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The Effects of Speech and Speechlike Maskers on Unaided and Aided Speech Recognition in Persons with Hearing Loss

Benjamin W. Y. Hornsby*
Todd A. Ricketts*
Earl E. Johnson*

Abstract

Speech understanding in noise is affected by both the energetic and informational masking components of the background noise. In addition, when the background noise is everyday speech, the relative contributions of the energetic and informational masking components to the overall difficulties in understanding speech are unclear. This study estimated informational masking effects, in conversational speech settings, on the speech understanding of persons with and without hearing loss. The benefits and limitations of amplification in settings containing both informational and energetic masking components were also explored. Speech recognition was assessed in the presence of two types of maskers (speech and noise) that varied in the amount of informational masking they were expected to produce. Persons with hearing loss were tested both unaided and aided. Study results suggest that background noise, consisting of individual talkers, results in both informational and energetic masking. In addition, the benefits of amplification are limited when the background noise contains both informational and energetic masking components.

Key Words: Hearing aids, hearing loss, informational masking, perceptual masking, speech intelligibility

Abbreviations: HI = hearing impairment; HINT = Hearing in Noise Test; NH = normal hearing; NM = speech modulated noise masker; SM = speech masker; SNHL = sensorineural hearing loss

Sumario

La comprensión del lenguaje en medio del ruido se ve afectada por los componentes de energía y de información del enmascaramiento producido por el ruido de fondo. Además, cuando el ruido de fondo es el lenguaje cotidiano, no es claro cuáles son las contribuciones relativas de los componentes de energía y de información del enmascaramiento, en relación con las dificultades globales para entender el lenguaje. El estudio estimó los efectos del enmascaramiento sobre la información en situaciones de lenguaje de conversación, para efectos de comprensión del lenguaje en personas con y sin

*Department of Hearing and Speech Science, Vanderbilt Bill Wilkerson Center, Vanderbilt University

Benjamin Hornsby, Vanderbilt University Medical Center, Dan Maddox Hearing Aid Research Laboratory, Department of Hearing and Speech Sciences, Room 8310 Medical Center East, South Tower, 1215 21st Ave. South, Nashville, TN 37232-8242; Phone: 615-936-5132; Fax: 615-936-5013; E-mail: ben.hornsby@vanderbilt.edu

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trastornos auditivos. También se exploraron los beneficios y limitaciones de la amplificación en situaciones que involucraban tanto los componentes energéticos como los de información del enmascaramiento. El reconocimiento del lenguaje se evaluó en presencia de dos tipos de enmascaradores (lenguaje y ruido), que variaron en la cantidad de enmascaramiento de la información esperado. Las personas con hipoacusia fueron evaluados con y sin auxiliares auditivos. Los resultados del estudio sugieren que el ruido de fondo, constituido por hablantes individuales, confiere tanto un enmascaramiento energético como de información. Además, los beneficios de la amplificación son limitados cuando el ruido de fondo contiene componentes tanto de enmascaramiento de la energía como de la información.

Palabras Clave: Auxiliares auditivos, pérdida auditiva, enmascaramiento de la información, enmascaramiento perceptual, inteligibilidad del lenguaje

Abreviaturas: HI = instrumento auditivo; HINT = Prueba de Audición en Ruido; NH = audición normal; NM = enmascarador de ruido con lenguaje modulado; SM = enmascarador de lenguaje; SNHL = hipoacusia sensorineural

The negative effects of background noise on the speech understanding of persons with hearing impairment are well documented (e.g., Van Tasell, 1993; Humes, 2002). Although improving audibility through amplification can result in improvements in speech understanding in noise, the benefits are often less than that observed for persons without hearing loss listening under conditions of comparable audibility (Plomp, 1986; Rankovic, 1991; Ching et al, 1998; Turner and Henry, 2002; Hornsby and Ricketts, 2003). This difficulty understanding in noise is due largely to the masking effects of the background competition. When listening to speech in a background of noise consisting of other talkers, at least two types of masking may occur. The most well-described masking effects originate in the auditory periphery (i.e., cochlea or proximal portions of the auditory nerve) and occur when the excitation or neural response in a given frequency range, due to the target, is less than that produced by the background noise. This type of masking has been referred to as "energetic masking," and its effects on threshold and speech understanding are, on average, quite predictable, at least for persons with normal hearing (e.g., French and Steinberg, 1947; American National Standards Institute, 1997).

When the background noise contains speech, however, "perceptual" or "informational" masking may occur in addition to energetic masking (Carhart et al, 1969; Carhart et al, 1975; Hawley et al, 1999, 2004; Brungart, 2001a; Brungart et al, 2001; Arbogast et al, 2002, 2005). Carhart and colleagues (1969) used the term "perceptual masking" to refer to the additional masking observed when the masker consisted of actual talkers compared to modulated noise. More recently the term "informational masking," which was originally used to describe results from certain types of masking experiments with nonspeech stimuli, has been used to describe this effect (e.g., Hawley et al, 1999; Brungart, 2001a; Arbogast et al, 2005).

A precise definition of informational masking is currently a matter of debate. In general, however, informational masking may be described as masking that is not energetic in nature, thus implying more "central" masking effects (e.g., Durlach et al, 2003). Informational masking may occur with nonspeech signals when there are high levels of uncertainty regarding the target stimulus or masker (Watson et al, 1976; Lutfi, 1989). Informational masking may also occur, with speech signals, particularly when the background competition is also speech. In cases where informational masking occurs, both the target speech and competition are audible to the listener, yet the listener has difficulty separating the target and competition due to similarities in their temporal and/or semantic structure (Brungart, 2001a; Brungart et al, 2001). Although energetic masking may exist in these types of situations, it does not appear to be the only factor limiting speech understanding given that, by definition, both the target and masking speech are intelligible.

Under some experimental conditions, informational masking effects in speech tasks have been shown to be quite large. Brungart and colleagues (Brungart, 2001a; Brungart et al, 2001) estimated informational masking effects, in persons with normal hearing, using the Coordinate Response Measure test (CRM; Bolia et al, 2000; Brungart, 2001b). The CRM is a speech recognition test in which the target and masker sentences have the same semantic and syntactic structure, making them highly confusable and therefore useful in exploring informational masking effects. In one experiment, Brungart et al (2001) compared speech understanding using CRM sentences as maskers (high informational masking condition) to speech understanding when listening to a primarily energetic, modulated noise masker with the same long-term spectral shape and the long-term temporal envelope of the CRM speech maskers. When four maskers were used, the authors reported an approximate 80% decrease in monaural speech understanding. Specifically, the performance of persons with normal hearing was evaluated in the presence of a four-talker speech masker and a noise modulated with the envelope of a four-talker speech masker (Brungart et al, 2001). In this example, however, the decrease in speech recognition was due to a combination of energetic and informational masking (as is the case when any broadband stimulus is used as both the target and masker). In addition, because potential differences in the energetic masking properties of the speech and noise maskers exist, it is difficult to parse out the magnitude of the informational and energetic masking effects on these results.

