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Word-Recognition Performance in Interrupted Noise by Young Listeners with Normal Hearing and Older Listeners with Hearing Loss

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Abstract

Background: The most common complaint of adults with hearing loss is understanding speech in noise. One class of masker that may be particularly useful in the assessment of speech-in-noise abilities is interrupted noise. Interrupted noise usually is a continuous noise that has been multiplied by a square wave that produces alternating intervals of noise and silence. Wilson and Carhart found that spondaic word thresholds for listeners with normal hearing were 28 dB lower in an interrupted noise than in a continuous noise, whereas listeners with hearing loss experienced only an 11 dB difference.

Purpose: The purpose of this series of experiments was to determine if a speech-in-interrupted-noise paradigm differentiates better (1) between listeners with normal hearing and listeners with hearing loss and (2) among listeners with hearing loss than do traditional speech-in-continuous-noise tasks.

Research Design: Four descriptive/quasi-experimental studies were conducted.

Study Sample: Sixty young adults with normal hearing and 144 older adults with pure-tone hearing losses participated.

Data Collection and Analysis: A 4.3 sec sample of speech-spectrum noise was constructed digitally to form the 0 interruptions per second (ips; continuous) noise and the 5, 10, and 20 ips noises with 50% duty cycles. The noise samples were mixed digitally with the Northwestern University Auditory Test No. 6 words at selected signal-to-noise ratios and recorded on CD. The materials were presented through an earphone, and the responses were recorded and analyzed at the word level. Similar techniques were used for the stimuli in the remaining experiments.

Results: In Experiment 1, using 0 ips as the reference condition, the listeners with normal hearing achieved 34.0, 30.2, and 28.4 dB escape from masking for 5, 10, and 20 ips, respectively. In contrast, the listeners with hearing loss only achieved 2.1 to 2.4 dB escape from masking. Experiment 2 studied the 0 and 5 ips conditions on 72 older listeners with hearing loss, who were on average 13 yr younger and more varied in their hearing loss than the listeners in Experiment 1. The mean escape from masking in Experiment 2 was 7 dB, which is 20–25 dB less than the escape achieved by listeners with normal hearing. Experiment 3 examined the effects that duty cycle (0–100% in 10% steps) had on recognition performance in the 5 and 10 ips conditions. On the 12 young listeners with normal hearing, (1) the 50% correct point increased almost linearly between the 0 and 60% duty cycles (slope = 4.2 dB per 10% increase in duty cycle), (2) the slope of the function was steeper between 60 and 80% duty cycles, and (3) about the same masking was achieved for the 80–100% duty cycles. The data from the listeners

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with hearing loss were inconclusive. Experiment 4 varied the interburst ratios (0, –6, –12, –24, –48, and –∞ dB) of 5 ips noise and evaluated recognition performance by 24 young adults. The 50% points were described by a linear regression ($R^2 = 0.98$) with a slope of 0.55 dB/dB.

Conclusion: The current data indicate that interrupted noise does provide a better differentiation both between listeners with normal hearing and listeners with hearing loss and among listeners with hearing loss than is provided by continuous noise.

Key Words: Auditory perception, escape from masking, hearing loss, speech perception, speech recognition in interrupted noise

Abbreviations: AM = amplitude modulation; BBN = broadband noise; GLM = General Linear Model; HFPTA = high-frequency pure-tone average (1000, 2000, and 4000 Hz); IBI = interburst interval; IBR = interburst ratio; ips = interruptions per second; PTA = pure-tone average (500, 1000, and 2000 Hz); QuickSIN = Quick Speech in Noise test; rms = root mean square; S/N, SNR = signal-to-noise ratio; SSN = speech-spectrum noise; WIN = Words-in-Noise Test

INTRODUCTION

Auditory masking studies involving speech intelligibility typically use a continuous broadband noise (BBN), speech-spectrum noise (SSN), or multitalker babble as the masking agent. The BBN and SSN waveforms exhibit little amplitude modulation (AM), whereas, depending on the number of talkers, multitalker babble usually has a larger AM characteristic. The importance of an AM characteristic is that during the low point in the waveform fluctuation (often referred to as a "dip" or "valley") the signal-to-noise ratio (S/N, SNR) is increased, thereby offering the listener a "glimpse" of a portion of the target speech signal (Miller and Licklider, 1950; Cooke, 2006). A recent study from our laboratory (Wilson et al, 2007a) examined speech intelligibility in SSN and in multitalker babble when the two noises were adjusted to the same root mean square (rms) levels. Young listeners with normal hearing had better performance by 2 dB in multitalker babble than in SSN, which can be expressed as a 2 dB release or escape from masking (i.e., the masking difference between the performance in babble and in SSN).[1] The advantage was attributed to the amplitude modulations in the multitalker babble waveform. In contrast, the older listeners with hearing loss had only about a 0.5 dB better performance in multitalker babble. Similar results were reported by Duquesnoy (1983) and Hygge and colleagues (1992) using slightly different paradigms. The 1.5 dB advantage to the listeners with normal hearing was not a large advantage, which is consistent with the observation that the fluctuations in the multitalker babble were not very substantial. As demonstrated in the Wilson and colleagues study, fluctuations in multitalker babble provide some escape from masking, but there is another class of maskers that provides an even larger escape from masking, namely, interrupted maskers that can be constructed to provide controlled, substantial AM characteristics that can be varied to provide a multitude of paradigms.

An interrupted masker used with speech stimuli typically is a BBN or SSN that has been multiplied by a square wave. Certain descriptors are used to define the various characteristics of interrupted noise. As Pollack (1954, 1955) described, interrupted noise is composed of successive noise bursts that are separated systematically or randomly either by silent segments or by noise segments at levels below the levels of the noise bursts. Systematic interruption rates are described in terms of interruptions/second (ips). The portion of the period that a noise is *on* is the *duty cycle*, which is expressed in percent (duty cycle is also referred to as the *noise-on fraction* and other similar terms). For example, a 5 ips noise with a 40% duty cycle is a noise that is *on* for 80 msec and *off* for 120 msec of each 200 msec cycle. The burst level is the sound pressure level of the noise burst. With a 50% duty cycle, the noise is *on* half the period and *off* half the period. Thus, using the power formula, the rms expressed in decibels over the period of a signal with a 50% duty cycle would be 3 dB less than the rms of the noise with a 100% duty cycle. Typically, however, the levels reported with interrupted noises do not include the overall level but, rather, only the level of the noise during the burst (e.g., Dubno et al, 2003, p. 2086). The *interburst interval* (IBI) describes the segment between successive noise bursts, with the *modulation depth* or *interburst ratio* (IBR) used to define the difference between the level of the noise burst and the level of the segment between noise bursts. For example, if the IBI were "silent," then the IBR would be –∞ dB, whereas if the IBI were 12 dB below the level of the noise burst, then the IBR would be –12 dB. In the context of interrupted noise, *escape from masking* or *release from masking* (expressed in percent correct or in a decibel quantity like SNR) refers to the performance obtained in a reference condition (continuous noise) *minus* the performance in the experimental condition (interrupted noise).

The classic studies of Miller (1947) and Miller and Licklider (1950) described the effects that interrupted noise had on the intelligibility of speech for listeners with normal hearing. Miller and Licklider studied the intelligibility of PB-50 words presented in BBN that was interrupted <1 to >1000 times/sec (50% duty cycle). Recognition performance maximized around 10 ips (50% duty cycle and $-\infty$ dB IBR). Wilson and Carhart (1969) extended this work to include both listeners with normal hearing and listeners with sensorineural hearing loss. They observed with spondaic words a 28.3 dB escape from masking for the listeners with normal hearing. In contrast, listeners with sensorineural hearing loss only achieved an 11.2 dB escape from masking. In a similar study that incorporated monosyllabic words, Dirks and colleagues (1969) reported for listeners with normal hearing a 30 dB escape from masking under the same continuous and interruption noise conditions. Subsequently, Shapiro and colleagues (1972), using monosyllabic words and 1, 4, 20, and 100 ips BBN, observed for all conditions poorer recognition performance by individuals with sensorineural hearing loss than by listeners with normal hearing. The 28 to 30 dB escape from masking achieved by listeners with normal hearing in the Wilson and Carhart and Dirks and colleagues studies is a substantial auditory effect, especially considering that listeners with hearing loss appear to achieve considerably less escape from masking under the same conditions.

The usual interrupted noise paradigm involves a noise that is interrupted at a fixed rate with a fixed duty cycle, which typically is 50%. There are at least two variants of the classical interrupted noise paradigm. First, in one of their experiments, Miller and Licklider (1950, p. 172, Fig. 11) randomized both the interruption rate and the duty cycle of the noise and observed essentially the same result that was obtained when both masker variables were fixed. In a modification of that paradigm, Phillips and colleagues (1994) developed an interrupted noise in which the noise bursts and silent intervals varied randomly from 5 to 95 msec, which corresponds to interruption rates of 100/sec to 5.26/sec, with the duty cycle maintained at 50% (Stuart, 2005). This irregular interrupted noise paradigm also provides escape from masking but to a lesser degree than a noise that is interrupted regularly 10/sec. For example, estimates from the graphic analyses and calculations from the linear regression equations of Stuart and Phillips (1996, p. 482, Figs. 4–5, p. 483, Fig. 6) indicate that young adults with normal hearing obtained about 12 dB escape from masking at the 50% points on the continuous and interrupted noise functions. The 12 dB escape is reasonable when consideration is given to the differences in escape from masking that occur at the interruption rates between 5 ips and 100 ips that have been observed in other studies. For example, in the Dirks and colleagues (1969) monosyllabic word data the escape from masking was 30.5 dB for 10 ips, dropping to 3.1 dB for 100 ips. The average escape from masking from these two extreme conditions (10 and 100 ips) is about 16 dB (Dirks et al, 1969, p. 904, Table 5), which approximates the 12 dB escape from masking observed by Stuart and Phillips. Because of the relatively small escape from masking provided by the Phillips and colleagues interrupted noise paradigm, the focus of the current project is on paradigms involving periodic interrupted noises that provide a larger escape from masking.

The second variant of the classical interrupted noise paradigm involves a continuous noise multiplied by a sinusoid (e.g., Festen and Plomp, 1990; Eisenberg et al, 1995; Gnansia et al, 2008). By definition, the waveform mimics a sine wave as opposed to a square wave. Whereas the square-wave modulated noise has definable, alternating intervals of noise and silence, the sine-wave modulated noise basically has no silent intervals in the waveform, only differences in the amplitude of the continuous waveform, which is similar to a square-wave modulated noise with IBRs of, for example, –12 dB. The Takahashi and Bacon (1992) essay is a good example of the masking effects that an 8 Hz sine-wave modulated noise has on speech recognition. At the 50% point, young listeners obtained a ~6 dB escape from masking, whereas the escape from masking attained by older listeners with mild, high-frequency hearing loss was on the order of 2.5 to 4 dB. The smaller escape from masking that is achieved with the sine-wave modulated noise probably reflects the lack of a relatively substantial "silent interval" that is provided by square-wave modulated noise during which time recognition information at a favorable SNR is available to the listener.

Studies in the past 20 yr using a variety of interrupted noise paradigms continue to demonstrate that young listeners with normal hearing are able to take advantage of the periods of improved SNR that are provided by AM noises, whereas older listeners with and without sensorineural hearing loss are not able to gain the same advantage (e.g., Festen and Plomp, 1990; Middelweerd et al, 1990; Takahashi and Bacon, 1992; Dubno et al, 2002, 2003; George et al, 2006). The underlying mechanism or phenomenon that limits listeners with hearing loss from being able to take advantage of the momentary SNR improvements that are provided by the fluctuations in interrupted noise is not known. George and colleagues report that audibility is certainly a factor that must be considered along with suprathreshold factors. In addition to the audibility factor, Bacon and colleagues (1998) and Dubno and colleagues (2002) attribute the decrease in the escape from masking associated with older listeners with hearing loss to forward and backward masking. One potential explanation relates to the observation that cochlear hearing loss often is associated with poor temporal resolution (e.g., Reed et al, 2009). Additionally, as Fitzgibbons and Gordon-Salant (1996) have observed, older listeners with and without hearing loss often have poorer temporal resolution abilities than do younger listeners with normal hearing. Data from earlier studies on young listeners with normal hearing (Samoilova, 1959; Elliott, 1962a, 1962b; Dirks and Bower, 1970; Wilson and Carhart, 1971) indicate that the so-called silent intervals in interrupted noise are not completely silent but, rather, are contaminated by the effects of temporal masking, that is, forward and backward masking. These effects have prompted some investigators (e.g., Stuart and Phillips, 1996) to suggest that the interrupted noise paradigm provides a measure of temporal processing (in)abilities.

