The Impact of Noise and Hearing Loss on the Processing of Simultaneous Sentences

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Objectives: To examine the impact of hearing impairment on a listener's ability to process simultaneous spoken messages.

Design: Nine young listeners with bilateral sensorineural hearing loss and nine young listeners with normal hearing participated in this study. Two messages of equal level were presented separately to the two ears. The messages were systematically degraded by adding speech-shaped noise. Listeners performed a single task in which report of one message was required and a dual task in which report of both messages was required.

Results: As the level of the added noise was increased, performance on both single and dual tasks declined. In the dual task, performance on the message reported second was poorer and more sensitive to the noise level than performance on the message reported first. When compared to listeners with normal hearing, listeners with hearing loss showed a larger deficit in recall of the second message than the first. This difference disappeared when performance of the hearing loss group was compared to that of the normal-hearing group at a poorer signal to noise ratio.

Conclusions: A listener's ability to process a secondary message is more sensitive to noise and hearing impairment than the ability to process a primary message. Tasks involving the processing of simultaneous messages may be useful for assessing hearing handicap and the benefits of rehabilitation in realistic listening scenarios.

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INTRODUCTION

In crowded listening environments, selective attention enables information to be extracted from a talker of interest. However, in many cases, it is desirable to retrieve information from a talker who is outside the immediate focus of attention (e.g., when two people talk at once). Although some early studies showed that listeners with normal hearing perform poorly when asked to recall messages from unattended talkers (Cherry 1953), subsequent studies indicate that listeners are able to process unattended speech to some extent (Moray 1959; Conway et al. 2001; Rivenez et al. 2006) and can perform remarkably well at following two talkers when instructed to do so in advance (Best et al. 2006; Gallun et al. 2007; Ihlefeld & Shinn-Cunningham 2008).

A recent survey of listeners with hearing loss (Gatehouse & Noble 2004) revealed that the self-perception of communication handicap is strong in listening situations calling for divided or rapidly shifting attention, such as following two talkers at once, catching the beginning of what a new speaker says, or engaging in conversation with a group of people. Given these subjective reports, we hypothesized that hearing loss impairs one's ability to deal effectively with simultaneous messages and that this difficulty would be revealed in objective dual-task listening experiments.

Although several studies have examined divided listening in listeners with hearing impairment (Strouse et al. 2000; Mackersie et al. 2001; Humes et al. 2006; Singh et al. 2008), the majority have used older listeners, making it difficult to factor out the differential contributions of age and hearing loss to the results. For this reason, we recruited a group of young listeners with sensorineural hearing loss and compared their performance to a similar group of young listeners with normal hearing.

We chose a task in which listeners were required to respond to two simultaneously presented messages (see Best et al. 2006; Ihlefeld & Shinn-Cunningham 2008). To focus on the task of *processing* two simultaneous messages, we made an effort to eliminate other factors that might interfere with the ability of hearing-impaired listeners to *hear out* the messages. First, the overall presentation level was adjusted on an individual basis to reduce audibility as a factor in the hearing-impaired group. Second, the two messages were presented dichotically (one to each ear) to avoid peripheral interference between the stimuli that would be likely to impair speech intelligibility in the hearing-impaired group (Duquesnoy 1983; Festen & Plomp 1990; Summers & Leek 1998). Note that this design is similar to the classic dichotic digits paradigm introduced by Broadbent (1954) and used or adapted by others since to study attention (Treisman 1971), hemispheric dominance effects (Kimura 1961; Bryden 1963; reviewed by Hugdahl 2003), and auditory processing disorders (Fifer et al. 1983; Jerger & Martin 2006).

Finally, the difficulty in speech reception was varied parametrically by adding noise to the messages over a range of signal to noise ratios (SNRs). This allowed us to assess dual-task performance for various levels of listening difficulty within a group, but more importantly enabled us to compare the two groups at SNRs that roughly equated their speech-reception performance.