In a series of well-controlled studies, Arbogast et al (2002, 2005) attempted to isolate the effects of informational and energetic maskers by creating sinewave speech targets and maskers. Sinewave speech is created by modulating pure tones of a given frequency with the amplitude envelope of actual speech filtered at that center frequency. In one condition the masker consisted of sinewave speech with frequency components that were in disparate frequency bands than those for the sinewave target speech, thus minimizing energetic masking effects. In this condition an additional 22 dB of masking was observed in participants with normal hearing, compared to that seen with a primarily energetic masker.

Although informational masking effects can be quite large in some laboratory conditions, the magnitude of informational masking that occurs in everyday speech environments is unclear. Several factors that are common in everyday speech environments are known to reduce informational masking, such as knowledge of the target speaker (reduced uncertainty), spatial separation of the target and masking speech, and differences in vocal characteristics between the target and masking speech (e.g., Hawley et al, 1999, 2004; Brungart, 2001a; Noble and Perrett, 2002; Arbogast et al, 2002, 2005). In addition, there is substantial research suggesting that it is the relationship between the amplitude spectrum of the speech and masker (i.e., the signal-to-noise ratio or SNR) that dictates speech understanding in many noise backgrounds, not the similarity in semantic and temporal structure of conversational speech and background talkers (French and Stienberg, 1947; Miller, 1947; Dirks and Bower, 1969; American National Standards Institute, 1997). Thus, it is possible that informational masking in everyday environments plays only a small role in the speech understanding difficulties of persons with hearing loss.

There has been relatively little work exploring the interaction between hearing loss and informational masking. Kidd et al (2002), using nonspeech stimuli, suggested that hearing loss may limit the ability to perceptually segregate components of complex sounds. This is a potentially important factor in our ability to understand speech in a background noise containing speech and suggests that the presence of hearing loss may increase susceptibility to informational masking. In contrast, some recent work suggests that informational masking effects are either relatively unaffected or actually reduced by the presence of hearing loss (Micheyl et al, 2000; Alexander and Lutfi, 2004; Arbogast et al, 2005). Alexander and Lutfi (2004), using nonspeech stimuli, reported less informational masking in persons with hearing loss. They measured thresholds for a 2000 Hz pure tone in the presence of a masker designed to produce varying amounts of informational masking while limiting energetic masking. When tested at equal sound pressure levels (SPLs), the authors found the participants with hearing impairment (HI) showed significantly less informational masking than the participants with normal hearing (NH). In contrast, when SPLs were reduced for the NH group and they were retested at sensation levels (SLs) comparable to the HI group, informational masking effects were quite similar. The authors suggest that masker variance, and hence uncertainty, is reduced at the lower SL experienced by the HI participants, resulting in reduced informational masking. Arbogast and colleagues (2005) also reported less informational masking in persons with hearing loss compared to an age-matched control group with normal hearing. These differences were reduced when differences in SL between the normal hearing and hearing-impaired groups were taken into account.

The influence of SL on informational masking has implications in terms of amplification for persons with hearing loss. Recent results suggesting that, in some conditions, informational masking actually increases as SL increases (Alexander and Lutfi, 2004; Arbogast et al, 2005) implies that the use of hearing aids could actually increase informational masking effects. It is not clear whether the benefits of increased audibility through the use of hearing aids would offset any potential increase in informational masking. Current rehabilitation methods often focus on methods to reduce energetic masking effects (i.e., FM systems, directional microphones). Understanding the benefits and limitations of hearing aids in the presence of informational maskers, however, may be necessary to optimize rehabilitation strategies and speech understanding. If traditional amplification strategies are not effective, alternative schemes may need to be developed, or minimally, counseling strategies will need to incorporate this limitation.

The primary purpose of the current study was to estimate the effects of informational masking, present in everyday conversational settings, on the speech understanding of persons with and without hearing loss. We were also interested in the benefits and limitations of amplification in settings containing both informational and energetic masker components.

PROCEDURES

Participants

Two groups of adults participated in this study. One group consisted of a control group of 15 participants (12 female, 3 male) with hearing thresholds ≤25dB at 250–8000 Hz bilaterally (NH). The age range of the control group spanned from 20–58 years (mean 29 years). The second group (HI) consisted of fifteen persons (3 female, 12 male) with symmetrical (<15 dB difference between ears at any audiometric test frequency), mild-to-moderately severe flat or sloping sensorineural hearing losses (SNHL). SNHL was defined as having no significant air-bone gap (<10 dB) at any frequency tested and no history of conductive pathology. All HI participant's hearing thresholds were between 30–75 dBHL at 500 Hz and between 30–85 dBHL at 3000 Hz, bilaterally (see Figure 1).

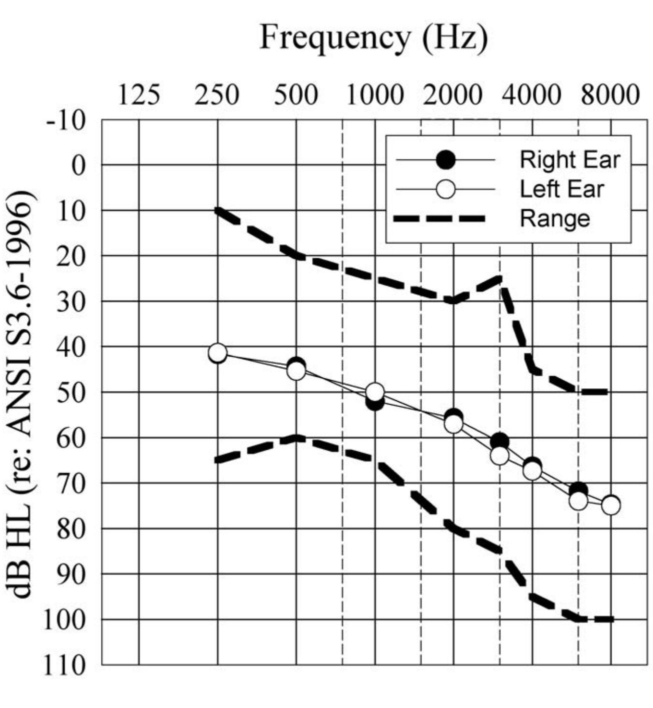

Figure 1. Average audiograms of study participants with hearing loss. Open and filled symbols are for the left and right ears, respectively. The range of hearing losses included in this study is shown by dashed lines.

Participants with hearing loss ranged in age from 41–85 years (mean 72 years).

