years (mean = 46.6 years). In addition to these listeners, a limited group of eight elderly listeners, ranging in age from 65 – 83 years (mean = 72.8 years), also participated. Their inclusion served to provide a reference for performance in the senescent auditory system. All young and middle-aged listeners had normal hearing, with audiometric thresholds ≤ 20 dB HL across the octave frequencies 250 – 8000 Hz (ANSI, 1996). The elderly listeners had audiometric thresholds ≤ 20 dB HL across the octave frequencies 250 – 4000 Hz, except for one listener whose threshold at 4000 Hz was 40 dB HL. The listeners were tested in two subgroups defined by the conditions to which they listened. Subgroup 1 consisted of 11 young, 10 middle-aged, and all 8 elderly listeners. Subgroup 2 consisted of 11 young and 15 middle-aged listeners. It should be noted that inclusion into Subgroup 2 required that the listener pass a screening test for temporal pattern discrimination, as described in more detail below. One potential listener who was middle-aged did not pass the screening test and was excluded from participation. A total of 4 young and 2 middle-aged listeners were common to both subgroups (i.e., they listened to all conditions).

2. Stimuli—The acoustic markers of the silent gaps were tonebursts consisting of 10-ms cosine-squared rise/fall ramps with no plateau, giving a total duration of 20 ms. The frequency of the leading marker was always 432 Hz; the frequency of the trailing marker was either 458 Hz or 2188 Hz. Relative to 432 Hz, these latter frequencies correspond to spectral separations of one semitone and 13 equivalent rectangular bandwidths ([ERBs], Moore and Glasberg, 1987), respectively. This permitted the assessment of both within-frequency-channel (432 – 458 Hz) and across-frequency-channel (432 – 2188 Hz) temporal processing. The duration of the gap between the two acoustic markers was defined as the interval between the 0-voltage points of the leading and trailing marker ramps. Stimuli were generated at a sampling rate of 10 kHz (TDT AP2), output through a digital-to-analog converter (TDT PD1), anti-alias filtered at 4 kHz (Kemo VBF8), and presented monaurally through a Sennheiser 518 headphone. The presentation level was 80 dB peSPL.

3. Procedure—The listener’s task was to detect an increment in the duration of the gap between the leading and trailing markers. Because the frequencies of the leading and trailing markers were never identical, and because the gap was defined as the interval between the 0-voltage points on successive 10-ms fall-rise ramps, the two gap markers were never perceived as a continuous sound even for a gap duration of 0 ms. The task was therefore one of gap duration discrimination, hereafter referred to as the GDD task. A 3-interval, forced-choice (3AFC) procedure was used to measure GDD that incorporated a 3-down, 1-up stepping rule to converge on the 79.4% correct point on the psychometric function. Gap duration was adjusted by a factor of 1.2 at each reversal point. Each threshold track continued for a total of 10 reversals, and the threshold estimate for that track was computed as the geometric mean of the duration increments over the final 6 reversals. In order to exclude threshold estimates based on tracks that included spuriously large excursions, a statistic was employed which computed the ratio of the gap increment duration one standard deviation above the mean to the mean gap increment duration itself. If this ratio exceeded 1.35, the threshold run was rejected and a replacement run undertaken. At least three valid threshold estimates, but usually four, were collected from a listener for any particular condition, and the final threshold for that condition and listener was taken as the geometric mean of all estimates collected.

All listeners were well-practiced before data collection commenced. For Subgroup 1, training consisted of repeating the entire experiment twice – once for practice and once for data collection. Since the experiment for this Subgroup consisted of eight conditions (see below), all eight conditions were cycled through once (including the multiple repetitions for each condition) and then repeated for data collection. Of the 20 listeners who were unique to Subgroup 2, six underwent the same training regimen wherein the entire experiment was repeated once for practice and once for data collection. The remaining listeners underwent a different approach wherein each condition administered to a listener was replicated until performance appeared to reach an asymptotic level; at this point, data collection for that condition was initiated and at least four threshold estimates were collected.

In the core conditions administered to both subgroups of listeners, GDD was measured for standard gap durations of 0 and 35 ms. Subgroup 1 was also presented with an additional standard gap duration of 250 ms. The gap durations of 35 ms and 250 ms coincide with those tested in Grose et al. (2001). For each standard gap duration tested, GDD was measured for both within-frequency-channel (WFC) markers and across-frequency-channel (AFC) markers. These six conditions can therefore be identified with the nomenclature: (1) WFC_0, (2) WFC_35, (3) WFC_250, (4) AFC_0, (5) AFC_35, and (6) AFC_250.

For the standard gap duration of 35 ms, additional conditions were administered which were designed to increase task complexity (and consequentially the processing load placed on the listener). For Subgroup 1, the added complexity consisted of incorporating the pair of gap marker tonebursts into a train of three tonebursts, as shown in the upper panel of Fig. 1. Here, the 432-Hz leading marker of the gap was itself preceded by a 20-ms, 432-Hz toneburst. The interval between the offset of this preliminary toneburst and the onset of the leading gap marker had a nominal duration of 70 ms, but the actual duration varied randomly from 40 – 100 ms (70 ms ± 30 ms, with random draws from a rectangular distribution) on each and every presentation. The reason for the random variation was to prevent the listener from using a cue based on the rhythm of the three-tone sequence. The listener now had to discriminate the duration of the gap between the second and third tonebursts of a three-toneburst train. This manipulation of adding a preliminary 432-Hz toneburst was applied to both the within-frequency-channel and across-frequency-channel conditions. Accordingly, these two conditions are identified with the nomenclature WFC_35_CPX1 and AFC_35_CPX1, respectively.

For Subgroup 2, the added complexity for the standard gap duration of 35 ms consisted of requiring the listener to make two concurrent temporal judgments. The first temporal judgment was the basic GDD decision. The second temporal judgment was the sequential pattern of the three observation intervals in a 3AFC trial. Here, the nominal pauses between the first and second observation intervals and between the second and third observation intervals were either 300 ms & 450 ms, respectively, or 450 ms & 300 ms, respectively, at random. This gave the observation intervals of the 3AFC trial the rhythmic temporal pattern of ‘short – long’ or ‘long – short’, respectively. The lower panel of Fig. 1 depicts a stimulus schematic for this manipulation. Following each 3AFC trial, the listener therefore had to make the basic GDD decision (which interval contained the longer gap) as well as the temporal pattern judgment (‘short – long’ or ‘long – short’). This manipulation of requiring two concurrent temporal judgments was applied to both the within-frequency-channel and across-frequency-channel conditions. Accordingly, these two conditions are identified with the nomenclature WFC_35_CPX2 and AFC_35_CPX2, respectively.

All responses were entered via button presses on a hand-held response box, and feedback was provided after each trial via LED indicators on the box. For Subgroup 2, a rudimentary measure of response time was also included in this procedure wherein the time between the end of stimulus presentation at the conclusion of a 3AFC trial and the moment of button press when selecting the interval with the longest gap was recorded. However, the listener was not aware that response time was being monitored.

Because the manipulation of task complexity for Subgroup 2 required the listener to discriminate a ‘short – long’ *vs.* ‘long – short’ temporal pattern, it was necessary to first determine that the listener could indeed make this judgment in isolation, apart from the GDD task. Prior to being enrolled in the experiment, therefore, prospective listeners were administered a simple screening test in which they had to judge the temporal patterns of the pauses between 3AFC observation intervals (300 ms – 450 ms or 450 ms – 300 ms) where the intervals themselves contained clearly audible 150-ms, 432-Hz pure tones. Performance at a level of 90% correct or better was required to participate in the experiment.

In summary, this experiment measured GDD as a function of listener age, where the stimulus parameters of marker frequency, standard gap duration, and the acoustic context of the gap markers were systematically manipulated. Table 1 summarizes the various conditions tested.

