Published in final edited form as:

J Speech Lang Hear Res. 2012 April ; 55(2): 511–531. doi:10.1044/1092-4388(2011/10-0205).

Informational Masking and Spatial Hearing in Listeners with and without Unilateral Hearing Loss

Ann M. Rothpletz, Frederic L. Wightman, and Doris J. Kistler

Department of Psychological and Brain Sciences, University of Louisville

Abstract

Purpose—This study assessed selective listening for speech in individuals with and without unilateral hearing loss (UHL) and the potential relationship between spatial release from informational masking and localization ability in listeners with UHL.

Method—Twelve adults with UHL and 12 normal-hearing controls completed a series of monaural and binaural speech tasks that were designed to measure informational masking. They also completed a horizontal localization task.

Results—Monaural performance by participants with UHL was comparable to that of normal-hearing participants. Unlike the normal-hearing participants, the participants with UHL did not exhibit a true spatial release from informational masking. Rather, their performance could be predicted by head shadow effects. Performance among participants with UHL in the localization task was quite variable, with some showing near-normal abilities and others demonstrating no localization ability.

Conclusions—Individuals with UHL did not show deficits in all listening situations but were at a significant disadvantage when listening to speech in environments where normal-hearing listeners benefit from spatial separation between target and masker. This inability to capitalize on spatial cues for selective listening does not appear to be related to localization ability.

Keywords

unilateral hearing loss; informational masking; spatial release from masking; binaural; monaural; localization; selective listening

Most of us listen to the world binaurally. Sounds are encoded in the auditory system via two auditory pathways, which produce an impression of an auditory scene. It is well established that binaural listening offers significant communication advantages, particularly in complex auditory environments containing multiple sources (Bronkhorst & Plomp, 1989; Licklider, 1948; MacKeith & Coles, 1971). These advantages accrue because of the various ways that the auditory system processes interaural differences in the sounds reaching the two ears. For example, interaural differences allow listeners to localize and thus better segregate individual sound sources in the environment. Individuals with unilateral hearing loss (UHL) lose many of these advantages, because their auditory experience derives mainly from the sound present at one ear. Consequently, listeners with UHL have been shown to exhibit deficits on tasks that depend to some degree on binaural processing, namely, sound localization and speech understanding in noise (Bess, Tharpe, & Gibler, 1986; Bosman, Hol, Snik, Mylanus, & Cremers, 2003; Gatehouse & Cox, 1972; Linstrom, Silverman, & Yu,

2009; Ruscetta, Arjmand, & Pratt, 2005; Slattery & Middlebrooks, 1994). The current study was designed to expand our understanding of the deficits experienced by listeners with UHL in settings in which spatial cues would normally enhance speech recognition ability.

Speech Understanding by Normal-Hearing Listeners in Multisource Environments

Decades of research have examined how normal-hearing listeners perceive speech in multi-source environments. The earliest studies focused on listening conditions characterized by spectral and temporal overlap of the target and masker (French & Steinberg, 1947; Licklider, 1948), so-called *energetic masking conditions*. More recently, investigators have differentiated the effects of energetic masking from the effects of *informational masking*, which occur beyond that which can be explained by overlapping excitation patterns between masker and target in the auditory periphery (Durlach et al., 2003). Informational masking occurs when the masker is qualitatively similar to the target or is characterized by uncertainty. Whereas energetic masking is thought to affect more peripheral auditory processes, informational masking is thought to affect cognitive/attentional processes (Brungart, 2001; Freyman, Helfer, McCall, & Clifton, 1999; Leek, Brown, & Dorman, 1991). Both energetic and informational masking are present in most real-world listening environments; however, one of the masker types is often dominant.

In environments dominated by energetic masking, normal-hearing listeners are known to take advantage of two binaural cues, namely the head shadow effect and binaural interaction. The *head shadow effect* or *better-ear effect* occurs when spatial separation between the target and masker signals results in a better target-to-masker ratio in one of the ears, relative to the case where the target and masker are co-located. Thus, to the extent that a listener can attend to the ear with the better target-to-masker ratio, speech recognition is improved. This head shadow effect is between 3 dB and 8 dB, depending on the acoustical environment and the difference in azimuth between the speech target and masker (Bronkhorst & Plomp, 1988). The second binaural cue available in noisy environments to listeners with normal hearing is known as *binaural interaction*. Binaural interaction occurs when the target and interfering masker have different interaural timing delays (or phases), resulting in better speech detection or intelligibility than in conditions in which interaural timing delays of the target and masker are the same (Culling, Edmonds, & Hodder, 2006; Licklider, 1948). This effect is attributed to interaural differences in the absence of information that cues spatial location. A manifestation of the binaural interaction effect is the “binaural intelligibility level difference (BILD).” The BILD refers to the roughly 5–8 dB improvement in speech recognition threshold in noise under headphones produced by inverting the speech target in one ear with the masker presented diotically (Beutelmann, Brand, & Kollmeier, 2009; Goverts & Houtgast, 2010; Johansson & Arlinger, 2002; Levitt & Rabiner, 1967a, 1967b). Binaural interaction and head shadow effects can account for the advantages afforded by binaural hearing in most listening conditions that are dominated by energetic masking.

