The effect of hearing loss on auditory spatial attention

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To understand better how hearing loss affects spatial listening abilities in complex multi-talker situations, we investigated auditory spatial attention in 8 older adults with normal audiometric thresholds below 4 kHz and 8 older adults with bilateral sloping sensorineural hearing losses ranging from moderate to severe in the higher frequencies. In a condition with real spatial separation, a target sentence from the Coordinate Response Measure (CRM) corpus was presented from one spatial location and competing sentences from two different locations, with pre-trial cues specifying the target's identity and location. In a condition with simulated spatial separation, corresponding perceived spatial locations of the target and competitors were achieved through exploitation of the precedence effect. Seven different probability specifications indicated the likelihood of the target being presented at the three locations (100-0-0, 80-0-20, 60-0-40, 0-0-100, 20-0-80, 40-0-60, and 50-0-50, respectively for 0°, 45°, and 90° azimuth). As expected, hearing-impaired listeners performed worse than normal-hearing listeners across all listening conditions, but especially in conditions where the location of the target was less certain. For both groups, performance was superior when the target was presented from the more probable location than when it was presented from the less probable location. Implications for clinical practice and future research will be discussed.

INTRODUCTION

Recently, there has been increased interest in investigating speech perception in complex and more realistic and ecologically valid listening situations. Historically, research in auditory perception has predominantly focussed on listening situations where targets and maskers are presented from fixed spatial locations. We argue, however, that in many everyday environments, listeners may not have advanced knowledge of where the next sound may come from; for example, in a situation where an individual who is hard of hearing is having a group conversation. Speech may suddenly alternate from one person to another, and the talker of interest to a listener could change from one moment to the next. An added complexity is that more than one individual may be speaking at a given point in time, and shifting between and attending to one (or more than one) speaker presents a non-trivial challenge for a listener.

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Previous research suggests that there is a cost associated with uncertainty about the spatial location of a target (e.g., Spence and Driver, 1994). Under such conditions, slower reaction times and reduced accuracy in identifying tonal stimuli have been found for younger adult listeners with normal hearing (Mondor and Zatorre, 1995; Arbogast and Kidd, 2000). The adverse effects of spatial uncertainty have also been observed when speech was used as both the target and masker (Kidd *et al*., 2005; Brungart and Simpson, 2007). In a study in which younger and older adults with normal hearing sensitivity below 4 kHz were tested, the performance for both groups was similarly decreased as certainty about the spatial location of the target was reduced (Singh *et al*., 2008). The relative contributions of the acoustic and cognitive mechanisms underlying auditory spatial attention and spatial uncertainty were further investigated by comparing performance when the target and competing sentences were presented with real or simulated spatial separation. In the simulated conditions, perceived spatial separation was achieved using the precedence effect such that the contribution of some of the natural binaural cues that are available in real spatial separation conditions were reduced (for a detailed discussion consult: Freyman *et al*., 1999; Li *et al*., 2004; Singh *et al*., 2008). It is unknown how uncertainty about the spatial location of a sound source affects listeners who are hard of hearing. The purpose of the current study is to examine how spatial uncertainty affects the performance of listeners with moderate-to-severe high-frequency hearing loss. Because uncertainty about the spatial location of a target increases the need for listeners to search auditory scenes and because sound localization is compromised in listeners who are hard of hearing (e.g., Noble *et al*., 1994), spatial uncertainty may be particularly taxing for them.

METHOD

Participants

Eight participants (mean age = 71.5 years, *SD* = 2.9) with clinically normal audiometric pure-tone air-conduction thresholds (≤ 25 dB HL) from 0.25 to 3 kHz (inclusive) bilaterally and eight participants (mean age = 77.8 years, *SD* = 4.1) with bilateral sloping sensorineural hearing loss, ranging from moderate to severe in the higher frequencies participated in the study (see Table 1). The bilateral four-frequency (500, 1000, 2000, and 4000 Hz) pure-tone average (4PTA) was 10.7 dB HL (*SD* = 5.4) for normal-hearing participants and 39.1 dB HL (*SD* = 6.0) for hearing-impaired listeners. Each participant exhibited symmetrical audiograms, where an asymmetry was defined as an interaural asymmetry > 10 dB at more than two adjacent test frequencies between 250 and 8000 Hz. All participants reported that they were native English speakers, in good overall health, and that they had never previously worn hearing aids.