MATERIALS AND METHODS

Participants

The participants were nine listeners with normal hearing (NH group; four men and five women) and nine listeners with sensorineural hearing loss (HL, group; three men and six women). The NH group ranged in age from 18 to 29 yrs (mean, 22 yrs), and the HL group ranged from 18 to 42 yrs (mean, 27 yrs). The NH group was screened to ensure pure-tone thresholds in the normal range (no greater than 20 dB HL) for octave frequencies from 250 to 8000 Hz. The HL group had mild to moderately severe, bilateral, symmetric, sloping, sensorineural hearing losses. Seven of the nine were regular bilateral hearing-

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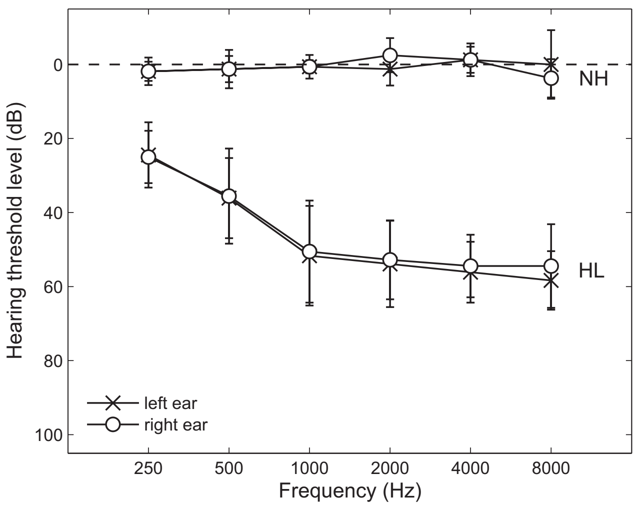

Fig. 1. Mean audiograms for listeners with normal hearing (NH) and sensorineural hearing loss (HL). Error bars indicate across-subject standard deviations.

aid wearers, but participated in the experiment with their aids removed. Mean audiograms for both groups are shown in Figure 1. All listeners were paid for their participation. The experimental protocols were approved by the Boston University Charles River Campus Institutional Review Board.

Stimuli

Digital stimuli were generated on a PC using MATLAB software (MathWorks Inc., Natick, MA). The stimuli were digital-to-analog converted and attenuated using Tucker-Davis Technologies hardware (System II or III) and presented over headphones (HD 580 or HD 265 linear, Sennheiser, Wedemark, Germany). Listeners were seated in a sound-treated booth fitted with a monitor and mouse. In all conditions, they indicated their responses by clicking with the mouse on a graphical user interface.

Speech materials were taken from the Coordinate Response Measure corpus (Bolia et al. 2000), which consists of sentences of the form "Ready <call sign>, go to <color> <number> now." Only sentences spoken by the four male talkers in the corpus were used. For monaural stimuli, one sentence with the call sign "Charlie" was selected at random. For dichotic stimuli, two sentences with call signs "Charlie" and "Baron" were selected randomly with the constraints that each was spoken by a different talker and that the colors and numbers in the two utterances differed. No attempt was made to time align the keywords across pairs of sentences, although there is considerable overlap in the sentences by design.

The sentences were presented at a level that was fixed for each listener (see below) and were presented in either quiet or with speech-shaped noise added. Speech-shaped noise was created by filtering randomly generated broadband noises with the average frequency spectrum of the set of sentences used in the experiment. For dichotic stimuli, the noise was independent in the two ears but equal in level. In blocks where noise was added, the level of the noise was selected randomly from trial to trial from a set of four levels chosen separately for each listener group. The resulting SNRs were −12, −9, −6, −3 dB and −9, −6, −3, 0 dB for the NH and HL groups, respectively. The choice of these ranges was based on pilot experiments conducted on the first listener from each group.

Presentation Level

In an attempt to compensate for differences in the audibility of speech signals between the two listener groups, presentation levels were set to a fixed sensation level (SL) chosen separately for each listener. Levels were set by measuring quiet sentence identification thresholds for each listener and presenting the speech stimuli at a fixed level above this threshold. Note that although this approach equates overall SL, it does not ensure an equal SL across frequencies. An adaptive procedure consisting of 20 trials was used to measure thresholds. On each trial, a randomly drawn sentence was presented to one ear only. Listeners identified the color and number of each sentence and were scored as correct only if both words were correct. The presentation level was varied using a one-up, one-down adaptive rule that tracks the 50% correct point on the psychometric function. The initial step size was 4 dB; after three reversals, the step size was decreased to 2 dB. The threshold calculation was based on all reversals after the first three (or four, to give an even number of reversals). One threshold was collected for each ear and then these two thresholds were averaged. Where possible, stimuli were presented at 45 dB SL. This was possible in only four of the nine listeners in the HL group. The remaining five listeners found this level uncomfortable; for these listeners, the level was reduced to a comfortable level (the lowest final level was 35 dB SL). The absolute level of the speech stimuli delivered by the headphones ranged between 80 and 103 dB SPL (as measured in a KEMAR artificial head) in the HL group.