Test Setting

A 3.2-meter square (2 meters high) sound-treated room, modified with reflective panels, served as the test environment. Frequency-specific reverberation times (Rt_{60}; time required for 60 dB decay after signal offset) were measured at the position of the listener's head (without the listener present) using frequency-modulated tones. Measured Rt_{60} values, at octave frequencies, were 485 msec (250 Hz), 440 msec (500 Hz), 400 msec (1000 Hz), 310 msec (2000 Hz), and 220 msec (4000 Hz).

Hearing Aids

The BTE version of the Phonak Claro™ was used as the test instrument in the aided conditions. This is a digital, 20-channel, low-threshold, fast-acting compression aid. The devices were fit bilaterally in omnidirectional mode using the manufacturer's fast-acting digital perception processing (fast-acting DPP™) compression algorithm. Digital noise reduction, known as fine scale noise cancellation, was disabled for all testing. Work by Moore and colleagues (1999) suggests that multichannel, fast-acting compression may provide optimal benefit for the types of maskers used in this study (e.g., provide maximum gain in the temporal dips of the maskers). Participants with hearing loss were fit bilaterally using custom made full shell earmolds with venting appropriate for the degree and configuration of hearing loss. Hearing aid fittings, based on the NAL-RP prescriptive method, were verified using the composite noise test signal on the Frye Systems Fonix 6500 real ear analyzer. For a 65 dB SPL input, measured insertion gain values were, on average, within -7 to +1 dB of prescribed gain values at test frequencies of 250, 500, 1000, 2000, 3000, 4000, and 6000 Hz (see Table 1). Nominal compression thresholds, read from the software fitting screen, varied with frequency and ranged from 34–50 dB SPL. Likewise, nominal compression ratios varied substantially between participants and across frequencies, with minimum and maximum values of 1:1 and 3.8:1, respectively.

Speech and Masking Stimuli

Speech understanding in noise was assessed using a modified version of the Hearing in Noise Test (HINT; Nilsson et al, 1994). The modifications to the HINT procedure were all related to the presentation and type of competing noise used as described below. The HINT is an adaptive procedure used to determine the SNR necessary to achieve 50% correct sentence recognition. Using this test, the sentence level is adaptively varied in the presence of a constant level background noise to determine threshold. Each experimental condition was evaluated using two ten-sentence lists. Experimental condition and list order were randomly assigned to each participant using a latin square design. In addition, for the HI participants, the aided/unaided presentation order was counterbalanced. Speech materials were presented through a single loudspeaker (Tannoy System 600) at a 0° azimuth located approximately 1.2 meters from the participant.

Table 1. Average, Measured, and Target Real Ear Insertion Gain (in dB) for the Right and Left Ear

	Average Right			Average Left		
Frequency (Hz)	Target (dB)	REIG (dB)	Mean Difference and SD (dB)	Target (dB)	REIG (dB)	Mean Difference and SD (dB)
250	4.0	4.2	-0.2 (3.0)	4.2	4.3	-0.1 (2.3)
500	13.6	10.8	2.8 (2.8)	14.1	11.3	2.8 (2.7)
1000	24.1	22.6	1.5 (2.7)	24.2	22.9	1.3 (2.6)
2000	23.5	24.9	-1.4 (2.5)	24.1	24.7	-0.6 (2.2)
3000	24.2	18.6	5.6 (4.6)	24.8	19.5	5.3 (5.0)
4000	25.7	18.3	7.5 (6.0)	26.3	19.8	6.5 (2.7)
6000	27.3	21.9	5.4 (8.0)	28.4	25.4	3.0 (11.0)

Previous research has shown that the magnitude of informational masking produced by speech maskers varies with the number of maskers with the largest effects seen in the presence of a minimal number of maskers (e.g., Carhart et al, 1975; Brungart et al, 2001). Therefore, speech understanding was measured in three masker configurations (two, four, and seven maskers) to provide an estimate of the magnitude of informational masking across a range of everyday situations. In each masker configuration, speech understanding was assessed using two types of maskers that varied in the amount of informational masking they were expected to produce (for a total of six speech and masker conditions). The maskers consisted of male talkers reading on a specific topic (more informational masking) and speech-shaped modulated noises (less informational masking).

Given that a primary goal of the study was to provide an estimate of the magnitude of informational masking in everyday speech environments, each masker was presented from a separate loudspeaker that was spatially separated from the target speech, which was located at a 0° azimuth. Although spatially separating the speech and noise provides a more realistic test configuration, it should be noted that this configuration was expected to reduce the amount of informational masking compared to that measured in many previous laboratory studies (Hawley et al, 1999, 2004; Arbogast et al, 2002, 2005).

In the two-masker configuration, speakers were located at azimuths of 135° and 315°. In the four-masker configuration, two additional speakers were placed at azimuths of 45° and 225°. Finally, in the seven-masker configuration, three additional speakers were placed at azimuths of 90°, 180°, and 270°. Figure 2 shows a schematic of the three masker configurations. All maskers were presented from Definitive Technology BP-2X bipolar loudspeakers placed 1.2 meters from the listener. Informal testing confirmed that, although difficult, listeners with normal hearing could attend to the speech of individual speech maskers even when all seven were presented simultaneously.

In each test condition, the combined level of the maskers (at the position of the listener's head with the listener absent) was a constant 65 dBA. The level of each individual masker was equated prior to adjusting the overall level of the combined maskers to 65 dBA. Calibration prior to each test session was performed to assure an overall level of 65 dBA (±1 dB; Larson Davis 814 sound level meter) in all experimental conditions.