Stimuli

The stimuli consisted of sentences from the Coordinate Response Measure (CRM) corpus spoken by the four male talkers (Bolia *et al.*, 2000). The sentences have the format: "*Ready (callsign) go to (color) (number) now*", with all possible combinations of eight callsigns (*Arrow, Baron, Charlie, Eagle, Hopper, Laker, Ringo, Tiger*), four colors (*red, white, blue, green*), and eight numbers (*1, 2, 3, 4, 5, 6, 7, 8*).

Equipment

All testing was conducted in a 3.3 m^2 single-walled sound-attenuating booth. The stimuli were controlled and presented via custom software. The stimuli were routed from a Dell computer to a Tucker-Davis Technologies (TDT) System III to a Harmon/Kardon (model HK3380) amplifier. Sentences were converted to analog (RP2.1) at a sampling rate of 24.414 kHz by a 24-bit D/A converter, attenuated (PA5), conditioned (SA1), and presented over loudspeakers located at approximately the same height as the listener's head when seated. Visual cues were displayed on a 17-inch touch-screen monitor on a table at a height of 0.46 m in front of the listener, including visual cueing prior to each trial to specify the callsign word in the target sentence and cueing prior to each block of trials to specify the probability of the target being presented at each of the three possible locations. The response choices were also displayed visually, as was feedback regarding whether or not each response was correct.

	Left ear									Right ear								
	0.25	0.5	1	1.5	2	3	4	6	8	0.25	0.5	1	1.5	2	3	4	6	8
NH1	15	15	20	20	25	25	30	25	35	10	10	15	20	25	25	30	55	45
NH2	5	0	15	5	10	30	30	50	65	5	-5	15	10	15	10	20	55	75
NH3	0	-5	0	20	25	20	15	30	35	5	-5	0	10	20	25	20	15	15
NH4	10	0	10	5	5	20	25	65	60	10	10	10	5	10	15	25	50	55
NH5	-10	-5	-5	0	-5	10	25	40	50	-5	-5	0	0	0	0	10	25	45
NH6	10	0	0	5	5	25	30	40	80	5	5	0	0	5	20	40	50	75
NH7	10	5	5	5	5	20	20	40	50	0	5	0	0	10	25	35	45	50
NH8	15	10	0	0	15	15	25	25	65	10	0	0	5	5	10	10	35	60
HI1	25	25	15	25	55	60	55	60	60	15	15	20	30	40	50	45	55	60
HI2	25	40	45	45	55	55	55	55	75	35	40	45	45	55	60	65	65	75
HI3	30	30	35	35	45	45	55	70	70	30	30	30	30	35	40	45	65	75
HI4	15	25	25	35	45	55	65	75	75	10	20	30	45	45	60	65	70	75
HI5	20	25	25	35	40	55	65	70	75	15	25	30	35	45	60	60	75	80
HI6	15	25	40	45	45	50	65	65	65	20	30	40	60	55	55	60	65	65
HI7	20	20	15	20	35	50	55	55	50	25	30	15	20	35	50	50	50	50
HI8	15	15	30	45	45	45	50	65	75	20	20	30	40	50	45	40	40	60

Table 1: Hearing thresholds (dB HL) for normal-hearing (NH) and hearing-impaired (HI) participants. Test frequencies are expressed in kHz.