In settings in which informational masking is thought to play a major role, research has shown that listening performance is better when the target and masker originate from different locations in auditory space than when they are co-located (Arbogast, Mason, & Kidd, 2002, 2005; Brungart & Simpson, 2007; Freyman, Balakrishnan, & Helfer, 2001; Freyman et al., 1999). This effect is called *spatial release from masking*, and although it occurs with energetic maskers because of head shadow, the effect is considerably larger when the masker is primarily informational. The aforementioned studies by Arbogast et al. employed digitally processed stimuli to maximize energetic or informational masking in various experimental conditions. The target sentences were presented simultaneously with same-band noise or sentence maskers (i.e., energetic maskers), a different-band noise masker, or a different-band sentence masker (i.e., an informational masker). The masker

stimuli were presented in two spatial positions, co-located (i.e., target and masker both presented at 0° azimuth) and 90° to the right of the target (i.e., target presented at 0° and masker at +90° azimuth). In the co-located condition listeners exhibited an average of 22 dB greater masking with a different-band speech masker than with a different-band noise masker. Because the different-band noise masker and the different-band sentence masker did not contain significant spectral overlap with the target, the 22 dB poorer thresholds with the different-band sentence masker were attributed to the effects of informational masking, rather than energetic masking. In the conditions in which the different-band sentence masker stimuli were presented 90° to the right of the target, listeners received up to an 18 dB release from masking relative to the co-located condition. This is compared to a 6–7 dB spatial release that the listeners received when the same-band noise masker (i.e., an energetic masker) was separated from the target by 90° azimuth. Thus, the spatial benefits that listeners receive on informational masking tasks have been described as a “perceptual” (Arbogast et al., 2002, p. 2097) and are much larger than the binaural advantages that listeners achieve by virtue of the head shadow and binaural interaction effects. Another study has shown that even compared to conditions where the better-ear signal is presented diotically, spatial separation provides a far greater release from informational masking (Best, Ozmeral, Gallun, Sen, & Shinn-Cunningham, 2005).

Speech Understanding by Listeners with UHL in Multi-source Environments

Given the value of binaural cues for listening in complex auditory environments, it is not surprising that many individuals with UHL report communication difficulties in everyday listening situations. Studies conducted over the last several decades have confirmed that listeners with UHL exhibit speech understanding deficits relative to normal-hearing listeners in sound field environments having one or more sources of noise (Bess, Tharpe, et al., 1986; Bovo et al., 1988; Linstrom et al., 2009; Ruscetta et al., 2005; Sargent, Herrmann, Hollenbeck, & Bankaitis, 2001; Tønning, 1971; Welsh, Welsh, Rosen, & Dragonette, 2004). Three of the more comprehensive studies examined children and reveal that children with UHL perform more poorly than their normal-hearing counterparts, even in the most favorable listening conditions where the speech was directed toward the listener’s normal-hearing ear and the noise was directed toward the impaired ear (Bess, Klee, & Culbertson, 1986; Bovo et al., 1988; Ruscetta et al., 2005). Studies examining the performance of adults with UHL have shown similar results (Linstrom et al., 2009; Sargent et al., 2001; Welsh et al., 2004). For example, Sargent et al. (2001) reported poor monosyllabic word recognition and sentence recognition in adults with UHL as compared to normal-hearing adults when the noise source was directed toward the good ear and when the noise source was directed toward both ears. In another study, Linstrom et al. (2009) compared sentence recognition of listeners with UHL who were fitted with bone-anchored hearing aids to that of normal-hearing controls. In this study the Hearing in Noise Test (HINT; Nilsson, Soli, & Sullivan, 1994) was presented in various listening conditions in which the noise or speech was presented directly in front of the listener or 90° toward the listener’s normal or impaired ear. Aided and unaided performance of the listeners with UHL was poorer than that of the normal-hearing controls across all listening conditions. These studies are consistent with others that offer anecdotal reports of listening difficulties in noise by adults with UHL (Colletti, Fiorino, Carner, & Rizzi, 1988; Giolas & Wark, 1967).

The previous studies of speech recognition in noise by individuals with UHL used paradigms in which the target speech was always presented from a different spatial location than the masker. In these conditions, normal-hearing listeners would be expected to capitalize on the binaural cues to improve recognition of the target message. We are not aware of any studies that have compared listening in noise by individuals with UHL to that of normal-hearing individuals in listening conditions where the target and masker were co-

located (i.e., in conditions in which spatial cues are minimal). Examining performance of listeners with UHL in co-located conditions is important because it would establish whether or not listeners with UHL have general deficits in speech understanding in noise, or if their deficits are limited to listening conditions in which normal-hearing listeners take advantage of binaural cues afforded by spatial separation between the target and masker. Therefore, one of the objectives of the current study was to measure performance in both spatially separated and co-located conditions.