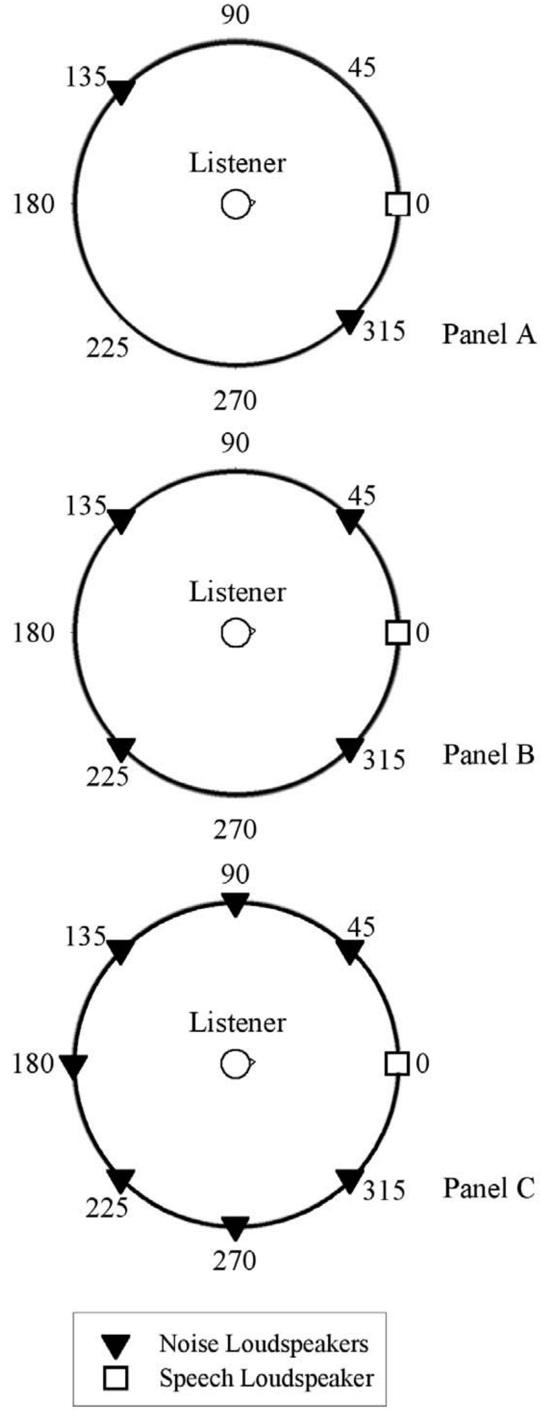

Figure 2. Panels *A*, *B*, and *C* show the masker configurations for the two-, four-, and seven-masker conditions used in this study. Speech and noise loudspeaker locations are shown by the open square and filled triangles, respectively.

Derivation of Masker Materials

The maskers used in this study included individual talkers and speech-shaped noises modulated by the envelope of the individual talkers. Each loudspeaker presented a different talker or talker-matched noise from a separate spatial location. Masker configurations using individual talkers as maskers consisted of two, four, or seven loudspeakers, each outputting a single male talker reading test passages from the Connected Speech Test (CST; Cox et al, 1987, 1988). Each CST passage consists of approximately ten sentences describing a specific topic (e.g., lemons). The passages were derived from a children's educational reading source (see Cox et al, 1987, for details). The CST passages were chosen as masking materials because they provide a contextually rich dialogue, rather than single unrelated sentences, that may result in informational masking more consistent with that present in everyday communication settings.

Male talkers were used in an attempt to create masking conditions that were both realistic yet highlighted informational masking effects. Specifically, the HINT test materials are also spoken by a male talker, and informational masking is higher when the target speaker and maskers are of the same sex (Brungart, 2001a; Brungart et al, 2001). At the same time, realistic environments exist in which the target and masking speech are predominately of a single sex. Recordings of the individual talkers reading the CST passages were made in an anechoic chamber and stored on a computer hard disk. All talkers were native speakers of American English. Offline digital filtering, using the FIR2 function and a 1000th order FIR filter implemented in Matlab™, was used to match the long-term rms spectra of each CST passage recorded by each talker to that of the long-term rms spectra of the HINT materials.

The modulated noise maskers used in this study were derived from uncorrelated segments of Gaussian noise that were first spectrally shaped, using the FIR2 function and a 1000th order FIR filter implemented in Matlab™, to match the long-term rms spectrum of the HINT materials. The shaped noises were then modulated using the envelopes of the same single talkers reading the CST passages. The envelopes of the single-talker maskers were derived in Matlab™ by implementing half-wave rectification of a given single-talker passage, followed by low-pass filtering of the half-wave rectified signal, using a sixth-order butterworth filter with a 30 Hz low-pass cutoff frequency. The envelope was then applied to the shaped noise providing a primarily energetic masker that retained the long-term spectral and temporal patterns of the single-talker maskers. The long-term spectrum of all individual talker and modulated noise maskers closely approximated the long-term spectrum of the HINT sentences. The mean error, across 1/3-octave bands from 160 to 8000 Hz, between individual talkers, modulated noises, and the HINT spectrum was 0.19 and -0.22 dB, respectively, with standard deviations less than 1 dB. The maximum error, in a given 1/3-octave band, for any individual talker or modulated noise was ~3 dB.

RESULTS

Effects of Masker Type: Normal-Hearing Participants

The current study examined the effects of type and number of maskers on speech understanding of persons with and without hearing loss. The performance of the NH control group was examined first, using a two-factor, repeated-measures ANOVA. The within-subjects independent variables were masker type (speech or noise) and number of maskers (two, four, or seven); the dependent variable was the HINT score in each masker condition. A 0.05 level of significance was used in all analyses described here. Summary results of the primary analyses are shown in Table 2.

The results from the two-factor ANOVA revealed a significant main effect of number of maskers (two, four, and seven) but not type of masker (SM and NM). In addition, a significant interaction between type and number of maskers was observed. Follow-up analyses were conducted using a series of single-factor ANOVAs that compared HINT thresholds, in speech and noise maskers, separately in the two-, four-, and seven-masker configurations. Results in the seven-masker configuration revealed significantly

Table 2. Results from a Two-Factor, Repeated Measures ANOVA on Participants with Normal Hearing

Effect	NH df	F	p-level
Type	1,14	0.87	0.367
Num_masker	2,28	65.57	<0.001
Type x Num_masker	2,28	14.57	<0.001

Note: Type = speech or noise masker; Num_masker = number of maskers (i.e., two, four, or seven).

poorer HINT thresholds when using the speech maskers. In contrast, HINT thresholds were significantly *better* in the two-masker configuration in the speech, compared to noise maskers, and no significant difference between performance in the speech and noise maskers was observed in the four-masker configuration. These results suggest that spatially separated individual talkers, similar to everyday settings, do cause some informational masking. However, the relative effect of the informational masking components of our masking speech varied based on the number of maskers, being most apparent in the seven-masker configuration. Figure 3 shows HINT thresholds for the NH participants, in the two-, four-, and seven-masker (speech [SM] and noise [NM]) configurations.

Effects of Hearing Loss on Speech Recognition in the Presence of Speech and Noise Maskers

Following this initial analysis, differences in the effects of masker type (speech versus speech-modulated noise) in the NH and HI participants were compared. We were interested in whether the pattern of performance in the various masker conditions differed from that of the NH group. For comparative purposes, HINT thresholds for the NH, unaided HI, and aided HI participants are shown together in Figure 4.