Speech-in-noise tests increasingly are becoming an integral part of a routine audiologic evaluation (Strom, 2006). A recent study demonstrated how effective two speech-in-noise tests (Quick Speech in Noise test [QuickSIN; Killion et al, 2004]; Words-in-Noise [WIN] Test [Wilson, 2003]) are at differentiating between recognition performance by listeners with normal hearing and performance by listeners with hearing loss (Wilson et al, 2007b). Both instruments use multitalker babble as the masking agent presented at multiple SNRs, with the metric of interest the SNR at which 50% recognition is achieved. As the data from Wilson and colleagues demonstrate, typically mean recognition performance by listeners with normal hearing is 8 to 10 dB lower (i.e., at poorer SNRs) on the QuickSIN and WIN, respectively, than performance by listeners with hearing loss. Interrupted noise provides an even larger separation between the two groups of listeners.

The data from Wilson and Carhart (1969) on spondaic words in interrupted noise indicate a 17 dB difference between the mean escape from masking achieved by listeners with normal hearing (28.3 dB) and the mean achieved by listeners with hearing loss (11.2 dB), which is a wider range of recognition performance between listeners with normal hearing and listeners with hearing loss than is provided by either the QuickSIN or the WIN. The major purpose of this series of experiments was to determine whether this wider range of recognition performance on a speech-in-interrupted-noise paradigm can be used to better differentiate between listeners with normal hearing and listeners with hearing loss and among listeners with hearing loss. The purpose of Experiment 1 was to determine (1) if the known effects of interrupted noise on speech intelligibility could be replicated with monosyllabic words in a simple descending-presentation-level psychometric procedure and (2) the masking differences obtained with various interruption rates. The effect of interruption rate (5, 10, and 20 ips; 50% duty cycle) was studied on 24 young listeners with normal hearing and 24 older listeners with hearing loss (in this context, hearing loss is with reference to the pure-tone audiogram). Experiment 2 examined the effect that 5 ips noise had on a wider age and hearing loss range of listeners with hearing loss ($N = 72$) than was included in the first experiment. Experiment 3 examined the effects that changes in duty cycle (0–100% in 10% steps) had on the word-recognition performance of 12 listeners with normal hearing and 48 listeners with hearing loss. Both 5 and 10 ips conditions were studied at multiple SNRs. The purpose of Experiment 4 was to determine how recognition performance was changed as the amount of masking within the IBIs of a 5 ips noise was varied from –6 to –∞ dB. Because listeners with hearing loss exhibit minimal escape from masking under the most favorable IBI condition (–∞ dB), only listeners with normal hearing were studied.

GENERAL METHODOLOGY

The four experiments described in this report had several common attributes in terms of the stimulus materials, experimental design, and analysis. The commonalities are detailed in this section, with the unique methods detailed in the description of each experiment.

Materials

All experiments were conducted with the WIN paradigm by substituting the requisite continuous or interrupted SSN for the multitalker babble used with the WIN (Wilson, 2003; Wilson and McArdle, 2007). The WIN presents 10 unique, monosyllabic words at each of seven or eight SNRs nominally from 24 to 0 dB in 4 dB decrements.[2] The 80 WIN words are from the Northwestern University Auditory Test No. 6 (Tillman and Carhart, 1966) recorded by a female speaker (Department of Veterans Affairs, 2006). The metric of primary interest, in addition to the psychometric function, is the 50% correct point that is calculated with the Spearman-Kärber equation (Finney, 1952). For some of the experimental conditions the range of SNRs and the decrement size were extended below 0 dB S/N to encompass the complete psychometric function.

The noise started as a 4.3 sec sample of SSN that had a flat spectrum, ±2 dB, to 1000 Hz with a 12 dB/octave slope above 1000 Hz. The onset of the noise segment was edited to the first negative point of the negative-going zero crossing, and the offset of the noise was edited to the last positive point of the negative-going zero crossing. Thus, when the noise samples were concatenated, there were smooth transitions between noise segments. This is a so-called *frozen noise*, in that the same sample of noise was time locked to each carrier phrase and word segment. The basic three interrupted-noise conditions (5, 10, and 20 ips) with a 50% duty cycle and –∞ dB IBRs were constructed from the 4.3 sec sample of SSN (see Figure 1). An in-house batch file was

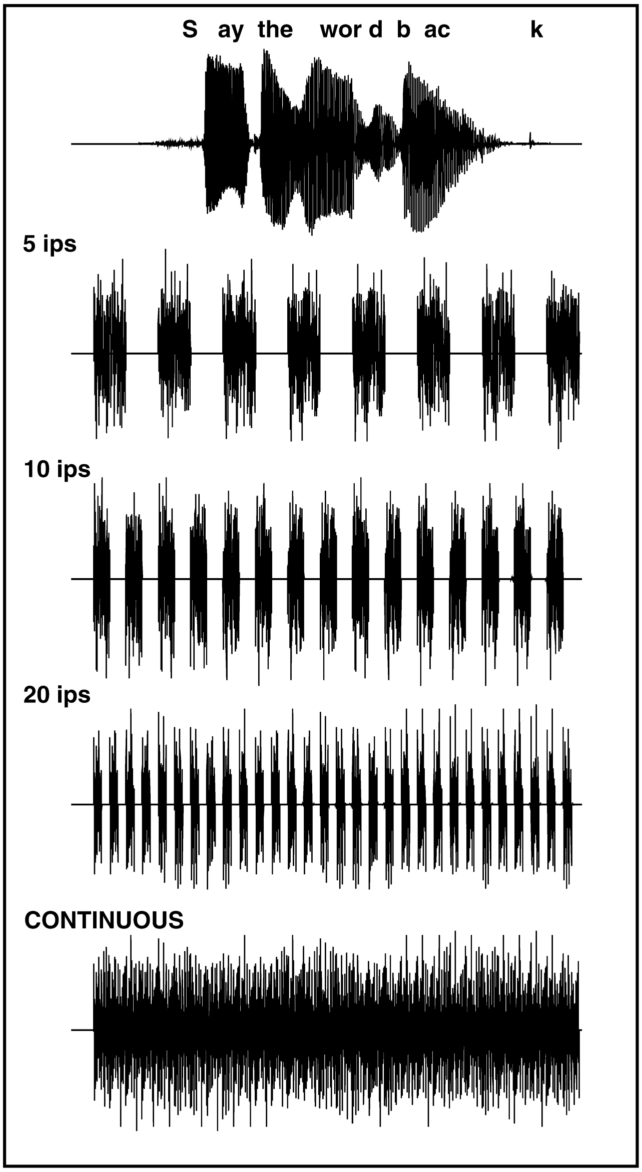

Figure 1. The waveforms of an example carrier phrase and word ("Say the word back") and the various noises (5, 10, and 20 ips and continuous or 0 ips).

used to create the interrupted noises. The program took advantage of a feature of the waveform editor (CoolEdit Pro) that maintained the temporal continuity of the waveform when a segment of the waveform was swapped with the second channel that had been set to zero. In this manner the IBIs were set to zero. Variations of the batch file were used to create the interrupted noise used in Experiments 3 and 4, in which duty cycle and IBR were the respective variables of interest. For all conditions, the level of the noise was fixed and the level of the speech was varied.

Each of the audio files for the 80 words contained the words on the left channel and the 4.3 sec noise sample (in the various configurations) on the right channel. For each of the noise conditions, multiple randomizations of the words were made by concatenating the individual word files using an in-house routine into two 40-word lists (Wilson and Burks, 2005). Once compiled, the words were adjusted digitally to achieve the necessary SNRs, the speech and noise signals were mixed and recorded on the left channel, and a monitor channel with only the words at a constant level was recorded on the right channel. The materials were recorded on a CD (Hewlett-Packard, Model GWA-4162B).

Procedures

The stimuli were reproduced by a CD player (Marantz, Model CDR-500) and routed through an audiometer (Interacoutics, Model AC-40) to an earphone (Etymōtic, Model ER-3A). Calibration of the interrupted noise was to the level of the noise burst and did not include a correction for the various IBIs. The right ear of even-numbered listeners and the left ear of odd-numbered listeners served as the test ear. The testing was conducted in a sound booth, and the (in)correctness of the verbal responses of the listeners was recorded into a spreadsheet. Each listener served in only one of the four experiments, and no practice was provided on any of the conditions.

EXPERIMENT 1

Experiment 1 had two main purposes. One purpose was to determine if the descending-presentation-level psychometric procedure and the monosyllabic words used with the WIN Test (Wilson, 2003) provided results that were similar to the results obtained in earlier investigations for listeners with normal hearing and for listeners with hearing loss (e.g., Dirks et al, 1969; Wilson and Carhart, 1969). Another purpose was to determine with monosyllabic words what, if any, masking differences were produced by interruption rates of 5, 10, and 20/sec on listeners with normal hearing and listeners with hearing loss. Most previous studies involving interrupted noise have included 10 ips, which with a 50% duty cycle has 50 msec IBIs. The 5 and 20 ips conditions were included to determine the effect that doubling the IBI to 100 msec (5 ips) and halving the IBI to 25 msec (20 ips) would have on word-recognition performance, especially by listeners with hearing loss.

Method

Subjects

Twenty-four young adult listeners (mean = 24.1 yr, SD = 2.2 yr) with normal hearing for the octave frequency between 250 and 8000 Hz (≤20 dB HL [American National Standards Institute, 2004]) served in the experiment. The mean three-frequency (500, 1000, and 2000 Hz) pure-tone average (PTA) was 8.0 dB HL (SD = 5.1 dB), and the mean high-frequency pure-tone average (HFPTA; 1000, 2000, and 4000 Hz) was 7.3 dB HL (SD = 4.8 dB). The 24 older listeners (mean = 74.9 yr, SD = 6.3 yr) met the following inclusion criteria for the test ear: (1) 60 to 85 yr of age, (2) 500 Hz threshold ≤30 dB HL, (3) 1000 Hz threshold ≤40 dB HL, (4) PTA ≤40 dB HL, and (5) word recognition in quiet on the NU-6 materials >40% correct. The mean PTA was 34.2 dB HL (SD = 5.1 dB), and the HFPTA was 50.7 dB HL (SD = 6.6 dB). The mean audiogram for the test ear is shown in Figure 2 (filled circles).

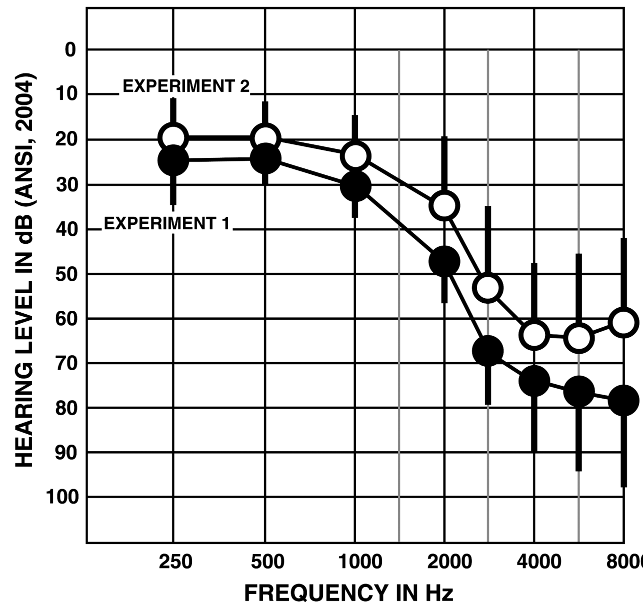

Figure 2. Mean test-ear audiograms for the listeners with hearing loss in Experiment 1 (filled circles; $N = 24$) and in Experiment 2 (open circles; $N = 72$). The vertical lines connected to each datum point represent one standard deviation.