For five of the nine listeners in the NH group thresholds were collected in the same way and the speech stimuli were presented at 45 dB SL (absolute levels of 56–74 dB SPL). For the other four listeners in this group, a fixed level of 65 dB SPL was used.*

Procedures

Listeners performed three tasks, presented in different blocks of trials. In "control" trials, only one message (containing the call sign Charlie) was presented to one ear and listeners reported the color and number keywords of this message. The stimulated ear was chosen randomly on each trial, with each ear being chosen an equal number of times over the course of a block. In "single-task" trials, two messages were presented (one to each ear) and listeners were asked to report the color and number keywords from the message containing the call sign Charlie. The ear receiving the Charlie message was randomly chosen on each trial and the other ear received a message containing the call sign Baron. The assignment of call signs to ears was balanced such that each ear received the Charlie message 50% of the time. In "dual task" trials, dichotic messages (statistically identical to those presented in single-task trials) were presented and listeners were asked to report the color and number keywords from the Charlie message followed by the color and number keywords from the Baron message. These instructions encouraged listeners to prioritize the processing of the Charlie message over that of the Baron message.

*Four listeners in the NH group completed the study before the HL group began and the threshold measurement was introduced.

Trials were organized into blocks of 80, with the task fixed within a block. Noise was added on a trial-by-trial basis such that each block contained 20 repetitions at each of the four predefined SNRs (see above). One block of each task (in the order control, single, dual) comprised a session and took approximately 30 min. Four sessions were completed by each listener.

In addition to being tested over the range of SNRs described above, the HL group and five of the NH group were also tested in quiet. One 40-trial block of each task in quiet (in the order control, single, dual) was completed before the main experimental sessions.

RESULTS

Mean Performance as a Function of SNR

Mean performance across listeners in each listener group is plotted in Figure 2 as a function of SNR for the control task, the single task, and for the messages reported first (M1) and second (M2) in the dual task. Note that the range of SNRs tested was different for the two listener groups. Scores are averaged across trials in which the Charlie message was presented to the left ear and trials in which it was presented to the right ear. A small effect of ear of presentation was observed, consistent with previous reports of "right-ear dominance." Specifically, when the Charlie message was presented to the right ear, performance was slightly better in the single task and for M1 in the dual task compared to when Charlie was presented to the left ear. Similarly, performance for M2 in the dual task was slightly better when Baron was presented to the right ear. This effect of ear of presentation was not statistically significant and was much smaller than the effect of report order, as expected based on previous studies showing that an imposed response order overrides ear dominance effects (Wilson et al. 1968).

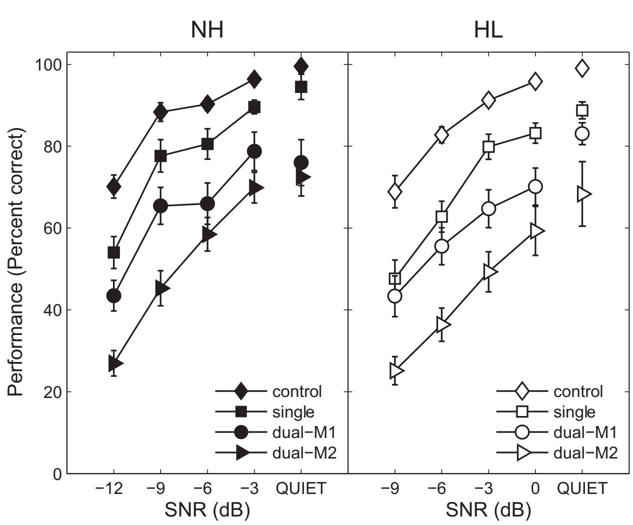

Fig. 2. Performance for listeners with normal hearing (NH: left panel) and hearing loss (HL: right panel) as a function of signal to noise ratio (SNR). The different lines in each panel show across-subject mean scores in the control task (diamonds), the single task (squares), and the dual task for M1 (circles) and M2 (triangles). For the NH group, the data point for the quiet condition represents the mean of only five of the nine listeners. Error bars indicate standard errors of the mean.