In environments dominated by energetic masking, one may predict performance of listeners with UHL from the relative target-to-masker ratio of the target arriving at the listeners' normal-hearing ear. For example, in conditions in which the target is in front of the listener or on the side of the normal-hearing ear, and the masker is on the side of the impaired ear, the listener with UHL may receive some spatial benefit because the target-to-masker ratio at the normal-hearing ear would be better than if the target and masker were co-located. This benefit would be presumably limited to that afforded by the head shadow effect. In contrast, if the target is in front of the listener or on the side of the impaired ear, and the energetic masker is on the side of the normal-hearing ear, the target-to-masker ratio would be poorer at the normal-hearing ear than if the target and masker were co-located. The effect of the head shadow would put the UHL listener at a disadvantage in this condition.

It is more difficult to predict the effect of spatial separation on the performance of listeners with UHL in conditions characterized primarily by informational masking. In spatially separated conditions, listeners with normal hearing are thought to perceive the target and masker as coming from different locations and to use that information to direct their attention to the target talker and away from the other talker(s), resulting in spatial unmasking. For people with UHL, the availability of only one functioning ear precludes the comparison of auditory input from the two ears, which would presumably make determining the direction of the target and masker more difficult. Therefore, using the direction of the target and masker to achieve a spatial benefit for listening may be impossible for many listeners with UHL.

Localization in Listeners with and without UHL

Although it is not known if the processes by which listeners use binaural cues for localizing are the same as those they use for listening to speech in complex listening environments, it is reasonable to speculate that difficulties experienced by individuals with UHL in these tasks may be related to localization difficulties. For listeners with normal hearing, sound localization is dependent on two primary cues, interaural time difference (ITD) and interaural level difference (ILD). An ITD refers to the brief (less than 700 microseconds) time lag in the signal at the ear that is farther from the sound source relative to the ear that is closer to the sound source. An ILD refers to the difference in intensity of the sound between the ear nearest to the sound source and the more distal ear. A large body of research on sound localization has focused on the relative salience of these two interaural difference cues, as well as other cues, such as the directional-dependent spectral shaping of input sounds by the pinnae.

Localization deficits in listeners with UHL are well documented in the literature (Agterberg et al., 2010; Bess, Tharpe, et al., 1986; Bosman et al., 2003; Gatehouse & Cox, 1972; Humes, Allen, & Bess, 1980; Newton, 1983; Slattery & Middlebrooks, 1994; Van Wanrooij & Van Opstal, 2004; Viehweg & Campbell, 1960; Wazen, Ghossaini, Spitzer, & Kuller, 2005). These studies have reported that listeners with UHL demonstrate poor localization performance relative to their normal-hearing counterparts, and that they tend to shift (or "bias") localization responses toward the side of the normal-hearing ear. These findings are generally consistent with those of studies that compared monaural and binaural localization

in normal-hearing listeners using test paradigms in which one ear was plugged for monaural conditions (Abel & Lam, 2008; Oldfield & Parker, 1986; Slattery & Middlebrooks, 1994; Van Wanrooij & Van Opstal, 2007; Wightman & Kistler, 1997).

Although many listeners with UHL show very limited or no ability to localize sounds on the horizontal plane, some listeners with UHL in the aforementioned studies have shown reasonable localization performance (Agterberg et al., 2010, 2011; Gatehouse & Cox, 1972; Slattery & Middlebrooks, 1994; Van Wanrooij & Van Opstal, 2004). Some investigators have concluded that the performance of listeners who demonstrate some ability to localize can be explained to a large extent by their reliance on intensity cues provided by head shadow (Van Wanrooij & Van Opstal, 2004). That is, on tests of localization in which the stimuli are kept at a fixed intensity, these listeners will capitalize on level cues by localizing low intensity stimuli closer to the impaired ear and higher intensity sounds closer to the normal-hearing ear. Head shadow cues are arguably unreliable in real world listening environments and can be effectively eliminated in localization tasks by roving the intensity of the stimuli over trials. Still, a few listeners with UHL have shown surprisingly good performance on localization tasks even when roving intensity paradigms were employed, leading several investigators to suggest that these listeners have learned to localize sounds using monaural spectral cues that arise from direction-dependent filtering by the pinna (Newton, 1983; Slattery & Middlebrooks, 1994; Van Wanrooij & Van Opstal, 2004).