Procedures

Word-recognition performance in quiet was measured with the NU-6 words (Department of Veterans Affairs, 2006) presented at 48 and 80 dB SPL to the listeners with normal hearing and at 80 and 104 dB SPL to the listeners with hearing loss. These levels corresponded to the word-presentation levels in noise at –32 and 0 dB S/N for the listeners with normal hearing and to 0 and 24 dB S/N for the listeners with hearing loss. These measures in quiet were made to ensure that decreases in performance at the more difficult SNRs were not owing to decreased performance at the lower presentation levels. With the interrupted noise paradigms, SNRs different from the SNRs used with the WIN were required because of the extended response range that the interrupted paradigm afforded the listeners with normal hearing. To encompass the psychometric function from minimal to maximal performance, pilot data indicated that the following SNRs in 4 dB decrements were needed for the listeners with normal hearing: (1) 20 to –8 dB with 0 ips, (2) –12 to –40 dB with 5 ips, and (3) –8 to –36 dB with 10 and 20 ips. With the listeners with hearing loss, SNRs from 24 to 0 dB were used with all conditions. For both groups of listeners, the level of the noise was set to 80 dB SPL and the level of the speech was varied to achieve the SNRs. To equalize the effects of learning and fatigue among the four conditions, different randomizations of Lists 1 and 2 were presented to each listener for each of the conditions.[3] The test session was divided in halves, with Lists 1 and 2 each given twice in each half. A further constraint was that each of the four conditions was administered in each half session. Following data collection, the data from the two lists given in each condition were combined.

Results and Discussion

To determine the effect of interruption rate on escape from masking, the data were examined in two ways. First, the 50% points on the mean psychometric functions and the slopes of those functions at the 50% points were calculated from the polynomial equations used to describe the data. Second, the 50% points for each listener in each condition were calculated with the Spearman-Kärber equation. This second measure provided intersubject variability data and was the basis of the inferential statistical analyses.[4]

The psychometric functions for the two groups of listeners are shown in Figure 3 for the four interruption conditions. The two pluses and two asterisks in each panel indicate the percent correct recognition obtained by the listeners with normal hearing and by the listeners with hearing loss, respectively, on the NU-6 words presented in quiet. Performance in quiet by the listeners with normal hearing was 72% at 48 dB SPL, which was the word-presentation level for the –32 dB S/N condition, and 98% at 80 dB SPL, which was the word-presentation level for the 0 dB S/N condition. Even for the poorest SNRs, performance was substantially better than performance in the interrupted noise. For the listeners with hearing loss, recognition performance in quiet at 104 dB SPL was about 10% poorer than recognition performance obtained with the words presented at that level in noise. The reason for this relation is unknown, as typically equal performances are obtained on words presented in quiet and in noise at such a favorable SNR. At the lower presentation level in quiet (80 dB SPL), 46% correct was obtained, which is substantially above the performances achieved in any of the noise conditions by the listeners with hearing loss. Table 1 includes the 50% points and the slopes of the functions at the 50% points that were calculated from

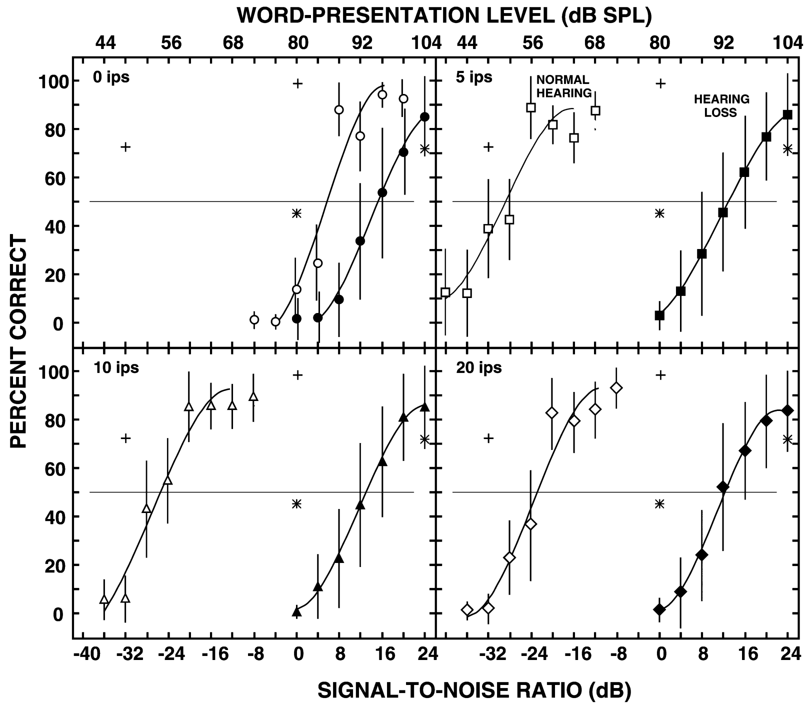

Figure 3. The mean psychometric functions for 24 listeners with normal hearing (open symbols) and 24 listeners with hearing loss (filled symbols) obtained at the four interruption rates in Experiment 1. The vertical lines represent ±1 SD. The lines through the datum points are the best-fit, third-degree polynomials used to describe the data. The pluses at 48 and 80 dB SPL and the asterisks at 80 and 104 dB SPL are the mean percent correct obtained by listeners with normal hearing and listeners with hearing loss, respectively, on the NU-6 words in quiet.

the polynomials in Figure 3. The differences in recognition performances between the two groups of listeners are listed in the table along with the escape from masking (re: 0 ips or continuous noise) that was achieved with each of the interrupted-noise conditions. The functions for the two groups of listeners are relatively similar in the 0 ips condition, with a 9.7 dB separation at the 50% points. With the three interrupted-noise conditions, the differences between the groups at the 50% points increased fourfold to 35.3 to 41.8 dB. The listeners with normal hearing attained a 28.7 to 34.5 dB escape from masking across the three interrupted-noise conditions, whereas the listeners with hearing loss were only able to attain a 2.4 to 3.1 dB escape from masking for the same conditions.

The mean 50% points in dB SNR (and standard deviations) for the 24 listeners with normal hearing and the 24 listeners with hearing loss calculated from the individual data with the Spearman-Kärber equation are depicted in Figure 4. Again, it can be seen that at 0 ips the listeners with normal hearing (open circles) performed better (i.e., at a poorer SNR) than listeners with hearing loss (filled circles; 6.3 vs. 15.7 dB S/N). Also, as anticipated from examination of the psychometric functions, the effects of interruption rate on the 50% points were substantially different for the two groups of listeners. The values for escape from masking (re: 0 ips) were within 1 dB of those reported in Table 1 for both groups of listeners, with minimal escape evidenced by the listeners with hearing loss for each of the three interrupted-noise conditions (ranging from 2.1. to 2.4 dB). In contrast, the listeners with normal hearing demonstrated substantial escape from masking, equaling 34.0, 30.2, and 28.4 dB for 5, 10, and

Table 1. 50% points (dB S/N) Calculated from the Polynomial Equations, the Escape from Masking (dB, re: 0 ips 50% point), and the Slope of the Psychometric Function (%/dB) at the 50% Point from Experiment 1

Interruptions per Second	Normal Hearing			Hearing Loss			50% Difference
	50%	Escape	Slope	50%	Escape	Slope	
0	5.7	–	6.7	15.4	–	5.4	9.7
5	–28.8	34.5	4.7	13.0	2.4	4.3	41.8
10	–25.6	31.3	5.1	13.1	2.3	5.1	38.7
20	–23.0	28.7	5.6	12.3	3.1	5.4	35.3

Note: The rightmost column is the difference between 50% points (dB) for the two groups of listeners.

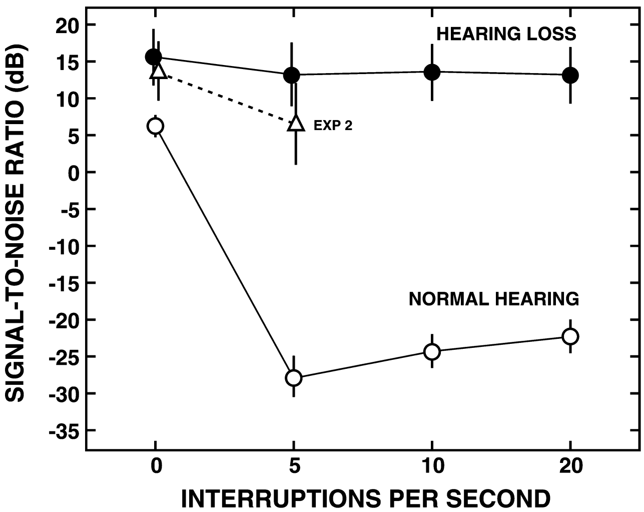

Figure 4. The mean 50% points (in dB SNR) for the 24 listeners with normal hearing (open circles) and the 24 listeners with hearing loss (filled circles) at four interruption rates in Experiment 1 and for the 72 listeners with hearing loss in Experiment 2. The 50% points were calculated from the individual subject data with the Spearman-Kärber equation. The vertical lines through each datum point represent ±1 SD.

20 ips, respectively. Note that the largest escape from masking achieved by the listeners with normal hearing was with the 5 ips condition, which had the longest "silent" intervals between noise bursts (i.e., 100 msec IBIs), and as the IBIs decreased with increased interruption rates, the escape from masking systematically decreased. The length of the IBI affected performance for the listeners with normal hearing but made little difference for the listeners with hearing loss. Finally, from Figure 4, the (intersubject) standard deviations depicted by the vertical bars were (1) smallest in the 0 ips condition (continuous noise) and about the same for the three interrupted-noise conditions for the listeners with normal hearing; (2) smaller for the listeners with normal hearing than for the listeners with hearing loss, even though the mean values for the listeners with normal hearing were much larger; and (3) about the same across the four noise conditions for the listeners with hearing loss.

The statistical significance of the observed dissimilarity in the effect of interruption rate for each listener group was confirmed through separate General Linear Model (GLM) repeated-measures analyses of variance with one within-group variable (i.e., interruption rate). For each listener group, the main effect of interruption rate was significant ($F[3, 69] = 1951.1$, $p < .001$, young listeners with normal hearing; $F[3, 69] = 21.3$, $p < .001$, older listeners with hearing loss). Post hoc analyses using Bonferroni corrections for multiple t-tests confirmed that all differences among ips conditions were statistically significant for the younger listeners with normal hearing. This was not the case for the older listeners with hearing loss. The differences between the 0 ips condition and each of the other three interrupted conditions were statistically significant, but the differences among the three interrupted conditions were not. These results confirm the conclusions reached from the graphic analyses of the data presented in Figures 3 and 4. That is, listeners with normal hearing experience a considerable escape from masking with interrupted noise, which systematically decreases with increasing noise interruption rates, whereas listeners with hearing loss exhibit only a minimal escape from masking, which is independent of noise interruption rate.

The 28–34 dB escape from masking achieved by the young listeners with normal hearing is in good agreement with earlier data. With spondaic words, Wilson and Carhart (1969, p. 1002, Table 2) reported a 28.3 dB escape from masking with a 10 ips broadband noise. Similarly, with young listeners with normal hearing, Dirks and colleagues (1969, p. 901, Table 2, p. 904, Table 5) reported escapes from masking with 10 ips BBN of 34.5 dB and 35.5 dB for spondaic words and monosyllabic words, respectively. The close agreement of results among these studies indicates that the psychophysical technique and the frozen noise sample used in the current experiment have good convergent validity.