B. Results and discussion

The core conditions of experiment 1 measured GDD for standard gap durations of 0 ms and 35 ms for both within-frequency-channel markers and across-frequency-channel markers (conditions WFC_0, WFC_35, AFC_0, and AFC_35). Subgroup 1 listened to an additional standard gap duration of 250 ms (conditions WFC_250 and AFC_250). The geometric means for these conditions are shown in Fig. 2 for the three age groups (Young = circles, Middle-aged = squares, Elderly = triangles) for both the within-frequency-channel (filled symbols) and across-frequency-channel (open symbols) conditions.[2] The primary focus of this experiment was whether the young and middle-aged listeners differed in the core conditions of 0- and 35-ms standard gap durations. Accordingly, these data, combined across both Subgroups, were submitted to a repeated-measures analysis of variance (ANOVA) with one between-subjects factor (age: young, middle-aged) and two within-subjects factors (standard gap duration: 0 ms, 35 ms; frequency channel: within, across). All statistical analyses were performed on log transforms of the data in order to maintain homogeneity of variance across conditions. The analysis indicated significant main effects of age ($F_{1,39} = 6.863$; $p = 0.012$), standard gap duration ($F_{1,39} = 91.59$; $p < 0.001$), and frequency channel ($F_{1,39} = 263.306$; $p < 0.001$). The only significant interaction was between standard gap duration and frequency channel ($F_{1,39} = 44.367$; $p < 0.001$). Means comparisons using Bonferroni correction indicated that this interaction was due to the difference between within- and across-frequency-channel conditions being greater for the standard 0-ms gap than the 35-ms gap, although both differences were significant ($t_{40} = 14.328$ and 9.427, respectively; $p < 0.01$). Overall, this pattern of results indicates that the middle-aged listeners performed more poorly than the young listeners across the four core conditions.

Two subsidiary questions were anticipated in association with these core conditions: (1) Does the age effect extend to longer standard gap durations?; and (2) How do young and middle-aged listeners perform relative to elderly listeners? To address these questions, Subgroup 1 was also tested using a standard gap duration of 250 ms; in addition, this Subgroup included a cohort of eight elderly listeners. A repeated-measures ANOVA on the data from Subgroup 1 alone was therefore undertaken that included one between-subjects factor (age: young, middle-aged, elderly) and two within-subjects factors (standard gap duration: 0 ms, 35 ms, 250

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[2] The maximum gap increment allowed by the procedure was 250 ms. For the rare instances where a listener was unable to perform the task reliably below this ceiling, a threshold value of 250 ms was entered. This occurred for three listeners: (1) one elderly listener for condition AFC_250; (2) one elderly listener for condition AFC_35_CPX1; and (3) one middle-aged listener for conditions AFC_250 and AFC_35_CPX1.

ms; frequency channel: within, across). The results indicated significant main effects of age ($F_{2,26}$ = 11.618; $p < 0.001$), standard gap duration ($F_{2,52}$ =184.031; $p < 0.001$), and frequency channel ($F_{1,26}$ = 135.968; $p < 0.001$). Again, the only significant interaction was between standard gap duration and frequency channel ($F_{2,52}$ = 58.485; $p < 0.001$). Post-hoc analysis using the Tukey HSD test indicated that the middle-aged and elderly listeners had significantly higher GDD thresholds than the young listeners, but that the two older age groups did not themselves differ significantly. Simple contrasts showed that, for all age groups, performance declined significantly as standard gap duration increased both for within-frequency-channel and across-frequency-channel conditions. In summary, this analysis showed that the age effect extended to a standard gap duration of 250 ms; in addition, it showed that middle-aged listeners performed more like elderly listeners than like young listeners on this GDD task. Based on the work of Lister et al. (2002), this latter result was not expected. In that study, the elderly listeners performed substantially worse on a GDD task than either the young or middle-aged listeners. The reason for this discrepancy is not clear, although it is possible that the criterion of relatively normal hearing (≤ 20 dB HL across the octave frequencies 250 – 4000 Hz) in the small group of elderly listeners tested here may have resulted in the selection of a cohort with particularly resilient auditory function.

It was hypothesized that potential age effects would be exacerbated by increasing the complexity of the task. For Subgroup 1, task complexity was increased by embedding the 35-ms gap markers into a 3-toneburst train. For Subgroup 2, task complexity was increased by requiring listeners to make two concurrent temporal judgments. Dealing first with Subgroup 1, Fig. 3 shows the group mean GDD thresholds for the 35-ms standard gap presented both in isolation and in the complex context. It is evident that for all age groups and conditions, performance declined when task complexity was increased. This was confirmed using a repeated-measures ANOVA that included one between-subjects factor (age: young, middle-aged, elderly) and two within-subjects factors (complexity: absent, present; frequency channel: within, across). The analysis indicated significant main effects of age ($F_{2,26}$ = 10.999; $p < 0.001$), complexity ($F_{1,26}$ = 158.962, $p < 0.001$), and frequency channel ($F_{1,26}$ = 48.643; $p < 0.001$). None of the interaction terms were significant. Post-hoc analysis using the Tukey HSD indicated that the performance of the middle-aged and elderly listeners was significantly poorer than that of the young listeners but that the two older age groups did not themselves differ significantly.

It could be argued, however, that the pertinent issue is not whether the middle-aged listeners performed more poorly than the young listeners in the complex task, but whether their decline in performance relative to the basic task was proportionally greater than that for young listeners. That is, age differences tend to be exacerbated by increases in task complexity and therefore it was expected that the added complexity would compound the difficulty for the middle-aged listeners. To address this, a ratio was computed for each listener that related the difference in GDD thresholds between the basic and complex conditions to the basic condition threshold itself. This Weber-like ratio was computed for both the within-frequency-channel and across-frequency-channel conditions. (i.e., [WFC_35_CPX1 - WFC_35]/WFC_35 or [AFC_35_CPX1 - AFC_35]/AFC_35). An ANOVA on the resulting Weber ratios indicated no effect of age ($F_{2,26}$ = 0.564; $p = 0.576$) or frequency channel ($F_{1,26}$ = 0.429; $p = 0.518$). This indicates that the decline in GDD performance due to embedding the 35-ms standard gap into a 3-toneburst sequence was proportionally the same for all age groups, and did not depend on within- *vs*. across-frequency channel conditions. The finding that the relative decline in GDD performance for the embedded standard gap did not depend on listener age was contrary to expectations. A number of studies comparing young and elderly listeners have shown that temporal processing deficits associated with advanced age are exacerbated by increased stimulus complexity, such as the use of stimulus trains (e.g., Fitzgibbons and Gordon-Salant, 1995).

For Subgroup 2, task complexity was increased by requiring the young and middle-aged listeners to make two concurrent temporal judgments. It was expected that GDD performance would decline under conditions where more than one temporal feature had to be monitored at the same time. Accordingly, GDD thresholds for the 35-ms standard gap in the basic task (WFC_35 or AFC_35) and the GDD thresholds in the respective complex task (WFC_35_CPX2 or AFC_35_CPX2) were compared using Weber ratios as described above. The group mean ratios are shown in Fig. 4. The ratio for one young listener in the within-frequency-channel comparison was excluded on the grounds of it being an outlier: the ratio in question was close to three standard deviations away from the group mean. It is apparent from Fig. 4 that the relative decline in performance with the added task complexity was greater for the middle-aged listeners than for the young listeners. This was confirmed using a repeated-measures ANOVA that included one between-subjects factor (age: young, middle-aged) and one within-subjects factor (frequency channel: within, across). The effect of age was significant ($F_{1,23} = 8.762$; $p = 0.007$) but no other effects or interactions were significant. These results indicate that the middle-aged listeners experienced proportionally greater difficulty with the GDD task than the young listeners when the added complexity of making two concurrent temporal judgments was imposed.

