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Psychometric functions for gap detection in noise measured from young and aged subjects

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Psychometric functions for detection of temporal gaps in wideband noise were measured in a ''yes/no'' paradigm from normal-hearing young and aged subjects with closely matched audiograms. The effects of noise-burst duration, gap location, and uncertainty of gap location were tested. A typical psychometric function obtained in this study featured a steep slope, which was independent of most experimental conditions as well as age. However, gap thresholds were generally improved with increasing duration of the noise burst for both young and aged subjects. Gap location and uncertainty had no significant effects on the thresholds for the young subjects. For the aged subjects, whenever the gap was sufficiently away from the onset or offset of the noise burst, detectability was robust despite uncertainty about the gap location. Significant differences between young and aged subjects could be observed only when the gap was very close to the signal onset and offset. © *1999 Acoustical Society of America.* [S0001-4966(99)02408-X]

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INTRODUCTION

Gap detection is used as one measure of the temporal resolving power of the auditory system, i.e., the ability to follow rapid changes over time. The typical threshold for detection of a gap in a wideband noise burst is 2 to 3 ms (Green, 1985). Plomp (1964) suggested that temporal resolution is limited by the decay of sensation produced by the first part of the stimulus, which would fill in the gap. In a recent study (Zhang *et al.*, 1990) measuring neural correlates of gap detection in eighth-nerve fibers from chinchilla, the decay in neural response was found to be inversely related to the characteristic frequency (CF) of the unit, about 1 ms for high-CF units and 5 ms for fibers with CF$<$1000 Hz. According to Zhang *et al.*, the neural representation of gap detection was characterized by a modulation of the firing rate in the peristimulus-time (PST) histogram with an abrupt drop followed by a sharp increase. The modulation was a function of gap length. As the gap length increased, the firing rate during the gap systematically decreased, and when the gap was 10 ms long the firing rate decreased to below the spontaneous rate of the unit. Also, the firing rate at the onset of the second part of the noise burst increased with increasing gap length. Thus, in some respects, the neural representations of gap detection resemble psychometric functions obtained in psychophysical measurements (Green and Forrest, 1989; Moore and Glasberg, 1988).

A distinctive feature of the psychometric function for gap detection is its steep slope, which, as suggested by Moore *et al.* (1992), would assure a high precision (or a low within-subject variability) in measurement of the gap-detection threshold. However, the steep slope does not guarantee good agreement among studies. Indeed, considerable controversy exists in the gap-detection literature regarding several factors, such as noise-burst duration, subject age, and gap location.

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A. Effect of noise-burst duration

In many auditory perception tasks, performance decreases with decreasing stimulus duration (Garner and Miller, 1947; Moore, 1973; Hall and Fernandes, 1983; Florentine, 1986; Viemeister, 1979; Sheft and Yost, 1990; Lee, 1994; Lee and Bacon, 1997), thus suggesting a common underlying temporal integration process. However, reports of the noise-burst duration effect on gap detection are inconsistent. Forrest and Green (1987) found little difference ($<$1 ms) in gap threshold for noise-burst durations ranging from 5 to 400 ms with a minimum at 25 and 50 ms. For noise durations shorter than 25 ms, the trend was different than that reported by an earlier study (Penner, 1975), where the gap threshold progressively increased from 1 to 3 ms as the noise duration increased from 5 to 20 ms. Forrest and Green attributed the inconsistency to procedural differences. In their study, the overall duration of the noise burst was kept constant, whereas Penner used a pair of identical noise bursts so that the total duration varied with gap length. This duration cue became increasingly significant as the noise-burst duration decreased. In a large-sample study, Muchnik *et al.* (1985) showed that gap-detection thresholds of young, normally hearing subjects increased as noise burst duration decreased from 85 to 10 ms. A similar trend was observed for subjects in two other age groups (40–60 and 60–70 years) in the same study. There were age-related differences in the increment of gap thresholds when the noise-burst duration decreased; however, this potential age effect could be confounded by the subjects' hearing loss.

B. Effect of subject age

The effects of subject age on gap-detection ability are not clear. Schneider *et al.* (1994) reported that gap thresholds of elderly subjects were more variable and about twice as large as those from young subjects. Although Moore *et al.* (1992) also observed an age-related difference, these authors noted that the mean differences were mainly due to the data of a few elderly subjects who had markedly large gap thresholds, and that the majority of elderly subjects had gap thresholds within the range of young subjects. Although considerable overlap in gap thresholds between young and aged subjects was also reported by Snell (1997), her conclusion differed from that of Moore *et al.* in that mean gap thresholds were larger for aged subjects than for young subjects in all conditions studied. Analyses of individual data led Snell to conclude that the mean differences between age groups reflected shifts in the distributions of the aged subjects toward poorer temporal resolution.

A confounding factor in measuring temporal resolution for elderly subjects may be hearing loss, which is commonly associated with age. Numerous studies have reported degraded gap-detection ability associated with sensorineural hearing loss (Boothroyd, 1973; Fitzgibbons and Wightman, 1982; Irwin *et al.*, 1981; Florentine and Buus, 1984; Salvi and Arehole, 1985). In a large-scale study, Lutman (1991) found that gap detection deteriorated with hearing loss but not with age for three groups of subjects aged 50–59, 60–69, and 70–79 years. Recently, however, using a related paradigm, Fitzgibbons and Gordon-Salant (1995, 1996) measured difference limen for gaps from both young and aged subjects with or without hearing loss and reported that elderly listeners performed more poorly than young listeners, and that hearing loss had no systematic effect on gap detection.

C. Effects of location and uncertainty of gap as related to speech perception

Studies of the effects of age on temporal resolution are motivated, in part, by the search for auditory factors that contribute to difficulties in speech understanding experienced by elderly individuals (CHABA, 1988). Many studies (e.g., Humes and Christopherson, 1991; van Rooij and Plomp, 1990; Dubno *et al.*, 1984; Gordon-Salant, 1987) found that reduced audibility of the speech signal can account for a large portion of the differences between young and aged subjects. This conclusion is applicable to speech recognition with no temporal waveform distortion. However, there is a relatively large body of evidence showing age-related differences in the perception of temporally distorted speech. For example, in a series of studies on the relationship between temporal processing and speech perception (Gordon-Salant and Fitzgibbons, 1993; Fitzgibbons and Gordon-Salant, 1995), a robust aging effect was observed in recognition of speech stimuli modified by several temporal factors: speech rate, time compression, and/or reverberation. This aging effect was also found to be independent of and additive to the effect of hearing loss. Although these observations suggest that impaired temporal resolution may contribute to the diminished speech perception of aged subjects, a straightforward relationship between speech perception and temporal resolution has not been established (Tyler *et al.*, 1982; Glasberg and Moore, 1988; Strouse *et al.*, 1998).

Gap stimuli used in psychoacoustic studies are acoustically analogous to voice-onset time (VOT) for consonants in speech. However, unlike a conventional gap-detection paradigm, where the gaps are typically fixed at the center of a stimulus burst, the acoustic gaps in a continuous speech stream occur pseudorandomly at different locations. These differences in paradigm might explain the poor correlation between speech perception and gap detection noted in some studies, especially for aged subjects (e.g., Strouse *et al.*, 1998). In a recent report (Phillips *et al.*, 1997), gap detection was measured between a leading wideband noise burst and a 300-ms narrow-band noise burst as a function of the duration of the leading noise burst. When the leading noise burst was 5 to 10 ms, the threshold was about 30 ms for young, normally hearing subjects. This value is close to the VOT boundary that separates voiced and unvoiced consonants (Strouse *et al.*, 1998).