Using a series of three-factor, mixed-model ANOVAs, NH performance was compared to HI performance separately in the unaided and aided conditions. The between-

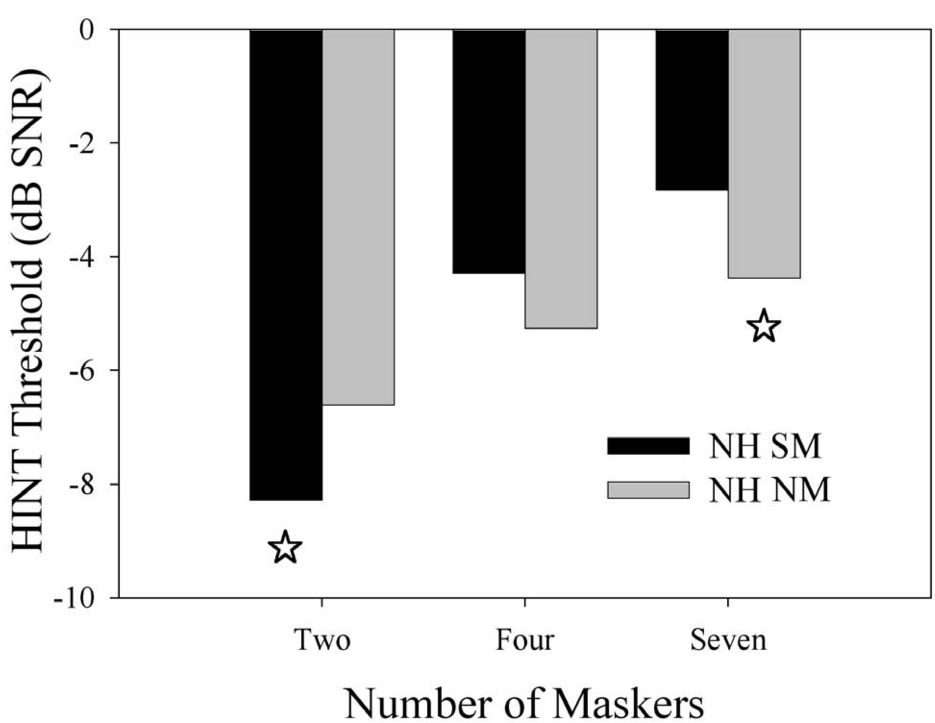

Figure 3. Thresholds for 50% sentence recognition (HINT thresholds) for participants with normal hearing (NH) obtained in the presence of single-talker (black bars) and modulated speech shaped noises (gray bars) as a function of number of maskers (two, four, or seven). Stars show conditions where performance in the modulated noise maskers (NM) and single-talker speech (SM) maskers were significantly different.

subjects independent variable was group (NH and HI unaided or HI aided), and the within-subjects independent variables were masker type and number of maskers. The dependent variable was the HINT score in each masker condition.

An analysis of NH and unaided HI performance revealed significant main effects of group (HI and NH), type of masker (SM and NM), and number of maskers (two, four, or seven). As expected, and as seen in Figure 4, performance was poorer for the unaided HI group across all test conditions. In addition, averaged across groups, performance was poorer as the number of maskers increased, and performance was significantly poorer, although the difference was small, when speech was used as a masker compared to the speech-modulated noise maskers.

In addition, significant two-way interactions were observed. Consistent with past research, a significant interaction between number of maskers and group was observed. Averaged across masker types, performance for the NH group systematically improved as the number of maskers decreased while no such release from masking was observed for the HI participants. Additionally, a significant interaction between type and number of maskers was observed with patterns consistent with those described in the NH analysis. That is, in the seven-masker configuration performance, averaged across groups, was *poorer* when the maskers were speech than when they were speech-modulated noises. In contrast, in the two-masker configuration, performance was *better* when the maskers were speech. Finally, no significant two-way interaction between group and type of masker or three-way interaction was observed. The lack of a significant interaction between group and masker type suggests that the masking effects of our speech and speech-modulated noise were similar for the NH and unaided HI participants in this study. Summary results of the ANOVA analyses on the NH and unaided HI participants are shown in Table 3.

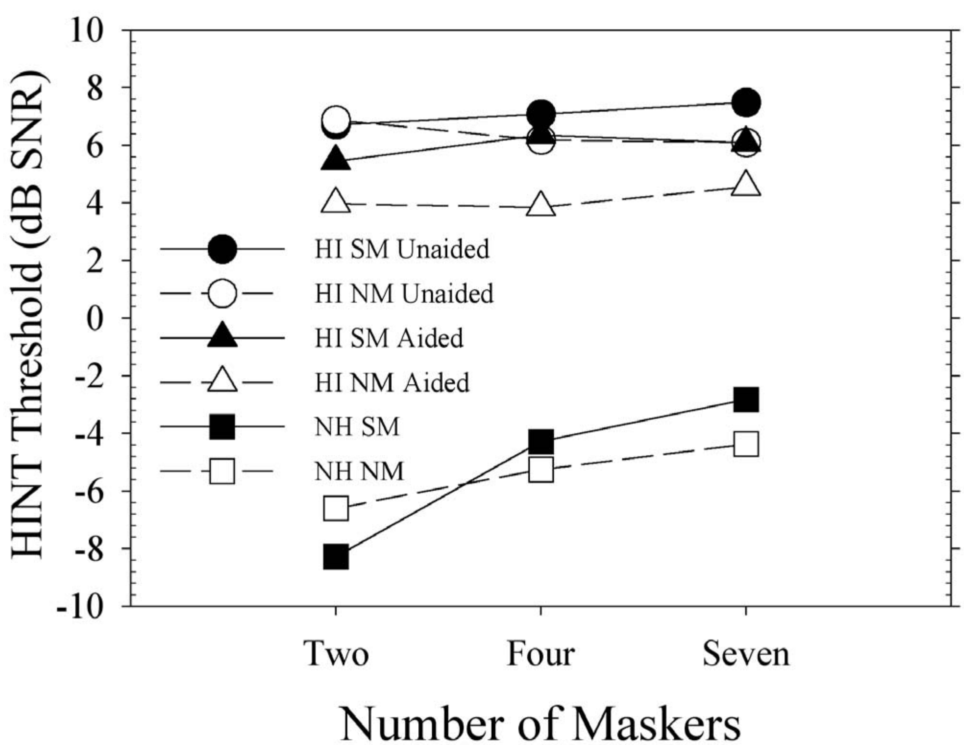

Figure 4. Thresholds for 50% sentence recognition (HINT thresholds) obtained in the presence of single-talker speech maskers (SM; filled symbols) and modulated speech shaped noise maskers (NM; open symbols) as a function of number of maskers (two, four, or seven). Results for NH (squares) and unaided (circles) and aided (triangles) HI participants are shown separately.

Aided Speech Recognition Performance in the Presence of Speech and Noise Maskers

Another focus of this study was on the benefits and limitations of hearing aids in the presence of informational maskers. One way to examine this question is to compare the performance of aided HI participants to the "gold standard" provided by the NH control group. Specifically, we can ask whether hearing aids restore speech understanding in noise for HI persons to levels comparable to NH individuals, when the background noise contains an informational masking component. To compare NH and aided HI performance, a three-factor, mixed-model ANOVA was performed on the NH and aided HI participants' HINT thresholds. Summary results of the ANOVA analysis are shown in Table 4.