To be included in Subgroup 2, all listeners had to demonstrate high accuracy (≥ 90% correct) in making the interval pattern judgment in isolation. It was of interest to determine whether the young and middle-aged listeners differed in the degree to which this accuracy was compromised when the interval pattern judgment formed one of the two concurrent temporal judgments in the complex listening conditions. Fig. 5 shows the average arcsine-transformed percent correct scores for interval pattern identification for the young and middle-aged listeners in both the within- and across-frequency channel conditions. A repeated-measures ANOVA on the arcsine-transformed data with one between-subjects factor (age: young, middle-age) and one within-subjects factor (frequency channel: within, across) showed a significant effect of age ($F_{1,24} = 4.645$; $p = 0.041$), but not frequency channel ($F_{1,24} = 0.846$; $p = 0.367$). The interaction between these factors was not significant. Thus the younger listeners were not only better than the middle-aged listeners at discriminating increments in gap duration in the complex listening task, they were also more accurate in the concurrent temporal order judgment.

A final metric that was collected for Subgroup 2 was the time-to-respond for the GDD decision following each 3AFC trial. The group mean data are shown in Fig. 6 for the within-frequency-channel (left panel) and across-frequency-channel (right panel) conditions. Each panel depicts two entries for the standard gap duration of 35 ms: one for the basic task where only the GDD decision was required (T1), and one for the complex task where two concurrent temporal judgments were required (T2). It is apparent that response time was quite variable across listeners, as evidenced by the large standard deviations. Nevertheless, it can be seen that the middle-aged listeners (squares) took consistently longer to respond than the young listeners (circles). This was confirmed with a repeated-measures ANOVA on the log transforms of the response data, with one between-subjects factor (age: young, middle-aged) and two within-subjects factors (gap condition: 0 ms, 35 ms T1, 35 ms T2; frequency channel: within, across). The analysis indicated significant effects of age ($F_{1,24} = 8.714$; $p = 0.007$), gap condition ($F_{2,48} = 38.516$; $p < 0.001$), and frequency channel ($F_{1,24} = 6.471$; $p = 0.018$). None of the interaction terms were significant. Simple contrasts on the data for the different gap conditions indicated that response times did not differ between the basic 0-ms and 35-ms standard gap durations, but were significantly longer for the complex conditions. This pattern of results indicates that the middle-aged listeners responded more slowly in general than the younger listeners. It should be underscored that the listeners were not aware that response time was being measured, and were not instructed to respond as quickly as possible.

In summary, the purpose of experiment 1 was to test the hypothesis that temporal processing deficits are evident in middle age for listening tasks that involve brief stimuli, across-frequency-channel processing, and/or significant processing loads. The results support some aspects of this hypothesis:

1. Middle-aged listeners performed more poorly than the young listeners in the GDD task. However, this difference was equally apparent for both within-frequency-channel and across-frequency-channel conditions.
2. Increased task complexity compounded the performance differences between young and middle-aged listeners. However, this proportional decline occurred only when the added complexity consisted of making two concurrent temporal judgments and not when it consisted of embedding the gap markers into a 3-toneburst train.
3. Middle-aged listeners were less accurate at temporal rhythm judgments in complex listening tasks, and were generally slower in responding than young listeners.

One of the limitations of experiment 1 was that marker duration was fixed at 20 ms. Because of this, overall stimulus duration (two markers + gap) covaried with gap duration. Thus, it is not possible to differentiate between sensitivity to the duration of the silent interval alone and sensitivity to overall stimulus duration. It has long been known that gap detection performance declines markedly when the durations of the gap markers are random (Penner, 1976). Randomizing gap marker duration forces the listener to monitor the duration of the silent interval alone and renders the cue of overall stimulus duration unreliable. In order to determine whether the results of experiment 1 held strictly for *gap* discrimination, listeners from Subgroup 2 undertook a supplementary experiment that used random-duration markers.

III. EXPERIMENT 2. GAP DURATION DISCRIMINATION FOR RANDOM-DURATION MARKERS

A. Method

1. Listeners—Ten young and 14 middle-aged listeners from Subgroup 2 participated. The young listeners ranged in age from 18 – 25 yrs (mean = 21.4 yrs); the middle-aged listeners ranged in age from 40 – 54 yrs (mean = 45.7 yrs).

2. Stimuli—The gap markers were tonebursts with nominal durations of 40 ms, but whose actual duration varied by 50% (40 ± 20 ms, with random draws from a rectangular distribution) on a presentation-by-presentation basis. All other parameters, and the method of stimulus generation, were the same as in experiment 1.

3. Procedure—The same six conditions that Subgroup 2 underwent in experiment 1 were repeated here, except that marker duration was variable rather than constant. These six conditions included the four basic GDD conditions of WFC_0, WFC_35, AFC_0, AFC_35, and the two complex conditions of WFC_35_CPX2 and AFC_35_CPX2 where concurrent temporal judgments of GDD and the temporal order of the observation intervals were required. All other procedural details were the same as described for experiment 1.

B. Results and discussion

The group mean data for the six conditions are displayed in Fig. 7. As expected, performance became poorer and more variable in general, relative to the fixed marker durations of experiment 1 (cf. Fig. 2). A repeated-measures ANOVA on the six conditions was undertaken that included one between-subjects factor (age: young, middle-aged) and two within-subjects factors (gap condition: 0 ms, 35-ms basic, 35-ms complex; frequency channel: within, across). As with experiment 1, statistical analysis was performed on the log transforms of the data to maximize homogeneity of variance. The analysis indicated significant main effects of age ($F_{1,22} = 8.386$; $p = 0.008$), gap condition ($F_{2,44} = 28.15$; $p < 0.001$), and frequency channel ($F_{1,22} = 15.211$; $p = 0.001$). The only significant interaction was between gap condition and frequency channel ($F_{2,44} = 6.113$; $p = 0.005$). Means comparisons using Bonferroni correction indicated that this interaction was due to the difference between within- and across-frequency-channel conditions being greater for the standard 0-ms gap than for either the basic or complex 35-ms gap. The difference for the 0-ms gap was significant ($t_{23} = 4.612$; $p < 0.001$) whereas that for the two 35-ms gaps failed to reach significance ($t_{23} = 1.894$, $p = 0.071$; $t_{23} = 1.758$, $p = 0.092$, for the basic and complex gaps, respectively). In terms of the four core conditions (WFC_0, WFC_35, AFC_0, AFC_35), this pattern of results is similar to that observed in experiment 1, and indicates that the middle-aged listeners performed more poorly than the young listeners across the four core conditions.

The repeated-measures ANOVA also addressed the effect of task complexity. The significant main effect of age noted above, with no interaction between age and gap condition, confirms that the middle-aged listeners performed more poorly than the young listeners on both the basic and complex 35-ms gap tasks. Means comparisons using Bonferroni correction indicated that all listeners exhibited elevated thresholds in the more challenging complex conditions, both for the within-frequency-channel conditions ($t_{23} = 2.957$; $p = 0.007$) and the across-frequency-channel conditions ($t_{23} = 3.763$; $p = 0.001$). There is no indication in Fig. 7, however, that the poorer GDD performance of the middle-aged listeners was compounded in the complex conditions. This was confirmed by a repeated-measures ANOVA on the Weber ratios that showed no significant effects of age group or frequency channel, indicating that the decline in performance in the complex conditions was equivalent for both age groups, irrespective of frequency channel.