Two presentation methods were used which differed in the availability of the acoustical cues serving the perception of spatial location. For the first method, real spatial separation (RSS), the target sentence was presented from one loudspeaker and the two competing sentences were presented from two different loudspeakers (one sentence per loudspeaker). Thus, three loudspeakers were used to present stimuli and one sentence was played from each loudspeaker. Each loudspeaker was located 1.6 m from the participant's head at 0°, 45°, and 90° azimuth in the horizontal plane. The second method, simulated spatial separation (SSS), used the precedence effect so that each of the three sentences was perceived to appear at one of three locations: in front, the front-side, or the right side of the listener. For the SSS condition, four loudspeakers were used where each loudspeaker was located 1.6 m from the listener's head at ±45° and ±90° azimuth. Inter-loudspeaker lead-lag times of 3 ms were used to simulate the left and right locations. An utterance appeared to come from the frontal spatial location when the signal was played from -45° and +45° at the same time, an utterance appeared to come from the front-side location when the loudspeaker located at +45° led the loudspeaker located at -45° by 3 ms, and an utterance appeared to come from the side loudspeaker location when the +90° loudspeaker led the -90° loudspeaker by 3 ms.

Procedures

The listener's task was to identify the color and number key words in the target sentence that was presented simultaneously with two competing sentences. On each trial, the three sentences were randomly selected, and differed with respect to the color, number, callsign, and talker of the sentence. Both the color and number had to be correct for a response to be scored as correct. Feedback (*correct* or *incorrect*) was provided after every trial and summary scores were presented at the end of each block. At the start of each visit, or whenever a new presentation method was employed, participants completed practice trials.

The visual cue indicating the probability specification for the block and the identity callsign of the target sentence was displayed 1 s before each trial. Four probability specifications, expressed by a set of three numbers, indicated the proportion of trials in which the target would be presented from the front (0°), front-side (45°), or side (90°) location. For targets referenced to the front location, the probability specifications were 100-0-0, 80-0-20, 60-0-40, and 50-0-50, and for targets referenced to the side location, the probability specifications were 0-0-100, 20-0-80, 40-0-60, and 50-0-50. On any given trial, the location of the target sentence was randomly selected from the front or side locations, with the constraint that the probability cues were accurate over the block. Participants were instructed to face directly ahead for the duration of the stimulus. Each sentence was presented at 60 dBA.

Design

Word recognition was measured when listeners were required to attend to one talker in a multi-talker auditory scene. Listeners were asked to identify two key words from a target sentence presented concurrently with two highly similar competing sentences. Word recognition accuracy was measured using a 2 (reference position: front (0°) or right side (90°)) x 4 (target location certainty for the three locations, 0°, 45°, and

90°: 100-0-0, 80-0-20, 60-0-40, and 50-0-50 for the front reference positions or 0-0-100, 20-0-80, 40-0-60, and 50-0-50 for the side reference positions) x 2 (presentation method: RSS and SSS) design. All participants completed every condition. The order of testing was counterbalanced, with half of the normal-hearing and half of the hearing-impaired participants starting with the RSS presentation method and the remainder starting with the SSS presentation method. Similarly, the reference position to be tested first was also counterbalanced, with half of the participants starting with the probability cue referenced to the front position and the remaining participants starting with the probability cue referenced to the side position. For each presentation method, there were eight testing sessions, usually with four sessions completed in a 2-hour visit. The trials in each session were presented in four blocks, with one of the sets of four probability specifications assigned randomly without replacement so that a different target certainty condition was assigned for each block. Each block consisted of 30 trials. For each of the 16 conditions, participants completed 120 trials. In total there were 1920 trials per participant.

RESULTS

Overall results

The results for all participants are depicted in Fig. 1. We observed significant main effects on performance of all four variables. Specifically, mean performance was higher for the following: (i) normal-hearing listeners compared to hearing-impaired listeners; (ii) location certainty referenced to the front compared to the side; (iii) more compared to less target location certainty; and (iv) real compared to simulated spatial separation.

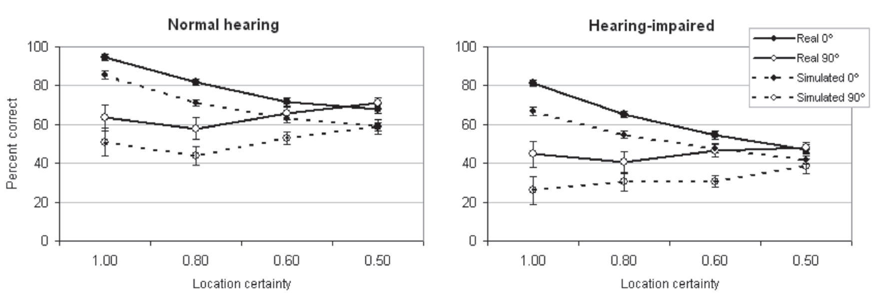

Fig. 1: Word-recognition performance for normal-hearing and hearing-impaired listeners when the location certainty was referenced to 0° or 90° with either real or simulated spatial separation. Error bars indicate SEMs.

