The effect of spatial separation on informational masking of speech in normal-hearing and hearing-impaired listeners

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The ability to understand speech in a multi-source environment containing informational masking may depend on the perceptual arrangement of signal and masker objects in space. In normal-hearing listeners, Arbogast *et al.* [J. Acoust. Soc. Am. **112**, 2086–2098 (2002)] found an 18-dB spatial release from a primarily informational masker, compared to 7 dB for a primarily energetic masker. This article extends the earlier work to include the study of listeners with sensorineural hearing loss. Listeners performed closed-set speech recognition in two spatial conditions: 0° and 90° separation between signal and masker. Three maskers were tested: (1) the different-band sentence masker was designed to be primarily informational; (2) the different-band noise masker was a control for the different-band sentence; and (3) the same-band noise masker was designed to be primarily energetic. The spatial release from the different-band sentence was larger than for the other maskers, but was smaller (10 dB) for the hearing-impaired group than for the normal-hearing group (15 dB). The smaller benefit for the hearing-impaired listeners can be partially explained by masker sensation level. However, the results suggest that hearing-impaired listeners can use the perceptual effect of spatial separation to improve speech recognition in the presence of a primarily informational masker. [DOI: 10.1121/1.1861598]

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I. INTRODUCTION

The "cocktail party" environment (Cherry, 1953) is particularly difficult for many listeners with sensorineural hearing loss.[1] This environment contains multiple speech sources and often a listener faces the problem of understanding one talker while ignoring one or more others speaking at the same time. Cherry (1953) identified spatial separation between sound sources as one of several potential means by which listeners solve the cocktail party problem. A speech signal masked by speech is affected by at least two types of masking: *energetic* and *informational* (Freyman *et al.*, 1999, 2001; Brungart, 2001; Brungart *et al.*, 2001; Arbogast *et al.* 2002; see also earlier work by Carhart *et al.*, 1968). A noise, on the other hand, generally produces primarily energetic masking.

Energetic masking originates in the peripheral auditory system where the response of the auditory nerve to the masker does not change appreciably when the signal is added. Informational masking, on the other hand, originates at some point beyond the auditory periphery and occurs despite an adequate representation of the signal in the system. At the simplest level, informational masking is masking that cannot be accounted for by energetic masking, similar to what Carhart *et al.* (1968) referred to as "perceptual masking." Informational masking is believed to occur due to listener uncertainty and/or to a high degree of similarity between the masker and the signal along one or more relevant stimulus dimensions (e.g., Watson, 1987; Neff and Green, 1987; Kidd *et al.*, 2002b; Durlach *et al.*, 2003b). There is currently considerable discussion about how best to define or compute informational masking and how to relate the results from different speech and nonspeech tasks (e.g., Durlach *et al.*, 2003a). For the purposes of the current study and for these stimuli and experimental task, informational masking is defined as masking beyond that which can be accounted for by energetic masking and is largely due, we believe, to similarity between the signal and masker, often causing them to be confused or attention to be directed to the wrong source.

In normal-hearing listeners the benefit of spatial separation of sources depends on the type of masking. Using nonspeech stimuli, Kidd *et al.* (1998) found a significantly larger spatial release from an informational masker (5–40 dB) than from an energetic masker (less than 10 dB) for the identification of pure-tone frequency patterns. Freyman *et al.* (1999), using natural speech stimuli, found no spatial release from a noise masker when the precedence effect was used to create a *perceived* spatial separation between signal and masker. However, there was a 4- to 10-dB spatial release for a speech masker. They concluded that the release was from the informational portion of the masking produced by the speech masker and due to perceptual segregation of the two sources in space (Freyman *et al.*, 1999, 2001). However, natural speech signals and maskers played simultaneously have substantial spectral overlap and thus are likely to contain significant amounts of energetic masking. They also produce an amount of informational masking that is difficult to quantify or control. Therefore, Arbogast *et al.* (2002) used

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processed speech stimuli in order to control, as best as possible, the ratio of informational to energetic masking. They measured the spatial release from masking for a 90° separation of signal and masker and found an 18-dB release from a primarily informational masker and a 7-dB release from a primarily energetic masker. The larger advantage for the informational masker was attributed to the perceptual effect of spatial separation, similar to the interpretation of Freyman *et al.* (1999, 2001). Hearing-impaired listeners generally obtain a spatial release from masking (noise or natural speech masking) that is smaller than normal-hearing listeners (e.g., Peissig and Kollmeier, 1997; Duquesnoy, 1983; Bronkhorst and Plomp, 1989; Hawley, 2000). However, it is not known if these listeners can use the perceptual effect of spatial separation to improve performance in the presence of a masker that is primarily informational.

Previous studies using pure-tone stimuli have found that hearing-impaired listeners can use segregation cues to obtain a release from informational masking, but the release is either smaller or requires a more obvious cue than for normal-hearing listeners [Grose and Hall (1996) for a melody recognition task; Kidd *et al.* (2002a) for detection of a spectro-temporally coherent tone in a spectro-temporally incoherent masker]. It is not known whether listeners with hearing loss can use spatial separation cues to overcome informational masking. Sound sources in realistic environments are often located in different places, affording potential cues for perceptually segregating the sounds they produce. Therefore, it is of considerable interest to determine how well listeners with hearing loss can use spatial cues to reduce informational masking.

The current study investigated the effect of informational versus energetic masking and normal versus impaired hearing on spatial release from masking. Listeners with normal hearing were included to provide age-matched controls. This study used the same stimuli and procedures as Arbogast *et al.* (2002). These stimuli and procedures have the advantage of retaining a high degree of speech intelligibility in a straightforward task that is perhaps less abstract than some nonspeech detection/discrimination tasks while providing better isolation of informational masking than is possible using natural speech. The speech stimuli in the current experiments were a modified version of cochlear implant simulation speech (Shannon *et al.*, 1995) processed in a way that greatly reduces spectral overlap between signal and masker, providing greater isolation of informational masking. In addition to the masker designed to produce primarily informational masking, two other maskers were included. One masker was a control for any potential energetic masking caused by the informational masker. The other was constructed to maximize energetic masking and minimize informational masking, and was included in order to compare the spatial release from masking obtained for primarily informational and primarily energetic maskers. Therefore, the effect of spatial separation was examined as a function of three types of maskers that generate different amounts of masking and which are assumed to originate primarily in either the peripheral (energetic) or the central (informational) portions of the auditory system. The current methods and procedures were nearly identical to Arbogast *et al.* (2002) and therefore will only be described briefly here.

TABLE I. Demographic and audiologic data for the hearing-impaired listeners. PTA is the pure-tone average of 500, 1000, and 2000 Hz, in dB HL. WRS (R/L)=word recognition score (right/left). HA=hearing aid.