The ability to use monaural spectral cues for localization is complicated by the fact that the sound present at the eardrum includes both the spectral features provided by the pinna and the spectral features in the source itself. Thus, the pinna filtering characteristics must be decoupled from the characteristics of the corresponding sound source (Wightman & Kistler, 1997). A few studies have suggested that learning to use monaural spectral cues for localization may take considerable time and practice. For example, Abel and Lam (2008) examined horizontal localization ability by normal-hearing listeners with a monaurally occluded ear, and found that these listeners showed no improvement following mass practice over a period of a few days. This is consistent with animal studies that showed it took several months of practice for monaurally occluded ferrets to show improvement in localization performance (King et al., 2001). Findings from Slattery and Middlebrooks (1994) also suggest that monaural localization skills require time to acquire. In this study, the listeners with long-term UHL demonstrated better localization ability than the normal-hearing listeners who were tested with monaural occlusion. However, the conclusion that extensive monaural listening experience is a pre-requisite for capitalizing on monaural spectral cues was disputed by Shub, Carr, Kong, and Colburn (2008). They used a testing paradigm that involved feedback and reference stimuli and found no differences between listeners with UHL and those with normal hearing on a monaural listening task. These investigators suggested that the testing paradigm has greater influence on monaural localization performance of participants than does monaural listening experience.

The Relationship between Localization and Speech Understanding in Multisource Environments

Binaural listening to speech in noise is thought to be facilitated, at least in part, by a listener's ability to separately localize a target speech sound and other distracting sounds. One explanation is that because the target and masker appear to be coming from different directions, listeners may make a conscious effort to attend in the perceived direction of the target talker and away from the perceived direction of the distracting talker (Balakrishnan & Freyman, 2008; Freyman et al., 2001; Freyman et al., 1999; Gallun, Mason, & Kidd, 2005; Ihlefeld & Shinn-Cunningham, 2008a; Kidd, Arbogast, Mason, & Gallun, 2005). In general, these studies have found that listeners receive greater benefit from spatial separation between masker and target when they have a priori knowledge of the target location than

when the target location is uncertain. Thus, in environments characterized by considerable informational masking (e.g., “cocktail party” environments), directed attention appears to play an important role for listening. However, other studies dispute a possible role of sound localization in spatial release from masking (Culling, Hawley, & Litovsky, 2004; Drullman & Bronkhorst, 2000; Hawley, Litovsky, & Colburn, 1999). For example, Drullman and Bronkhorst (2000) tested speech recognition in both monaural and binaural conditions using virtual display in which the number and the location of competing talkers was varied. In addition, they measured the ability of the participants to localize the target talker among competing talkers using a closed-set, 5-alternative forced choice paradigm. Although target talker localization performance in the virtual condition was quite poor (i.e., 43–57%), the ability to recognize the target talker’s message in the virtual conditions was relatively good (i.e., approximately 70–88%) in the various competing talker conditions. These results suggest that the impact of spatial separation on speech recognition may not relate directly to the ability to localize the target talker.

A recent study by Gallun et al. (2008) also casts some doubt on the speculation that listeners use perceived location as a cue to distinguish target and masker in complex listening environments. This study measured detection of a 500 Hz tone masked by noise (energetic masker) or random tones (informational masker) using a variety of interaural manipulations of the target. Findings indicated that the perceived location of the target was not related to listeners’ responses for either energetic or informational maskers. This study suggests that at least for tonal maskers, location may not be the salient cue that listeners use to achieve a spatial release from informational masking.

The Present Study

The current study was motivated by three related questions. The first was whether the speech understanding deficits exhibited by listeners with UHL arise primarily in conditions in which normal-hearing listeners are known to benefit from spatial cues or if individuals with UHL exhibit more global listening deficits. The second was whether or not individuals with UHL demonstrate any spatial release from informational masking on a speech recognition task. These first two questions were addressed by measuring performance in a speech recognition task in which the target and masker were co-located (i.e., no binaural cues provided) and in conditions in which the target and masker were spatially separated by 90° on the horizontal plane. The third question was whether or not there is a relationship between directional hearing and selective listening for speech in listeners with UHL. This question was studied in a sound localization task.

General Methods

Individuals with UHL and with normal hearing were tested in three experiments, two of which were speech informational masking tasks either with or without spatial cues, while the third was a sound localization task.

Participants

Participants with unilateral hearing loss and participants with normal hearing were recruited via local audiology clinics and internet advertisements. Most of the individuals with UHL participated in all three experiments. Normal-hearing individuals in roughly the same age range served as controls in each of the experiments. All participants were native English speakers. Participants were paid \$10/hr. Testing sessions lasted two hours and were scheduled at the participants’ convenience. The participants were offered breaks during the testing sessions, and most completed all the experimental testing in fewer than six sessions

(10–12 hours). All aspects of this project were conducted under the approval of the Human Subjects Protection Program at the University of Louisville.