Spatial uncertainty had a larger effect on mean performance scores for hearing-impaired compared to normal-hearing listeners when sentences were presented with either real or simulated spatial separation (see Fig. 2). Although all listeners performed worse for targets presented when location certainty was 0.80 compared to 1.0, only hearing-impaired listeners exhibited further performance reductions with further decreases in target location certainty.

There was a difference between the patterns of performance in the real and simulated spatial separation conditions that depended on location certainty and the spatial position referenced. In conditions where there was less certainty about the spatial location of the target, performance was higher when sentences were presented with real compared to simulated spatial separation. However, the difference between scores in the real compared to simulated conditions was smaller when location certainty was referenced to the front as opposed to the side location.

The influence of location certainty also differed depending on the reference position. Whereas performance always declined with increasing target location uncertainty, when target sentences were more likely to come from the front position, scores were relatively flat compared to when the target sentences were more likely to come from the side location.

This description of the pattern of results was confirmed statistically with a 2 (group: normal-hearing and hearing-impaired) x 2 (presentation method: RSS and SSS) x 4 (location certainty: 1.0, 0.8, 0.6, and 0.5) x 2 (reference position: front and side) repeated-measures ANOVA. We observed a significant main effect of group [$F(1, 14) = 20.04$, $p < 0.001$], presentation method [$F(1, 14) = 75.13$, $p < 0.001$], location certainty [$F(3, 42) = 54.07$, $p < 0.001$], and reference position [$F(1, 14) = 83.52$, $p < 0.001$]. Significant two-way interactions of presentation method and reference position [$F(1, 14) = 5.96$, $p < 0.05$], presentation method and location certainty [$F(3, 42) = 3.39$, $p < 0.05$], and reference position and location certainty [$F(3, 42) = 71.88$, $p < 0.001$], and a significant three-way interaction of group, presentation method, and location certainty were also observed [$F(3, 42) = 3.64$, $p < 0.05$]. No other effects reached statistical significance.

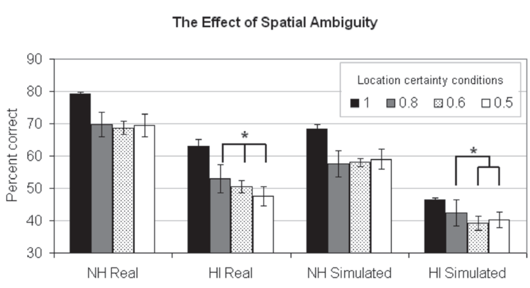

Fig. 2: Word-recognition performance for normal-hearing (NH) and hearing-impaired (HI) listeners with real and simulated spatial separation across the four location certainty conditions. Key significant differences are highlighted with an asterisk. Error bars indicate SEMs.

Spatial listening expectations

The following analysis concentrates on the results from the intermediate (0.8 and 0.6) location certainty conditions where both "expected" and "unexpected" trials occurred. An expected trial occurred when the target was presented from the spatial location with the highest probability of occurrence (i.e., the front spatial position when the reference position was 0º or the side spatial position when the reference position was 90º), whereas an unexpected trial occurred when the target was presented from a spatial location with a lower probability of occurrence (i.e., the side spatial location when the reference position was 0º or the front spatial position when the reference position was 90º). By comparing performance at each spatial location depending on whether or not the target was more likely to occur at that position, it was possible to gauge the contribution of spatial listening expectations. For ease of presentation, the results are collapsed across the two location certainty conditions since they produced similar patterns of results.