	Age	Sex	Length of loss (years)	PTA	WRS (R/L)	Etiology	HA use
HI1	21	F	5	36	100/96	probably genetic	none
HI2	74	M	10	28	88/92	unknown/age/ noise?	none
HI3	47	F	7	33	92/96	ototoxicity—vancomycin	bilateral, occasionally, $1\frac{1}{2}$ years
HI4	68	F	5	33	92/88	unknown	none
HI5	54	F	10	39	100/96	probably genetic	bilateral, frequently, 3 years
HI6	19	F	19	40	80/92	congenital/ pre-natal	bilateral, frequently, $1\frac{1}{2}$ years
HI7	26	F	18	37	92/96	unknown/ genetic?	none
HI8	37	F	37	43	96/92	genetic	bilateral, frequently, 32 years
HI9	67	F	60	48	72/80	unknown/ genetic?	bilateral, frequently, 35 years
HI10	79	F	several years	48	80/88	unknown/ age?	bilateral, occasional, 1 year

II. METHODS

A. Listeners

Two groups of ten listeners were tested. Listeners received monetary compensation for their participation. The normal-hearing (NH) group had audiometric pure-tone thresholds of 20 dB HL or better in each ear for frequencies between 250 and 6000 Hz. In order to ensure a similar age range in each listener group, each NH listener was roughly matched in age (within a decade) to a HI listener. NH listeners ranged in age from 19 to 77 years. Hearing-impaired listeners ranged in age from 19 to 79 years. The hearing-impaired (HI) group was composed of listeners with bilateral, symmetrical sensorineural hearing loss of probable cochlear origin. Symmetrical loss was defined as pure-tone audiometric air-conduction thresholds within ±10 dB in each ear at most audiometric frequencies between 250 and 6000 Hz. Table I details demographic and audiologic information about the HI listeners. The duration and etiology of hearing loss, as well as hearing aid use, was obtained from a listener questionnaire. Listeners were ordered from lowest to highest threshold in quiet for the speech stimuli used in this study.

The reported duration of hearing loss ranged from 3 to 60 years. The degree of loss ranged from mild to moderate and the configuration ranged from flat to gradually sloping. The mean pure-tone average (of 500, 1000 and 2000 Hz) was

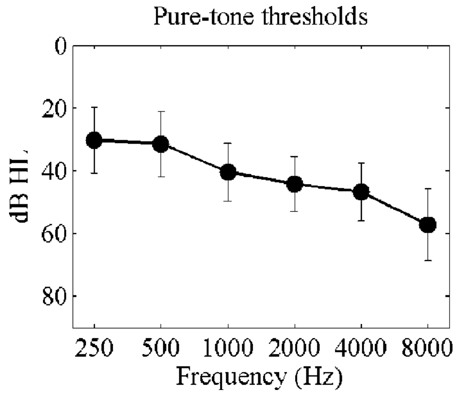

FIG. 1. Mean audiometric thresholds in dB HL for the hearing-impaired listeners. Error bars are ± 1 standard deviation.

37 dB HL. Word recognition scores ranged from 72% to 100% correct but were within $\pm 12\%$ between the ears of any individual listener, using standard, monosyllabic materials. Six of the ten HI listeners wore hearing aids (all bilaterally; testing was unaided). Figure 1 plots mean audiometric thresholds (obtained using standard clinical procedures) in dB HL for the HI group.

B. Stimuli

The stimuli were the same as those used by Arbogast *et al.* (2002) and are described in detail in that article. A brief description is given here. The four male talkers of the coordinate response measure (CRM) corpus of sentences (Bolia *et al.*, 2000) were used. Each sentence had the structure: "Ready [*callsign*] go to [*color*] [*number*] now." Signal sentences had the callsign "Baron" and each was paired with a randomly chosen masker sentence with a different callsign, color, number, and talker. Each sentence was digitally preprocessed to produce a set of 15 pure tones modulated by the speech envelope in the $\frac{1}{3}$-octave band centered at each frequency. Center frequencies were evenly spaced on a logarithmic scale from 215 to 4891 Hz. For details of the preprocessing, see Arbogast *et al.* (2002). Signal sentences were generated by combining eight (out of 15) randomly chosen bands. Each masker sentence was used to create three different types of maskers (described below). Signal and masker sentence onset was simultaneous.

1. Different-band sentence (DBS) masker

The different-band sentence (DBS) masker was generated by combining six randomly chosen bands excluding the eight bands used for the signal. Therefore, each signal/DBS masker pair contained mutually exclusive bands. The top panel of Fig. 2 shows the magnitude spectra of a signal/DBS masker pair. The signal is gray and the masker is black. The DBS masker was intended to produce primarily informational masking because it did not overlap the signal in frequency and was similar to the signal sentence in terms of intelligibility (Brungart *et al.*, 2004), overall sound quality due to the pure-tone carriers, and use of the same speech corpus for signal and masker.

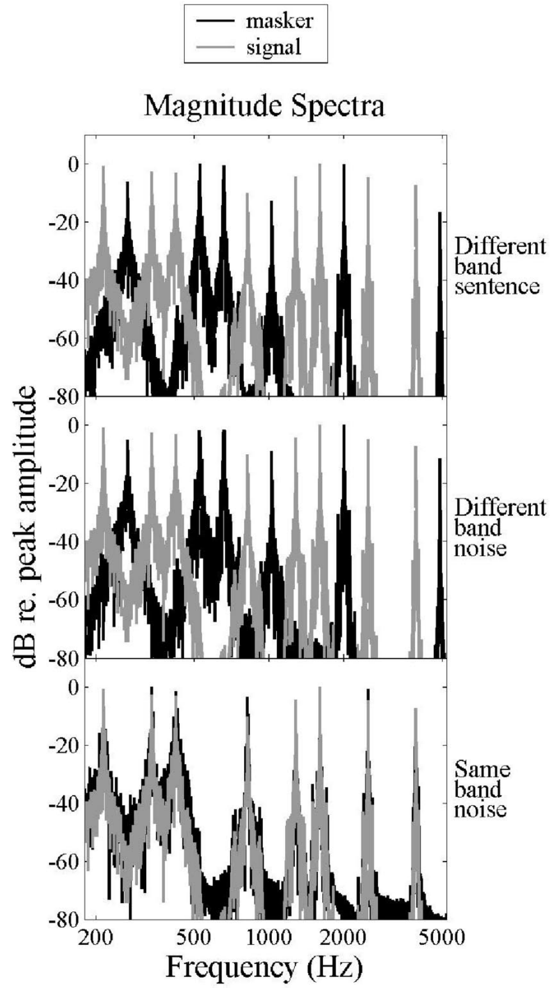

FIG. 2. Magnitude spectra for a sample signal sentence and the three types of processing for the masker sentence. The same signal sentence is plotted in gray in each panel. The black indicates the masker sentence for the different-band sentence masker (top panel), the different-band noise masker (middle panel), and the same-band noise masker (bottom panel).