Figure 8 summarizes the accuracy with which the temporal order judgment (short – long *vs*. long – short) was made in the complex listening task in terms of the arcsine-transformed percent correct data. A repeated-measures ANOVA on the data showed significant effects of age ($F_{1,22} = 6.155$; $p = 0.021$) and frequency channel ($F_{1,22} = 18.461$; $p < 0.\ 001$). The interaction between these factors was not significant. These results indicate that the young listeners were more accurate in their judgment of temporal order, in addition to being more sensitive to increments in gap duration. Also, irrespective of age, listeners were more accurate in temporal pattern identification in the across-frequency-channel condition, although no explanation is offered for this finding. Finally, the response time data are shown in Fig. 9. A repeated-measures ANOVA on the log-transformed response times showed significant effects of age ($F_{1,22} = 6.754$; $p = 0.016$) and gap condition ($F_{2,44} = 37.042$; $p < 0.001$), but not of frequency channel ($F_{1,21} = 0.117$; $p = 0.735$). None of the interaction terms were significant. Simple contrasts on the gap condition results indicated that response times did not differ between the 0-ms and 35-ms basic conditions, but were significantly longer for the complex conditions. The pattern of results for the response time data therefore indicates that the middle-aged listeners generally took longer to respond than the young listeners, but that all listeners took longer to respond when task complexity was increased.

In summary, the results of experiment 2 are essentially the same as those of experiment 1. Even though the use of random-duration markers made the task generally more challenging for all listeners, middle-aged listeners were still less sensitive to increments in gap duration than young listeners. In the complex task, where two concurrent temporal judgments were required, middle-aged listeners were both poorer at discriminating gap increments and less accurate in their temporal order judgments. Finally, middle-aged listeners were generally slower at responding than are young listeners. Overall, these results support the hypothesis that temporal processing deficits are evident in middle age. However, not all aspects of the hypothesis as originally proposed are supported. For example, age effects are not necessarily more pronounced for across-frequency than within-frequency configurations, and performance deficits for middle-aged listeners are not necessarily exacerbated relative to young listeners in the more complex listening conditions.

Although the results of experiments 1 and 2 indicate that deficits in temporal processing are evident relatively early in the aging process, it is not clear that these deficits necessarily translate to actual performance differences in ‘real-world’ listening tasks. Accordingly, a final experiment was undertaken that compared young and middle-aged listeners in a categorical perception task that depended on silent gap duration.

IV. EXPERIMENT 3. /s/ - /st/ PERCEPTION AS A FUNCTION OF GAP DURATION

A number of studies have pointed out that silent intervals, or segments of low energy, in speech constitute an information-bearing feature of the acoustic waveform. For example, these gaps can provide cues for voice-onset time (Strouse et al., 1998; Phillips, 1999), as well as the presence of stop consonants that abut voiceless sibilants (Bailey and Summerfield, 1980; Best et al., 1981; Dorman et al., 1985; Nittrouer et al., 1998). In light of this, there has been an interest in determining whether psychoacoustic measures of temporal resolution, such as gap detection, relate to speech performance measures for stimuli that involve silent intervals (Formby et al., 1993; Nelson et al., 1995; Lister and Tarver, 2004). One particular study of relevance here measured gap detection for noise-band markers that displayed some speech-like characteristics, and related this measure to the duration of the silent interval between the sibilant /s/ and the ensuing vowel /ei/ that forms the categorical boundary between the words ‘say’ and ‘stay’ (Nelson et al., 1995). Although that study did not find a dependency of categorical perception on gap *detection* ability, it did demonstrate that both the gap detection task and the categorical perception task were able to differentiate among listener groups (in this case, categories of hearing loss). In light of this, the present experiment was undertaken to determine whether a difference between young and middle-aged listeners could be identified in a similar categorical perception task.

A. Method

1. Listeners—Twenty-four normal-hearing listeners participated: 12 young and 12 middle-aged. The young listeners ranged in age from 19 – 27 yrs (mean = 20.9 yrs) and the middle-aged listeners ranged from 41 – 55 yrs (mean = 47.8 yrs). Three of the young and six of the middle-aged listeners also participated in either experiments 1 or 2.

2. Stimuli—The stimuli consisted of five sibilant-vowel words recorded by a male speaker. The five words were: ‘say’, ‘sigh’, ‘sow’, ‘see’, and ‘sue.’ Four tokens of each word were digitized at a sampling rate of 11.025 kHz (TDT PD1) after low-pass filtering at 4 kHz (Kemo VBF-8). Using a waveform editing program (Sound Edit™), the sibilant segment of each digitized token was excised and stored in one sound file, while the remaining vowel segment was stored in a separate sound file. For presentation of a particular word, a sibilant-segment sound file and a vowel-segment sound file were randomly selected from this library of eight sound files associated with the four tokens of that word, and digitally spliced together to form a single waveform. Silent gaps were introduced between the sibilant and vowel segments by introducing 0-voltage points between the two waveform segments. The imposed gap varied in duration from 5 ms to 100 ms in 5-ms steps. The stimuli were presented to the listeners through one earphone of a Sennheiser HD580 headset at a comfortable listening level.

3. Procedure—Each listener was presented with 525 stimuli in random order (5 words X 21 gap durations X 5 replications). The task was to indicate via a response box whether the perceived word was of the form sibilant-vowel (i.e., ‘say’, ‘sigh’, ‘sow’, ‘see’, or ‘sue’) or of the form sibilant-stop-consonant-vowel (i.e., ‘stay’, ‘sty’, ‘stow’, ‘stee’, or ‘stew’). For each listener and word, the percent /st/ perception (sibilant-stop-consonant-vowel) was plotted as a function of gap duration. Each individual categorical function was then fit with a logit function, and the gap duration associated with the 50% point derived.

B. Results and Discussion

The group mean data are displayed in Fig. 10 which shows the gap duration at the categorical boundary between /s/ and /st/ for each of the five contrasts tested. There is scant published data against which to compare these results. However, it is of interest that the gap duration associated with the categorical boundary between synthesized ‘say-stay’ tokens for normal listeners is about 37 ms (Nelson et al., 1995; high F1 stimulus). For the young normal-hearing listeners and natural ‘say-stay’ stimuli used here, the boundary is about 38 ms. With reference to Fig. 10, it is apparent that the middle-aged listeners tended to require longer silent intervals between the sibilant segment and the ensuing vowel segment to perceive the word as containing a stop consonant. This observation was confirmed using a repeated-measures ANOVA with one between-subjects factor (age: young, middle-aged) and one within-subjects factor (five words). The analysis indicated a significant effect of age ($F_{1,22} = 5.174$; $p = 0.033$) and a significant effect of word ($F_{4,22} = 17.094$; $p < 0.001$), but no interaction between these two factors. This analysis confirms that the gap durations associated with the categorical boundaries for the /s/ - /st/ contrasts tested here were longer for the middle-aged listeners than the young listeners. Interestingly, the mean gap durations at the categorical boundary measured here are longer than those found for discrimination thresholds for similar sibilant-vowel stimuli measured by Lister and Tarver (2004). This suggests that the silent interval at the categorical boundary was supra-threshold for all listeners but that the weighting applied to the gap duration in assigning the categorical boundary differed. In conclusion, the finding that an age effect is present in a task related more closely to speech perception suggests that the deficits in temporal processing measured in the GDD tasks of experiments 1 and 2 may have meaningful consequences in everyday listening environments.

V. SUMMARY AND CONCLUSION

The purpose of this study was to test the hypothesis that temporal processing deficits are evident in the pre-senescent (middle-aged) auditory system for listening tasks that involve brief stimuli, across-frequency-channel processing, and/or significant processing loads. Several aspects of this hypothesis were supported. Experiments 1 and 2 showed that GDD thresholds for middle-aged listeners were consistently higher than for young listeners at standard gap durations of 0 and 35 ms. This effect held both for fixed- and random-duration markers, as well as basic and complex temporal tasks. In addition, experiment 1 showed that, for complex listening conditions where two concurrent temporal judgments are required, the added processing load compounded the performance deficits of the middle-aged listeners relative to the young listeners. In contrast, other aspects of the hypothesis were not supported. The results of both experiments 1 and 2 indicated that the temporal processing deficits associated with the middle-aged listeners were not generally restricted to (or necessarily exacerbated by) across-frequency-channel processing. Conditions designed to increase task complexity, and therefore processing load, did not necessarily compound the differences between young and middle-aged listeners. For example, embedding the gap markers in a tonal sequence (experiment 1) or requiring concurrent temporal judgments for random-duration markers (experiment 2) did not exacerbate the performance deficits of middle-aged listeners relative to young listeners. In this vein, it is noteworthy that preliminary work from our laboratory that sought to increase GDD task complexity by incorporating a non-temporal task did not show a difference between young and middle-aged listeners (Grose et al., 2004). In that report, task complexity was increased by requiring the listener to judge the frequency direction of the gap marker sequence concurrently with the GDD task. The general finding from experiments 1 and 2, however, is that temporal processing deficits are evident in the middle-aged auditory system under many conditions that employ brief stimuli.