Similar to the data reported for the current experiment, the older listeners with hearing loss in the Wilson and Carhart (1969) study performed poorer in interrupted noise than did younger listeners with normal hearing. Thus the findings from both studies exemplify the difficulties that older listeners with hearing loss have understanding speech in a fluctuating background noise. In contrast to the present experiment, however, in which the listeners with hearing loss achieved no greater than a 2.4 to 3.1 dB escape from masking, dependent on the method used to obtain the 50% point, the listeners with sensorineural hearing loss in the Wilson and Carhart study demonstrated an 11.2 dB escape from masking. Because of differences between the two studies in terms of age (mean = 57.1 yr vs. 74.9 yr), speech stimuli (spondaic words vs. monosyllabic words), and probably pure-tone hearing loss (Wilson and Carhart only mention that their group had speech-recognition thresholds ≤60 dB HL), it is difficult to reconcile the resulting differences without additional experiments.

EXPERIMENT 2

Experiment 2 was conducted to include a broader range of listeners with respect to age and pure-tone hearing loss than were included in Experiment 1. In comparison to Experiment 1, the listeners in Experiment 2 were 13 yr younger and had better pure-tone thresholds in the test ear, with the mean PTA 8 dB better and the mean HFPTA 10 dB better.

The pure-tone differences are obvious in the audiograms depicted in Figure 2. Because in Experiment 1 the recognition performance by the listeners with hearing loss was the same for the three interrupted-noise conditions, Experiment 2 included only the 0 and 5 ips conditions. For a direct comparison of recognition performance in interrupted noise and multitalker babble, the WIN (Wilson, 2003; Wilson and McArdle, 2007) also was included in Experiment 2.

Method

Materials

The same 0 and 5 ips conditions and materials used in Experiment 1 were used in Experiment 2. List 1 of the WIN Test was administered to the listeners (Wilson and Burks, 2005; Department of Veterans Affairs, 2006). List 1 consists of five words at each of seven SNRs from 24 to 0 dB in 4 dB decrements, with the 50% point computed with the Spearman-Kärber equation.

Subjects

Seventy-two adults (mean = 62.0 yr, SD = 11.1 yr, range = 28 to 83 yr) met the following inclusion criteria: (1) 21 to 85 yr of age, (2) a threshold at one of the 250–8000 Hz octave frequencies of ≥40 dB HL, and (3) word recognition in quiet on the NU-6 materials >40% correct. The mean PTA was 26.4 dB HL (SD = 6.9 dB), and the HFPTA was 40.4 dB HL (SD = 8.5 dB). The mean audiogram is depicted in Figure 2 (open circles).

Procedures

Initially in the test session, the NU-6 materials were presented in quiet at 80 and 104 dB SPL, followed by the traditional WIN Test and finally by two randomizations of Lists 1 and 2 of the WIN words presented in 0 and 5 ips SSN from 24 to 0 dB S/N in 4 dB decrements. Again, the test session was divided into halves during which each list was presented for each of the two conditions. The level of the multitalker babble and SSN was fixed at 80 dB SPL, with the level of the speech varied from 104 to 80 dB SPL. The materials were reproduced by a CD player (Sony, Model CDP-CE375) and fed through an audiometer (Grason-Stadler, Model 61) to a TDH-50P earphone encased in an MX-41/AR cushion. The nontest ear was covered with a dummy earphone. The testing was conducted in a sound booth, with the verbal responses of the listeners recorded into a spreadsheet.

Results and Discussion

The psychometric functions obtained for the three conditions in Experiment 2 (0 ips, 5 ips, and WIN) are shown in Figure 5. The two asterisks in the figure indicate performance on the NU-6 materials in quiet by the listeners with hearing loss in Experiment 2. At the higher presentation level in quiet (104 dB SPL), recognition performance in quiet and in either interrupted or continuous SSN and in multitalker babble is the same. At the lower presentation level in quiet (80 dB SPL), performance in quiet was about 60% better than performance in any of the noise conditions. This is a good demonstration that the decrease in performance observed at the less favorable SNRs is more the result of degradation by the introduction of noise than the result of audibility issues. For comparative purposes, the functions for the 0 and 5 ips conditions for the 24 listeners with hearing loss from Experiment 1 also are included in the figure as open and filled circles, respectively. The 50% points calculated from the mean polynomial functions for the 72 listeners with hearing loss in Experiment 2 were 13.1 dB S/N (0 ips) and 7.6 dB S/N (5 ips), with slopes of the functions at the 50% point of 5.7%/dB and 4.8%/dB, respectively. A paired t-test indicated that the 5 ips 50% point was significantly better (i.e., at a lower SNR) than the 0 ips 50% point ($t[71] = 21.9$, $p < .001$). In comparison to the functions for the 0 and 5 ips conditions in Experiment 1, both the 0 and 5 ips functions in Experiment 2 are displaced to the less favorable SNRs, indicating better recognition performance by the participants in Experiment 2. The WIN function in Figure 5 (squares and dotted line) is between the 0 and 5 ips functions, with a 50% point at 11.4 dB S/N and a slope at the 50% point of 6.1%/dB.

The mean 50% points calculated from the individual data with the Spearman-Kärber equation and standard deviations are listed in Table 2 and are shown as open triangles in Figure 4. For the 0 ips condition (continuous noise), the mean 50% point (13.8 dB S/N) was 2 dB lower than the comparable mean 50% point observed on the listeners with hearing loss in Experiment 1 (15.7 dB S/N). The listeners with hearing loss in Experiment 2, however, attained a significantly greater mean escape from masking in the 5 ips condition (7 dB) when compared to the 2 dB mean escape from masking achieved by the listeners with hearing loss in Experiment 1 ($t[64] = –9.8$, $p < .001$). The mean 7 dB escape from masking achieved by the listeners with hearing loss continues to pale in comparison to the mean 34 dB escape from masking achieved by the listeners with normal hearing in Experiment 1. To put the escape from masking difference between the two groups of listeners in perspective, the minimal escape from masking by the listeners with normal hearing was 28.4 dB, which is 13 dB more than the maximum 15.6 dB escape from masking attained by one of the listeners with hearing loss in Experiment 2.

The 50% points for the WIN and for the 0 and 5 ips conditions were also calculated using the Spearman-

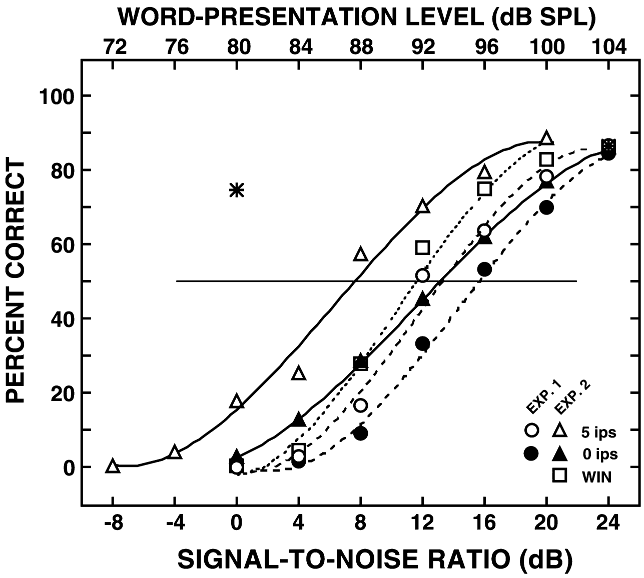

Figure 5. The mean psychometric functions for the 72 listeners with hearing loss in Experiment 2 generated with the 0 ips (open triangles), 5 ips (filled triangles), and WIN (squares and dotted line) conditions. The lines through the datum points are the best-fit, third-degree polynomials used to describe the data. The asterisks at 80 and 104 dB SPL are the mean percent correct obtained by the listeners with hearing loss on the NU-6 words in quiet. For comparison, the corresponding psychometric functions from the 24 listeners with hearing loss from Experiment 1 are depicted (open and filled circles).

Kärber equation and are listed in Table 2. Similar to the 50% points calculated using the functions, the 5 ips condition produced the lowest 50% point (6.7 dB S/N), followed by the WIN 50% point (12.5 dB S/N), with the 0 ips condition producing the highest 50% point (13.8 dB S/N). The standard deviations for the three conditions were about the same, ranging from 3.9 to 5.6 dB. It was hypothesized that the performance on the WIN would closer approximate the performance on the 0 ips condition than on the 5 ips condition given that both 0 ips and multitalker babble involve relatively small amplitude modulations, especially in comparison to the 5 ips condition. A Pearson-Product Moment correlation showed a significant relationship between the WIN 50% point and the 0 ips 50% point ($r = 0.85$, $p < .001$). The mean 50% point for the WIN, however, was significantly better (1.3 dB) than the mean 50% point for the 0 ips condition ($t[71] = -5.1$, $p < .001$).

A further understanding of the differences between the listeners with hearing loss in Experiments 1 and 2 is demonstrated by the data in Figure 6, which is a bivariate plot of the 50% correct recognition points for the 0 and 5 ips conditions (ordinate) versus the HFPTA (abscissa). With the 0 ips condition (Fig. 6, top panel), the datum points are intermingled in an interesting way. If consideration were given only to the datum points in the >40 dB HL range of HFPTAs, then in general the 24 listeners from Experiment 1 performed better (i.e., at lower SNRs) than did the listeners with hearing loss from Experiment 2 who were in the same range. Some of the culprit here might be that the listeners in Experiment 1 had twice as much experience listening in noise as did the listeners in Experiment 2 (four conditions vs. two conditions). The regression lines are parallel (slopes = 0.32 and 0.31 dB/dB), with the only difference being a direct current shift that is reflecting the similar relationships between the two variables for the two groups of listeners. Pearson-Product Moment correlations showed similar relationships between HFPTA and the 0 ips conditions for Experiment 1 ($r = 0.57$, $p < .001$) and for Experiment 2 ($r = 0.69$, $p < .001$).

Table 2. Mean Percent Correct Recognition and Standard Deviations for the 72 Listeners with Hearing Loss for the Three Stimulus Materials Used in Experiment 2

	0 ips		5 ips		Words-in-Noise	
Variable	Mean	SD	Mean	SD	Mean	SD
dB S/N						
24	87.5	14.8			86.4	18.9
20	79.0	20.8	89.0	15.0	83.1	21.1
16	64.2	24.9	80.0	20.2	75.3	24.1
12	52.2	31.8	70.6	22.8	59.2	33.0
8	17.1	18.9	57.8	31.1	28.3	23.7
4	3.6	7.2	25.8	22.5	4.7	10.9
0	0.6	2.3	18.3	19.1	0.6	3.3
–4			4.2	9.2		
–8			0.6	1.7		
Spearman-Kärber 50%	13.8	3.9	6.7	5.6	12.5	4.1
Polynomial 50%	13.1		7.6		11.4	
Slope	5.7		4.8		6.1	

Note: The mean 50% points obtained with the Spearman-Kärber equation and with the polynomial equation are listed, along with the slope of the functions at the 50% point.

In the 5 ips condition (Fig. 6, bottom panel), there is a different relation between the two groups of listeners that is reflected in the slope differences of the two linear regressions, 0.46 dB/dB (Experiment 2) versus 0.29 dB/dB (Experiment 1). The steeper slope reflects the larger overall escape from masking that was attained by the listeners in Experiment 2, who had milder pure-tone hearing losses. Pearson-Product Moment correlations between HFPTA and the 5 ips condition were significant for both Experiment 1 ($r = 0.47$, $p < .05$) and Experiment 2 ($r = 0.71$, $p < .001$); however, the strength of the relationship for the participants in Experiment 2 was greater.