Few studies have examined the effect of the temporal location of the gap within a noise burst and the effect of randomness of the gap location. Forrest and Green (1987) measured gap thresholds with the gap fixed at 10, 30, 50, 70, or 90 ms after onset of a 100-ms noise burst. They found that the location had essentially no effect on gap threshold except for the location of 30 ms, where the detection threshold was slightly lower. However, an earlier study (Penner, 1977) showed that when the second noise-burst duration was kept constant (2 ms), the detectability of a gap between two noise bursts was decreased by increasing the duration of the first noise burst. In this paradigm, changing the duration of the first noise burst actually changed the relative location of the gap. Thus, the effect of varying the relative location of a temporal gap within a noise burst remains unclear.

In a later paper (Green and Forrest, 1989), the effect of uncertainty of gap location was investigated. When the gap threshold was measured with gaps located randomly from 6% to 94% of a 500-ms noise burst, the gap threshold averaged 1.4 times larger than with the gap fixed at the center of the noise burst. Because there were no comparisons of gap detection at specific locations between fixed and random presentations, it is not clear whether the observed differences were due to the effect of uncertainty, the effect of location, or a combination of both effects.

D. Purpose of this study

To further assess the psychophysical bases for the effects of age on speech perception, gap detection was measured here from young and aged subjects. Factors relevant to speech understanding, namely, the duration of noise bursts, gap location, and uncertainty were examined. Given that large variability exists in the literature regarding these effects on gap detection, a more comprehensive psychophysical paradigm, a constant stimuli procedure measuring the psychometric function, was applied in this study. Obtaining psychometric functions is more time-consuming than measuring thresholds using an adaptive procedure. However, the former can provide estimates not only of the threshold but also of the variability of the subject's performance in terms of the slope of the psychometric function. Green and Forrest (1989) measured psychometric functions for detection of partial and complete gaps, temporally centered in a 500-ms noise burst. They found that the function became progressively steeper as the gap changed from partially filled to complete silence. The present study was designed to assess the effects of noise-

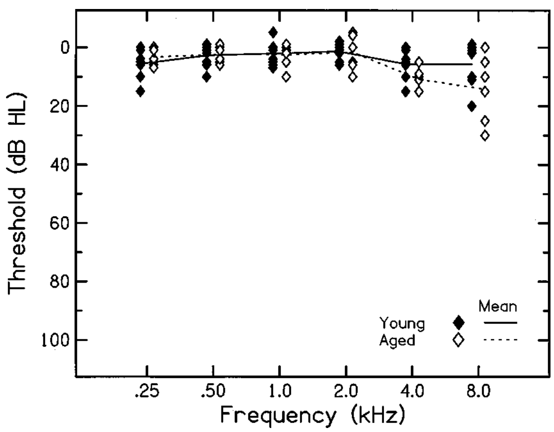

FIG. 1. Pure-tone thresholds (dB HL) for six aged and seven young subjects. Note the closely matched means of the two age groups.

burst duration, gap location, uncertainty in gap location, and subject age on the threshold and steepness of the psychometric function for gap detection.

I. GENERAL METHODS

Three experiments measuring gap detection from both young and aged subjects were conducted. In experiment 1, the effect of noise-burst duration was examined with the gap fixed at the temporal center of the noise burst. In experiment 2, the effect of uncertainty of gap location was examined. Comparisons were made between gap detection measured with the gap fixed at the middle of the noise burst and at random locations ranging from 15% to 85% of the total noise duration. Experiment 3 was designed to test simultaneously the effects of location and uncertainty by measuring gap detection for several gap locations in both fixed and random conditions.

A. Subjects

Six aged subjects (four female and two male) and seven young subjects (four female and three male) participated in this study. In each experiment, six subjects from each age group were tested. The average age was 31.9 years with a standard deviation (s.d.) of 8.1 for the young subjects, and 70.5 years with s.d. of 5.4 for the aged subjects. The subjects were recruited with the goal of matching audiograms between the two age groups, in addition to meeting the requirement of normal hearing (ANSI, 1989). Figure 1 shows individual pure-tone thresholds (dB HL) and group means for young subjects (solid symbols and line) and aged subjects (open symbols and dotted line). All subjects had pure-tone thresholds of 20 dB HL or better for frequencies from 0.25 to 8.0 kHz, except for two aged subjects (A1 and A5), whose pure-tone thresholds at 8.0 kHz were 30 and 25 dB HL, respectively. Differences in mean thresholds between the two groups were 5 dB or less, except at 8.0 kHz where the difference was 8.5 dB. Thus, the possible confounding effect of hearing loss was minimized in our data. Although some subjects had previous experience in other psychophysical experiments, such as intensity discrimination and frequency discrimination, none had previous experience with gap detection.

B. Stimuli

Low-pass filtered noise bursts with a cosine-squared rise/fall time of 5 ms were digitally generated by custom software. The cutoff frequency was 5 kHz with a roll-off slope of 80 dB/octave. The sampling frequency was 20 kHz, which also determined a 0.05-ms temporal accuracy for the stimuli. The noise bursts were either 100 or 400 ms in duration. In this study, duration is specified by the time between the zero-volt points at the onset and offset of the noise burst. Similarly, the 5-ms rise/fall refers to the time between the 0% and 100% points on the stimulus waveform. For each experimental condition, ten noise-burst samples were sequentially downloaded onto both channel 1 and 2 of a 16 $\times$16-bit waveform synthesizer (Pragmatic, 2201A). One of these noise bursts was randomly chosen during each stimulus presentation to prevent the subjects from becoming familiar with the characteristics of a single noise burst. The beginning portion of the chosen noise burst from channel 1 and the ending portion from channel 2 were assigned to a third channel, a carrier channel whose amplitude was zero across time. By specifying the length of each noise portion and its temporal location in the carrier channel, the output of the third channel was a noise burst with a silent gap of specific length and temporal location. The internal rise/fall time of the gap was 0 ms, and the noise was constrained to end and start at zero amplitude to minimize spectral energy spread. The spectra of the noise with and without a gap were essentially identical. The stimuli were then passed through an antialiasing filter (Krohn-Hite 3202R, low-passed at 5 kHz), attenuated (Hewlett-Packard, 350D), power-amplified (Yamaha, P2050), and delivered into the subject's ear canal through an insert earphone (Etymotic Research, ER-2). The overall level was 70 dB SPL. Stimulus timing and presentation, as well as collection of subjects' responses, were controlled by custom software implemented on a PC.

For all experiments, the total duration of the noise burst was kept constant during successive trials, a paradigm used by Forrest and Green (1987). All gap locations are referenced to the center of the gap. The minimum gap was zero (i.e., no gap). The maximum gap, hence the range, was predetermined to be 10 ms based on results from the literature (Green, 1985; Zhang *et al.*, 1990) as well as pilot data from both young and aged subjects. The range was further adjusted for each subject during practice (see below). Although in the more difficult random condition, shallower psychometric functions were sometimes observed, for fixed gap locations (i.e., 5%, 50%, or 95% of the 400-ms noise burst and 50% of the 100-ms noise burst), the 10-ms maximum gap provided a sufficient range for a psychometric function to cover the responses from 0% to 100%. However, two aged subjects required longer gaps in some conditions. For subject A4, the maximum gap had to be 15 ms when the noise burst was 100 ms. For subject A6, a 15-ms gap range was used when the gap occurred at the beginning or ending locations of the noise burst. Note that a gap of 15 ms was an upper limit in this study to prevent the gap from falling close to the rise/fall portion of the noise burst when the gap occurred at the edge locations.

C. Procedure

A constant-stimulus method with a yes/no task was used and psychometric functions for gap duration were measured under different conditions. These will be further described in later sections for individual experiments. For each subject, the maximum gap was evenly divided into ten intervals. Unless otherwise specified, each of the gap durations was presented 50 times in random order (50 repetitions), and each psychometric function resulted from 550 presentation trials (11 gap durations×50 repetitions). To minimize possible fatigue effects introduced by a large number of consecutive trials, the 550 trials were divided into five 110-trial blocks. Each block began with an orientation trial, during which a pair of noise bursts was repeatedly presented every 2 s with no gap in the first noise burst (gap=0 ms) and the maximum gap in the second noise burst. The orientation terminated when the subject pressed a button on a votebox. In each of the trials that followed, only one noise burst was presented. Subjects were instructed to push a button labeled ''yes'' if they heard a gap and a ''no'' button if they did not. Each block lasted about 3 to 4 min and a short pause was given at the end. Therefore, the time to collect a complete psychometric function was about 20 to 30 min.