The results of experiment 3 indicate that these temporal processing deficits associated with the pre-senescent auditory system may have meaningful consequences for the processing of more ecologically-relevant stimuli. The finding of an age effect for the gap durations associated with categorical boundaries is noteworthy in light of the response time results of experiments 1 and 2. These latter measures indicated that middle-aged listeners had longer response times than young listeners. It could be argued that slower response times are indicative of a general slowing in decision-making mechanisms, and as such reflect higher-level processes such as memory, rather than temporal processing, *per se*. This important issue is considered carefully in Pichora-Fuller (2003). However, the categorical perception result of experiment 3 suggests that the age effects seen in the GDD tasks are indicative of performance deficits at the level of temporal processing. In conclusion, a large body of work has indicated that temporal processing declines with advanced age, and independently of hearing loss. This study extends this characterization to show that deficits in temporal processing are evident in the pre-senescent, or middle-aged, auditory system under certain conditions.

Acknowledgements

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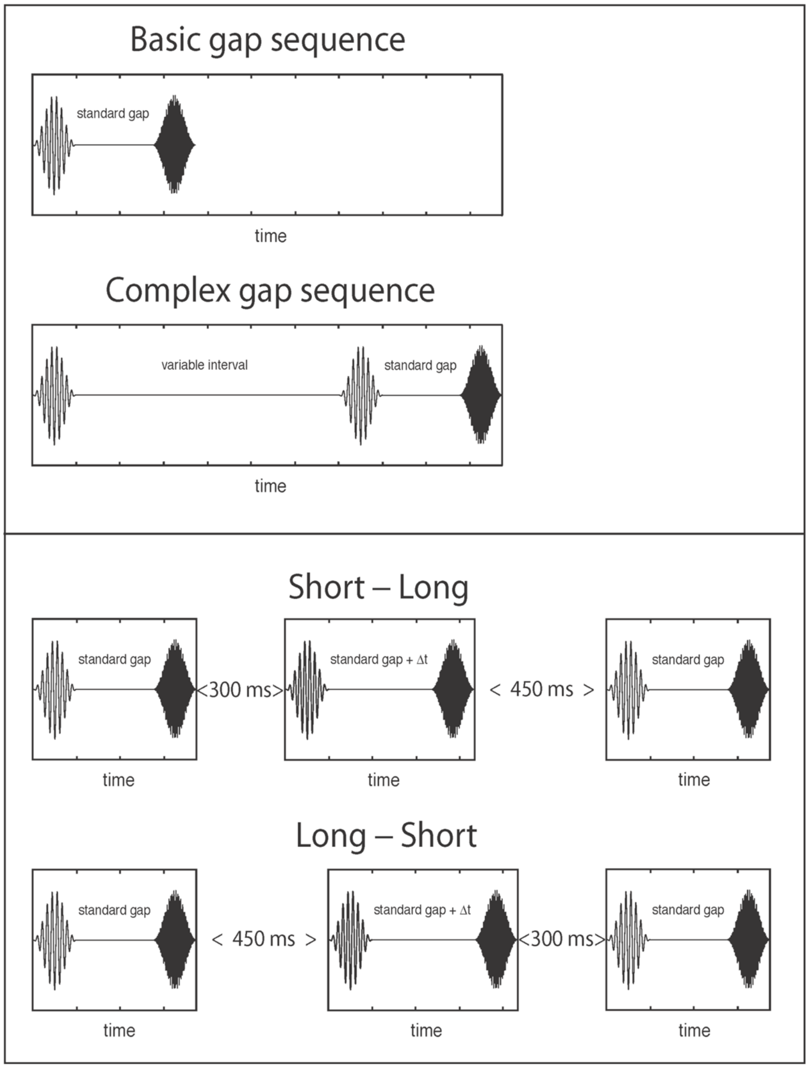

Fig. 1.

Stimulus schematics of complex conditions. Upper panel: The top trace shows the basic condition where a pair of tonebursts mark the standard gap; the lower trace shows the complex condition for Subgroup 1 where the gap marker pair is preceded at a variable interval by a preliminary toneburst to form a 3-toneburst sequence. Lower panel: Illustrative 3AFC trials for Subgroup 2 where the pauses between observation intervals provide either a short – long rhythm (top trace) or long – short rhythm (lower trace). In both illustrated trials, the signal interval for the GDD task is the second one.

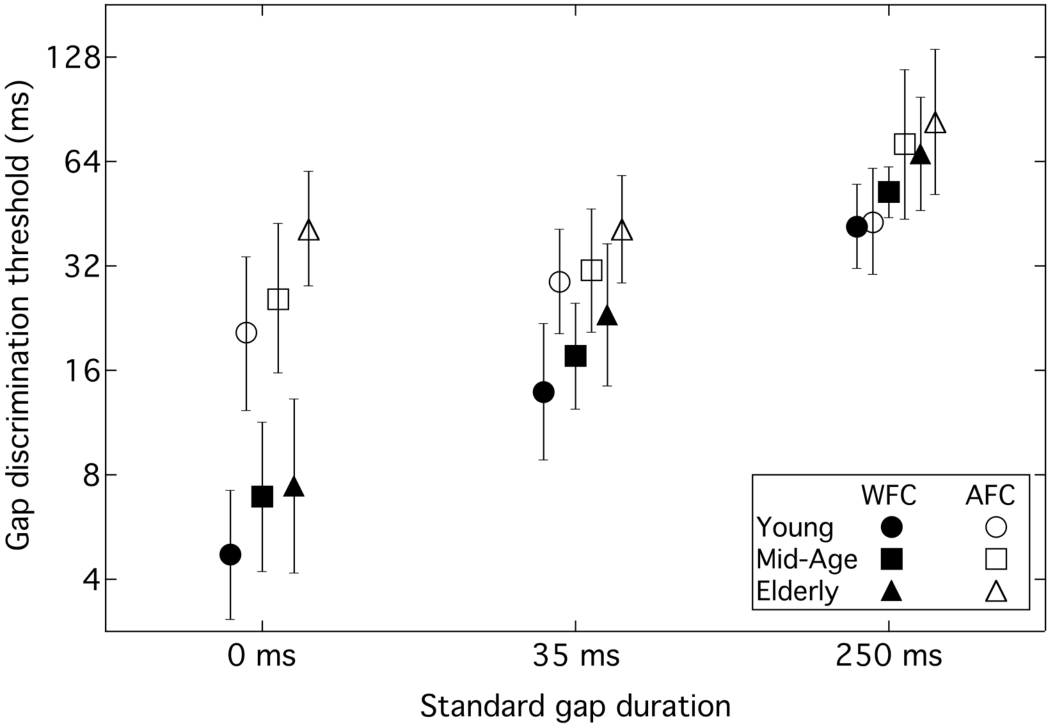

Fig. 2.

Group mean GDD thresholds plotted as a function of standard gap duration for 3 age groups (Young: circles; Middle-aged: squares; Elderly: triangles). Filled symbols indicate within-frequency-channel conditions; unfilled symbols indicate across-frequency-channel conditions. Error bars indicate ± 1 standard deviation.