The finding of a systematic relationship between pure-tone averages and thresholds in continuous and interrupted noise support previous conclusions by Punch (1978). In examining spondee thresholds in interrupted noise as a function of sensation level, Punch concluded that the amount of escape from masking was determined by the difference between masked thresholds in continuous noise and thresholds in quiet

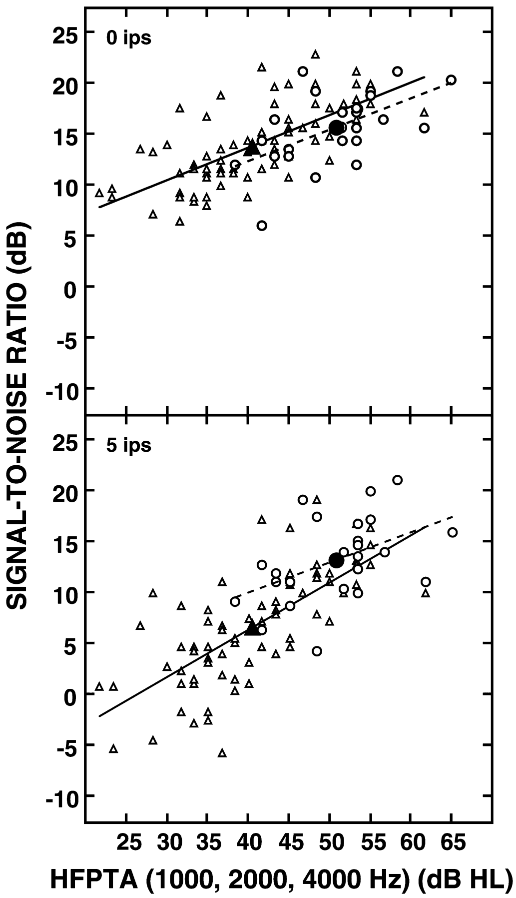

Figure 6. Bivariate plots of the 50% points of the individual recognition performances (ordinate) for the 0 ips (top panel) and 5 ips (bottom panel) conditions versus the high-frequency pure-tone average (HFPTA, abscissa) for the listeners with hearing loss in Experiment 1 (open circles; $N = 24$) and in Experiment 2 (open triangles; $N = 72$). The larger filled symbols depict the means of the respective conditions and the linear regressions used to fit the data from Experiment 1 (dashed lines) and Experiment 2 (solid lines).

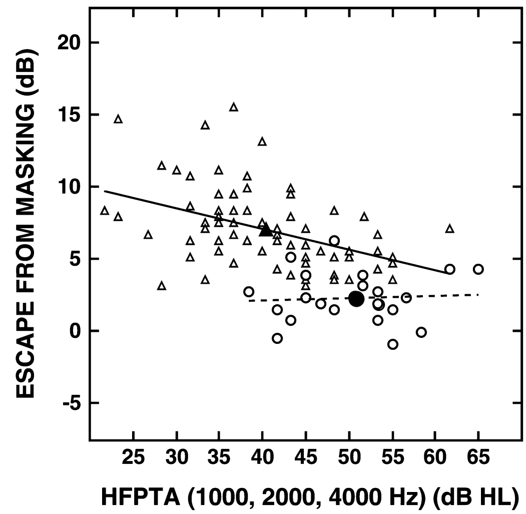

Figure 7. Bivariate plots of the escape from masking in the 5 ips condition (ordinate) versus the high-frequency pure-tone average (HFPTA, abscissa) for the listeners with hearing loss in Experiment 1 (open circles; $N = 24$) and in Experiment 2 (open triangles; $N = 72$). The larger filled symbols depict the means of the respective conditions, and the straight lines through the datum points are the linear regressions used to fit the data.

for individual listeners rather than the absolute sound pressure level of the masker.

The importance of hearing thresholds on escape from masking is highlighted further in Figure 7 for the two groups of listeners with hearing loss in Experiments 1 and 2. The Pearson-Product Moment correlation for HFPTA and escape from masking for Experiment 2 showed a significant negative relationship ($r = -0.44$, $p < .001$), whereas the same correlation for Experiment 1 was not significant ($r = 0.05$, $p = .82$). Generally, more escape from masking is associated with the better HFPTAs. Once the HFPTA is >40 dB HL, the escape from masking is consistently between 0 and 5 dB, evidenced by the flat regression for the listeners with hearing loss from Experiment 1 (circles).

Finally, the data in Experiment 2 permit comparison of recognition performance on the same word materials by three maskers, continuous SSN (0 ips), 5 ips SSN, and multitalker babble. The bivariate plots in Figure 8 provide these data, in which performance on the two SSN conditions (top and bottom panels) is plotted against performance on the WIN Test (abscissa), which incorporates multitalker babble. In the panels, the diagonal line represents equal performance on the two tasks. The dashed lines are regressions used to describe the data. The slopes of the regressions were 0.81 and 1.05 dB/dB for the 0 and 5 ips conditions, respectively, with R^2 values of 0.72 and 0.61. There is almost a one-to-one relation between performances on the two SSN conditions and on the multitalker condition, with the major difference being direct current shifts about the diagonal line. Recognition performance was poorer on the 0 ips condition than on the multitalker babble condition, whereas performance on the 5 ips condition was better than performance on the babble condition. These data from listeners with sensorineural hearing loss indicate that the WIN and the continuous or interrupted SSN provide similar results, varying only slightly in the magnitude of the masking effect.

EXPERIMENT 3

This experiment continued to examine escape from masking with the 0, 5, and 10 ips conditions, this time exploring the relation between recognition performance and the duty cycle of the 5 and 10 ips noises. As mentioned in the introduction, the portion of the period that an interrupted noise is *on* is the *duty cycle*, which is expressed in percent. For 5 ips the period of one cycle (i.e., noise *on* and noise *off*) is 200 msec, whereas for 10 ips the period is 100 msec. Thus, a 5 ips noise with

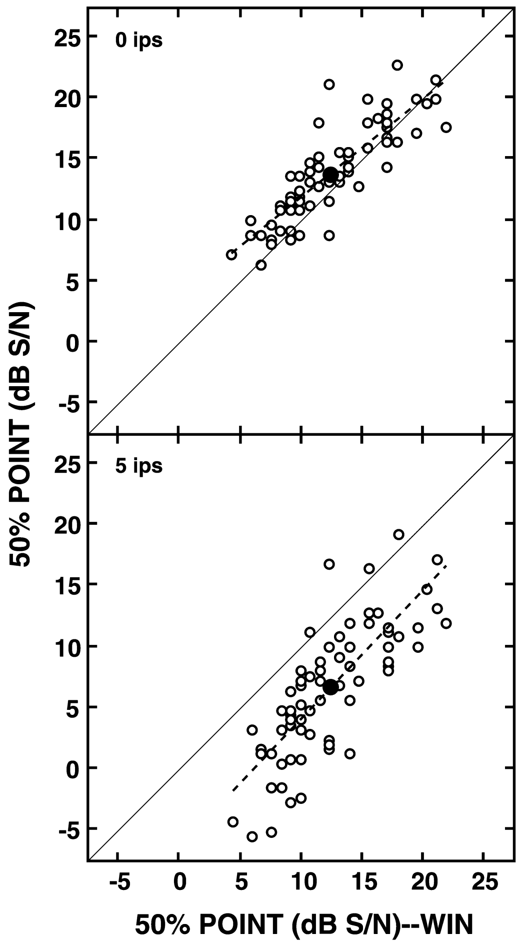

Figure 8. Bivariate plots of the 50% points of the individual recognition performances (ordinate) for the 0 ips (top panel) and 5 ips (bottom panel) conditions versus the 50% points on the WIN Test (abscissa) for the 72 listeners with hearing loss in Experiment 2. The larger filled symbols depict the means of the respective conditions, and the straight lines through the datum points are the linear regressions used to fit the data.

a 40% duty cycle has the noise *on* for 80 msec during the 200 msec period. The basic question was how recognition performance changes as the duty cycle evolves from 0% (i.e., noise on 0% of the time or quiet) to 100% (i.e., noise on 100% of the time or continuous) for listeners with normal hearing and listeners with hearing loss.

Method

Materials

Based on pilot data, 5 and 10 ips were selected as the interrupted-noise conditions with duty cycles from 10 to 90% in 10% increments. An in-house program in conjunction with the waveform editor was used to construct the various duty cycles. Recall that in Experiments 1 and 2, the duty cycle was fixed at 50% and the SNR was the variable parameter. In this experiment, the SNR was fixed at selected levels and the duty cycle was the variable parameter (0–100% in 10% steps). Examples of selected duty cycles of a 5 ips noise are illustrated in Figure 9. Because of word limitations with the WIN materials, the 11 duty cycles between 0 and 100% could not be studied with each group of listeners. Based on the previous data from the 5 and 10 ips 50% duty cycle conditions, different duty cycles were used for the listeners with normal hearing and the listeners with hearing loss. For the listeners with normal hearing, duty cycles of 0, 20, and 40–100% in 10% increments were studied, whereas for the listeners with hearing loss duty cycles of 0–70% in 10% increments and 100% were examined. These duty cycles were selected based on pilot data that indicated they were on the respective dynamic segments of the psychometric functions of the two groups of listeners.

In the protocol sequence, which progressed from easy to difficult at a given SNR, the list included five words at each duty cycle from 0 to 70%, with five words also presented at the 100% duty cycle. Once compiled, the levels of the words were adjusted to the appropriate SNR, and the speech signal and noise signal were mixed onto one channel with a speech-only signal on the second channel that was used for monitoring purposes. When concatenated, the interrupted noises were perceived as continuously interrupted with no variation in the interruption frequency. The change between duty cycles was subtle but perceptible. For the listeners with normal hearing, the following ranges of SNRs involving 8 dB steps were used:

1. 20 and 40% duty cycles, –24 to –48 dB S/Ns,
2. 50% duty cycle, –16 to –40 dB S/Ns,
3. 60% duty cycle, –8 to –32 dB S/Ns,
4. 70% duty cycle, 8 to –16 dB S/Ns, and
5. 80–100% duty cycles, 16 to –8 dB S/Ns.

For the listeners with hearing loss, all duty cycles employed the 20 to 8 dB S/Ns in 4 dB decrements. Two randomizations of each of the two WIN lists were developed, which produced 16 lists for the four SNR conditions. As in the previous experiments, the materials were compiled, adjusted to the appropriate levels, mixed, and recorded on CD. Delivery of and responses to the stimuli were the same as in Experiment 1.

Subjects

Twelve listeners (mean age = 23.1 yr, SD = 1.9 yr) with normal hearing for pure tones (≤20 dB HL [American National Standards Institute, 2004]) served in the study. The mean PTA in the test ear was 6.7 dB HL (SD = 4.8 dB), and the HFPTA was 6.1 dB (SD = 4.3 dB). A group of 24 older listeners (mean age = 64.7 yr, SD = 7.0 yr) with sensorineural hearing loss

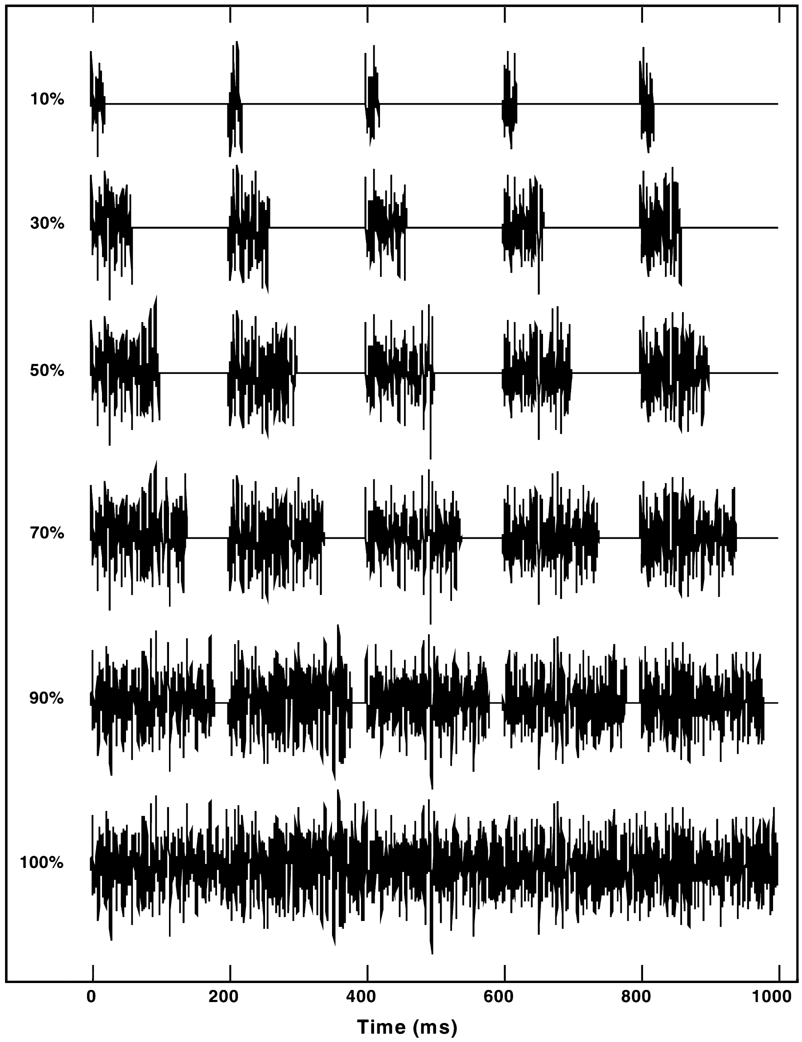

Figure 9. Example waveforms of a 5 ips SSN with duty cycles ranging from 10 to 100% (continuous).