2. Different-band noise (DBN) masker

The long-term complex spectrum of each DBS masker, described above, was used to shape the spectrum of a random, broadband Gaussian noise and the result was inverse fast Fourier transformed. This masker was intended to produce the same minimal amount of energetic masking as the DBS masker, but also to produce minimal informational masking because it was unintelligible and qualitatively dissimilar from the signal sentence.[2] This masker was included as a control for energetic masking in the DBS masker. The magnitude spectra of a DBN/signal sentence pair are shown in the middle panel of Fig. 2. The envelope of the DBN masker contains amplitude modulation because the stimulus is essentially the sum of multiple narrow-band noises.[3]

3. Same-band noise (SBN) masker

This masker was comprised of eight bands of noise that exactly overlapped the eight bands of the signal with which it was paired. The long-term complex spectrum of the eight-band masker sentence was used to shape the spectrum of a broadband Gaussian noise, and the result was inverse fast

Fourier transformed. The magnitude spectra of a SBN/signal sentence pair are shown in the lower panel of Fig. 2. Energetic masking was maximized because the magnitude spectra of signal and masker overlapped. Informational masking was minimized because the masker had no intelligibility and, as with the DBN masker, was qualitatively dissimilar to the signal sentence. The envelope of the SBN masker is similar to that of the DBN masker.

C. Procedures

The experiment took place in a soundfield, located within a single-walled, 12×13 ft^2, IAC sound booth. When two stimuli were present, they were played simultaneously via two Pioneer S-DF3-K speakers located 5 ft from the listener, one at 0° azimuth and the other at 90° azimuth to the right in the horizontal plane approximately level with the ears. The signal was always played from the speaker located at 0° azimuth. Stimuli were played through Tucker-Davis Technologies (TDT) hardware. The signal and the masker sentences were played through separate channels. Stimuli were converted at a rate of 50 kHz via a 16-bit, 8-channel D/A converter (DA8), low-pass filtered at 20 kHz (FT-6), and attenuated (PA-4). The signal was sent through a programmable switch (SS-1) to route it to the desired signal speaker. The signal and masker were sent to mixers where they were summed if presented to the same speaker. The stimuli were passed through power amplifiers (Tascam) and then to one or two speakers in the soundfield, depending on the experimental condition.

The task was one-interval forced-choice with two responses required on each trial. The first response (color) had four alternatives (blue, red, green, white), while the second response (number) had eight alternatives (1–8). Signal-alone thresholds were obtained using 30-trial blocks of a one-up, one-down adaptive procedure that estimates the 50% correct point on the psychometric function (Levitt, 1971). Masked data were collected with the method of constant stimuli. Four signal levels were chosen for each listener and condition individually in order to estimate the psychometric function. The aim was to produce performance ranging from just above chance to nearly 100% correct. The exact signal levels and level intervals varied depending on the listener, the condition, and the early psychometric function results. Signal levels were mixed randomly within every 50-trial block. On each trial, the listener was required to identify the color and number from the sentence with the callsign ‘‘Baron’’ by entering values on a computer keyboard. Response feedback was provided after each trial.

Each of the three types of maskers was tested in two spatial separation conditions, 0° and 90°, for a total of six masked conditions. In addition, one signal-only condition was tested. The signal sentence was always played at the 0° location and the masker, when present, was played at either the 0° or the 90° location. Each block of trials contained only one spatial separation condition and one masker type. The masker level was set for each listener to approximately 40 dB SL (above signal-alone threshold). However, if comfort or equipment limits were lower, then the highest possible masker level was used. The equipment limit was 88 dB SPL, but in order to allow for a +10 dB S/M (necessary in most cases to define the upper portion of the psychometric function), the highest masker level permitted was 78 dB SPL. Two blocks of signal-alone identification thresholds were collected first. Masked data were collected in sets of two blocks, each of the same masker/spatial separation condition. Sets of blocks containing each masker and spatial separation condition were alternated to balance any learning effects equally across all conditions. A minimum of 100 trials per signal level was obtained for each spatial separation and masker type. Data were collected within four sessions of 2 h each. Listeners were instructed to keep the head straight, facing the 0° location throughout stimulus presentation.

Training included a 50-trial block of practice of the signal-alone condition. The signal sentences were presented at a comfortable level from the 0° speaker. After achieving a minimum of 90% correct they completed four 50-trial practice blocks of the masked condition with the DBS masker only. This practice included two blocks each for the two spatial separation conditions. The S/M was fixed at +15 dB for the first block and +10 dB for the second block.

Each response was considered correct only if both the color and number of the signal sentence were identified accurately. The psychometric functions were fit by the Nelder-Mead simplex method (FMINS function in MATLAB) with a logistic of the form

$$p(c)=\alpha+((1.0-\alpha)/(1.0+e^{-k(x-m)})), \tag{1}$$

where $\alpha=0.031\,25$ (chance performance for 1 out of 32), k is the slope of the function, m is the level of the midpoint (about 51.5% correct), and x is the signal sentence level.

III. RESULTS

The amount of spatial release (SR) from masking was calculated as the S/M required for 51% correct performance for the 0° condition minus that for the 90° condition. The amount of informational masking created by the DBS masker was estimated by taking the difference between the midpoints of the psychometric functions for the DBS and DBN maskers presented at 0°. This estimate was based on the type of masking each of the two maskers was intended to produce as discussed above. The purpose of the estimate of informational masking in the current study was to provide a means of comparing performance between listeners and groups.

All listeners were able to perform the task with greater than 90% accuracy in quiet within the first one to two practice blocks. Practice performance for the signal presented with the informational masker was generally good, ranging from 76% to 100% correct, depending on spatial separation and S/M. Masker SLs for the NH group ranged from 33.5 to 43.9 dB with a mean of 38.4 dB. Masker SLs for the HI group ranged from 21.5 to 38.5 dB with a mean of 32.5 dB.

All psychometric functions were orderly and monotonic. Overall, the results were consistent with those from the earlier study (Arbogast *et al.*, 2002), which did not exhibit performance plateaus or dips at S/Ms just below 0 dB. The logistic fits to both the NH and HI data were very good. The

TABLE II. Signal-to-masker ratio at m for the normal-hearing listeners for the two spatial separation conditions. The results for each masker are given in separate subtables. Quiet threshold (Quiet) in dB SPL and masker sensation level (SL) in dB, as well as variance accounted for by the logistic fit (var), are also included. The final column gives the difference between spatial conditions for m.