In the control task, performance varied with SNR from 70 to 96% in the NH group (diamonds, left panel) and from 69 to 96% in the HL group (diamonds, right panel). In quiet, performance on the control task was near perfect in both groups (100 and 99%). In the single task, where there was an irrelevant sentence present in the ear opposite to the target, scores in both listener groups dropped (squares), indicating that the message in the unattended ear interfered with performance. The magnitude of this interference was 11 percentage points on average in the NH group when noise was present (5 percentage points in quiet) and 16 percentage points on average in the HL group when noise was present (10 percentage points in quiet). In the dual task, performance for M1 (circles) was consistently worse than single-task performance, dropping by 12 percentage points on average in the NH group when noise was present (19 percentage points in quiet) and 10 percentage points on average in the HL group when noise was present (6 percentage points in quiet). Performance for M2 (triangles) was consistently worse than performance on M1, by 13 percentage points on average in the NH group when noise was present (4 percentage points in quiet) and by 16 percentage points on average in the HL group (15 percentage points in quiet).

Separate two-way analyses of variances (ANOVAs) were conducted on the arcsin-transformed data for the two listener groups with factors of task/message (control, single task, dual task M1, dual task M2) and SNR.† These ANOVAs revealed significant main effects of task/message (NH: $F[3,24] = 53.4$, $p < 0.001$; HL: $F[3,24] = 144.7$, $p < 0.001$) and SNR (NH: $F[3,24] = 98.7$, $p < 0.001$; HL: $F[3,24] = 177.9$, $p < 0.001$). Post hoc comparisons with a Bonferroni correction indicated that all task/message conditions were significantly different from one another for both NH and HL groups, Moreover, all SNRs differed from one other except for the −9 and −6 dB SNRs in the NH group. The interaction between task/message and SNR was significant for the HL group ($F[9,72] = 2.0$, $p < 0.05$) but not for the NH group ($F[9,72] = 2.0$, $p = 0.06$).

Error Patterns

Examination of responses revealed that many errors in the single task resulted from listeners reporting one or two keywords from the irrelevant ear, and many errors in the dual task resulted from listeners reporting the messages in the wrong order. A breakdown of the errors is provided in Figure 3.

The top row of Figure 3 shows the rate of "confusion" errors, in which there was confusion between the ears for one or both keywords. For example, if the required keywords were "red one" and the keywords from the other message were "blue two," then responses of "blue two," "blue one," and "red two" would all constitute confusion errors. Confusion errors occurred on approximately 20% of the trials for both groups of listeners. This extent of across-ear interference was surprising, given that many previous studies have found no measurable interference in dichotic listening tasks (Cherry 1953; Drullman & Bronkhorst 2000). These errors may have been more prevalent in this study either because of the highly confusable nature of the speech materials in the corpus (c.f. Brungart 2001) or because the target ear varied from trial to trial in an unpredictable way and had to be selected on the basis of the

†The data collected in quiet were not included in these ANOVAs because not all subjects in the NH group completed the quiet condition.

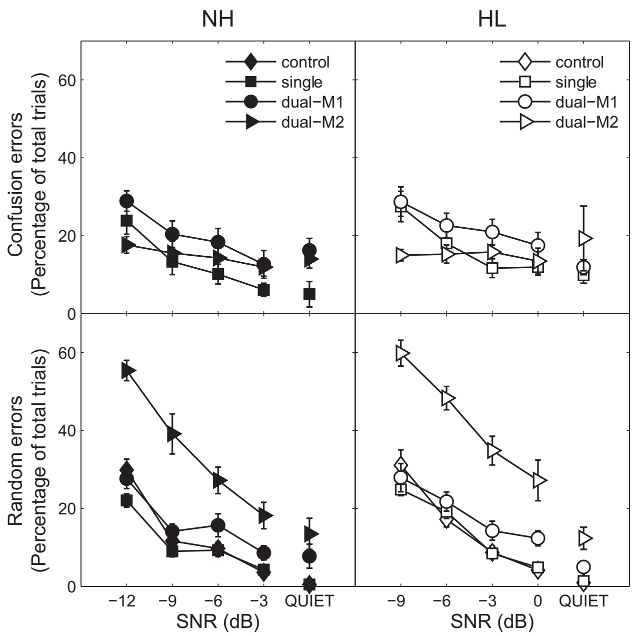

Fig. 3. Frequency of confusion errors (top row) and random errors (bottom row) for listeners with normal hearing (NH: left column) and hearing loss (HL: right column). The different lines in each panel show across-subject mean scores in the control task (diamonds), the single task (squares), and the dual task for M1 (circles) and M2 (triangles) as a function of signal to noise (SNR). Error bars represent standard errors of the mean.