Participants with unilateral hearing loss—Twelve individuals with UHL served as participants. Eleven were tested in all three experiments. One participant (UHL02) did not participate in Experiment 1. Table 1 presents demographic and audiologic information for each participant. Ages ranged from 17.3–64.1 years with a median age of 23.7 years. Degree of unilateral impairment ranged from mild to profound. All participants had sensorineural hearing loss, with the exception of participants UHL02 and UHL03 who had conductive hearing loss secondary to congenital aural atresia and congenital ossicular malformation, respectively. None of the participants reported current use of an amplification device, with the exception of participant UHL11 who used an implantable bone anchored hearing device (i.e., a Baha). The Baha device was turned off and the external portion was removed during testing. With one exception, all participants had thresholds ≤ 25 dB HL at 250–8000 Hz in the ear with normal hearing. Participant UHL09 had borderline mild hearing loss in the mid-frequency range (i.e., thresholds of 25–30 dB at 1000–4000 Hz) in the better hearing ear.

Participants with normal hearing—For each of the three experiments a group of 12 normal-hearing adults was recruited. For purely logistical reasons, only a few normal-hearing listeners participated in more than one experiment. The participants ranged in age from 18.8 to 60.9 years ($Mdn=24.7$ years) in Experiment 1, 18.9 to 60.9 years ($Mdn=24.6$ years) in Experiment 2, and 19.6 to 61.9 years ($Mdn=30.1$ years) in Experiment 3. Thus the ages of the normal-hearing participants were roughly comparable to the ages of the participants with UHL for Experiments 1 and 2 and slightly older than the participants with UHL for Experiment 3. All of the listeners with normal hearing underwent a hearing screening, which demonstrated normal-hearing sensitivity, bilaterally, as defined by audiometric thresholds ≤ 25 dB HL at all octave frequencies 250–4000 Hz. One of the participants with normal hearing had elevated thresholds, bilaterally at 4000 Hz, but her performance on the listening tasks was indistinguishable from the performance of the other normal-hearing listeners.

Experiment 1: Speech Target and Masker Presented Monaurally

Experiment 1 was designed to compare monaural listening performance under headphones of participants with UHL to those with normal hearing. The purpose of this baseline comparison was to determine if individuals with UHL (when listening with their normal ear) demonstrate performance comparable to that of normal-hearing individuals in monaural listening conditions containing primarily informational or energetic masking.

Method

Stimuli—Selective listening was measured using the Coordinate Response Measure (CRM) paradigm (Bolia, Nelson, Ericson, & Simpson, 2000), which has been shown to be a sensitive indicator of informational masking effects (Brungart, 2001; Brungart & Simpson, 2002, 2007; Brungart, Simpson, Ericson, & Scott, 2001; Wightman & Kistler, 2005). The CRM is a closed-set task that requires the listener to attend to a target phrase, while ignoring a highly similar masker phrase. For example, the listener is presented the target phrase, “Ready *Baron*, go to *green* 5 now” with the simultaneously presented masker phrase “Ready *Eagle*, go to *red* 8 now.” The CRM has been used in a number of studies examining energetic vs. informational masking and the effects of spatial separation (Arbogast et al., 2002, 2005; Ihlefeld & Shinn-Cunningham, 2008a, 2008b; Kidd, Mason, Brughera, & Hartmann, 2005; Marrone, Mason, & Kidd, 2008). The advantages of the CRM are that the speech material carries very little linguistic context and that the sentences may be reused

without memory influencing performance. Research by Brungart (2001) suggests that the single-talker masker in the CRM is primarily an informational masker, as evidenced by greater masking effects of speech maskers relative to spectrally and temporally comparable modulated noise maskers.

In one condition, both the speech target and speech maskers were selected from the corpus of sentences that form the basis of the CRM. Talker #0 served as the talker for all of the target sentences. The target sentences were drawn from those with the call sign *Baron*. Each target sentence was paired with a masker sentence spoken by a random selection of one of the remaining three male talkers. The masker sentence contained random selections from the remaining seven call signs, three colors, and seven numbers. The target and masker sentences were time-aligned, such that the word “Ready” of the target and masker sentences started at the same time. Because there were small variations in speaking rates among the talkers and small discrepancies in word length, the overall durations of the target and masker sentences were slightly different.

In a second condition the masker was a speech-spectrum noise that had the same long-term spectrum as the average CRM sentence. The amplitude of noise presented on each trial was modulated by the temporal envelope of a randomly selected (as in the first condition) CRM masker message. The envelopes were derived by full-wave rectifying the CRM sentence and then filtering the result with a 6th order low-pass Butterworth filter with a 50 Hz cut-off frequency.

Targets and maskers were attenuated, mixed digitally, and converted to analog form using a Digital Audio Labs Card Deluxe 24-bit sound card at a 48 kHz sampling rate. Beyer DT990-Pro headphones were used to present the stimuli monaurally to the normal-hearing ear of the participants with UHL or to the right ear of the participants with normal hearing.