Listener	Quiet	SL	0° separation S/M	0° separation var	90° separation S/M	90° separation var	0°–90° m
A. Different-band sentence masker							
1	16.5	33.5	−17.4	>0.99	−23.7	>0.99	6.3
2	21.9	38.1	4.3	0.98	−14.8	0.98	19.1
3	18.8	36.2	−0.1	>0.99	−10.0	0.96	10.0
4	16.7	38.3	1.1	>0.99	−14.9	0.97	16.0
5	18.0	42.0	−4.0	0.96	−19.7	>0.99	15.7
6	10.0	40.0	−0.9	0.98	−17.9	>0.99	17.0
7	6.1	43.9	−7.8	0.98	−22.8	0.99	15.0
8	11.4	38.6	−4.6	0.99	−26.0	0.95	21.4
9	13.1	36.9	−1.0	0.98	−14.7	>0.99	13.6
10	18.4	36.6	−1.3	0.99	−20.1	0.98	18.7
Average	**15.1**	**38.4**	**−3.2**	⋯	**−18.5**	⋯	**15.3**
s.d.	**4.8**	**3.0**	**6.0**	⋯	**4.9**	⋯	**4.5**
B. Different-band noise masker							
1	16.5	33.5	−27.4	0.99	−28.9	0.99	1.5
2	21.9	38.1	−22.3	0.98	−28.4	>0.99	6.1
3	18.8	36.2	−22.8	>0.99	−26.2	>0.99	3.4
4	16.7	38.3	−23.7	>0.99	−25.2	0.99	1.6
5	18.0	42.0	−23.5	>0.99	−25.7	>0.99	2.2
6	10.0	40.0	−25.6	>0.99	−30.0	>0.99	4.4
7	6.1	43.9	−28.8	>0.99	−32.4	0.99	3.5
8	11.4	38.6	−29.4	0.99	−33.6	0.92	4.1
9	13.1	36.9	−25.5	>0.99	−27.8	>0.99	2.3
10	18.4	36.6	−23.1	>0.99	−26.8	>0.99	3.7
Average	**15.1**	**38.4**	**−25.2**	⋯	**−28.5**	⋯	**3.3**
s.d.	**4.8**	**3.0**	**2.6**	⋯	**2.8**	⋯	**1.4**
C. Same-band noise masker							
1	16.5	33.5	−1.7	0.99	−7.3	0.99	5.6
2	21.9	38.1	1.9	0.99	−5.9	>0.99	7.8
3	18.8	36.2	−0.9	0.99	−5.0	0.99	4.1
4	16.7	38.3	2.4	0.99	−2.6	0.99	5.1
5	18.0	42.0	−0.2	>0.99	−4.1	>0.99	3.9
6	10.0	40.0	0.0	>0.99	−6.1	>0.99	6.2
7	6.1	43.9	−0.2	0.99	−8.9	0.99	8.7
8	11.4	38.6	−0.7	>0.99	−8.5	0.99	7.8
9	13.1	36.9	−0.6	>0.99	−4.9	0.98	4.3
10	18.4	36.6	−0.1	0.99	−5.8	0.99	5.7
Average	**15.1**	**38.4**	**0.0**	⋯	**−5.9**	⋯	**5.9**
s.d.	**4.8**	**3.0**	**1.3**	⋯	**1.9**	⋯	**1.7**

variance accounted for by the fit in each instance was greater than 92%, and in most cases it was 98% or better. Tables II and III list the S/M at the midpoint (m) from the fitted psychometric functions for NH and HI listeners, respectively. HI listeners are numbered in the same manner as in Table I (ordered by quiet threshold). Each NH listener was matched with a HI listener by age, and then given the same number as their HI counterpart.

A. Signal-to-masker ratios

Figure 3 plots the mean S/M at the midpoint of the psychometric function for the two listener groups and spatial separation conditions. Each panel is for a different masker.

The figure reveals that S/M varied with masker type, listener group, and spatial separation condition. The significance of these variations is discussed in more detail below in the context of a statistical analysis of the data.

1. Factors influencing S/M

The S/M data were submitted to an ANOVA with one between-subjects factor (group—NH/HI) and two within-subjects factors (masker and spatial separation). All three main effects were significant: masker [$F(2,36)=330.6$, $p<0.001$], spatial separation [$F(1,18)=237.6$, $p<0.001$], and group [$F(1,18)=20.6$, $p<0.001$]. *Posthoc* simple contrasts revealed that the average S/M ratio for each masker was significantly different from the others. The interaction of masker and spatial separation was significant [$F(2,36)=76.1$, $p<0.001$] as well as the interaction of masker and

TABLE III. Same as Table II, but for the hearing-impaired listeners.

Listener	Quiet	SL	0° separation S/M	0° separation var	90° separation S/M	90° separation var	0°–90° m
			A. Different-band sentence masker				
1	36.7	38.3	−3.3	>0.99	−16.2	0.98	12.9
2	37.0	31.0	1.9	0.98	−7.4	0.98	9.2
3	39.5	38.5	1.2	0.99	−10.9	0.99	12.0
4	40.4	37.6	2.4	0.95	−7.3	0.99	9.7
5	43.3	34.7	2.1	0.99	−6.3	0.99	8.4
6	43.5	34.5	−1.9	0.98	−15.2	0.99	13.3
7	44.0	34.0	−2.2	0.99	−14.8	>0.99	12.6
8	45.7	32.3	−2.0	0.99	−12.5	0.96	10.5
9	55.2	22.8	3.6	0.99	−0.4	>0.99	4.0
10	56.5	21.5	3.7	0.98	1.6	0.99	2.0
Average	**44.2**	**32.5**	**0.5**	⋯	**−8.9**	⋯	**9.5**
s.d.	**6.8**	**6.0**	**2.6**	⋯	**6.1**	⋯	**3.8**
			B. Different-band noise masker				
1	36.7	38.3	−18.7	0.98	−22.4	0.99	3.7
2	37.0	31.0	−15.4	>0.99	−22.5	0.99	7.0
3	39.5	38.5	−12.0	>0.99	−15.6	>0.99	3.5
4	40.4	37.6	−9.0	>0.99	−17.2	0.99	8.2
5	43.3	34.7	−7.8	>0.99	−12.3	0.99	4.5
6	43.5	34.5	−16.7	0.99	−18.3	>0.99	1.6
7	44.0	34.0	−15.7	0.99	−18.6	>0.99	2.9
8	45.7	32.3	−13.4	>0.99	−17.7	>0.99	4.3
9	55.2	22.8	−5.8	0.99	−7.2	>0.99	1.4
10	56.5	21.5	−3.5	0.98	−6.8	0.99	3.3
Average	**44.2**	**32.5**	**−11.8**	⋯	**−15.9**	⋯	**4.0**
s.d.	**6.8**	**6.0**	**5.1**	⋯	**5.5**	⋯	**2.1**
			C. Same-band noise masker				
1	36.7	38.3	−0.8	>0.99	−9.8	>0.99	9.0
2	37.0	31.0	1.3	>0.99	−7.7	0.99	9.0
3	39.5	38.5	0.6	0.99	−5.4	0.99	6.0
4	40.4	37.6	2.3	0.97	−3.4	0.99	5.7
5	43.3	34.7	1.6	>0.99	−4.7	>0.99	6.2
6	43.5	34.5	−1.1	>0.99	−6.9	0.99	5.8
7	44.0	34.0	−0.6	>0.99	−9.0	>0.99	8.4
8	45.7	32.3	−1.4	>0.99	−8.8	>0.99	7.4
9	55.2	22.8	1.5	0.99	−3.0	0.99	4.4
10	56.5	21.5	1.4	0.99	−0.5	0.96	1.9
Average	**44.2**	**32.5**	**0.5**	⋯	**−5.9**	⋯	**6.4**
s.d.	**6.8**	**6.0**	**1.3**	⋯	**3.0**	⋯	**2.2**