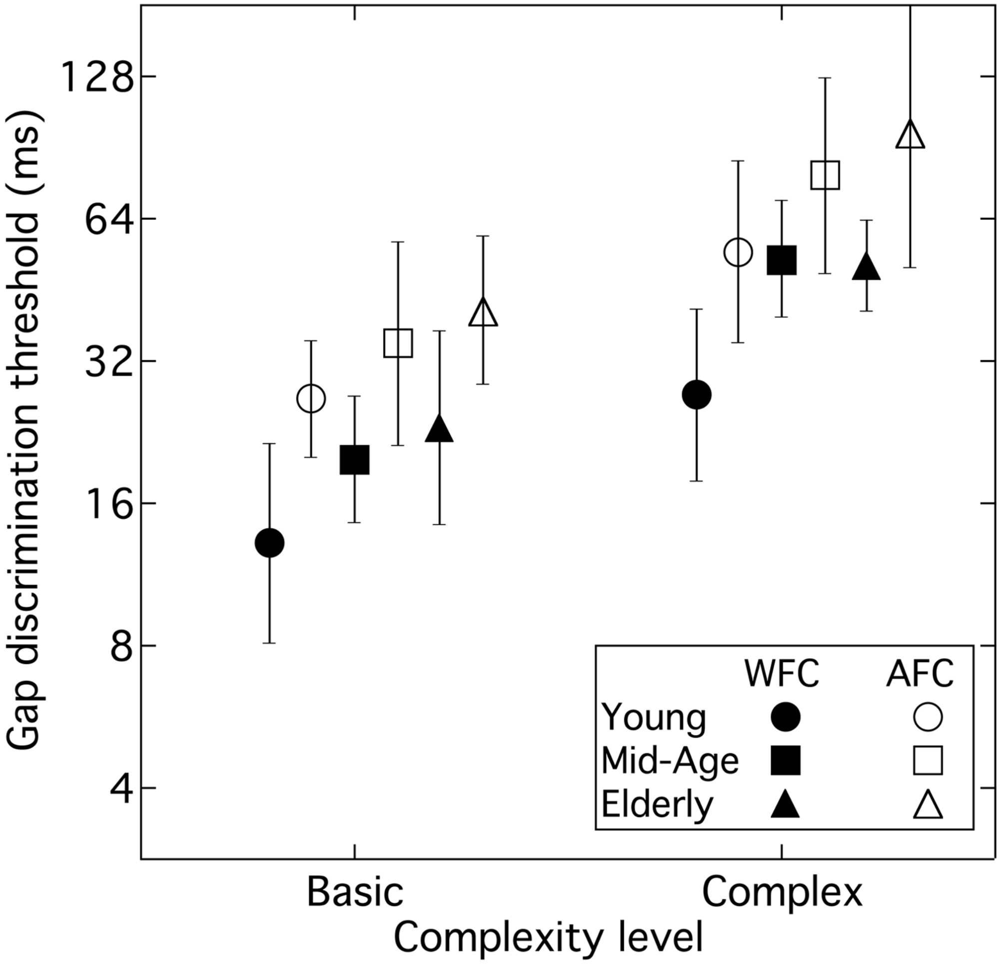

Fig. 3.

Group mean GDD thresholds for a standard gap duration of 35 ms presented in isolation (Basic) and as part of a 3-toneburst sequence (Complex) for 3 age groups (Young: circles; Middle-aged: squares; Elderly: triangles). Data are shown for both within-frequency-channel (filled symbols) and across-frequency-channel (unfilled symbols) conditions. Error bars indicate ± 1 standard deviation.

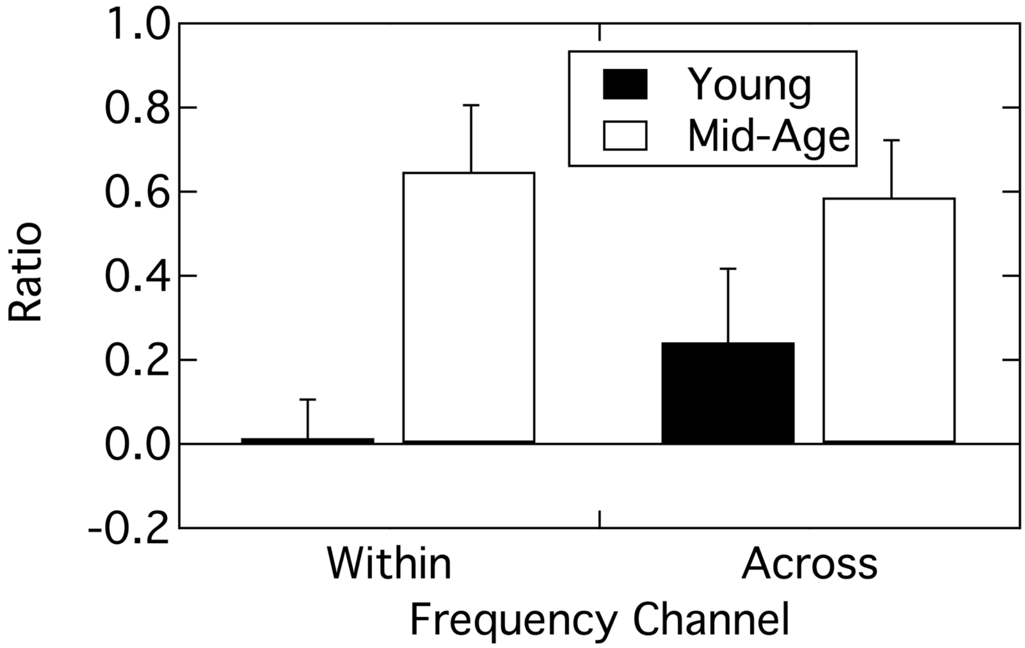

Fig. 4.
Group mean Weber ratios encoding the relative change in GDD threshold as a function of task complexity for Subgroup 2. Ratios are plotted for young (filled bars) and middle-aged (open bars) listeners for within- and across-frequency channel conditions. Error bars indicate one standard error of the mean.

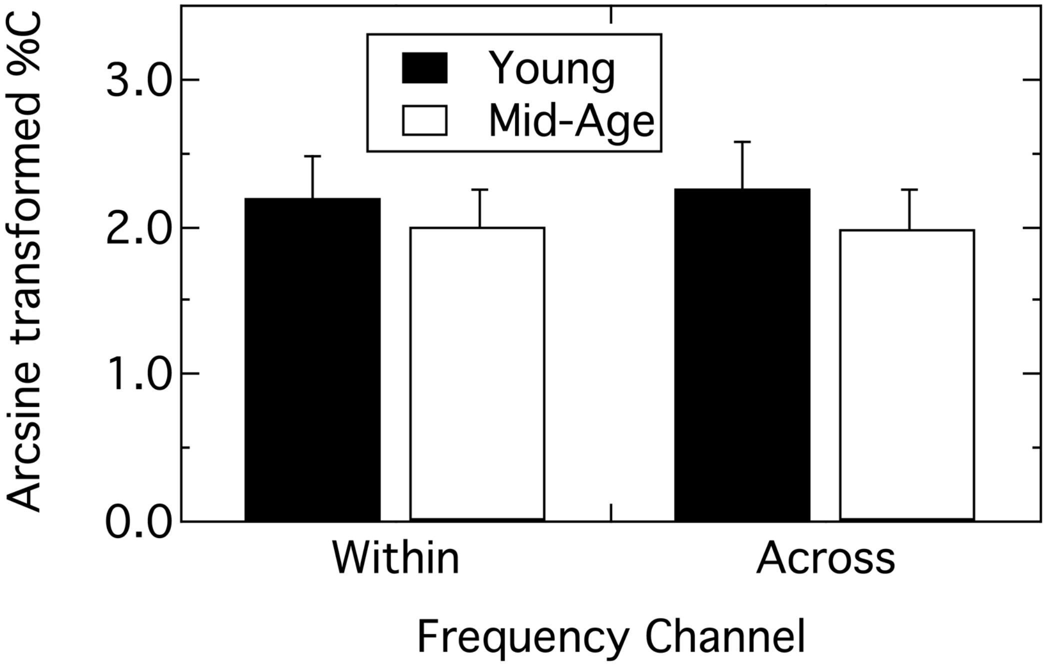

Fig. 5.
Group mean arcsine-transformed percent correct scores for interval pattern identifcation for young (filled bars) and middle-aged (open bars) listeners for within- and across-frequency channel conditions. Error bars indicate one standard deviation.