The majority of the subjects (five young and six aged) participated in all three experiments. For each of these subjects, a total of ten psychometric functions was measured, four with fixed gap locations and six with varying gap locations. The data were collected in several sessions, each lasting 1 to 2 h.

D. Parameters of psychometric function and threshold

The measured psychometric functions were recast by a logistic function (Green, 1993),

$$P(\text{yes}) = \alpha + (1-\alpha)/(1+e^{-k(X-m)}), \qquad (1)$$

where $P(\text{yes})$ is the probability of a yes response given to a specific gap, X and m are gap durations in ms (with m corresponding to the 50% point of the function and X as an independent variable), α is a false-alarm rate, which is the probability of a yes response given to the zero gap, and k is a factor defining the slope of the function. The parameters, α, k, and m were estimated in a curve-fitting procedure using a least-error method. Figure 2 shows an example of the curve fitting. The open squares represent raw data and the solid line represents fitted data. Given in the inset are estimated m, k, and α. Also presented is the rms difference between the raw and fitted data, indicating the goodness of fit. Note that the rms difference (0.02) was of the same order as the measurement resolution determined by the number of repetitions (1/50).

The parameter m could be used as the gap threshold. However, as shown in Eq. (1), m does not reflect the differences in α, the false-alarm rate. The false-alarm rate is related to the subject's decision criterion, which has been demonstrated to influence the threshold estimation (Gu and Green, 1994). Therefore, a threshold at $d'=1$ (Table I in the Appendix, Swets, 1964) was calculated based on each measured psychometric function. The resultant d' threshold is criterion-free because it is a function of false-alarm rate.

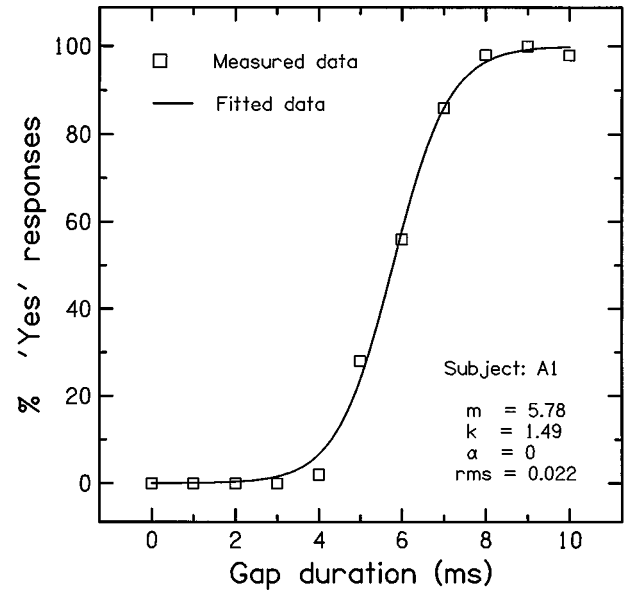

FIG. 2. An example of curve fitting of a logistic function to the measured psychometric function (Subject A1). Noise-burst duration was 100 ms. The estimated parameters: m (middlepoint)=5.78 ms, k (slope)=1.49; α (false-alarm rate)=0. The rms difference between fitted and measured data is 0.022.

E. Practice

For each experiment, practice was given to subjects prior to data collection. Three fixed gap locations for the 400-ms noise burst (5%, 50%, and 95%) and one fixed location for the 100-ms noise burst (50%) were practiced. During practice, psychometric functions were repeatedly measured in the same way described above, but with only ten repetitions per gap duration. There was no intention to improve subjects' thresholds through lengthy practice, but simply to assure that subjects were familiar with the stimuli and with the psychophysical procedure. The practice ended when ogive-shaped psychometric functions with reasonably steep slopes were obtained. All subjects met this criterion after about 30 min of practice for each condition. Extra practice time was provided to two aged subjects (A4) and (A6) when they experienced more difficulty than the others in detection of gaps occurring in the 100-ms noise burst or at edges of the 400-ms noise burst. The ranges of gap durations were adjusted for individual subjects during practice.

II. EXPERIMENT 1: EFFECT OF NOISE DURATION

A. Methods

For this experiment, the gap was always positioned at the temporal center of the noise burst. For each of six young and six aged subjects, psychometric functions for gap detection were measured for 100- and 400-ms noise bursts.

B. Results and discussion

Figure 3 shows psychometric functions measured from six young subjects (top two rows) and six aged subjects (bot-

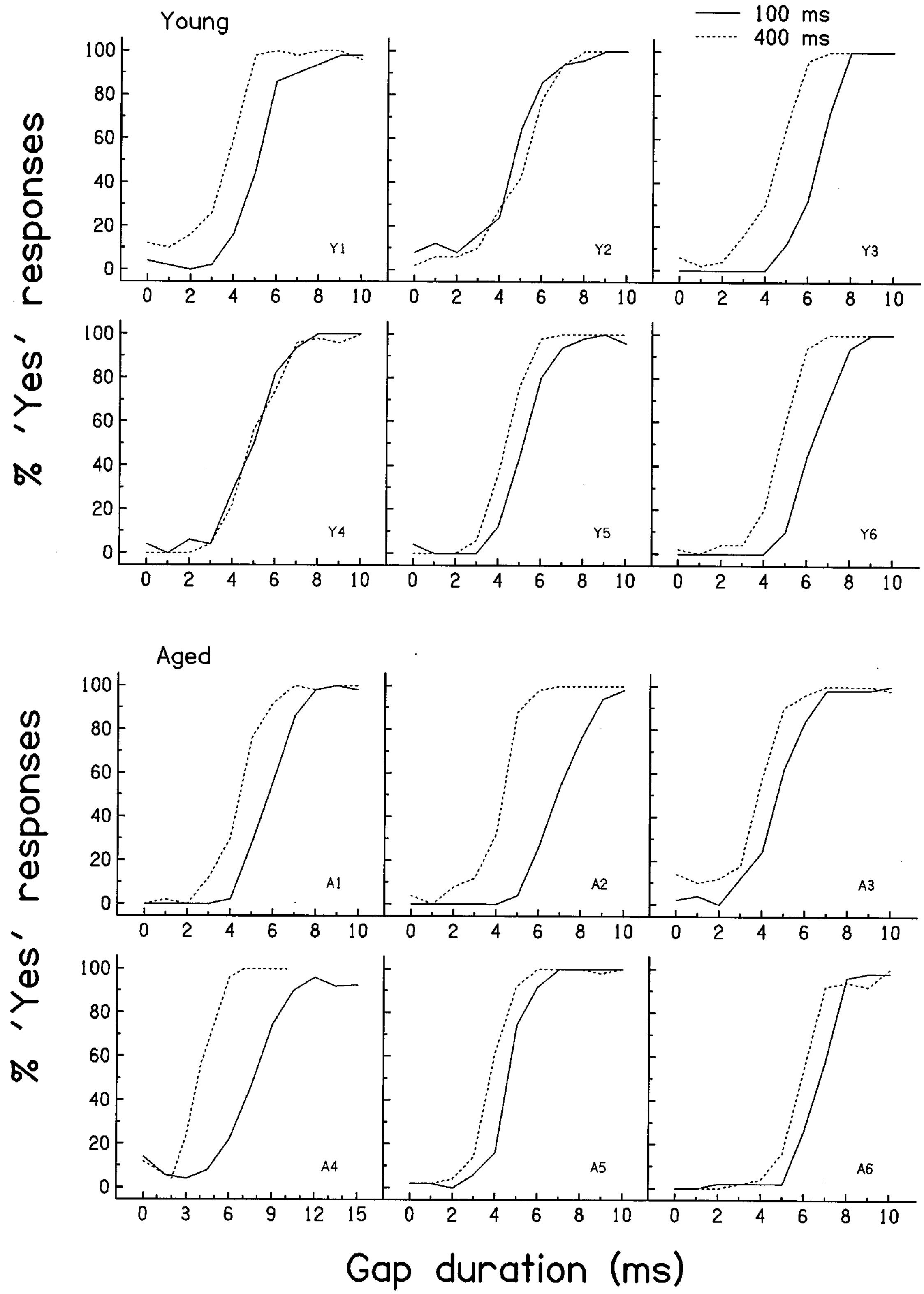

FIG. 3. Psychometric functions measured with 100-ms (solid lines) and 400-ms (dashed lines) noise bursts. Data of six young subjects are presented in the upper two rows and those of six aged subjects in the bottom two rows.