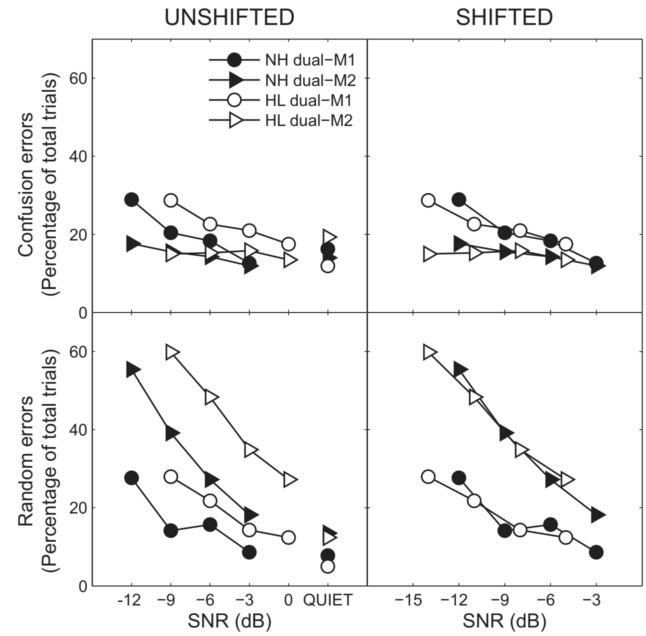

Fig. 4. Frequency of confusion errors (top row) and random errors (bottom row) in the dual task for listeners with normal hearing (NH: filled symbols) and hearing loss (HL: open symbols). The different lines in each panel show across-subject mean scores for M1 (circles) and M2 (triangles). The left column shows data replotted from Figure 3 on the same signal to noise ratio (SNR) axis (error bars have been omitted to aid visualization but statistical comparisons are given in the text). The right column shows the same data but with the HL group shifted to the left by 5 dB.

call sign (Gallun et al. 2007). The added noise also influenced confusion errors, as shown by the tendency of these errors to decrease with increasing SNR. The bottom row of Figure 3 shows the rate of "random" errors in which one or both of the reported keywords were not from either message. In the above example, a response such as "red three" or "green three" would fall in this category. Random errors dropped off with increasing SNR and occurred with similar frequency in the control and single tasks, as well as for M1 in the dual task. In the case of M2, random errors were far more frequent and more sensitive to SNR (compare slopes in bottom panels of Fig. 3).

Comparison of Dual-Task Errors for NH and HL Groups

For those listeners who completed the initial "quiet" session (rightmost points in Fig. 3), two separate ANOVAs were conducted on the arcsin-transformed error rates in quiet in the dual task (with message, M1 or M2, as a within-subjects factor and listener group as a between-subjects factor). For confusion errors, the analysis revealed no significant effect of message ($F[1,12] = 0.1$, $p = 0.7$) or listener group ($F[1,12] = 0.02$, $p = 0.9$), and no interaction ($F[1,12] = 0.6$, $p = 0.5$). For random errors, there was a significant effect of message ($F[1,12] = 6.4$, $p < 0.05$), but no significant effect of listener group ($F[1,12] = 0.1$, $p = 0.8$) and no significant interaction ($F[1,12] = 0.5$, $p = 0.5$). Thus, there is no evidence that the listener groups differed with respect to their dual-task performance in quiet.

To compare performance for the two listener groups in the dual task when noise was present, Figure 4 (left column) shows mean error rates replotted on the same axis for both groups (NH: filled symbols, HL: open symbols) and both messages (M1: circles, M2: triangles). The top left panel shows confusion errors and the bottom left panel shows random errors.

For both groups, confusion errors were more common and more sensitive to SNR for M1 than M2. Confusion errors for the HL group were higher than the NH group for M1, but the groups were similar for M2. A repeated-measures ANOVA was conducted on the arcsin-transformed confusion error rates over the common range of SNRs, with message and SNR as within-subjects factors and listener group as a between-subjects factor. The analysis revealed significant main effects of message ($F[1,16] = 26.6$, $p < 0.001$) and SNR ($F[2,32] = 5.1$, $p < 0.05$), but no main effect of listener group ($F[1,16] = 1.8$, $p = 0.2$). The two-way interaction between message and SNR was significant ($F[2,32] = 8.5$, $p < 0.005$), consistent with the observation that M1 confusion errors were more sensitive to the SNR than M2 confusion errors. The interaction between message and listener group was also significant ($F[1,16] = 5.2$, $p < 0.05$), supporting the observation that the HL group made more M1 errors than the NH group. No other interactions were significant.