Procedure—Participants were seated in front of a computer screen either in a sound-isolated semi-anechoic room ($T_{60}=0.06s$) or in a double-walled sound-isolated room (IAC 1200). The screen displayed a start button and 32 response buttons organized in four color matrices (i.e., *red, white, green, and blue*), each containing eight buttons (numbered 1–8). The participants were instructed to attend only to the speech message containing the call sign *Baron* and to ignore any distracting stimulus. Using a computer mouse, the participants initiated each trial by clicking on the start button displayed in the middle of the screen and responded by clicking on the button corresponding to the heard color and number spoken by the talker with the call sign *Baron*.

Prior to the experimental trial blocks, the participants completed 30 practice trials in a no-masker baseline condition in which the level of the target was varied over a 20 dB range. The baseline condition was administered to familiarize the participants with the task and to assure perfect performance at each target level in the absence of a masker. During each 60-trial experimental block, the overall level (RMS) of the masker was held constant at 60 dB SPL. From trial to trial the level of the target was randomly assigned one of five levels, 5 dB apart, spanning a range of 20 dB. This procedure permitted estimation of a complete psychometric function, in which performance ranged from near chance (3%) to 100% correct as a function of target-to-masker ratio. For some participants it was necessary to adjust the range of target levels following the first couple of trial blocks in order to capture a full range of performance. Each participant completed no fewer than five blocks of 60 trials. The first trial block in each condition was considered practice and was not included in the analyses. Thus, with some minor exceptions, each estimate of proportion correct was based on a minimum of 48 trials. Trial by trial feedback was not provided. Participants first received one block of trials in the modulated noise masker condition, followed by one block

of trials in the speech masker condition. The conditions were then presented in an alternating manner until the participants completed 5 blocks in each condition.

Data analysis—Psychometric functions obtained with CRM speech targets and CRM speech maskers are often non-monotonic (Brungart, 2001; Brungart & Simpson, 2002; Wightman & Kistler, 2005; Wightman, Kistler, & Brungart, 2006). This is thought to result from the notion that, for Target/Masker (T/M) ratios between -15 and 0 dB, some listeners can attend to the “softer” speech sound, thus using intensity as an additional cue for segregating target from masker. The use of this level cue results in a plateau in performance, between approximately -15 and 0 dB T/M ratios. For this reason, psychometric function data from this experiment were not fit with smooth curves in order to estimate threshold and slope. Instead, individual data and group means are plotted. For each participant a mean proportion correct score was computed over T/M levels from -15 to 0 dB for the speech masker condition and over T/M levels from -15 to -5 dB for the modulated noise masker. These levels were chosen because each participant contributed at least 24 responses at each of these T/M levels. Mann-Whitney U tests were then used to compare mean proportion correct scores over these T/M levels between listeners with UHL and listeners with normal hearing.

Results

All participants demonstrated near-perfect performance (97–100% correct) in the baseline condition (no masker), at all target levels. For all but one participant target levels were between 30 dB SPL and 55 dB SPL. One participant had borderline mild hearing loss in the “normal” hearing ear and was tested with target levels between 45 dB SPL and 65 dB SPL. At these levels, she scored 97% correct.

Figure 1 (left hand side) shows the results from the condition in which a speech masker was presented. Data from the participants with UHL are displayed in the top panel and data from participants with normal hearing are displayed in the middle panel. The bottom panel shows the mean performance at each T/M ratio from both participant groups. As can be seen in Figure 1, there were large individual differences in performance from both participant groups in this condition. This is consistent with the results from previous studies of normal-hearing participants in comparable conditions (Wightman & Kistler, 2005; Wightman et al., 2006). Note that three of the participants with UHL and several of the normal-hearing participants exhibited a plateau in performance between -15 dB and 0 T/M ratios that has been ascribed to the use of intensity cues. As can be seen in the bottom panel of Figure 1, the mean performance of the participants with UHL resembles that of the participants with normal hearing. This is supported by the overlapping 95% confidence intervals of the group means at each T/M. A Mann-Whitney U Test indicated no significant difference between groups in proportion correct scores computed across T/M levels of -15 to 0 dB in the speech masker condition, $U(n_1=11, n_2=12)=70, p=.81$. Thus, in this monaural listening condition, in which the target and masker were presented to their normal-hearing ear, participants with UHL performed comparably to normal-hearing listeners.

The right-hand side Figure 1 shows the results from the condition in which a modulated noise was used as the masker. There are two obvious differences between the results from the modulated noise masker condition and those from the speech masker condition. First, the psychometric functions from the modulated noise condition show none of the irregularities evident in the psychometric functions from the speech masker condition. Second, individual differences in performance with the noise masker are much smaller than with the speech masker. The data from both groups are comparable to data reported by Brungart (2001).