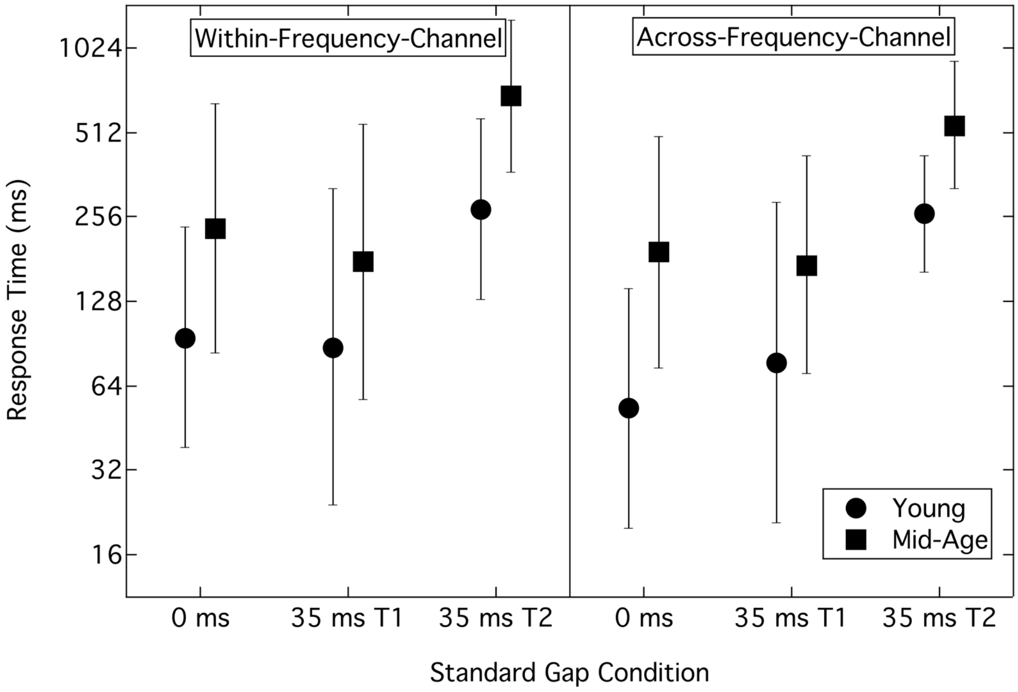

Fig. 6.

Group mean response times for within-frequency-channel (left panel) and across-frequency-channel (right panel) conditions. Response times are plotted for young (circles) and middle-aged (squares) listeners for standard gap durations of 0 and 35 ms. The 35-ms gap was tested in the basic condition (T1) and in the complex condition where two concurrent temporal judgments were required (T2). Error bars indicate ± 1 standard deviation.

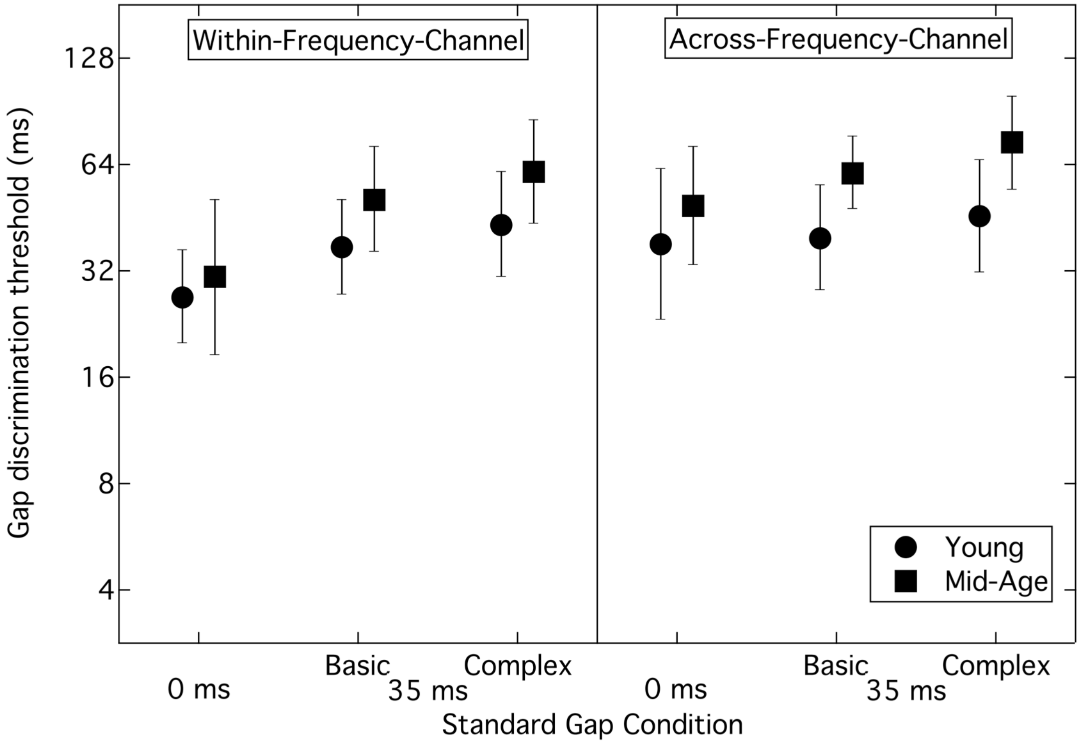

Fig. 7.

Group mean GDD thresholds for the six conditions of experiment 2. Within-frequency-channel data is shown in the left panel; across-frequency-channel data in the right panel. The parameter is age groups (Young: circles; Middle-aged: squares). Error bars indicate ± 1 standard deviation.

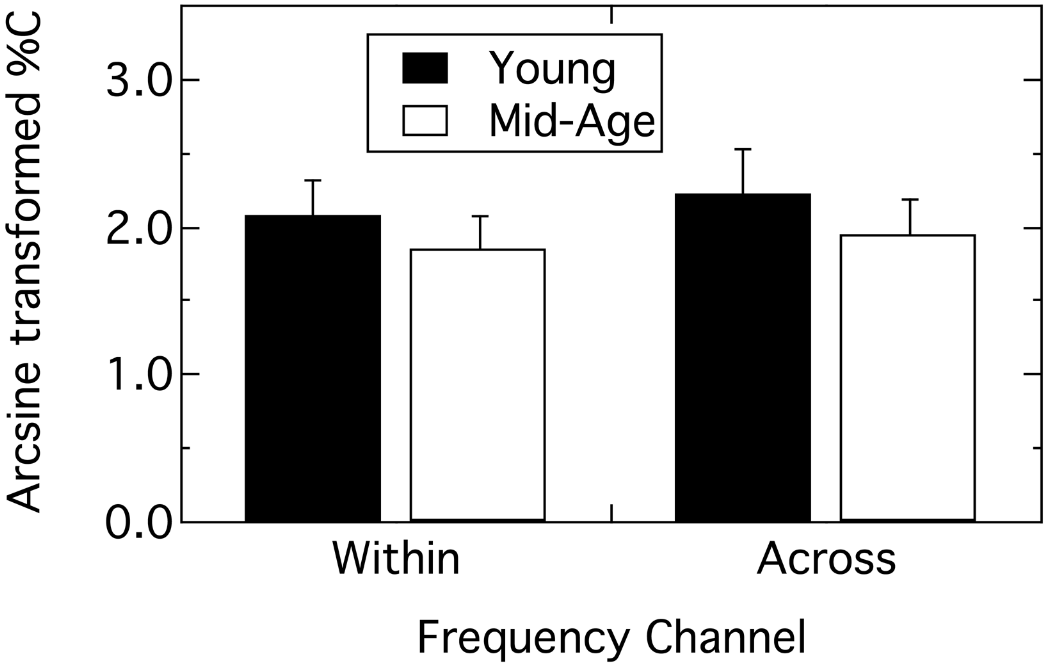

Fig. 8.
Group mean arcsine-transformed percent correct scores for young (filled bars) and middle-aged (open bars) listeners for within- and across-frequency channel conditions for experiment 2. Error bars indicate one standard deviation.