tom two rows). In each panel, the solid line represents data for 100-ms noise bursts, and the dashed line, 400-ms. All psychometric functions were sigmoidal in shape with steep slopes and reached >95% yes responses at the 10-ms gap value except for one (subject A4, 100 ms). For subject A4, the maximum gap was 15 ms for the 100-ms noise burst, with the 10-ms gap resulting in only about 80% yes responses.

Gap detection generally improved with the longer noise burst, especially for the aged subjects. For the aged subjects (bottom rows), the psychometric functions for the longer stimulus shifted to smaller gap durations compared to the shorter stimulus. For the young subjects (top rows), the duration effect on gap threshold was not as clear as that for the aged subjects due to greater intersubject variability. While four of the young subjects showed sizable differences between 100-ms and 400-ms noise-burst durations, two (Y2 and Y4) did not.

The steepness of the functions does not appear to be influenced by the duration of the noise burst for either age group. For most subjects, the psychometric functions for 100- and 400-ms noise bursts were parallel, except for two aged subjects (A2 and A4), who showed shallower slopes for the shorter stimulus. The group mean k for the young subjects was 1.61 (s.d.$=$0.17) for the 100-ms burst and 1.71 (s.d.$=$0.40) for the 400-ms burst. For the aged subjects, the k averaged 1.58 (s.d.$=$0.59) and 2.05 (s.d.$=$0.44) for the 100- and 400-ms noise bursts, respectively. Thus, the mean slope for the 400-ms noise burst was slightly steeper than for the 100-ms noise burst for both age groups, but this trend was not consistent among individual subjects. A repeated-measures analysis of variance (ANOVA) on slope, k, with age as a grouping factor and the noise-burst duration (100 vs 400 ms) as the repeated measure, did not show significant effects of age $[F(1,10)=0.6618,\ p=0.4349]$ or noise duration $[F(1,10)=3.4105,\ p=0.0945]$. Given that the slope was generally uniform, differences in gap detection can therefore be adequately described by a single parameter, namely the horizontal placement of the psychometric function, or gap threshold.

The average gap threshold $(d'=1)$ for the young subjects was 4.14 (s.d.$=$0.60) ms for the 100-ms noise burst, and 3.46 (s.d.$=$0.29) ms for the 400-ms noise. For the aged subjects, the threshold averaged 4.78 ms (s.d.$=$1.20) for the 100-ms condition and 3.57 (s.d.$=$0.62) ms for the 400-ms condition. Although these gap thresholds (for both 100- and 400-ms noise bursts) were slightly larger than the 2 to 3 ms suggested by Green (1985), these differences could be attributed to procedural differences (yes/no vs forced choice). The duration-related differences observed in the present study averaged 0.68 ms for the young subjects and 1.21 ms for the aged subjects. Given the steepness of the psychometric function for gap detection, such differences can introduce large changes in subjects' performance. This was confirmed by a repeated-measures ANOVA on thresholds showing that the gap threshold for the 100-ms burst was significantly higher than the threshold for the 400-ms noise burst $[F(1,10)=12.2891,\ p=0.0057]$. However, gap thresholds for young and aged subjects were not significantly different $[F(1,10)=1.2426,\ p=0.2911]$, a finding consistent with Moore *et al.* (1992), who argued against a robust age effect. Finally, threshold differences due to noise-burst duration were consistent for both age groups, as indicated by the nonsignificant age by duration interaction $[F(1,10)=0.9664,\ p=0.3488]$.

This duration effect is contrary to the findings of some previous studies which showed either no change in gap detection (Penner, 1975) or small changes in the opposite direction from our results (Forrest and Green, 1987). Note that both of these previous studies used smaller sample sizes (two or three subjects). Furthermore, the trend was not consistent among subjects in Forrest and Green's study. Intersubject variability was also observed in our young subjects' data (Fig. 3), where two out of six subjects showed no shift of the psychometric function with increasing noise duration. Our findings regarding the duration effect were more similar to those of the young subjects in a large-sample study by Muchnik *et al.* (1985).

Improved detection with increasing stimulus duration has been observed in other temporal measurements, namely detection of amplitude modulation (AM) and beats (Viemeister, 1979; Sheft and Yost, 1990), as well as discrimination of AM rate and depth (Lee, 1994; Lee and Bacon, 1997). This suggests that a temporal integration process may be a fundamental property of auditory perception, including temporal resolution. This issue will be discussed further with the more comprehensive data of experiment 3.

III. EXPERIMENT 2: EFFECT OF VARYING GAP LOCATION

A. Methods

The paradigm used in this experiment was similar to that of Green and Forrest (1989) except that in this study the noise burst was 100 ms. For each trial, the gap occurred at a location randomly chosen from 15% to 85% of the total duration from the onset. The results were compared to those measured when the gap was fixed at the temporal center of the 100-ms noise burst (for most subjects, these data were from experiment 1).

B. Results and discussion

Figure 4 compares gap detection measured with fixed (solid lines) and random (dashed lines) gap locations. Six young subjects' data are plotted in individual panels in the top two rows, and six aged subjects' data in the bottom two rows. As shown in Fig. 4, the general placement of the psychometric function does not appear to be affected by the randomness of the gap location; for all subjects, the functions measured in fixed and random conditions generally overlap. The condition-related difference was smaller than the between-subject variability, indicating high reliability of individual subjects' performance. Below the 50% point (i.e., at the shorter-gap durations), differences between the two functions were minimal, which resulted in small differences in thresholds $(d'=1)$. The most obvious difference was the reduced detectability at longer gap durations in some subjects, which resulted in shallower slopes of the functions for the random as compared to the fixed condition.

For both groups, the estimated $d'=1$ thresholds were similar for fixed and random conditions. For the young subjects, thresholds averaged 4.29 (s.d.$=$0.53) ms for the fixed condition and 3.92 (s.d.$=$0.54) ms for the random condition. For the aged subjects, the average thresholds were 4.88 (s.d. $=$1.27) and 5.00 (s.d.$=$2.08) for the fixed and random conditions, respectively. A repeated-measures ANOVA on $d'=1$ threshold with age as a grouping factor and a repeated measure on uncertainty (fixed vs random) did not find a significant effect of age $[F(1,10)=1.5025,\ p=0.2484]$ or un-