The most important result of the modulated noise condition is evident in the bottom right panel of Figure 1, which shows the mean data from both participant groups. Note that the performance of the participants with UHL is virtually identical to the performance of the normal-hearing participants who are listening monaurally. A Mann-Whitney U Test indicated no significant difference between groups in proportion correct scores computed across T/M levels from -15 to -5 dB in the modulated noise masker condition, $U(n_1=11, n_2=12) = 63, p = .85$. Thus, when listening with their normal hearing ear, individuals with UH appear to achieve normal levels of monaural speech understanding performance in the presence of either a purely energetic masker (modulated noise) or a primarily informational masker (speech).

Experiment 2: Speech Target and Masker Spatially Separated

Experiment 2 was designed to compare speech understanding performance of participants with UHL to those with normal hearing in the sound field. In one of the conditions the target and masker were co-located in front of the participant. The purpose of this condition was to measure performance when no spatial cues were present. In the other conditions the target was in front of the participant and the masker was spatially separated from the target by 90° . Comparison of performance in the co-located and spatially separated conditions provided an index of spatial release from masking.

Previous research had shown that normal-hearing listeners obtain greater benefit from spatial separation between target and masker when a primarily informational masker is used (Arbogast et al., 2002, 2005). Thus, in Experiment 2, we use a paradigm which is dominated by informational masking. This was accomplished by digitally processing the CRM stimuli to diminish spectral overlap between the target and masker messages, thus minimizing energetic masking. In addition, the processed stimuli minimized talker cues (i.e., the processing made it difficult to recognize and distinguish the target talker's voice from that of the masker talker), thus further isolating spatial separation as the cue under examination.

Method

Stimuli—The speech targets and maskers were the same CRM sentences used in Experiment 1. Speech targets and maskers were digitally processed to minimize spectral overlap between target and masker using the procedure described by Arbogast et al. (2002, 2005). The processing involved high-pass filtering with a first-order Butterworth filter at 1200 Hz and passing the output through a filterbank that consisted of 15 non-overlapping filters with equal bandwidths on a log-frequency scale. The bandpass filters were $1/3$ octave, fourth-order Butterworth filters with center frequencies ranging from 215 Hz to 5461 Hz. The envelope of the output of each filter, extracted by half-wave rectification and low-pass filtering at 50 Hz, was used to modulate a sinusoid with a frequency equal to the center frequency of the band. The target sentence on each trial was constructed by summing a random selection of 8 of the 15 modulated sinusoids. The masker sentence was constructed by summing the remaining 7 sinusoids. Thus, the target and masker consisted of non-overlapping modulated sinusoids. Figure 2 shows the magnitude spectra of a sample pair of a target sentence (gray) and a masker sentence (black). As seen in Figure 2, the target and masker do not overlap (except where they are more than 40 dB below peak levels.) Thus energetic masking is expected to be minimized in the target/masker presentation. Stimuli were presented using a 48 kHz sampling rate from loudspeakers (Cambridge Sound Works) positioned at an ear-level height, 1.2 m from the listener at angles of -90° , 0° , and $+90^\circ$ azimuth relative to the listener on the horizontal plane. The target sentences were always presented from the 0° loudspeaker. The masker sentences were presented either from the 0° , -90° , or $+90^\circ$ loudspeaker, depending on the experimental condition.

Procedure—Participants were seated in a semi-anechoic room ($T_{60}=0.06\text{s}$) and were asked to respond on each trial by verbally naming the color and the number that was spoken by the target talker using the call sign “Baron.” The participant’s voice was picked up by a microphone, and an experimenter outside the room recorded the responses for each trial on a computer. Trial by trial feedback was not given.

The level of the masker was held at a fixed intensity level of 55 dB. For a few participants the masker level was adjusted by ± 5 dB for a block of trials to capture a full range of performance (i.e., approximately 0–100%) while ensuring target audibility. For each block of trials, the level of the target was varied randomly from trial to trial over a 20 dB range in order to estimate the psychometric function relating performance to the target/masker ratio. There was some variation in target levels across blocks of trials in order to obtain performance near chance at the lowest target level and near 100% at the highest target level.

Participants completed between 60 and 120 practice trials in the baseline condition before data were collected. The baseline condition was presented without a masker in order to familiarize the participants with the processed stimuli and to assure perfect performance at each target level. The first 30 baseline trials involved listening and responding to unprocessed CRM stimuli. Then the participant completed 30 baseline trials with the processed stimuli. Additional practice trials with the processed CRM sentences were administered until the participant demonstrated perfect or near-perfect performance at all target levels. After completing the baseline condition, listeners with UHL were tested in three experimental conditions:

1. Co-located: The target and masker were digitally attenuated and mixed and presented from a single speaker positioned at 0° azimuth.
2. Masker Impaired: The target was presented at 0° azimuth, and the masker was presented at 90° azimuth on the side of the participant’s impaired ear.
3. Masker Normal: The target was presented at 0° azimuth, and the masker was presented at 90° azimuth on the side of the participant’s normal-hearing ear.