group [$F(2,36)=41.1$, $p<0.001$]. The three-way interaction between masker, group, and spatial separation was also significant [$F(2,36)=13.1$, $p<0.001$].

Three important points regarding the S/M data were confirmed by the ANOVA results. First, the masker by group interaction revealed that S/M was greater for the HI group than the NH group for the DBS and DBN maskers, but not for the SBN masker. Perhaps most importantly, for the DBN masker the HI group S/M was 13 dB greater than for the NH group. Recalling that the DBN masker estimates energetic masking in the DBS masker, this indicates that the HI group experienced significantly more energetic masking than the NH group for both the DBN and DBS maskers. Second, the main effect of masker and posthoc tests revealed that the DBS masker resulted in a significantly greater S/M than the DBN masker, suggesting that a substantial amount of informational masking was produced by the DBS masker. At 0° the DBS masker caused an additional 22.0 dB of masking in the NH group and an additional 12.3 dB of masking in the HI group. Third, SR depends on both the type of masker and the listener group.

This three-way interaction is illustrated in Fig. 4 which plots the SR obtained by each group for each of the three maskers. To investigate this interaction further, three one-way ANOVAs were performed on the SR data, one for each masker type, with group as the single between-subjects factor. The results revealed that the SR for the DBS masker was significantly greater for the NH group (15.3 dB) than for the HI group (9.5 dB) [$F(1,18)=9.9$, $p<0.01$]. However, the SR for the other two maskers was similar for the two groups (3.3 and 4.0 for the DBN [$F(1,18)=0.9$, $p=0.37$]; 5.9 and 6.4 for the SBN [$F(1,18)=0.3$, $p=0.59$], for NH and HI, respectively).

Although the HI group obtained a smaller SR than the NH group for the DBS masker, the HI group's advantage was still larger for this masker than it was for the SBN masker (by about 3 dB on average). However, this 3-dB mean difference in SR between the DBS and SBN maskers for the HI

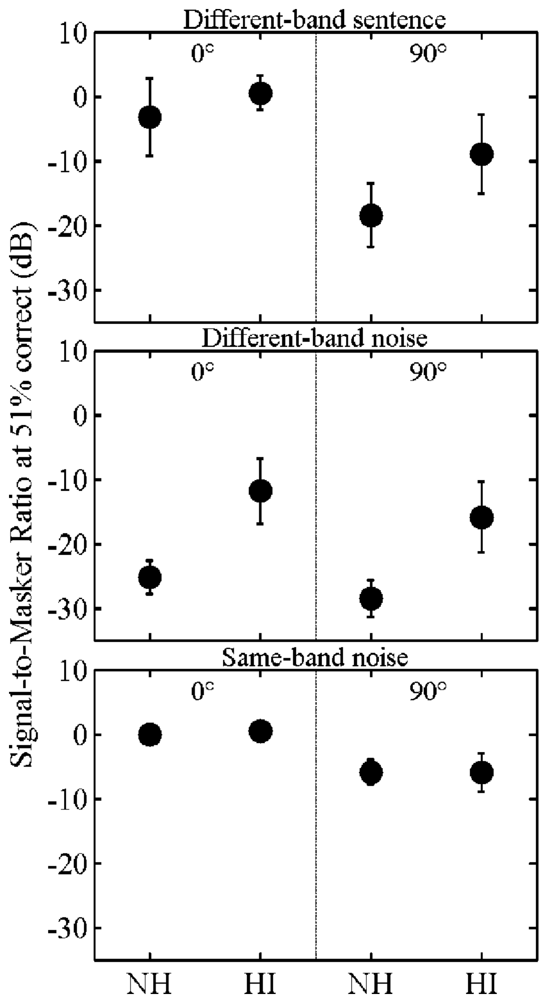

FIG. 3. Group mean signal-to-masker ratios at the 51% correct point on the psychometric function plotted for each listener group (NH/HI). The top panel is for the DBS masker, the middle is for the DBN masker, and the bottom panel is for the SBN masker. Data for the 0° separation condition are plotted in the left half of each panel, and the 90° separation data are plotted in the right half of each panel. The error bars are ±1 standard deviation.

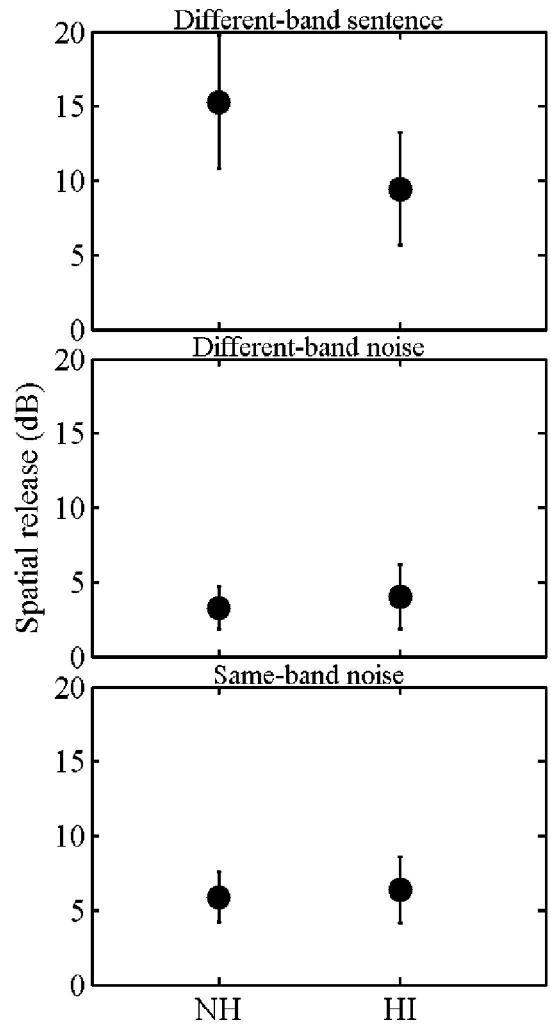

FIG. 4. Spatial release from masking for the two listener groups. The top panel is for the DBS masker, the middle panel is for the DBN masker, and the lower panel is for the SBN masker. The data are group means and the error bars are ±1 standard deviation.

group is small relative to the nearly 10-dB difference found for the NH group.