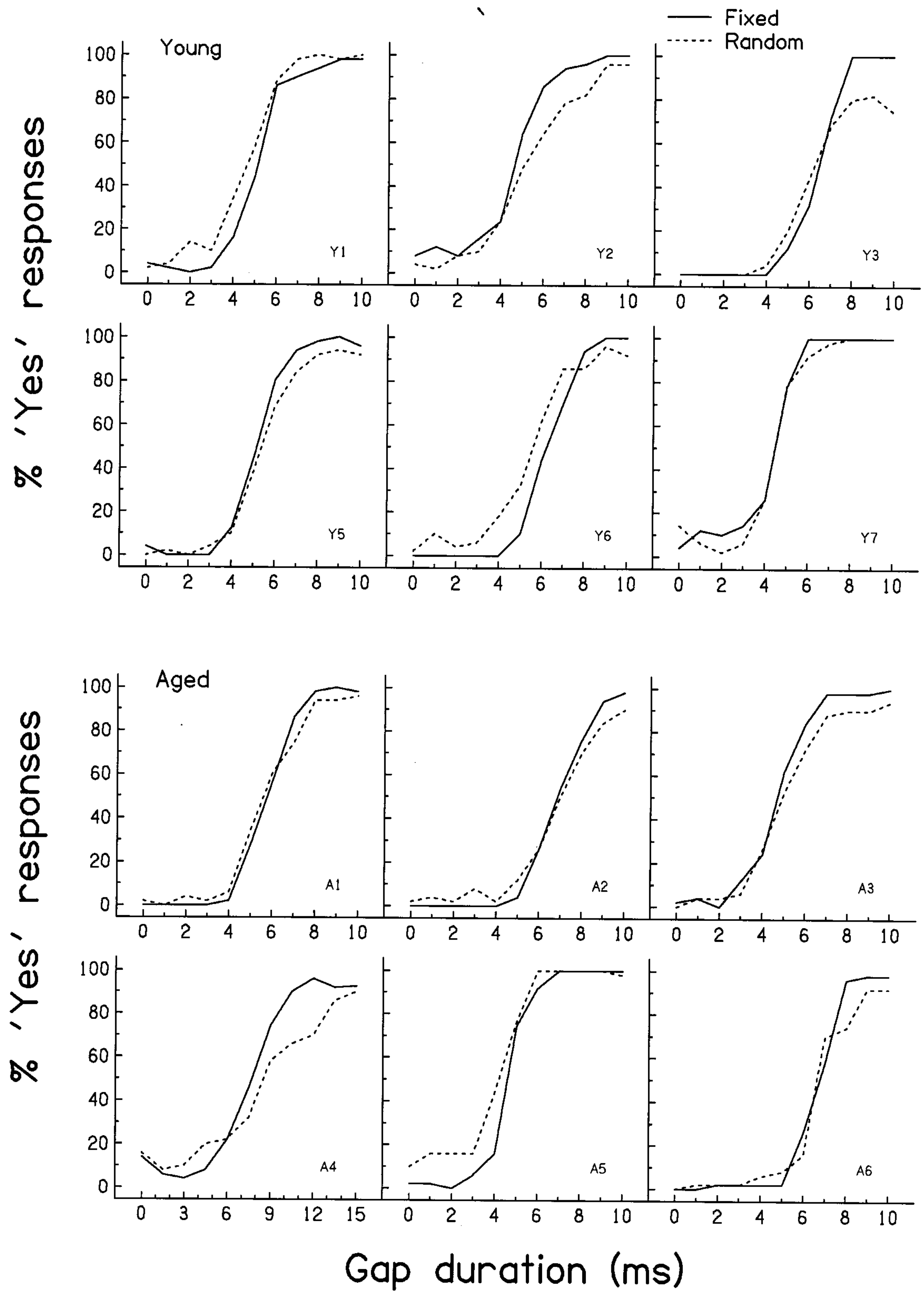

FIG. 4. Psychometric functions measured with gap position fixed at the temporal center of the noise burst (solid lines) or randomly varied over a range from 15% and 85% of the total duration from the onset (dashed lines). The total duration of the noise burst was 100 ms. Data of six young subjects are presented in the upper two rows, and those of six aged subjects in the bottom two rows.

certainty [$F(1,10)=0.7385$, $p=0.4103$], nor was their interaction significant [$F(1,10)=1.4475$, $p=0.2566$].

In contrast to the $d'=1$ thresholds, differences in the average slope (k) were sizable between the fixed and random condition for the young group [1.84 (s.d.=0.39) vs 1.42 (s.d. =0.55)] and the aged group [1.26 (s.d.=0.3) vs 0.85 (s.d. =0.3)]. This was confirmed by the ANOVA, which showed a significant main effect of uncertainty [$F(1,10)=56.2206$,

$p < 0.001$]. However, there was no significant effect of age [$F(1,10) = 0.9757$, $p = 0.3466$], nor was the interaction of age and uncertainty significant [$F(1,10) = 0.3062$, $p = 0.5922$], indicating a consistent trend for both age groups.

Using a forced-choice adaptive procedure, Green and Forrest (1989) observed that gap thresholds with random gap locations were 1.3 to 1.5 times higher than those with a fixed gap location. A significant difference in thresholds was not observed in the present study, but the average slope for the fixed condition was 1.30 times larger than that for the random condition for the young subjects, and 1.48 times larger for the aged subjects. Because the variability of a subject's response is inversely related to the slope of the psychometric function (Green, 1993), the shallower slope of the psychometric function observed in this experiment may be an indication of increased variance of performance in the random condition.

Green and Forrest (1989) attributed the observed differences between random and fixed conditions in their study to the uncertainty of gap location. However, the result could also be affected by differences in gap location or a combination of both factors. The experimental design used in the Green and Forrest study and in the current experiment 2 was not sufficient to differentiate these two factors. A separate assessment of these factors requires the comparison of gap detection obtained at identical gap locations presented in both fixed and random conditions, as will be described in the next experiment.

IV. EXPERIMENT 3: EFFECT OF LOCATION VS UNCERTAINTY

A. Methods

The duration of the noise burst used in this experiment was 400 ms. Results of experiment 1, showing that gap detection was basically the same for young and aged subjects when the gap was fixed at the center of a 400-ms noise burst, provided a common baseline for both young and aged subjects to further assess effects of location and uncertainty of the gap. In this experiment, gap detection was measured under two conditions.

In condition 1, gap detection was measured in three runs of 50 repetitions for each gap duration. In each run, the gap was fixed at either 5%, 50%, or 95% of the total noise duration (one at the temporal center and the other two at the beginning and ending locations, i.e., 20 ms from the onset and offset of the noise burst, respectively).

In condition 2, gap detection was measured with gap location randomly chosen from five values: 5%, 27.5%, 50%, 72.5%, and 95% of the total duration. Each of these five locations was presented 50 times at each gap duration. Each combination of gap location and gap duration was presented to the subject in random order. For each subject, data were collected from a total of 2750 trials (5 locations$\times$11 gap durations$\times$50 repetitions), which were broken into 25 blocks, each with 110 trials. The data were then sorted according to the gap location and duration, resulting in five psychometric functions, each with 50 repetitions at each gap duration and each associated with a specific gap location (11 gap locations$\times$50 repetitions$=$550 trials).

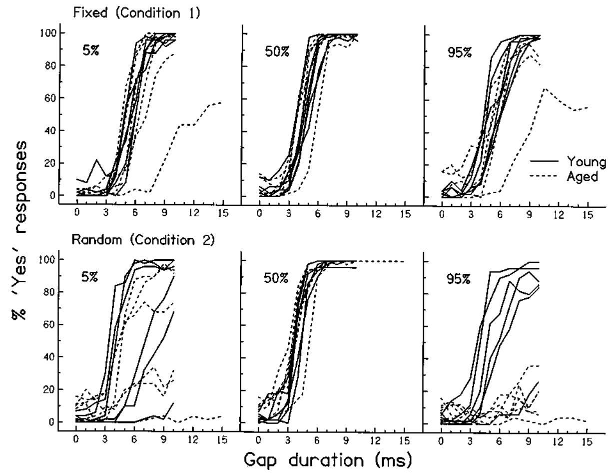

FIG. 5. Psychometric functions measured from both young (solid lines) and aged subjects (dashed lines) in experiment 3. Data in the top row were obtained in condition 1, where the gap was fixed from trial to trial at either 5%, 50%, or 95% of the total duration of the noise burst. Data in the bottom row were measured from condition 2 with the gap randomly occurring from trial to trial at one of five different locations: 5%, 27.5%, 50%, 72.5%, and 95%. For comparison with the fixed data, only data of three locations are presented. The total duration of the noise burst was 400 ms.