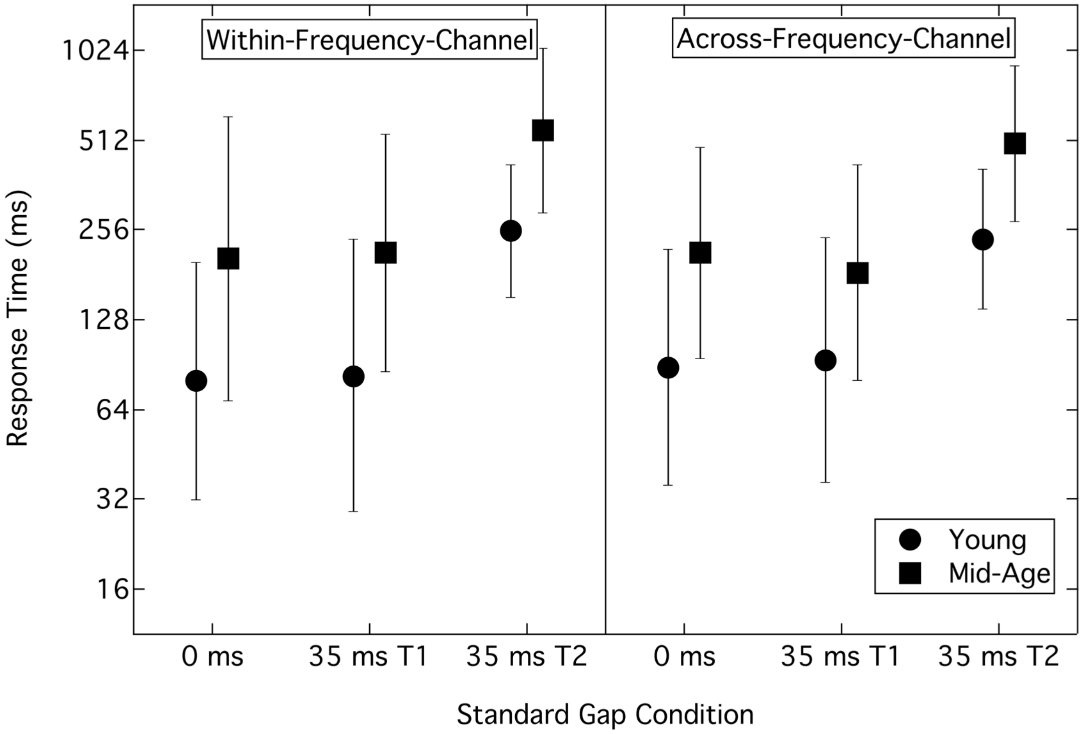

Fig. 9.

Group mean response times for within-frequency-channel (left panel) and across-frequency-channel (right panel) conditions for experiment 2. Response times are plotted for young (circles) and middle-aged (squares) listeners for standard gap durations of 0 and 35 ms. The 35-ms gap was tested in the basic conditions (T1) and in the complex condition where two concurrent temporal judgments were required (T2). Error bars indicate ± 1 standard deviation.

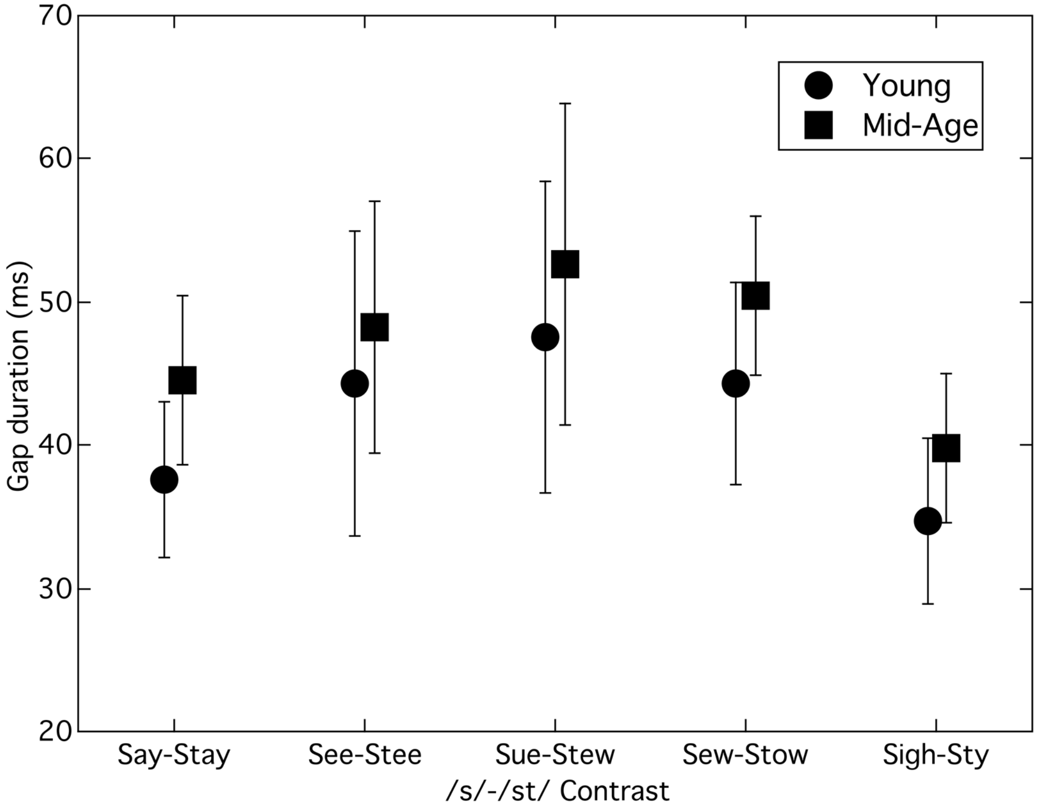

Fig. 10.

Group mean gap durations at the /s/ - /st/ categorical boundary for young (circles) and middle-aged (squares) listeners. Error bars indicate ± 1 standard deviation.

Table 1

Conditions and associated listener groups for experiment 1.

Condition	Listeners	Marker freqs.	Stand. gap dur.	Complexity
WFC_0	Subgroups 1 & 2	432–458 Hz	0 ms	-
WFC_35	Subgroups 1 & 2	432–458 Hz	35 ms	-
WFC_250	Subgroup 1	432–458 Hz	250 ms	-
AFC_0	Subgroups 1 & 2	432–2188 Hz	0 ms	-
AFC_35	Subgroups 1 & 2	432–2188 Hz	35 ms	-
AFC_250	Subgroup 1	432–2188 Hz	250 ms	-
WFC_35_CPX1	Subgroup 1	432–458 Hz	35 ms	+ Prelim. tone
AFC_35_CPX1	Subgroup 1	432–2188 Hz	35 ms	+ Prelim. tone
WFC_35_CPX2	Subgroup 2	432–458 Hz	35 ms	+ 2nd judgment
AFC_35_CPX2	Subgroup 2	432–2188 Hz	35 ms	+ 2nd judgment