Random errors in M2 for both groups were far more common than those in M1 and more sensitive to SNR. Random errors were more prevalent in the HL group than in the NH group, especially for M2. A repeated-measures ANOVA conducted on the arcsin-transformed random error rates over the common range of SNRs revealed significant main effects of message ($F[1,16] = 148.3$, $p < 0.001$), SNR ($F[2,32] = 134.0$, $p < 0.001$), and listener group ($F[1,16] = 13.9$, $p < 0.005$). The two-way interaction between message and SNR was significant ($F[2,32] = 9.1$, $p < 0.005$), indicating that random errors in M2 were more sensitive to the SNR than those in M1. The two-way interaction between message and listener group was also significant ($F[1,16] = 5.9$, $p < 0.05$), consistent with the observation that the HL group showed a greater deficit for M2. No other interactions were significant.

Listeners with hearing loss often perform as well as listeners with normal hearing on speech intelligibility tasks when given a more favorable SNR. Because performance was examined at a range of SNRs in the current experiment, it was possible to examine whether a simple SNR increase would also eliminate differences in performance between groups on a dual task. A calculation was done to determine the shift (in decibels) that best aligned the error functions for the two groups on the single task (minimized the absolute error between groups across the two error types‡) and this shift was then applied to the error patterns for the dual task. The right column of Figure 4 shows error data identical to that in the left column but with the HL data shifted along the SNR axis by this optimal shift (5 dB).

The shifted error functions line up well for the two groups. In fact, the 5-dB shift, which minimized the mean absolute error between groups for the single task (mean absolute error across the two error types of 1.3 percentage points) also minimized the error between groups for the dual task (mean absolute error across the two error types and two messages of 1.6 percentage points). Note that this shift not only aligned error functions that were fairly similar between groups (all confusion errors and M1 random errors) but also the error functions that differed greatly between groups (M2 random errors). The fact that M2 random errors are more sensitive to SNR means that a given improvement in SNR gives rise to a larger reduction in errors. In other words, the effective drop in SNR caused by hearing loss has a larger impact on M2 random errors than on M1 random errors because M2 error functions are steeper.

DISCUSSION

Performance for M1 and M2 in the Dual Task

In our dual task, performance was poorer for each message than for the one message reported in the single task. For M1, the difference was relatively small and was caused by both an increase in confusion errors (where having to report both messages increased the chances of subjects interchanging the keywords) and an increase in random errors (which may be a consequence of processing load). For M2, the deficit relative to the single task was far greater because of a much larger occurrence of random errors.

More than 50 years ago, Broadbent (1954) proposed that simultaneous inputs to the auditory system are processed serially to some extent. He presented two sequences of digits simultaneously to the two ears and observed that, although listeners could recall all digits, responses were always made to one ear before the other. Broadbent (1957, 1958, chap. 9) postulated that simultaneous sensory inputs are stored temporarily via immediate auditory memory and then processed serially by a limited capacity mechanism (see also Lachter et al. 2004). A consequence of such a scheme is that the secondary message in the pair must be stored while the primary message is processed. Our results, showing large differences in performance for the message reported first and second, are consistent with this idea (see also Ihlefeld & Shinn-Cunningham 2008).

However, one difficulty with the dual-response design is that the responses themselves must be made sequentially. Specifically, it is possible that the poorer performance on M2 is related to the fact that it must be retained in memory longer than M1 during the response interval (Sperling 1960). However, the response method used (one mouse click per message on a grid of color-coded/numbered buttons) minimized this time delay; thus, we believe that the performance differences observed for M1 and M2 are primarily due to differences in the order in which they are processed (or by the mechanism underlying their processing). An alternative approach could have been used to use a "partial report" procedure in which listeners are asked after stimulus presentation to report back just one of two messages (Sperling 1960; Darwin et al. 1972; Gallun et al. 2007), but this design has the disadvantage that performance on both M1 and M2 could not be evaluated within a single trial. Further experiments will be required to confirm that differential performance for M1 and M2 truly reflects different processing mechanisms.

The Effect of Noise on the Processing of Simultaneous Messages

In both NH and HL groups, we found that increasing the noise level affected the performance for M1 in the dual task in nearly the same way that it affected performance in the single task. In contrast, the ability to report M2 decreased more dramatically with increasing noise level due to a sharp rise in random errors. These results support the conclusion that the processing of simultaneous messages interacts with the quality of the inputs.