B. Results and discussion

1. Comparison of center location with 5% and 95% locations

Figure 5 shows psychometric functions measured with gaps occurring at the 5%, 50%, or 95% locations of the noise burst presented in fixed (top row) and in random conditions (bottom row). The solid lines represent data of the young subjects and the dashed lines, the aged subjects. When the gap was at the center of the noise burst (50%, middle panels), gap detection was independent of the uncertainty of gap location for both young and aged subjects. Furthermore, there was only a small difference in performance between the two age groups in either condition. The mean gap thresholds ($d' = 1$) at the 50% location for the young subjects were 3.46 (s.d.$=$0.29) and 3.27 (s.d.$=$0.23) ms for the fixed and random conditions, respectively. For the aged subjects, the comparable values were 3.57 (s.d.$=$0.60) and 3.23 (s.d. $=$0.89) ms.

When the gap was located away from the center position to the two extreme end locations (5% and 95%), performance declined. In the fixed condition (top row), the functions for the 5% and 95% gap locations shifted toward larger gap durations, compared to the 50% location. The aged subjects also showed increased intersubject variability, mainly due to the extremely poor performance of one aged subject (A6). Also, at the fixed 95% location, there are data from only five elderly subjects because subject A4 was unable to perform this task. This was the same subject who required extended gap length for the 100-ms noise burst in experiments 1 and 2. For the young subjects, gap thresholds averaged 4.21 (s.d.$=$0.54) ms for the 5% location and 3.57 (s.d. $=$0.56) ms for the 95% location. For the aged subjects, the mean thresholds were 5.07 (s.d.=1.63) ms and 4.80 (s.d. =0.78) ms for the 5% and 95% locations, respectively.

This location-related effect intensified when gap location was random (condition 2, bottom row). Significant intersubject variability was observed for both young and aged subjects at the 5% location, where half of the subjects from each group showed a large reduction in the percentage of yes responses. The gap-detection threshold averaged 5.03 (s.d. =2.68) ms for the young subjects and 7.40 (s.d.=4.81) ms for the aged subjects. Note that data of subject A6 were not included in the averages, because this subject's yes responses were <5% across gap durations. At the 95% location, all aged subjects performed below 50% for all gap durations tested. However, four of them (A1, A2, A3, and A5) still showed increased detectability with increasing gap duration which allowed parameters m, k, and α to be estimated. Based on these estimates, the psychometric function was reconstructed and extended so that the $d'=1$ threshold could be calculated. Certainly, the estimation of the slope was less accurate and the calculation of the threshold was somewhat artificial. Nevertheless, the resultant parameters reflected the general tendency as well as individual differences. The mean threshold at the 95% location for these four aged subjects was 12.35 (s.d.=4.22) ms. For the young subjects, the gap threshold averaged 4.41 (s.d.=1.99) ms.

A repeated-measures ANOVA on the $d'=1$ threshold with age as a grouping factor and repeated measures on gap location (5%, 50%, or 95%) and uncertainty (fixed vs random) revealed that all main effects and interactions were significant. In view of the significant second-order interaction of uncertainty by location by age [$F(2,16)=5.6625$, $p=0.0138$], the simple uncertainty by location interaction was analyzed for each age group. *Post hoc* tests of multiple comparisons were performed using A and C matrices from the multivariate general linear model (Morrison, 1976). The results showed that the interaction was significant for the aged subjects [$F(1,8)=22.9402$, $p=0.0014$] but not for the young subjects [$F(1,8)=1.1860$, $p=0.3079$]. That is, for aged subjects only, the location-related differences in gap thresholds were larger for the random condition than for the fixed condition.

For the significant first-order interaction of age by uncertainty [$F(1,8)=7.1886$, $p=0.0279$], the simple uncertainty effect was analyzed for each age group. Again, a significant uncertainty effect was observed for aged subjects [$F(1,8)=16.8890$, $p=0.0034$], but not for young subjects [$F(1,8)=0.63$, $p=0.4501$]. That is, for aged subjects only, thresholds in the random condition were higher than in the fixed condition. This also accounts for the significant main effect of uncertainty [$F(1,8)=13.5825$, $p=0.0062$].

For the significant first-order interaction of age by location [$F(2,16)=7.1679$, $p=0.0060$], as well as for the significant location main effect [$F(2,16)=10.2076$, $p=0.0014$], simple location effects were further examined for each age group and across three levels of gap locations. Significant differences in gap thresholds between the center location (50%) and the two end locations (5% and 95%) were observed for aged subjects [$F(1,8)=38.3903$, $p=0.0003$], but not for young subjects [$F(1,8)=3.6937$, $p=0.0908$]. Comparing gap detection for the 5% and 95% locations, again, the significant location effect was observed for aged subjects [$F(1,8)=6.3424$, $p=0.0359$], but not for young subjects [$F(1,8)=0.3767$, $p=0.5564$]. Thus, for aged subjects only, gap-detection thresholds were significantly lower at the middle location than at the end locations, and were significantly lower at the 5% location than at the 95% location. In summary, the significant main effect of age [$F(1,8)=8.3436$, $p=0.0202$] was due to the significantly higher gap thresholds of the aged subjects when the gap was at the end locations and was presented randomly.

The steepness of the psychometric functions changed considerably with gap location, as shown in Fig. 5. First, when the gap was at the 50% location (middle panels), there was little difference in the slopes of the functions between random and fixed conditions for both age groups. The slope (k) averaged 1.71 (s.d.=0.40) for the young subjects and 2.05 (s.d.=0.44) for the aged subjects in the fixed condition, and 2.45 (s.d.=0.69) and 2.04 (s.d.=0.58) for the young and aged groups, respectively, in the random condition. When the gap was positioned at the end locations (5% and 95%), the functions became shallower, especially for the random condition. For the fixed condition (top row, first and third panels), the average slopes for the young group were 1.70 (s.d.=0.67) for the 5% location and 1.47 (s.d.=0.52) for the 95% location, whereas for the aged subjects, the slopes averaged 1.41 (s.d.=0.68) and 1.09 (s.d.=0.54) for 5% and 95% locations, respectively. When the gap was presented randomly (condition 2, bottom row, first and third panels), the mean slopes for the 5% location were 1.62 (s.d.=0.73) and 0.82 (s.d.=0.77) for the young and aged subjects, respectively. The average slope for the 95% location in the random condition was 1.11 (s.d.=0.56) for the young subjects and 0.44 (s.d.=0.13) for the aged subjects.

The repeated-measures ANOVA on the slope (k) did not show a significant age effect [$F(1,8)=1.6138$, $p=0.2397$], nor were interactions of age by location [$F(2,16)=0.8554$, $p=0.4437$] or age by uncertainty [$F(1,8)=4.4856$, $p=0.0670$] significant. This suggested that although the thresholds were significantly different between the young and aged subjects in these conditions, the slope was generally consistent for the two age groups. Significant F ratios were obtained only on the main effect of location [$F(2,16)=15.8258$, $p=0.0002$] and the interaction of uncertainty by location [$F(2,16)=5.0274$, $p=0.0202$]. *Post hoc* tests confirmed that the slope at the 50% location was steeper than those at the 5% and 95% locations for both age groups [$F(1,8)=20.3973$, $p=0.0020$], and that the center/end location difference was larger in the random condition than in the fixed condition [$F(1,8)=33.1792$, $p=0.0004$].