Average HINT thresholds from these conditions are shown in Figure 4 and clearly show that performance of the aided HI participants remains substantially poorer than the NH control group. The results of the statistical analysis, as seen by the significant effect of group, confirmed that overall aided HI performance remained significantly poorer than that of the NH control group. Consistent with the comparison of NH and unaided HI performance, a significant interaction between number of maskers and group was observed (i.e., HI performance does not improve as the number of maskers is decreased). In contrast to the unaided comparison, however, a significant two-way interaction between type of masker and group and a significant three-way interaction between type, number of maskers, and group was also observed. Follow-up analyses showed that, in contrast to NH performance, aided HI performance was consistently poorer in the presence of the speech maskers, compared to the noise maskers, regardless of the number of maskers presented. Recall that for the NH participants, performance in the two-masker condition was significantly better in the presence of the speech masker.

Effect of Hearing Aids on Informational Masking: Aided Benefit

Although the results from the previous analysis revealed that hearing aids did not restore speech understanding to normal, it is of interest to examine the benefit that hearing aids did provide to our study participants. To

Table 3. Results from Mixed-Model (NH vs. unaided HI) ANOVA

Effect	NH vs. Unaided HI Df	F	p-level
Type	1,28	6.21	<0.001
Num_masker	2,56	18.15	<0.001
Group	1,28	79.02	<0.001
Type x group	1,28	1.17	0.289
Num_masker x group	2,56	18.92	<0.001
Type x num_masker	2,56	11.84	<0.001
Type x num_masker x group	2,56	1.74	0.185

Note: Type = speech or noise masker; Num_masker = number of maskers (two, four, or seven); Group = with and without hearing loss.

Table 4. Results from Mixed-Model (NH vs. aided HI) ANOVA

Effect	NH vs. Aided HI Df	F	p-level
Type	1,28	18.42	<0.001
Num_masker	2,56	33.76	<0.001
Group	1,28	128.77	<0.001
Type x group	1,28	9.94	<0.01
Num_masker x group	2,56	17.89	<0.001
Type x num_masker	2,56	6.97	<0.01
Type x num_masker x group	2,56	4.35	<0.05

Note: Type = speech or noise masker; Num_masker = number of maskers (two, four, or seven); Group = with and without hearing loss.

investigate aided benefit, a three-factor repeated-measures ANOVA was performed on the HI unaided and aided HINT scores. As expected, a significant main effect of aid condition was observed with performance improving in the aided condition. Also, consistent with the previous analyses, a significant main effect of masker type was observed with performance being poorer in the speech masker conditions. Of primary interest, however, was the significant interaction between aid condition and type of masker. Averaged across number of maskers, persons with hearing loss received less benefit from hearing aids in the presence of the more informational masker (the speech maskers) than the speech-modulated noise (primarily energetic) maskers. Summary results of the ANOVA analysis are shown in Table 5.

To determine the source of this significant interaction, a series of two-factor ANOVAs, examining unaided and aided performance in the speech and noise maskers, were performed. These analyses showed a significant main effect of aid condition only in the presence of the speech-modulated noise with performance being significantly better in the aided condition. Follow-up testing comparing unaided and aided performance in the speech-modulated noise in the two-, four-, and seven-masker configurations revealed significantly better aided performance in the four- and two-masker conditions. Aided performance in the seven-masker condition followed a similar pattern, but the benefit was not statistically significant. A similar, but not statistically significant, pattern was observed in the speech masker conditions. In other words, on average, hearing aids did not significantly improve speech understanding, compared to unaided performance, when listening in the presence of speech maskers. Figure 5 shows aided benefit (i.e., the difference between unaided and aided HINT thresholds) in dB for both noise types as a function of number of maskers.

Quantifying Informational Masking Effects

A primary focus of this study was to estimate the effects of informational masking, present in everyday conversational settings, on persons with and without hearing loss. Informational masking was functionally defined as the additional masking observed in the presence of speech maskers (which contain both energetic and informational masking components) compared to that observed for a speech-modulated noise (which is primarily an energetic masker). We can use the analyses described above to identify the situations in which significant informational masking occurred. Informational masking effects (the difference in HINT thresholds measured in speech and speech-modulated noise maskers) for the NH, unaided HI, and aided HI groups, as a function of number of maskers, are shown in Figure 6. The stars identify the specific conditions where significant informational masking occurred.

When plotted in this fashion, informational masking effects appear present and similar in magnitude across groups in the seven-masker configuration. In addition, the pattern of informational masking effects appears similar for the NH and unaided HI in that informational masking appears to increase as the number of maskers increases. In contrast, the magnitude of informational masking remains relatively constant as the number of maskers increases for the aided HI group.

Table 5. Results from the Three-Factor Repeated Measures (HI unaided vs. aided) ANOVAs

	Unaided vs. Aided HI		
Aid condition	1,14	4.9	<0.05
Type	1,14	20.42	<0.001
Num_masker	2,28	0.55	0.582
Aid condition x Type	1,14	10.38	<0.01
Aid condition x Num_masker	2,28	0.36	0.699
Type x Num_masker	2,28	1.47	0.246
Aid x Type x Num_masker	2,28	1.21	0.314

Note: Type = speech or noise masker; Num_masker = number of maskers (two, four or seven); Aid condition = unaided or aided.