2. Factors related to spatial release from informational masking

The NH and HI groups differed in SR for the DBS masker only. Therefore, a correlational analysis was performed which focused on the SR from this masker. One of the factors investigated was an estimate of the amount of informational masking produced by the DBS masker. The DBS masker produced a mean of 22.0 dB of informational masking in the NH group, but a mean of only 12.3 dB of informational masking in the HI group. The majority of the difference between groups can be accounted for by the difference in S/M for the DBN masker (13 dB greater for the HI group than the NH group).

For the NH group, Pearson correlation coefficients were not significant ($p>0.05$) between SR for the DBS masker and the factors of age ($r=0.38$), quiet threshold ($r=-0.09$), or masker SL ($r=0.45$). SR in the NH group was significantly correlated with the estimated amount of informational masking ($r=0.74$, $p<0.02$). However, a single outlier (NH1) appeared to be responsible for this significant relation. When the outlier was excluded, the correlation was no longer significant ($r=0.3$, $p=0.39$).

For the HI group, SR was significantly correlated with the amount of informational masking ($r=0.76$, $p<0.01$). In addition, SR was correlated with age ($r=-0.81$, $p<0.01$), quiet threshold ($r=-0.81$, $p<0.01$), masker SL ($r=0.88$, $p<0.01$), and the mean word recognition score for the two ears ($r=0.65$, $p<0.05$). SR was not significantly related to hearing aid use ($r=-0.4$, $p=0.29$), length of hearing aid use ($r=-0.2$, $p=0.69$), or length of hearing loss ($r=-0.4$, $p=0.32$). Age and quiet threshold were not significantly correlated with each other ($r=0.39$, $p=0.27$) and, therefore, these two factors may have influenced SR independently. However, quiet threshold and masker SL were significantly correlated with each other ($r=-0.88$, $p<0.01$), as expected because the masker level was mainly determined by quiet threshold. However, the existence of this correlation means that the relation between SR and quiet threshold may have been a by-product of masker SL. In order to tease these variables apart, a stepwise regression analysis was performed with SR from the DBS masker as the dependent variable and amount of informational masking, age, quiet threshold, masker SL, and mean word recognition score as the independent variables. The analysis revealed that the combination of amount of informational masking, masker SL, and age explained 97% of the variance in SR from the DBS masker ($p < 0.05$ for all three variables). Quiet threshold and mean word recognition score did not significantly increase the variance accounted for ($p > 0.10$). Type II partial correlations (variable added last) revealed that the amount of informational masking accounts for 6%, masker SL accounts for 12%, and age accounts for 10% of the variance in SR from the DBS masker.

3. The influence of masker sensation level on spatial release from informational masking

Overall, the HI group was tested at a lower masker SL (32.5 dB) than the NH group (38.4 dB). While the mean difference in sensation level was not large, individual sensation levels ranged from 21.5 dB up to 43.9 dB. Therefore, the analysis above was repeated after excluding two from each group. The masker SL for each of these four listeners was more than 1 standard deviation from the mean masker SL of all 20 listeners. NH5, NH7, HI9, and HI10 were excluded. After excluding these listeners, group mean masker sensation levels were 37.3 dB for the NH group and 35.1 dB for the HI group.

SR for the DBS masker remained larger for the revised NH group (15.3 dB) than for the revised HI group (11.1 dB). However, SR for the revised HI group was larger than for the original HI group (9.5 dB). The small increase in SR was mainly due to better performance in the 90° condition. An independent-sample t-test revealed that the SR for the DBS masker was not significantly different between the revised NH and HI listener groups [$t(8.9) = 2.2$, $p = 0.06$].

Four of the NH listeners (NH2, NH5, NH8, and NH10) were retested using a lower masker sensation level. The mean masker SL was 38.8 dB for their first run through the experiment. The second time through the experiment, the mean masker SL was 25.8 dB. SR averaged 18.7 dB for the higher masker SL and 12.3 dB for the lower masker SL. This difference just missed reaching significance on a paired-sample t-test [$t(3) = 2.7$, $p = 0.07$], perhaps due to the small number of listeners. However, in all four cases, SR from the DBS masker was smaller for the lower masker SL than for the higher masker SL.

B. Errors

The proportion of incorrect responses matching the masker sentence was calculated excluding data at the lowest and highest signal levels tested for each listener. This left two signal levels in the middle of the psychometric function from which to analyze the error patterns. Very low S/Ms were excluded because listeners may have purposely responded with some other color/number combination than that heard clearly from the masker sentence in order to increase their chance of guessing correctly. Very high S/Ms were excluded because few errors occurred.

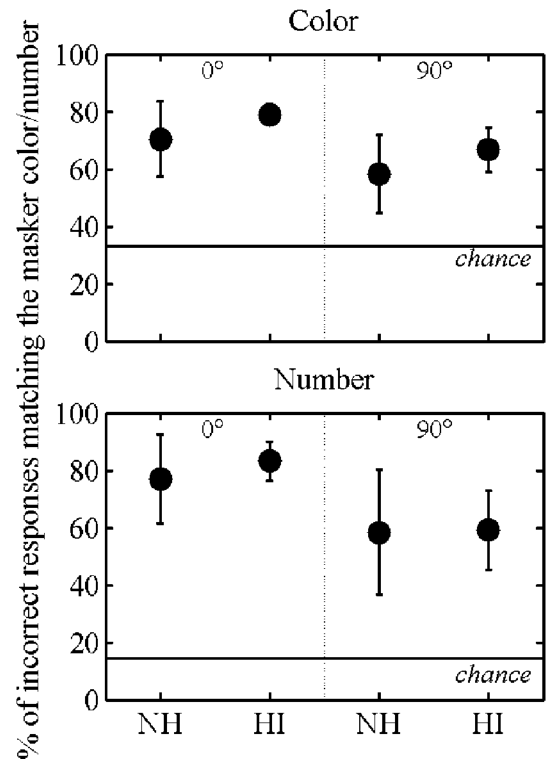

FIG. 5. Percent of incorrect responses that matched the DBS masker color (top panel) or number (lower panel) for the two listener groups. The 0° data are in the left half of each panel and the 90° data are in the right half. The data are group means and the error bars are ± 1 standard deviation. The percent of errors expected by chance is given by the solid line in each panel (33.3% for color and 14.3% for number).

Figure 5 shows the mean percent of errors that matched the DBS masker color and number for the two spatial separation conditions and listener groups. The top panel is for the color response and the lower panel is for the number response. The percent of errors expected for a random distribution of incorrect responses is indicated by the solid line in each panel (33.3% for color; 14.3% for number).