participated in the 5 ips condition. The test-ear PTA for the group undergoing the 5 ips condition was 31.5 dB HL (SD = 6.2 dB), with a HFPTA of 46.3 dB HL (SD = 9.5 dB); mean word recognition at 90 dB SPL in quiet on the NU-6 words was 87.4%. A second group of 24 different older listeners (mean age = 68.1 yr, SD = 7.3 yr) served in the 10 ips condition. The test-ear PTA for this group was 31.3 dB HL (SD = 6.9 dB), with a HFPTA of 44.2 dB HL (SD = 9.9 dB); mean word recognition at 90 dB SPL in quiet on the NU-6 words was 84.3%. Thus, the two groups of listeners with hearing loss were very similar in the pure-tone and word-recognition-in-quiet domains with mean audiograms, which are not illustrated, similar in shape to the previously shown mean audiograms from Experiments 1 and 2.

Procedures

To distribute the effects of learning/practice and fatigue across conditions, Lists 1 and 2 were counterbalanced across conditions with each condition presented once before any condition was repeated. Again, the level of the noise was fixed at 80 dB SPL (burst level) and the level of the speech studied at four SNRs for each condition. Thus for the listeners with normal hearing the presentation levels of the words ranged from 32 dB SPL (–48 dB S/N) to 96 dB SPL (16 dB S/N) in 8 dB steps, and for the listeners with hearing loss the presentation levels of the words ranged from 88 dB SPL (8 dB S/N) to 100 dB SPL (20 dB S/N) in 4 dB steps. The same instrumentation that was used in Experiment 2 was used in this experiment.

Results and Discussion

The mean 50% correct points (in dB SNR) calculated with the Spearman-Kärber equation from the individual data of the 12 listeners with normal hearing are shown in Figure 10 for the 5 ips (squares and dashed lines) and 10 ips (circles and solid lines) conditions. The second ordinal scale is the corresponding

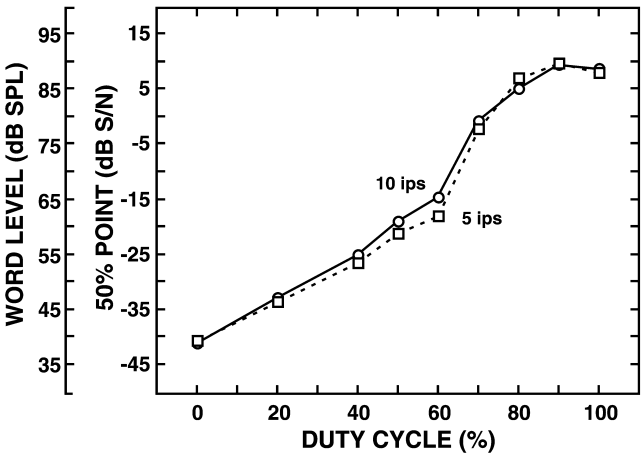

Figure 10. The 50% point (dB S/N) displayed as a function of the duty cycle for the 12 listeners with normal hearing in Experiment 3.

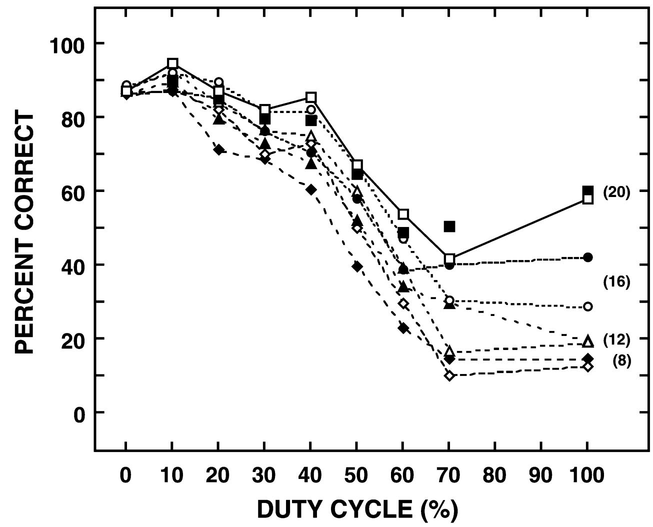

Figure 11. The mean percent correct recognition for the two groups of 24 listeners with hearing loss in Experiment 3 depicted as a function of duty cycle in percent of the 5 ips (open symbols) and 10 ips (filled symbols) conditions. The numbers in parentheses are the decibel SNRs for the respective condition pairs.

presentation level of the words (dB SPL). First note that the mean 50% points for the 0% duty cycle conditions (quiet) was about 39 dB SPL. This value is in excellent agreement with earlier data on the same NU-6 materials spoken by the same speaker in quiet in which the 50% point was about 38 dB SPL (Wilson et al, 1990, Table 1). The data in the figure demonstrate a direct relation between duty cycle and the 50% correct point. As the duty cycle increased from 0 to 60%, the 50% correct point increased almost linearly between the 0 and 60% duty cycles, which produced a slope of 4.2 dB per 10% increase in duty cycle. Between 60 and 80% duty cycles, the slope of the function is steeper, with the 80–100% duty cycles producing about the same masking effects. The shape of the function in Figure 10 is not unlike the sigmoidal-shaped function reported by Wilson and Punch (1971) for spondaic words masked by nine duty cycles of 10 ips BBN.

Because recognition performance at each of the duty cycles was obtained at the same four SNRs for the two groups of listeners with hearing loss, the mean percent correct recognitions are plotted in Figure 11 as a function of duty cycle with the parameter being SNR. (The 50% points [in dB S/N] that were calculated with the data from the listeners with normal hearing could not be calculated with the data from the listeners with hearing loss because of the restricted ranges of percent correct at many of the duty cycle conditions that are apparent in Figure 11. In future experiments a wider range of SNRs will have to be included to encompass the range necessary for the complete psychometric function.) Several features are noteworthy in Figure 11. First, for the most part, the 5 ips (open symbols) and 10 ips (filled symbols) data are the same at each of the four SNRs. Second, the slopes of the functions appear to be more gradual over the 10–30% duty cycle range than over the 40 to 60–70% range. Finally, recognition performance appears to be asymptotic at the duty cycles above 60–70%.

As previously noted, the restricted range of SNRs included in the paradigms used with the listeners with hearing loss precluded development of complete psychometric functions from which the 50% points could be calculated. This limitation makes a direct comparison between the listeners with normal hearing and the listeners with hearing loss impossible. Additionally, the results reported here must be viewed as preliminary and tentative, as the number of words at each SNR is limited, giving rise to unaccountable variability. Despite these limitations, some general comparisons can be made among and between the subject groups. First, it is interesting for the listeners with normal hearing that the functions for the two ips conditions in Figure 10 are almost identical. Second, the two groups of listeners with hearing loss produced results that were very similar for the two interruption conditions. Third, the general effect that duty cycle had on word-recognition performance was the same, though not identical, for listeners with normal hearing and listeners with hearing loss, in that performance decreased as duty cycle increased. Direct comparison of the recognition performances by the two groups of listeners awaits definition of the recognition performances at the 50% points by listeners with hearing loss. The data from Experiment 3 provide a good first approximation of the relations between duty cycle and recognition performance by listeners with normal hearing and listeners with hearing loss. What was not learned from this experiment, however, were the masking effects that the smaller duty cycles had on the recognition performance

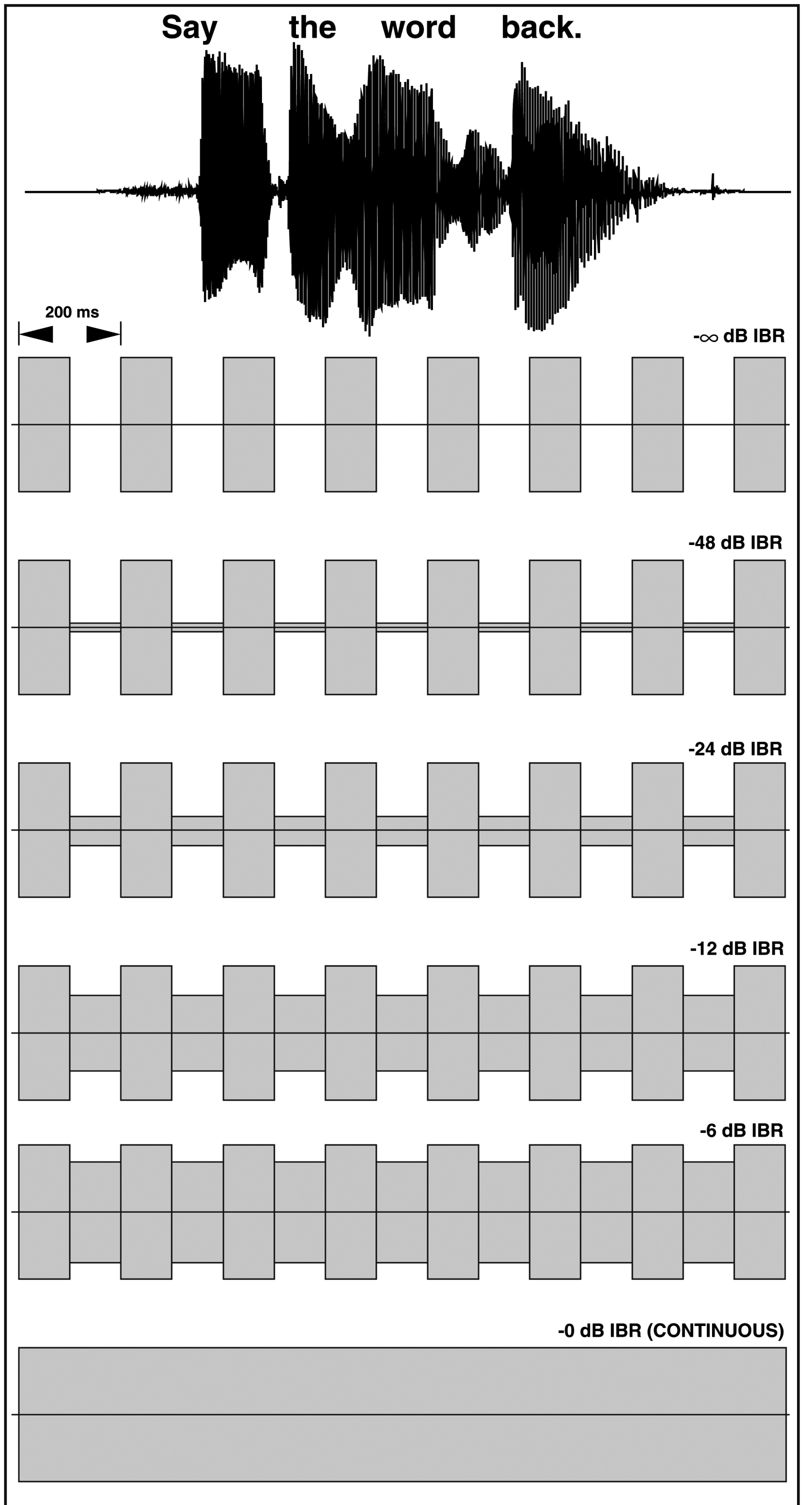

Figure 12. A schematic of the 5 ips waveforms with five IBRs ranging from –∞ to –6 dB. For comparison, a carrier phrase and word ("Say the word back") are shown.

of listeners with hearing loss. Further investigations are needed to define the fine-structure characteristics of the psychometric functions produced by changes in duty cycle, on both listeners with normal hearing and listeners with hearing loss for pure tones.