In the conceptual model described earlier in which simultaneous inputs are processed serially, the input that is processed second is held in the form of a raw sensory representation that is volatile and degrades with time (Broadbent 1957; Brown 1958; Durlach & Braida 1969). If this was the case, it would explain why performance for M2 is particularly sensitive to the integrity of the acoustic input. A degraded input will degrade even further in this store and may not even be useful by the time it is fully processed. In essence, there may be a trade-off between SNR and the time interval during which a sensory trace must be maintained. Note that the effect of noise on M2 was almost exclusively due to an increase in random errors; confusion errors were quite constant as a function of SNR (Figs. 3 and 4). This supports the idea that sensory degradation, not increased confusion between the streams, is responsible for the dramatic effect of noise on recall of M2. In related recent work, it has been suggested that reduced absolute signal level (in the absence of noise) can also disrupt echoic persistence and hence performance on a secondary task (Baldwin & Struckman-Johnson 2002; Baldwin 2007).

An alternative explanation of this result is that the increased difficulty of processing M1 in trials with a low SNR effectively drained a limited pool of processing resources, leaving fewer resources for processing M2. This rationale has been used

‡The error functions were first linearly interpolated to give a resolution of 0.5 dB. Then for each pair of error functions, the absolute error was calculated as the HL function was shifted to the left in 0.5-dB steps over the range 0 to 10 dB. The chosen shift value gave the smallest mean absolute error across the two error types in the single task.

previously to explain the effect of noise on the ability to store part of a single-attended message for later recall (Rabbitt 1968; Pichora-Fuller et al. 1995).

The Effect of Hearing Loss on the Processing of Simultaneous Messages

The primary goal of this study was to assess the effect of sensorineural hearing loss on the processing of simultaneous messages. Given previous reports that situations involving divided or rapidly switching attention are difficult for listeners with hearing loss, we expected to find a larger deficit in responses to a secondary message than to a primary message (relative to listeners with normal hearing). To focus on the task of processing simultaneous messages without confounding factors related to peripheral resolvability of the messages, we used dichotic presentation and an increased overall presentation level in the hearing-impaired group.

Dual-task error rates in the quiet condition did not differ significantly between the two groups of listeners. Thus, it seems that hearing impairment in the absence of noise does not necessarily mimic the effects of added noise in normally-hearing listeners. Note that this may be a ceiling effect, as error rates were quite low in the quiet condition for this task (particularly random errors, for which a difference between groups might be expected). In a previous study that used a more demanding dichotic digits task (with recall of three digits per ear required), a measurable deficit in quiet was observed for listeners with milder hearing impairments than those of our listeners (Neijenhuis et al. 2004).

In the presence of added noise, listeners with hearing loss performed worse than listeners with normal hearing at the same SNR. For M1, there was a small increase in confusion errors and a small elevation of random errors. For M2, there was in fact no increase in confusion errors but there was a very large elevation in random errors. This indicates that the ability to extract information from a second, simultaneous message is particularly poor in listeners with hearing loss when compared with listeners with normal hearing at the same SNR. However, when the two groups of listeners were compared at different SNRs (higher in the HL group by 5 dB), error rates for both M1 and M2 were similar in the two groups. In other words, our results suggest that in a simultaneous listening task, just as in many selective listening tasks, listeners with sensorineural hearing loss perform similar to normal hearing listeners given a poorer SNR. It seems that the addition of noise disrupts the processing of multiple sources and that the presence of a hearing impairment exacerbates this effect.

A key feature of the design of this study was that listeners were asked to give *multiple responses* to simultaneous messages, allowing us to compare performance on the two messages. This approach has not been widely adopted in listeners with hearing loss. Although several studies used a double-vowel paradigm in which listeners are asked to identify both of a pair of simultaneously presented vowels (Summers & Leek 1998; Arehart et al. 2005; Rossi-Katz & Arehart 2005), very few have used sentence-length speech in which memory can be assumed to play a more significant role (but see Mackersie et al. 2001; Neijenhuis et al. 2004). Mackersie et al. (2001) used a "simultaneous sentence test," in which listeners reported back two simultaneous messages (spoken by one male and one female voice, presented monaurally). Although the authors were primarily concerned with performance on one message (the one reported first; they only required listeners to report the second message to make the task more difficult), their results show that fewer keywords were reported correctly for the secondary message than for the primary message. This finding is consistent with the results from our task in which two messages spoken by two male talkers were presented to separate ears. In this previous study, listeners with hearing loss were able to recall an average of only 10% of the keywords from the second message. In contrast, although we find that hearing-impaired listeners are worse at reporting M2 than M1, performance is still approximately 25%, even at the lowest SNRs tested, and 40% if confusion errors are excluded. Part of this difference may be that the memory load in our task was relatively low: there were only two key words to be recalled from each message, and the messages came from a small, closed response set. However, in addition, the hearing-impaired listeners in the study of Mackersie et al. were older than their normally-hearing counterparts (mean ages 73 and 27 yrs, respectively); thus, it is possible that performance of the hearing-impaired group was lower because of age-related effects. Although aging may well contribute to poor performance in divided listening tasks (see also Humes et al. 2006; Singh et al. 2008), the results of this study suggest that hearing loss in otherwise healthy, young adults interferes with the ability to recall a second message during divided listening in noise.