The mean percents of errors from the masker for the NH group in the 0° condition were 70% and 77% for color and number, respectively; for the HI group they were 79% and 83%, respectively. This indicates that listeners in both groups often confused the signal and masker sentences when they were played from the same location. In the 90° condition, the percents of errors from the masker for the NH group were 58% each for color and number; and for the HI group they were 67% and 59% for color and number, respectively. Therefore, both groups of listeners confused the signal and masker sentences less often in the 90° condition than in the 0° condition. A repeated-measures ANOVA with group as the between-subjects factor and spatial separation as the within-subjects factor confirmed a significant main effect of spatial separation for both color [$F(1,18) = 32.37$, $p < 0.001$] and number [$F(1,18) = 28.86$, $p < 0.001$]. However, the main effect of group just missed significance for the color response [$F(1,18) = 4.3$, $p = 0.053$], and was not significant for the number response [$F(1,18) = 0.39$, $p = 0.54$]. The interaction of spatial separation and group was also not significant for color [$F(1,18) \sim = 0$, $p = 0.99$] or number [$F(1,18) = 0.50$, $p = 0.49$].

IV. DISCUSSION

A. Informational and energetic masking

Consistent with Arbogast *et al.* (2002), the DBS masker appears to have produced the intended type of masking in both normal-hearing and hearing-impaired listeners. The DBS masker caused 22 dB of informational masking for the normal-hearing group and 12 dB of informational masking for the hearing-impaired group. In a different group of normal-hearing listeners Arbogast *et al.* (2002) also found 22 dB of informational masking. The large proportion of confusions, in both listener groups, between the signal and DBS masker also supports the interpretation that a significant amount of informational masking was present (Brungart, 2001; Brungart *et al.*, 2001; Arbogast *et al.*, 2002). For the 0° condition, both listener groups responded with the masker color and number an average of 75% and 80% of the time, respectively. In the previous group of normal-hearing listeners, Arbogast *et al.* (2002) found the same.

However, the DBS masker produced less informational masking in the hearing-impaired group than in the normal-hearing group. This may be due to greater energetic masking in hearing-impaired than normal-hearing listeners as measured by the DBN masker,[4] probably as a result of wider auditory filters (e.g., Glasberg and Moore, 1986; Leek and Summers, 1993). The greater amount of energetic masking for the DBN masker for the hearing-impaired group suggests that they will experience a greater amount of energetic masking for the DBS masker also. There are at least two reasons why more energetic masking in the DBS masker might lead to less informational masking in that same masker. One reason is a ceiling effect. Given the baseline S/M due to energetic masking (DBN masker) for the hearing-impaired group (-12 dB), if the DBS masker produced the same amount of informational masking as in normal-hearing listeners (22 dB), one would expect the DBS masker to result in a mean midpoint S/M of about $+10$ dB for the hearing-impaired group (-12 dB $+22$ dB of informational masking$=+10$ dB). However, the actual mean for this group was close to 0 dB S/M. The hearing-impaired listeners may have been able to segregate the signal and masker sentences when the signal sentence was louder than the masker sentence. Therefore, there may have been a critical point just beyond 0 dB S/M for which the available/effective cues changed and the task became relatively easy. Most of the normal-hearing listeners did not reach that ceiling because of the lower S/M for the DBN masker. Brungart (2001), using the (unprocessed) CRM materials and test procedures, reported that performance in speech on speech masking for two different same-sex talkers (one target, one masker) was at about 60% correct at 0 dB S/M. Increasing the level of the target by only 6 dB increased performance to nearly 90% correct, consistent with the proposition that a positive S/M drives performance rapidly toward asymptote.

It is also possible that within a single masker, informational masking decreases when energetic masking increases. Kidd *et al.* (2003) measured harmonicity discrimination of a multi-tone complex in the presence of multi-tone informational maskers. The binaural advantage decreased as the number of components in the informational masker increased. The interpretation was that increasing the number of components resulted in an increase in energetic masking because masker components were more likely to fall close in frequency to signal components. The increase in energetic masking caused a decrease in informational masking, resulting in a reduced binaural advantage. Similarly, other studies have reported a decrease in informational masking when energetic masking was increased by increasing the number of tones in a multi-tone masker for the task of detecting a pure-tone signal (e.g., Neff and Green, 1987; Oh and Lutfi, 1998).

B. Spatial release from masking

1. DBN masker

The spatial release from the DBN masker averaged 3.7 dB for all 20 listeners, and was not significantly different for the two listener groups. This is very similar to the 3.6-dB release from this same masker found by Arbogast *et al.* (2002) in normal-hearing listeners. It is difficult to compare this result to that of previous research because the masking was off-frequency and mainly energetic. However, one might expect a smaller release from this masker than from an on-frequency energetic masker based on the results of Zwicker and Henning (1984). They found that the masking level difference decreased significantly when the signal and masker did not overlap in frequency than when they were spectrally matched.

2. SBN masker

The mean spatial release from the SBN masker was 6.1 dB for all listeners, and was also not significantly different for the two listener groups. This value is consistent with that found by Arbogast *et al.* (2002) for the same masker (6.9 dB). Similarly, previous research has found spatial release from energetic masking in the range of 5 to 10 dB (Hawley, 2000; Duquesnoy, 1983; Peissig and Kollmeier, 1997; Bronkhorst and Plomp, 1988, 1989, 1990, 1992; Freyman *et al.*, 1999; Zurek, 1993) for a 90° separation between signal and masker. Other studies of hearing-impaired listeners have found mean spatial releases from energetic masking for suprathreshold speech recognition that are somewhat smaller than that found for normal-hearing listeners in the same study (Peissig and Kollmeier, 1997; Duquesnoy, 1983; Bronkhorst and Plomp, 1989). However, similar to the current research, two studies have found that the hearing-impaired group obtained nearly the same release (within 1.5–2 dB) as the normal-hearing group (Bronkhorst and Plomp, 1990; 1992).

3. DBS masker

The mean spatial release from the DBS masker was significantly larger for the normal-hearing group (15.3 dB) than for the hearing-impaired group (9.5 dB). However, for both groups, the spatial release from the DBS masker was significantly larger than the spatial release from either of the other two maskers. The size of the effect for the normal-hearing listeners was smaller than the 18.4-dB release found by Arbogast *et al.* (2002) for the same masker. This difference may be attributed to the number and mix of listeners tested. The previous study tested four listeners and the range of spatial release produced was only 4 dB. All four listeners were fairly similar to each other for this task. In the current study, the range of spatial release was 15 dB. There were two listeners in particular (NH1 and NH3) with fairly small spatial releases. NH1 performed extremely well for the 0° condition and therefore could not improve by a large amount for the 90° condition. NH3, for some unknown reason, did not perform as well as the other normal-hearing listeners for the 90° condition.