EXPERIMENT 4

The final study in this series focused on the relation between recognition performance and the amount of masking present in the interburst intervals

Table 3. Mean Recognition Performance (and standard deviations) for the Six IBR Conditions in Experiment 4

	0 dB IBR		–6 dB IBR		–12 dB IBR		–24 dB IBR		–48 dB IBR		–∞ dB IBR	
Variable	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
dB S/N												
20	96.3	10.6	99.6	2.0								
16	99.2	2.8	98.8	3.4								
12	85.0	8.8	93.3	8.7	97.1	4.6						
8	98.3	3.8	96.3	7.1	95.0	5.9						
4	42.5	13.9	54.2	14.1	80.0	13.2	95.4	5.9				
0	14.2	10.2	26.7	13.4	92.5	10.3	89.2	11.8				
–4	1.7	4.8	1.7	3.8	37.1	10.0	82.1	12.2				
–8	0.0	0.0	0.0	0.0	21.7	14.6	93.3	7.6	89.2	8.3	86.7	7.0
–12					0.0	0.0	28.3	14.9	82.5	8.5	80.4	12.7
–16							16.3	14.1	67.1	12.3	69.2	16.1
–20							0.0	0.0	81.3	10.3	77.1	12.3
–24									18.8	12.3	20.4	13.7
–28									7.5	10.3	7.1	8.1
–32									0.0	0.0	0.0	0.0
Spearman-Kärber 50%	4.5	1.0	3.2	1.0	–2.9	1.2	–10.2	1.5	–19.9	1.3	–19.6	1.4
Polynomial 50%	4.4		3.2		–3.3		–10.8		–21.0		–21.0	4.4
Slope @ 50%	7.2		6.8		6.4		6.7		6.0		5.9	7.2

Note: The 50% points (dB S/N) calculated with the Spearman-Kärber equation and from the polynomial equation used to describe each psychometric function (see Figure 13) also are listed, along with the slopes of the functions at the 50% points (%/dB).

associated with interrupted noise. Because listeners with hearing loss exhibited minimal escape from masking when the IBR was at the extreme most favorable condition (–∞ dB), only young listeners with normal hearing for pure tones were studied.

Method

Materials

The stimuli for this experiment involved the 5 ips SSN with IBRs of 0, –6, –12, –24, –48, and –∞ dB (the 0 dB IBR is continuous noise), which are schematized in Figure 12. Again, the IBR refers to the level disparity between the noise level during the IBI and the noise level during the noise burst. To achieve these IBRs, the noise segments that had been moved to the second channel during construction of the noises for Experiments 1 and 2 were adjusted to the level required for each IBR and then added back to the first channel with the continuity of the waveform at the segment boundaries maintained. The 4.3 sec noise segments were added to the second channel of the word files, after which the word files were concatenated to form the various test lists. For each of the six IBR conditions, two randomizations of Lists 1 and 2 were compiled, the level of the words adjusted to achieve the necessary SNRs, the two channels mixed onto the left channel, a monitor channel provided on the right channel, and the materials recorded as 24 tracks on CD. Thus data from 10 words were generated from each listener for each datum point.

Subjects

Twenty-four young listeners (mean age = 22.5 yr, SD = 2.7 yr) with normal hearing for pure tones (≤20 dB HL [American National Standards Institute, 2004]) participated in the study. The mean PTA was 2.0 dB

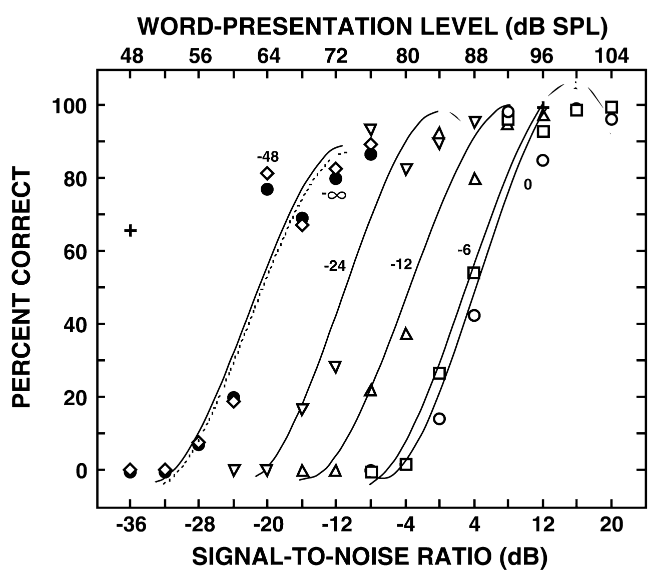

Figure 13. Psychometric functions for the six IBR conditions included in Experiment 4. The numbers beside each function indicate the IBR. The pluses show the data for the NU-6 materials presented in quiet at 48 and 96 dB SPL. The lines connecting the datum points are the best-fit, third-degree polynomials used to describe the data.

HL (SD = 5.8 dB), and the mean HFPTA was 3.3 dB HL (SD = 4.3 dB) in the test ear.

Procedures

Each listener initially was given a 25-word list of the NU-6 materials (Department of Veterans Affairs, 2006) at 48 and 96 dB SPL. The lower level corresponded to the presentation level of the words presented in the interrupted noise at the poorest SNR (–36 dB), whereas the higher level corresponded to the presentation level of the words presented at a favorable SNR (12 dB). Then the six IBR conditions were presented randomly, three with a randomization of List 1 and three with a randomization of List 2. Subsequently, each condition was repeated with the complementary lists randomly administered. The level of the noise was fixed at 84 dB SPL, with the level of the speech decremented in 4 dB steps over a 28 dB range that was condition dependent, varying from 20 to –8 dB S/N (0 and –6 dB IBRs) to –8 to –36 dB S/N (–48 and –∞ dB IBRs). The stimuli were delivered monaurally as described in the General Methodology section.

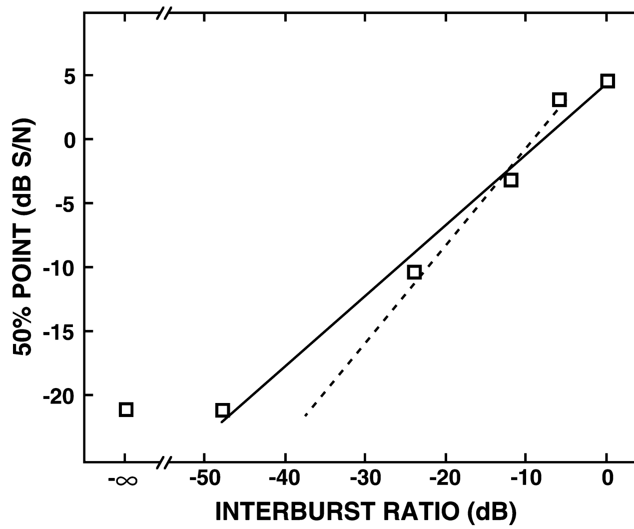

Figure 14. The 50% points obtained in Experiment 4 from 24 listeners with normal hearing for the six IBR conditions. The 50% points were calculated from the polynomial equations used to describe the data shown in Figure 13. The solid line is the regression through all five datum points, whereas the dashed line is the regression through the –6, –12, and –24 dB IBR datum points.

Results and Discussion

The mean recognition performance obtained at each of the SNRs for the six IBR conditions are listed in Table 3 along with the standard deviations. The mean psychometric functions are illustrated in Figure 13. The irregularities apparent in the functions in Figure 13 at the fourth-highest datum points are attributable to the few words (10) that were administered to each listener at each SNR. Because each function reflects the same irregularities, the intercondition relations are not appreciably compromised. The table also provides the mean 50% points calculated with the Spearman-Kärber equation and calculated from the polynomial equations used to describe the data. The general finding is that as the IBI is progressively voided of noise, recognition performance increases. The difference between the 50% points for the 0 and –6 dB IBRs was about 1 dB. Thus, lowering the level of the noise in the IBI by 6 dB provided 1 dB escape from masking, which was most evident in the data from the lower SNRs of the 0 and –6 dB IBR functions in Figure 13. The difference between the 50% points for the –6 and –12 dB IBRs increased to about 6 dB, which is probably only coincidently a one-to-one relation. The 12 dB change between the –12 and –24 dB IBRs produced a 7 dB change in the mean 50% point, whereas the 24 dB change between the –24 and –48 dB IBRs produced a 10–11 dB change in the mean 50% point.

The mean 50% points for the six conditions are plotted in Figure 14, with the five datum points fitted with a linear regression (solid line) that has a slope of 0.55 dB/dB.[5] The data appear systematic and are described accurately by the regression ($R^2 = 0.98$). Similarly, Howard-Jones and Rosen (1993) reported a slope of 0.64 dB/dB on a consonant-recognition task using a comparable range of duty cycles with a 10 ips noise. The equivalent 50% points for the –∞ and –48 dB IBRs (–21 dB S/N) indicate that the maximum escape from masking is obtained at an IBR less than –48 dB. The present data indicate that the minimal IBR at which the maximum escape from masking is attained is between the –24 and –48 dB IBRs. A refined estimate of the minimal IBR at which the maximum escape from masking is attained, however, can be calculated as the intercept of the linear regression fit to the –6, –12, and –24 dB IBRs (dashed line in Figure 14; $y = 6.95 + 0.756\times$) and the 50% point at the –∞ dB IBR (–21 dB S/N). The intercept is –37 dB IBR.

The SNR of the 50% points calculated with the Spearman-Kärber equation for the 24 listeners are depicted in Figure 15 as bivariate plots, with the 50% points for the 0 dB IBR (or continuous noise) condition on the abscissa and the 50% points for the six interrupted conditions (indicated in the upper portion of each panel) on the ordinate; the means are indicated with the large, filled circles. The data in the figure illustrate the relative homogeneity of the 50% points for each condition, which are reflected by the standard deviations listed in Table 3. To examine the effect of IBR, the data were examined using the GLM repeated-measures ANOVA. A significant main effect of IBR was found ($F[5, 115] = 2590.3$, $p < .001$). Post hoc analyses using Bonferroni corrections for multiple t-tests showed significant differences between each of the IBRs

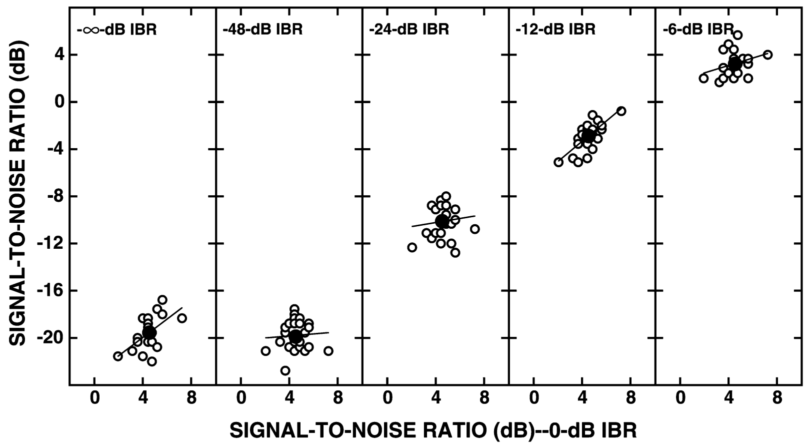

Figure 15. The individual 50% points for the 24 listeners with normal hearing in Experiment 4 plotted in a bivariate format with the SNR of the 50% point for the 0 dB IBR (continuous) noise on the abscissa and the remaining variables labeled in the top portion of each panel.

with the exception of –48 and –∞ dB, which were not different from each other.