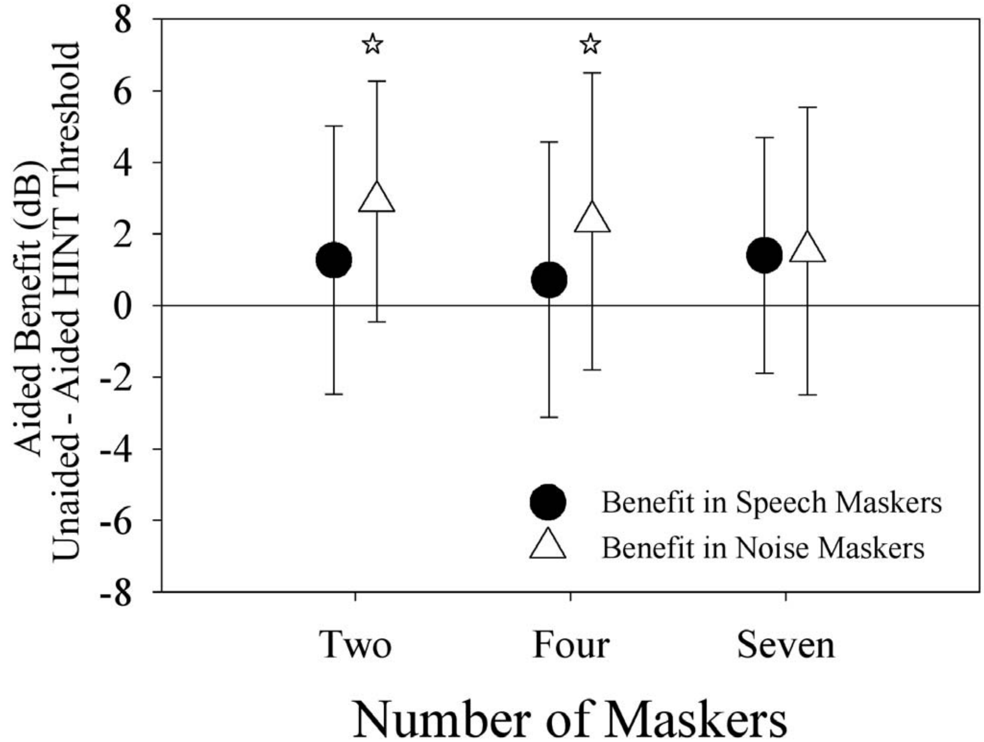

Figure 5. Aided benefit defined as the difference between unaided and aided HINT thresholds in both the speech (SM; circles) and noise (NM; triangles) maskers, as a function of number of maskers. A positive value is representative of aided benefit. Stars over a given symbol identify masker conditions that showed significant differences between the aided and unaided conditions.

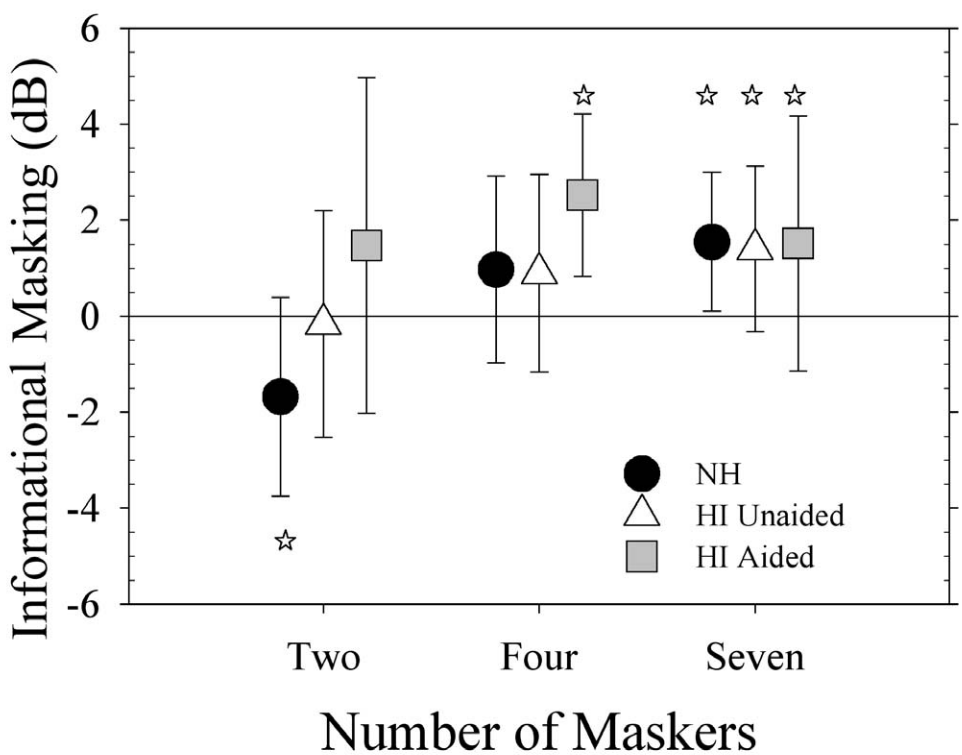

Figure 6. Informational masking effects, defined as the difference between the HINT thresholds in the speech masker (SM) minus the HINT thresholds in the noise masker (NM), as a function of number of maskers. Results for NH (circles), unaided HI (triangles), and aided HI (squares) are shown as separate symbols. Error bars represent one standard deviation around the mean. Stars over a given symbol identify masker conditions that showed significant differences between the SM and NM masker conditions.

DISCUSSION

The current study explored the magnitude of informational masking effects, present in everyday environments when the background noise consists of conversational speech maskers. We were interested specifically in how these effects would vary with the presence of hearing loss and whether hearing aids would be useful in limiting the negative effects of informational masking in everyday conversational speech settings. However, several factors, discussed below, may influence our estimate of informational masking effects and its interactions with hearing loss and hearing aids.

Energetic Masking Effects

One issue in estimating the magnitude of informational masking when using broadband signals and maskers (as was done in this study) is that energetic masking is also occurring. When using speech as both the target and masker, disentangling the contribution of the informational and energetic masking components is not a trivial task. In the current study, our estimates of informational masking are confounded, to some degree, by differences in energetic masking between our two masker types (i.e., speech and speech-modulated noise). Although the noise maskers matched the long-term spectral and temporal properties of the speech maskers, the short-term spectral and temporal properties of the speech and noise were not matched. Real speech contains rapid amplitude fluctuations that vary in a frequency-dependent fashion. These rapid spectro-temporal fluctuations are not present in the speech-modulated noise (only the long-term changes in the envelope are matched). It is likely that any given speech masker contained more spectro-temporal dips than its matched speech-modulated noise masker and thus provided less energetic masking at some instances than the modulated noise.

This potential difference in the energetic masking properties of the speech and noise maskers is likely the cause of the better performance seen in the NH participants in the two-talker speech masker configuration compared to the two speech-modulated noise maskers (see Figures 4 and 6). In the two-talker configuration, relatively large differences in the short-term spectro-temporal properties of the speech and noise maskers may exist, and the NH participants are able to take advantage of these to “listen in the dips.” As additional talkers are added, differences in the temporal properties of the individual speakers “fill in” the dips making the long- and short-term spectrum of the speech and noise maskers more comparable and more “steady-state” compared to the situation where only two talkers are used.

Despite differences in the energetic masking properties of the speech and noise maskers, these study results support the idea that “everyday” speech can cause both informational and energetic masking. This is supported by the fact that as additional maskers were added, essentially reducing the differences in spectro-temporal fluctuations between masker types, the speech maskers became more effective than the noise maskers (see Figure 6). If differences in performance when using the speech and noise maskers were due solely to differences in energetic masking, we would expect the noise maskers to continue to remain more effective than the speech maskers even as the numbers of maskers increased from two to seven. Figures 4 and 6 show that, at least for the NH and unaided HI groups, the speech maskers become more effective than the noise maskers as the number of maskers increases, suggesting factors other than energetic masking are impacting the results.