2. Comparing the 50% location with the 27.5% and 72.5% locations

Two more gap locations, 27.5% and 72.5% of the total noise duration, were tested in the random condition. The relatively robust responses for the 50% location, despite uncertainty (Fig. 5), extended to these two locations. Figure 6 plots psychometric functions for these two locations, 27.5% and 72.5% (left and right panels, respectively), and the 50%

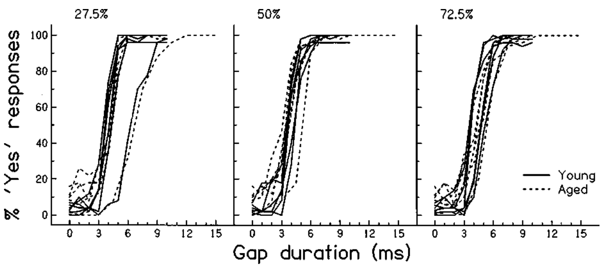

FIG. 6. Psychometric functions measured from both young (solid lines) and aged subjects (dashed lines) in the random condition of experiment 3 with the gap located at 27.5% (left panel), 50% (middle panel), and 72.5% (right panel) of the noise-burst duration (400 ms).

location (middle panel). The solid lines represent data for the young subjects and the dashed lines, the aged subjects. As shown in Fig. 6, the steepness and the overall placement were little affected by location, even though the gap was presented randomly. The intersubject variability was similar for both age groups and was generally constant across locations, except for the 27.5% location, where one subject from each group showed some departure from the rest of the group.

Gap thresholds for the young subjects averaged 3.53 (s.d.=0.83) ms for the 27.5% location and 3.58 (s.d.=0.43) ms for the 72.5% location. For the aged subjects, the mean thresholds were 3.88 (s.d.=0.49) ms and 3.85 (s.d.=0.46) ms. The values were symmetrical surrounding the thresholds at the 50% location, which were 3.27 ms for the young group and 3.23 ms for the aged group in the random condition. A repeated-measures ANOVA on the $d'=1$ thresholds obtained from condition 2 with age as the grouping factor and repeated measures on five levels of the gap location (5%, 27.5%, 50%, 72.5%, and 95%) showed significant effects of age $[F(1,8)=6.2221,\ p=0.0373]$ and location $[F(4,32)=11.2857,\ p<0.0001]$, as well as their interaction $[F(4,32)=7.1108,\ p=0.0003]$. This was expected because the analysis included the two end locations (5% and 95%), which were shown in the last section to significantly affect gap thresholds for the aged subjects. However, the main interest here was to compare the three central gap locations (27.5%, 50%, and 72.5%). The *post hoc* analysis revealed that the location-related difference (50% location vs 27.5% and 72.5% locations) was significant for the aged subjects $[F(1,8)=10.4325,\ p=0.0121]$, but not for the young subjects $[F(1,8)=1.5241,\ p=0.2520]$. Nevertheless, even for the aged subjects, these differences ($\leqslant$0.65 ms) were about an order of magnitude smaller than the differences between the center location and the 5% and 95% locations (5 to 10 ms), as shown in Fig. 5.

The slopes (k) of the psychometric functions were generally constant across these locations for both young and aged subjects. The average slopes for the young group were 2.16 (s.d.=0.50) and 2.19 (s.d.=0.73) for the 27.5% and 72.5%, respectively, which is close to that for the 50% location (2.45). For the aged subjects, the slope averaged 2.48 (s.d.=1.10) for the 27.5% and 1.48 (s.d.=0.15) for the 72.5% locations, as compared to 2.04 for the 50% location. A repeated-measures ANOVA on the slope with age as the grouping factor and repeated measures on five levels of the location (5%, 27.5%, 50%, 72.5%, and 95%) found no significant effect of age $[F(1,8)=2.9897,\ p=0.1221]$ but a significant effect of location $[F(4,32)=12.4157,\ p<0.0001]$. However, comparing only the 50% location with the 27.5% and 72.5% locations, the *post hoc* analysis revealed that the difference in slope was not significant for either young $[F(1,8)=1.1048,\ p=0.3239]$ or aged subjects $[F(1,8)=0.0938,\ p=0.7672]$.

3. Effect of signal onset and offset

In this experiment, effects of gap location and uncertainty were simultaneously examined. As shown in Fig. 5, the influence of gap location was more prominent than the influence of uncertainty. Both gap thresholds and the steepness of the psychometric functions were found to be affected by the gap location, especially for the aged subjects. For both age groups, the mean $d'=1$ threshold was lowest at the temporal center of the noise burst and increased as the gap moved away from the center, with the highest thresholds at the 5% and 95% locations. This trend suggested an influence of stimulus onset and offset, especially for the aged subjects. As shown in Fig. 6, when the gap was located sufficiently away from both ends of the noise burst (e.g., at 27.5% and 72.5%), perception was robust, regardless of the uncertainty about the gap location.

Now, a remaining question is whether this robust detection for the central gap locations is a function of the absolute duration of the noise burst or the proportion of the noise-burst duration. To answer this question, two aged subjects (A1 and A4) were further tested under condition 2 (random gap location) of experiment 3, with 100-ms noise duration and ten repetitions at each gap duration for each gap location. The resultant psychometric functions are presented in the left column of Fig. 7. The 400-ms data are included in the right column for comparison. Although the 100-ms functions obtained with ten repetitions (left) were not as smooth as the 400-ms data obtained with 50 repetitions (right), similarities between these two sets of data are obvious. In most cases, psychometric functions measured with the gap at central locations (32%, 50%, and 68% for the 100-ms noise burst, and 27.5%, 50%, and 72.5% for the 400-ms noise burst) can be differentiated from those obtained with the gap at end locations (14% and 86% for the 100-ms, 5% and 95% for the 400-ms noise burst). The full range of the psychometric function was consistently obtained for the three central gap locations for both the 100- and 400-ms noise bursts, despite large differences (in ms) in the absolute temporal locations of these gaps. On the other hand, for both 100- and 400-ms noise bursts, the gaps located near the onset and offset resulted in poor detection. These data confirmed that the effects of onset and offset are basically independent of noise-burst duration.

V. GENERAL DISCUSSION AND CONCLUSIONS

In this study, psychometric functions for gap detection were measured from six young and six aged subjects under several conditions. With pure-tone thresholds closely matched between subject groups, an aging effect could be

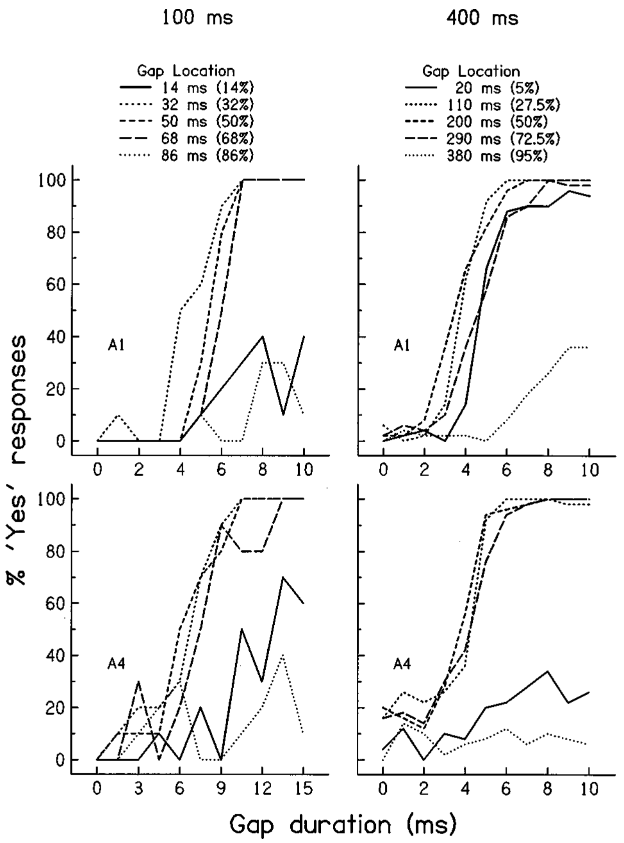

FIG. 7. Comparison of psychometric functions measured in the random condition of experiment 3 with 100-ms (left column) and 400-ms noise bursts (right column). Two aged subjects' data are presented. The parameter in each panel is gap location.

directly assessed. It should be pointed out that employing a small sample size may increase the possibility of missing some small- or medium-size effects. However, our data shared some features in common with other studies. Consistent with the reports by Moore *et al.* (1992) and Snell (1997), this study also observed a large overlap of data between the young and aged subjects.