Other studies have also found significant differences in spatial release between informational and energetic maskers. Kidd *et al.* (1998), using pure-tone stimuli, and Freyman *et al.* (1999), using natural speech stimuli, found that the spatial release from a masker producing a high proportion of informational masking was significantly larger than from a masker producing a high proportion of energetic masking. In Kidd *et al.* (1998), the release was 0 to 20 dB larger than the corresponding release from an energetic masker, depending on the listener and the signal frequency. In Freyman *et al.* (1999), the release was about 6 dB larger than from an energetic masker. Therefore, the larger spatial release found in the current study is consistent with the presence of a significant amount of informational masking. The expected spatial release due to binaural interaction and headshadow effects for the DBS masker can be estimated from the DBN masker, which had the same long-term magnitude spectrum as the DBS masker, but minimal informational masking. The release for this control masker was only 3.7 dB. Therefore 5 dB (for the hearing-impaired listeners) to 11 dB (for the normal-hearing listeners) of the spatial effect was beyond that expected for a primarily energetic masker with the same long-term magnitude spectrum as the DBS masker, and therefore most likely attributable to release from informational masking.

It is difficult to compare the results for the DBS masker to other speech research because, in addition to using natural speech stimuli (for which the ratio of informational to energetic masking likely is smaller), stimuli were configured in a way that inadvertently reduced informational masking (reduced stimulus uncertainty by holding the masker sentence constant and/or used a strong segregation cue such as male versus female) in order for the listener to be able to label the signal sentence. Therefore, energetic masking probably played the dominant role in much of this work and the results are more comparable to those found for the SBN masker of the current study. For normal-hearing listeners, Hawley *et al.* (2004) did find a larger spatial release (10–12 dB) from two- and three-talker maskers (where all talkers were the same as the signal talker) than from a two- or three-talker speech-shaped noise or speech-envelope-modulated speech-shaped noise (6–7 dB). However, these conditions were not tested in hearing-impaired listeners.

The results of previous research using pure-tone stimuli have suggested that hearing-impaired listeners do not benefit as much as normal-hearing listeners from segregation of a signal from an informational masker using cues other than spatial separation (cf. Kidd *et al.*, 2002a; Grose and Hall, 1996). Although the results of the current study appear to agree, two factors complicate this interpretation. One factor is that not all listeners in this study were tested at approximately the same masker sensation level and this appears to have at least partially influenced the results, as illustrated by the results of the reanalysis taking sensation level into account. The second factor, which may be related, is that the DBS masker did not produce as much informational masking in the hearing-impaired listeners as in the normal-hearing listeners. If both of these factors were carefully controlled, the difference between groups might very well diminish. Controlling for sensation level is entirely feasible, but controlling for informational masking may be more of a challenge.

Sensation level may have an impact on spatial release because both may be related to the amount of informational masking produced. Alexander and Lutfi (2003) found that informational masking decreased with decreasing masker sensation level in pure-tone stimuli. In addition, it is logical that as informational masking decreases, spatial release from informational masking will also decrease because there is less masking from which to be released. However, the reason for the relation between sensation level and amount of informational masking is not clear. The current research also found other factors relating to spatial release from the DBS masker in the hearing-impaired listeners, including (but not limited to) quiet threshold, age, and word recognition score.

Spatial release from informational masking was also reflected in the errors made by both groups of listeners. When the DBS masker was moved to the 90° position, the percents of incorrect responses matching the masker sentence dropped significantly by 12 and 20 percentage points for color and number responses, respectively. The decreased confusion between signal and masker implies a release from informational masking. This is similar to the finding of Brungart (2001) that when natural signal and masker sentences were segregated by voice fundamental frequency there was a decrease in the number of signal-masker confusions relative to when the two sentences were from the same talker or same-sex talkers.

The larger spatial advantage for the DBS masker than for the SBN masker implies that the perceptual effect of spatial separation between signal and masker (Freyman *et al.*, 1999, 2001; Arbogast *et al.*, 2002) can be used by both normal-hearing and hearing-impaired listeners to decrease informational masking. The ability to perceive that the signal and masker originate from separate locations in space allows the listener to label each sentence appropriately as "signal" or "masker," effectively reducing confusion between the two sentences, thus reducing informational masking. This implies that the higher-level processes that allow for this perceptual effect are functioning effectively in listeners with peripheral hearing loss. This is consistent with the results of Noble *et al.* (1997), showing that both normal-hearing and hearing-impaired listeners can correctly indicate when two simultaneously presented, equal-level, suprathreshold sources (speech and noise) are spatially separated by 54° more than 85% of the time. Larger azimuthal separations were not tested, but one could speculate that performance would be at least equal to, if not better than, 85% for a 90° separation. The current research, however, cannot determine if these higher-level processes in hearing-impaired listeners are functioning as well as they do in normal-hearing listeners. While the statistical results of the equal sensation level comparison suggest that they are, the hearing-impaired listeners still did not achieve the same spatial release as the normal-hearing listeners at equivalent sensation levels. In addition, the amount of informational masking created in each listener group differed, confounding the interpretation of the results. However, because listeners with hearing loss were able to benefit significantly from the perceptual effect of spatial separation, it is important to design and fit auditory prostheses in a way that retains the cues that underlie this perceptual effect. The most basic approach would be to provide bilateral amplification for bilateral hearing losses, when appropriate.

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[1]In the current document, the general term "hearing impaired," "hearing impairment," or "hearing loss" will always refer to sensorineural hearing loss, presumably of cochlear origin.

[2]Although unintelligible, we cannot rule out the possibility that the DBN masker produced a small amount of informational masking because of the trial-to-trial uncertainty about the frequencies of the bands comprising the masker.

[3]The temporal modulation characteristics of DBS and DBN maskers have recently been studied by Kidd *et al.* (2004). They found that the envelope spectra of the two are similar with maxima in the 1–5-Hz region and a reduction in magnitude above 10 Hz. The envelope spectrum for the DBN has a slightly higher dc component than the DBS and varies smoothly over the range measured. The DBS masker, however, has small peaks roughly corresponding to modulation frequencies that are the inverse of the durations expected of syllables and words. The measured correlation between the envelopes of the DBS and the DBN maskers derived from the same speech sample was near zero.

[4]This statement is made based on S/Ms at the midpoints of the psychometric functions for the DBN masker played at 0° (−25 dB for the NH group; −12 dB for the HI group). Another way to compare groups in terms of energetic masking is to calculate the threshold shift from quiet for the DBN masker. Using this method, the amount of energetic masking is still significantly larger in the HI group (20.7 dB) than the NH group (13.2 dB), but the difference between groups is smaller (7 dB) than when calculated using S/M (13 dB).

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