Figure 6 shows that the relative effect of informational masking resulting from conversational speech can be large in some conditions. A maximum informational masking effect (~2.5 dB change in SNR required to achieve 50% correct sentence recognition) was observed in the aided HI group when using four maskers. This change in SNR corresponds to a change in percent correct score that will vary based on the specific test material. Assuming a transfer function slope of 12%/dB, a change in SNR of 1–2.5 dB (as seen in the four- and seven-masker conditions in this study) would result in a 12%–30% change in sentence recognition (Sherbecoe and Studebaker, 2002). While significant, this change is substantially smaller than the 40%–80% change noted by Brungart and colleagues (2001) when using the CRM as the test material. This suggests that informational masking effects in more real-world settings, while potentially large, are likely to be less than those observed with test materials designed to highlight informational masking effects, such as the CRM.

Effects of Age and Hearing Loss and Sensation Level on Informational Masking

Our study results showed that informational masking effects were similar between persons without hearing loss and unaided persons with hearing loss, at least when differences in the energetic masking properties of the masking stimuli are small (e.g., in the seven masker configuration, see Figure 6). This is in contrast to some recent work suggesting that informational masking effects may be *smaller* in persons with hearing loss, at least when tested at comparable SPLs (Alexander and Lutfi, 2004; Arbogast et al, 2005).

Several factors, however, make it difficult to draw conclusions, based on the current study, about the effects of hearing loss per se on informational masking. As mentioned previously, the use of more "realistic" test settings and speech stimuli, while providing face validity, results in settings where informational masking effects are reduced. Thus, the fact that informational masking effects were similar between groups in the current study may be due to the fact that in "real world" settings informational masking effects are small compared to energetic masking effects, which were larger in the HI and likely dominate performance. In addition, previous work has shown that masker SL affects the amount of informational masking in a given test situation (Alexander and Lutfi, 2004; Arbogast et al, 2005).

Given that in the current study masker levels were fixed at 65 dB SPL for both the NH and HI groups, resulting in lower masker SLs for the HI participants, we might expect less informational masking for the HI participants in this study. In addition to the experimental configuration limiting informational masking (e.g., using spatially separated maskers), age differences between our NH and HI groups may have also played a role in our findings. Unfortunately, in the current study the age range of our HI participants is quite narrow and substantially different than that of the NH group. This coupled with the fact that substantial differences in hearing thresholds exist between our groups makes disentangling the effects of age from hearing loss quite difficult. We can, however, speculate on the potential impact. Although recent work by Li et al (2004) found no differences in the negative effects of speech distracters on young adults with normal hearing and older adults (the older adults had only mild high-frequency hearing loss), the ages of their older adults ranged from 63 to 75 years. In contrast, nine of the 15 HI participants in the current study were over the age of 75 with five between the ages of 80–85. Studebaker et al (1997) reported significant negative effects of age on speech understanding only for the oldest (over 70 years old) participants and particularly for those over 80 years of age. Given that general cognitive and central processing abilities are thought to be negatively affected by age (e.g., Wingfield and Tun, 2001; Pichora-Fuller, 2003), it is possible that older adults are more affected by informational maskers than younger adults. In the current study, at least in the unaided condition, the negative effect of age could have been offset by the reduction in informational masking due to the lower SL at which the older HI listened.

Our finding of significant informational masking in the HI group in the aided, four-masker condition supports this contention. A similar, but not significant, finding was observed in the aided, two-masker condition. In these conditions the hearing aids increased masker (and speech) SLs to levels more closely approximating the NH group. This increase in audibility led to improved performance. The largest improvements, however, occurred when listening in the modulated noise rather than the speech masker conditions. This resulted, by definition, in an increase in informational masking effects compared to the unaided condition. The reason a similar increase was not observed in the seven-masker configuration is not clear. It is possible that the change in audibility (and masker SL) was, because of fewer temporal dips, less in the seven-masker condition than in the two- and four-masker conditions.

Benefits and Limitations of Hearing Aids on Informational Masking

A primary result from this study, regarding hearing aids and informational masking, is that omnidirectional hearing aids were relatively ineffective in improving speech understanding when the masking noises were spatially separated from the speech and contained both energetic and informational masking components (i.e., speech masker conditions). The poorer-than-normal performance of the aided HI group, regardless of masker condition, is consistent with decades of past research showing a similar result (e.g., Plomp, 1986). Even when aided, substantial research has shown that HI performance in noise, particularly modulated background noises, is consistently poorer than performance of a NH control group (e.g., Bronkhorst and Plomp, 1992). These study results show that the decrement experienced by our HI participants was largest when the noise contained informational, as well as energetic, masking components, at least in the four- and seven-masker conditions (see Figure 6).

In addition, the use of hearing aids in the higher informational masking conditions (speech maskers) did not significantly improve speech understanding, over the unaided condition, for the HI participants. Hearing aids provided only limited benefit (~1.1 dB averaged across the three masker configurations) in the presence of the speech maskers (see Figure 5). As discussed earlier, this may be related in part to the age of our participants and the higher masker SLs experienced in the aided conditions. Regardless, hearing aids are designed, primarily, to restore audibility and are thus not expected to heavily impact the central factors (e.g., stimulus-masker uncertainty/similarity) that appear to be largely responsible for informational masking effects that occur in speech settings. Thus, the finding of limited benefit of hearing aids in the presence of informational maskers is not surprising. This does, however, highlight the limitations of omnidirectional hearing aids in real-world noisy environments, particularly those that contain speech signals as the primary masker. Given these limitations, there is a clear need for additional research investigating the utility of additional technological (e.g., directional microphones, FM systems) and counseling strategies (such as reducing background noises, improving lighting and access to visual cues, etc.) that may help reduce these deficits.

SUMMARY

The results from the current study suggest the following: (1) Speech maskers presented from discrete spatial locations, in most configurations, result in additional masking compared to a primarily energetic masker (speech-modulated noise). This finding supports the idea that background noise consisting of multiple spatially separated talkers, as occurs in everyday environments, results in both informational and energetic masking. (2) The relative effect of informational masking, resulting from spatially separated talkers, varies based on the number of talkers. When the number of talkers is small (e.g., two), the informational masking component of everyday conversational speech may be obscured by energetic masking effects. As the number of talkers increases from two to seven, both informational and energetic masking effects can be observed. (3) Informational masking effects due to spatially separated talkers appear to be similar for older adults with hearing loss, in the unaided condition, and younger adults without hearing loss. (4) When the masking noise contains both energetic and informational masking components, increasing audibility via the use of omnidirectional microphone hearing aids results in only limited improvements in speech understanding.

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