The thresholds and the slopes of the psychometric function for gap detection were analyzed separately and were found to be differentially affected by age and by experimental conditions.

A. Slope of psychometric function for gap detection

In this study, a typical psychometric function for the detection of a temporal gap in a broadband noise burst was characterized by a steep slope with a k value between 1.5 and 2 (Fig. 2, as an example). Given this steepness, a change in detectability from 20% to 80% corresponded to a difference in gap duration of about 2 ms. This is consistent with the observation of Green and Forrest (1989), who found that the psychometric function for detecting a silent gap measured in a forced-choice paradigm covered a range of only 2 ms of gap duration over 50% to 100% correct responses. A steep function indicates high precision and low variability for detection of a gap within a noise burst. As can be calculated from Eq. (1), with k values greater than 1, differences in gap duration as small as 0.5 ms may change the percentage of yes responses by 15% to 25% and may be significant.

Reductions in the steepness of the functions were observed in this study under more difficult conditions, i.e., when the gap was located at the beginning and end of the noise bursts, especially in the random condition (Fig. 5). However, the shallower psychometric functions observed in these conditions may have been due to the limited maximum gap duration. If an extended range of gap durations were possible, detectability may have increased with a steeper slope. Therefore, when the gap was sufficiently removed from the onset and offset of a broadband noise burst, the slope of the psychometric function for gap detection was independent of age, noise-burst duration, and the position and uncertainty of gap location.

A uniform slope is desirable for the efficiency and accuracy of many adaptive procedures which estimate specific points on the psychometric function. For gap detection in a broadband noise, as in this study, a uniform slope was obtained by using a linear duration scale. However, in the case of gap detection in a tone burst or in a narrow-band noise carrier, where larger ranges of gap thresholds (in ms) were included, a logarithmic scale of gap duration should be used to obtain a uniform slope (Florentine, Buus, and Geng, 1998). Note that with different scales, the value of the slope (k) will change accordingly.

B. Factors that influence gap-detection thresholds

With a generally uniform slope of the psychometric function for gap detection across experimental conditions, effects of noise-burst duration, gap location, and uncertainty about gap location can be accessed by a single parameter, namely, the horizontal placement of the psychometric function, which determines the gap threshold. As demonstrated by the results of experiment 1 (Fig. 3), when the gap was located at the center of the noise burst, the noise-burst duration had a significant effect on the gap threshold, but the effect was not age related. For both young and aged subjects, gap threshold decreased with increasing stimulus duration.

According to previous studies (Forrest and Green, 1987; Green and Forrest, 1989), gap-detection threshold was not affected by the location of the gap within the noise burst, but by the randomness of gap location. Results of experiment 3 (Figs. 5 and 6), with control of both factors, showed that the effects differed with age. For the young subjects, neither location nor uncertainty had a statistically significant effect on gap-detection thresholds. These observations were consistent with previous studies on the location effect, but contradicted previous research on the uncertainty effect. The disparity was likely due to differences in experimental design. For the aged subjects, the detection threshold was affected by both the gap location and uncertainty, and furthermore, the effects were not independent. The uncertainty effect was location related. As shown in Fig. 5, significant differences between fixed and random conditions were observed when the gap was located near the onset and offset of the noise burst, but not when the gap was at the center of the stimulus. The effect of gap location was more prominent. There was a general tendency for the gap threshold to increase as the gap moved from the center to the two ends of the noise burst (Figs. 5

and 6). This age-related location effect was also independent of noise-burst duration (Fig. 7).

Earlier in this paper, temporal integration was suggested as a mechanism explaining the improvement in gap detection with increasing noise-burst duration, consistent with previous studies of other temporal resolution measures (Viemeister, 1979; Sheft and Yost, 1990; Lee, 1994; Lee and Bacon, 1997). Temporal cues do not exist in isolation, but rather are conveyed by intensity changes over time. As discussed by Plack and Moore (1990, 1991), the task of gap detection may require both temporal resolution and intensity resolution, as evidenced by the finding of a significant correlation between gap detection and intensity discrimination in hearing-impaired subjects (Glasberg and Moore, 1989). Given that intensity resolution is a function of stimulus duration (Florentine, 1986), the involvement of temporal integration in gap detection is a reasonable assumption.

Increased gap-detection thresholds for gaps near the onset and offset of the noise burst may also be related to the ''overshoot'' phenomenon (Bacon and Viemeister, 1985). Under certain conditions, the threshold of a brief tonal signal presented soon after the onset of a masker can be 10 to 20 dB higher than a tone presented several hundred ms later within the masker. The time course of the overshoot effect has been measured by Bacon and Viemeister (1985), who showed that the tone threshold was high at the masker onset, followed by a rapid decrease as the tone moved toward the center of the masker, reaching a minimum at the center. The threshold then increased again as the tone moved further toward the end of the masker. Furthermore, these onset and offset effects were consistent for both 300- and 800-ms maskers (their Fig. 1). Their data bear a similarity to the gap-detection data obtained in this study regarding onset and offset effects, as well as stimulus duration effects. In their study, the minimum masked threshold obtained with the tone at the temporal center of the masker was slightly higher for the 300-ms masker than for the 800-ms masker, similar to our observation of the effect of noise-burst duration on gap detection, as shown in Fig. 3 of this study. This suggests that detection of a gap in a noise burst and detection of a signal in a masker may share a common underlying mechanism.

Adaptation of eighth-nerve fibers has been suggested as a possible explanation for the overshoot effect. The improved detection threshold for the signal is thought to result from improved signal-to-noise ratios during the course of adaptation (Smith and Zwislocki, 1975; Smith, 1979). In the case of gap detection, when a gap moves away from stimulus onset, improved signal-to-noise ratios help listeners identify the gap, or, more generally, the intensity decrement. Adaptation may also explain the effect of noise-burst duration, because a gap at the center of a short noise burst is closer to the noise onset than is its counterpart in a longer noise burst.

Nevertheless, adaptation cannot account for the offset effect. According to the adaptation mechanism, progressively improved gap detection would be expected as the gap location moved away from the onset, with the poorest detection at the 5% location and the best at the 95% location for the 400-ms noise burst. Obviously, the stimulus offset produced an additional effect on gap detection. Because the ''off'' response is rarely observable in auditory-nerve fibers (Kiang *et al.*, 1965), the site for the offset effect may be located more centrally where many age-related alterations have been reported (e.g., Caspary *et al.*, 1995; Boettcher *et al.*, 1996; Walton *et al.*, 1998). This explanation is supported by the data obtained in this study where, as shown in Fig. 5, gap thresholds were influenced by the offset of the noise burst more for aged subjects than for young subjects. Furthermore, for aged subjects, thresholds near the noise offset were significantly elevated compared to those near the noise onset. This age-related onset/offset difference may be related to observations from studies of speech recognition. Consonants at the final position of a syllable are more difficult to identify than those at the initial position for both young and aged subjects (Dubno *et al.*, 1982; Gelfand *et al.*, 1986), and this initial/final difference increased with age in noise conditions (Gelfand *et al.*, 1986).

Throughout this study, a significant age effect was only observed when the gap was at the edge locations (5% and 95%) of the noise burst. This age-related edge location effect for gap detection should be considered when results are assessed in conjunction with age-related changes in speech recognition. Although both gap detection and speech recognition involve detection of temporal gaps, the location of the gap is quite different in the two situations. In gap-detection paradigms which position the gap at the center of the stimulus, the detection, as we know now, is robust. In consonant perception, however, the temporal gaps associated with consonants usually occur more randomly and often at the edges of syllables, making them more difficult to detect. Therefore, gap thresholds obtained with gaps located at the center of a stimulus may not be good predictors of speech recognition, especially for aged subjects.

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