Similar to the overall results, a difference in performance was observed between normal-hearing and hearing-impaired listeners (see Fig. 3). Whereas normal-hearing listeners had a mean score of 61.9 percentage points, hearing-impaired participants scored a mean of 44.3 percentage points. Furthermore, performance tended to be better when sentences were presented with real (mean = 58.4 percentage points) compared to simulated (mean = 47.8 percentage points) spatial separation; however, unlike the pattern obtained with the overall results, scores were similar when location certainty was referenced to either the front (mean = 54.1 percentage points) or side (mean = 52.1 percentage points) spatial position. Finally, scores were approximately 9 percentage points higher when targets appeared at expected (mean = 57.4 percentage points) compared to unexpected (mean = 48.8 percentage points) spatial locations.

The contribution arising from target location expectations was further influenced by the spatial location where the target was presented. When targets were presented from the side location, mean performance for expected compared with unexpected trials was 36.8 versus 30.2 percentage points, respectively. When targets were presented from the front location, mean performance for expected compared with unexpected trials was 78.0 versus 67.5 percentage points, respectively.

In order to confirm these descriptions, a repeated-measures ANOVA was conducted with group (normal-hearing and hearing-impaired) as a between-subjects variable, and presentation method (RSS and SSS), spatial listening expectations (expected and unexpected), and reference position (0º and 90º) as within-subjects variables. We found significant main effects of group [$F(1, 14) = 24.49$, $p < 0.001$], presentation method [$F(1, 14) = 59.98$, $p < 0.001$], and spatial listening expectations [$F(1, 14) = 28.72$, $p < 0.001$]. We also observed a significant two-way interaction between spatial listening expectations and reference position [$F(1, 14) = 155.26$, $p < 0.001$]. All other effects failed to reach statistical significance.

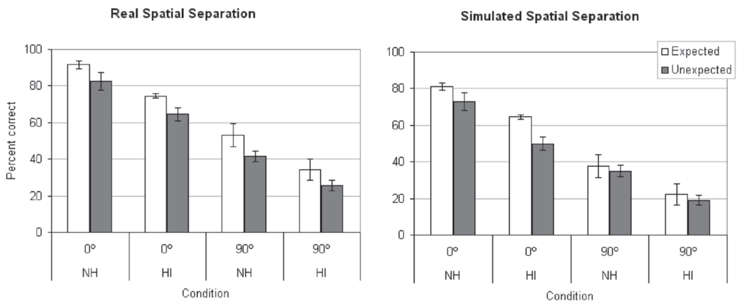

Fig. 3: Word-recognition performance for normal-hearing (NH) and hearing-impaired (HI) listeners for targets expected and unexpected at 0° and 90°. Error bars indicate SEMs.

DISCUSSION

The main goal of this experiment was to investigate how hearing impairment affects spatial listening abilities in a complex multi-talker situation where there is uncertainty about the spatial location of the target. Two important effects were observed. First, we found that, although all listeners performed worse when the location was uncertain, only hearing-impaired listeners continued to show further declines as certainty about the target location decreased. This finding may explain, in part, the difficulties experienced by hearing-impaired listeners in group conversations, and the need for clinicians to stress to their patients the importance of maximizing spatial certainty to guide attention in everyday listening situations. The finding that normal-hearing older adults maintained performance as certainty decreased is consistent with previous research (Kidd *et al*., 2005; Singh *et al*., 2008), which also found that normal-hearing younger and older adults perform similarly with decreasing certainty about target location. The fact that hearing-impaired listeners also demonstrated (slightly) poorer performance with decreasing certainty about the location of the target in SSS conditions further suggests that it is not the availability of natural binaural cue information *per se* that underpins the deficits observed when there is less certainty about the location of the target.

Second, in a follow-up analysis comparing performance on expected and unexpected trials, we were able to gauge the ability of listeners to allocate spatial attention. Importantly, although normal-hearing listeners outperformed hearing-impaired listeners, we failed to observe an impairment-related interaction when targets appeared at expected versus unexpected locations. This suggests that both groups exhibit a similar ability to allocate spatial attention and that the adverse effects of location certainty that hearing-impaired listeners experience do not arise because of an impaired ability to shift attentional resources from an expected to an unexpected location.

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