The older listeners with hearing loss in Experiment 1 attained 2.1 to 2.4 dB escape from masking (re: continuous noise), whereas the listeners with hearing loss in Experiment 2 achieved about 7 dB escape from masking, both under the most favorable IBR condition (–∞ dB). From the data in Experiment 4, the 2 to 7 dB escape from masking is equivalent to the escape from masking achieved by listeners with normal hearing when the IBRs ranged from –6 dB (1.3 dB) to –12 dB (7.5 dB). Although the listeners with hearing loss were listening in interrupted noise with –∞ dB IBRs, the responses were as if the IBIs contained noise that ranged from –6 to –12 dB.

SUMMARY

Increased use of speech-in-noise testing has become an integral part of routine audiologic evaluations (Strom, 2006). The goal of speech-in-noise testing is twofold: (1) to differentiate between listeners with normal hearing and listeners with hearing loss and (2) to differentiate among listeners with hearing loss. Although currently available clinical speech-in-noise tests that use multitalker babble as the masker can be used to accomplish these goals, the use of interrupted noise as the masker may provide more insightful information about the overall auditory functioning of the listener. The series of experiments reported here were designed to manipulate systematically the characteristics of interrupted noise that need to be considered in the development of a clinically useful speech-in-noise test that utilizes monosyllabic words as the stimuli and interrupted noise as the masking agent.

The data from Experiment 1 demonstrated escape from masking (re: 0 ips or continuous noise) by listeners with normal hearing of 34.0, 30.2, and 28.4 dB for 5, 10, and 20 ips noises, respectively. In contrast, the listeners with hearing loss achieved only 2.1 to 2.4 dB escape from masking. The close agreement between the results on listeners with normal hearing from earlier studies and from Experiment 1 indicates that the psychophysical technique and the frozen-noise sample used in the current experiment had good validity. Experiment 2 studied 72 listeners with hearing loss, who were on average 12 yr younger and had less hearing loss for pure tones than the listeners with hearing loss in Experiment 1. The listeners in Experiment 2 obtained a 7 dB mean escape from masking, which is 5 dB more escape than was achieved by the listeners with hearing loss in Experiment 1 but 20 to 25 dB less escape than was achieved by listeners with normal hearing. Experiment 3 examined the effects that 0–100% duty cycles had on recognition performance in the 5 and 10 ips conditions. For the 12 young listeners with normal hearing (1) the 50% correct point increased almost linearly between the 0 and 60% duty cycles (slope = 4.2 dB per 10% increase in duty cycle), (2) the slope of the function was steeper between 60 and 80% duty cycles, and (3) approximately the same masking was achieved for the 80–100% duty cycles. The data from the listeners with hearing loss were incomplete and could not be interpreted extensively. The stimulus paradigm used in Experiment 3, however, demonstrated promise as a clinical instrument that should be considered for further development. Experiment 4 varied the interburst ratios (0, –6, –12, –24, –48, and –∞ dB) of 5 ips noise and evaluated recognition performance by 24 young adults. The 50% points were described by a linear regression ($R^2 =$ 0.98), with a slope of 0.55 dB/dB, meaning a 10 dB increase in the IBR (e.g., –40 dB to –30 dB) produced a 5.5 dB increase in the 50% point (e.g., from –17.6 dB S/N to –12.1 dB S/N).

The studies presented here did not address all potential effects that can influence performance on an interrupted-noise task. For example, it is possible that the results reported are specific to the use of isolated words as the stimulus. The effects of interruption rate, duty cycle, and IBRs, either solely or in combination, may vary with sentence-level materials. Another limitation relates to the lack of inclusion of older adults with normal hearing thresholds. There is evidence that changes in cognition as a function of aging can decrease the benefits obtained from listening in the gaps. The data presented here do not allow for the observation of the individual roles of hearing loss and aging on performance with an interrupted-noise task. Further study and work are needed to develop an interrupted-noise instrument for clinic use that provides reliable and valid speech-recognition data with the goal of better differentiating performance among listeners with varying degrees of hearing loss.

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NOTES

1. Unless otherwise noted, the use of *normal hearing* in the article implies normal hearing for audiometric pure tones.
2. The clinic version of the WIN contains 70 words (10 words for each of seven SNRs), whereas the laboratory version of the WIN has an additional set of 10 words available to extend the range of SNRs.
3. The original WIN was composed of one list of 70 words. Subsequently, for clinic use the lists were divided into two 35-word lists (Wilson and Burks, 2005).
4. Often there are minor differences between mean 50% points based on the Spearman-Kärber equation and the 50% points calculated from a mean function described with a polynomial equation. Typically these differences are a fraction of a decibel and are of no concern.
5. The slope of the regression in Figure 14 is expressed as "dB/dB" because the ordinate is the 50% point that is in dB (S/N) and the abscissa is the interburst ratio that also is in dB.

REFERENCES

American National Standards Institute (2004) *Specification for Audiometers (ANSI S3.6 2004)*. New York: Author.

Bacon SP, Opie JM, Montoya DY. (1998) The effects of hearing loss and noise masking on the masking release for speech in temporally complex backgrounds. *J Speech Hear Res* 41:549–563.

Cooke M. (2006) A glimpsing model of speech perception in noise. *J Acoust Soc Am* 119:1562–1573.

Department of Veterans Affairs (2006) *Speech Recognition and Identification Materials. Disc 4.0*. Mountain Home, TN: VA Medical Center.

Dirks DD, Bower D. (1970) Effect of forward and backward masking on speech intelligibility. *J Acoust Soc Am* 47:1003–1008.

Dirks DD, Wilson RH, Bower D. (1969) Effects of pulsed noise on selected speech materials. *J Acoust Soc Am* 46:898–906.

Dubno JR, Horwitz AR, Ahistrom JB. (2002) Benefit of modulated maskers for speech recognition by younger and older adults with normal hearing. *J Acoust Soc Am* 111:2897–2907.

Dubno JR, Horwitz AR, Ahistrom JB. (2003) Recovery from prior stimulation: Masking of speech by interrupted noise for younger and older adults with normal hearing. *J Acoust Soc Am* 113: 2084–2094.

Duquesnoy AJ. (1983) Effect of a single interfering noise or speech source upon the binaural sentence intelligibility of aged persons. *J Acoust Soc Am* 74:739–743.

Eisenberg LS, Dirks DD, Bell TS. (1995) Speech recognition in amplitude-modulated noise of listeners with normal and listeners with impaired hearing. *J Speech Hear Res* 38:222–233.

Elliott LL. (1962a) Backward and forward masking of probe tones of different frequencies. *J Acoust Soc Am* 34:1116–1117.

Elliott LL. (1962b) Backward masking: monotic and dichotic conditions. *J Acoust Soc Am* 34:1108–1115.

Festen JM, Plomp R. (1990) Effects of fluctuating noise and interfering speech on the speech-reception threshold for impaired and normal hearing. *J Acoust Soc Am* 88:1725–1736.

Fitzgibbons PJ, Gordon-Salant S. (1996) Auditory temporal processing in elderly listeners. *J Am Acad Audiol* 7:183–189.

Finney DJ. (1952) *Statistical Method in Biological Assay*. London: C. Griffen.

George ELJ, Festen JM, Houtgast T. (2006) Factors affecting masking release for speech in modulated noise for normal-hearing and hearing-impaired listeners. *J Acoust Soc Am* 120:2295–2311.

Gnansia D, Jourdes V, Lorenzi C. (2008) Effect of masker modulation depth on speech masking release. *Hear Res* 239:60–68.

Howard-Jones PA, Rosen S. (1993) The perception of speech in fluctuating noise. *Acoustica* 78:258–272.

Hygge S, Rönnberg J, Larsby B, Arlinger S. (1992) Normal-hearing and hearing-impaired subjects' ability to just follow conversation in competing speech, reversed speech, and noise backgrounds. *J Speech Hear Res* 35:208–215.

Killion MC, Niquette PA, Gudmundsen GI, Revit LJ, Banerjee S. (2004) Development of a quick speech-in-noise test for measuring signal-to-noise ratio loss in normal-hearing and hearing-impaired listeners. *J Acoust Soc Am* 116:2395–2405.

Middelweerd MJ, Festen JM, Plomp R. (1990) Difficulties with speech intelligibility in noise in spite of a normal pure-tone audiogram. *Audiol* 29:1–7.

Miller GA. (1947) The masking of speech. *Psychol Bull* 44: 105–129.

Miller GA, Licklider JCR. (1950) The intelligibility of interrupted speech. *J Acoust Soc Am* 22:167–173.

Phillips DP, Rappaport JM, Gulliver JM. (1994) Impaired word recognition in noise by patients with noise-induced cochlear hearing loss: contribution of temporal resolution defect. *Am J Otol* 15: 679–686.

Pollack I. (1954) Masking of speech by repeated bursts of noise. *J Acoust Soc Am* 26:1053–1055.

Pollack I. (1955) Masking by periodically interrupted noise. *J Acoust Soc Am* 27:353–355.

Punch JL. (1978) Masking of spondees by interrupted noise in hearing-impaired listeners. *J Am Audiol Soc* 3:245–252.

Reed CM, Braida LD, Zurek PM. (2009) Review article: review of the literature on temporal resolution in listeners with cochlear hearing impairment: a critical assessment of the role of suprathreshold deficits. *Trends Amplif* 13:4–43.

Shapiro MT, Melnick W, VerMeulen V. (1972) Effects of modulated noise on speech intelligibility of people with sensorineural hearing loss. *Ann Otol Rhinol Laryngol* 81:241–248.

Samoilova IK. (1959) Masking of short tone signals as a function of the time interval between masked and masking sounds. (USSR) *Biophysics (Oxf)* 4:44–52.

Strom KE. (2006) The HR 2006 dispensing survey. *Hear Rev* 13(6): 16–39.

Stuart A. (2005) Development of auditory temporal resolution in school-age children revealed by word recognition in continuous and interrupted noise. *Ear Hear* 26:78–88.

Stuart A, Phillips DP. (1996) Word recognition in continuous and interrupted broadband noise by young normal-hearing, older normal-hearing, and presbyacusic listeners. *Ear Hear* 17:478–489.

Takahashi GA, Bacon SP. (1992) Modulation detection, modulation masking, and speech understanding in noise in the elderly. *J Speech Hear Res* 35:1410–1421.

Tillman TW, Carhart R. (1966) *An Expanded Test for Speech Discrimination Utilizing CNC Monosyllabic Words. Northwestern University Auditory Test No. 6*. Brooks Air Force Base, TX: USAF School of Aerospace Medicine Technical Report.

Wilson RH. (2003) Development of a speech in multitalker babble paradigm to assess word-recognition performance. *J Am Acad Audiol* 14:453–470.

Wilson RH, Burks CA. (2005) The use of 35 words to evaluate hearing loss in terms of signal-to-babble ratio: a clinic protocol. *J Rehabil Res Dev* 42:839–852.

Wilson RH, Carhart R. (1969) Influence of pulsed masking on the threshold for spondees. *J Acoust Soc Am* 46:998–1010.

Wilson RH, Carhart R. (1971) Forward and backward masking: interactions and additivity. *J Acoust Soc Am* 49:1254–1263.

Wilson RH, McArdle R. (2007) Intra- and inter-session test, retest reliability of the Words-in-Noise (WIN) test. *J Am Acad Audiol* 18: 813–825.

Wilson RH, Carnell CS, Cleghorn AL. (2007a) The Words-in-Noise (WIN) test with multitalker babble and speech-spectrum noise maskers. *J Am Acad Audiol* 18:522–529.

Wilson RH, McArdle R, Smith SL. (2007b) An evaluation of the BKB-SIN, HINT, QuickSIN, and WIN materials on listeners with normal hearing and listeners with hearing loss. *J Speech Lang Hear Res* 50:844–856.

Wilson RH, Punch J. (1971) Masked spondee thresholds: variable duty cycle and mask intensity. *J Aud Res* 11:270–275.

Wilson RH, Zizz CA, Shanks JE, Causey GD. (1990) Normative data in quiet, broadband noise, and competing message for Northwestern University Auditory Test No. 6 by a female speaker. *J Speech Hear Disord* 55:771–778.