An effect of hearing loss on the recall of speech stimuli has been reported previously (Rabbitt 1990; Pichora-Fuller et al. 1995; McCoy et al. 2005), often in tasks involving listening to and responding to a sentence or a sequence of numbers while at the same time storing a word from the sequence for later recall. Hearing loss seems to impair performance on the recall task, an effect that has been explained in terms of an "effort hypothesis." According to this hypothesis, hearing loss makes the immediate speech task more demanding, leaving fewer processing resources for storing the to-be-recalled items. This hypothesis is also supported by studies that have used a secondary task that is non-auditory and thus does not depend directly on the quality of the auditory stimuli. For example, Rakerd et al. (1996) showed that young hearing-impaired listeners perform more poorly than young normally-hearing listeners on a secondary task involving memorization of visually presented digits, when the primary task is to comprehend an ongoing speech passage.

For the task explored in this study, namely the immediate recall of simultaneous messages, we propose that hearing loss may also have a direct effect on the processing of M2 by degrading its spectrotemporal representation in the auditory system. In other words, hearing loss may compromise a listener's ability to process simultaneous messages in a similar way to added noise, by degrading the sensory trace that is used for the processing of a source outside the primary focus of attention (Shinn-Cunningham & Best 2008).

Implications of the Results

We find that listeners with hearing loss show a larger deficit (relative to their normally-hearing counterparts) on the processing of a secondary message than on the processing of a primary message when listening at a given SNR. However, the performance of these listeners could be equated with that of listeners with normal-hearing simply by improving the overall SNR. This suggests that technology, behavioral changes, or environmental modifications focused on improving the SNR should be very effective in aiding communication in complex environments for hearing-impaired listeners.

Our finding that improving the SNR has a larger impact on the processing of secondary talkers than on the processing of a primary talker may prove to be important in understanding the full extent of benefits available from bilateral hearing aids and bilateral cochlear implants. Until now, bilateral systems have been compared with unilateral configurations using a variety of selective listening and sound localization tasks. In these measures, the size of the "bilateral benefits" reported has varied substantially across listeners and studies (Brown & Balkany 2007; Ching et al. 2007; Boymans et al. 2008; Marrone et al. 2008). If bilateral systems were tested using a listening task in which listeners were required to extract information from two simultaneous messages, even larger benefits might be observed (see also Noble & Gatehouse 2006). Although the case tested in this study represented an extreme example (in which one message was delivered to each ear), there are many natural situations in which different sounds in the environment are spatially distributed such that they have different "better ears." In such cases, although good reception of a single sound requires a good SNR at one ear, the successful reception of multiple sounds may require a good SNR at both ears.

As a final note, it is possible that the task used in this study may underestimate the difficulty of simultaneous processing for listeners with hearing loss in more realistic situations. First, presenting the two simultaneous messages to separate ears alleviated the known difficulties that hearing-impaired listeners have with segregating simultaneous voices; this is evidenced by the fact that the drop in performance from the monaural control task to the dichotic single task was similar in the two listener groups. Second, the trial-based structure of the speech task meant that stimuli were always followed by a silent period in which listeners could make optimal use of temporarily "stored" sensory information. In more realistic situations, where conversations flow rapidly and continuously, such a catch-up strategy would be impossible and this may exacerbate the effects of a degraded sensory representation. Finally, the speech materials used in this study (where each sentence had only two keywords from a closed set) gave rise to primary and secondary tasks with modest cognitive demands. The effects we observed might be greater/exaggerated for tasks involving longer, open-set sentences; in such conditions, the primary speech task would require more sustained attention and the memory demands of the secondary task would be increased. This might be expected to increase overall difficulty, particularly for older listeners with hearing loss, as there seems to be an interaction between the effects of memory load and age (Gordon-Salant & Fitzgibbons 1997; Wingfield et al. 2005).

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