The normal-hearing participants were tested in the co-located condition and in a condition in which the target was presented from the 0° loudspeaker and the masker from the -90° loudspeaker on the participants left side. Participants completed a minimum of 300 trials in each of the conditions. The conditions were presented in an alternating manner in blocks of 60 trials. The presentation order of the condition blocks was selected randomly. The first block in each condition was treated as a practice block. A minimum of 48 trials was used to estimate proportion correct at each of the T/M levels tested.

Data analysis—The data from each condition (proportion correct at target/masker ratios) were fitted with three-parameter (midpoint, slope and upper asymptote) logistic functions in MATLAB using `psignfit` (Wichmann & Hill, 2001a, 2001b). Thresholds (i.e., T/M ratio corresponding to 51% correct) were estimated from the fitted functions for each listener in each of the experimental conditions. The 95% confidence intervals for threshold estimates were calculated using the bootstrapping procedure described by Wichmann and Hill (2001b).

Results

In this experiment speech targets and maskers were processed into non-overlapping modulated sinusoids to minimize energetic masking. Performance in the baseline condition (no masker) was nearly perfect (93–100% correct) at all target levels tested (range: 30–55

dB SPL). As with Experiment 1 the listener with borderline mild hearing loss in the “normal” ear required a range of 45–65 dB to achieve near perfect performance.

Figure 3 presents the raw data and the fitted psychometric functions for three representative participants with normal hearing. The error bars show the 95% confidence limits of the estimated thresholds (51% correct). As suggested by the data shown in Figure 3, there was considerable variability across participants in the estimated thresholds. Nevertheless, all participants produced monotonic psychometric functions that spanned nearly the entire range of performance from chance (3% correct) to perfect (100 % correct). Confidence intervals for the threshold estimates were approximately ± 1.5 dB. Note that for the participants whose data are shown in Figure 3, spatially separating the target and masker resulted in a large improvement in performance (a leftward shift of the psychometric function, toward lower T/M ratios). Such large improvements reflect spatial release from informational masking. For the participant whose data are shown in the middle panel, the spatial release was approximately 20 dB. Similar results from participants with normal hearing have been reported previously in several studies that used the CRM paradigm with processed stimuli (Arbogast et al., 2002, 2005). Spatial release has been shown to be greatest in experiments such as the current one in which the masker may be characterized as primarily informational. Spatial release from informational masking is usually much larger than the performance improvement produced by the head shadow effect, which results in a slight improvement in T/M ratio at the shadowed ear when the masking stimulus is to one side (Bronkhorst & Plomp, 1989).

Figure 4 is comparable to Figure 3 except that the data are from three representative participants with UHL. Recall that the participants with UHL were tested in three conditions, one in which the target and masker were both presented from the loudspeaker in front of the participant (Co-located), one in which the target was in front and the masker was on the side of the impaired ear (Masker Impaired), and one in which the target was in front and the masker was on the side of the normal-hearing ear (Masker Normal). For these three participants, presenting the masker on the side of the impaired ear produced a small improvement in performance and presenting the masker on the side of the normal-hearing ear produced a small decrement in performance.

Tables 2 and 3 summarize the results from Experiment 2. The tables list estimated thresholds (and 95% confidence intervals) in each condition for both normal-hearing participants and participants with UHL. Consider first the data obtained from the normal-hearing participants (Table 2). There are substantial individual differences in the thresholds in the Co-located condition, ranging from -11.4 dB to -0.2 dB (T/M ratio), with a mean of -5.1 dB. Such large individual differences are not uncommon in tasks dominated by informational masking (Wightman & Kistler, 2005; Wightman et al., 2006). T/M thresholds in the condition in which targets and maskers were spatially separated ranged from -28.1 to -13.8 dB with a mean of -20.5 dB. As seen in Table 2, spatial release (from informational masking) achieved by the participants with normal hearing ranged from 10 dB (listener NH06) to 27 dB (listener NH05), with a mean spatial release of about 15 dB. These findings are comparable to those of studies by Arbogast et al. (2002, 2005), which also showed a mean spatial release of about 15–18 dB.

Next, consider the results from the participants with UHL (Table 3). Although the range of estimated thresholds from the co-located condition was about the same as for the participants with normal hearing, most of the threshold estimates were higher, indicating poorer performance in this group. The mean co-located threshold for the participants with UHL was -0.5 , compared to a mean of -5.1 dB for the normal-hearing participants. This difference was significant ($t(22) = 2.97, p = .007, \eta^2 = .21$). Table 3 also shows that all UHL

participants achieved the best thresholds (lowest T/M ratio) in the Masker Impaired condition and the poorest threshold in the Masker Normal condition. Although the threshold differences across listening conditions in the UHL participant group were small, a repeated measures ANOVA showed that they were significant, $F(2, 22) = 76.4$, $MSE = 1.63$, $p < .001$, $\eta^2 = .87$. Post-hoc comparisons using the Bonferroni adjustment indicated that thresholds were lower in the Masker Impaired condition than in the Co-located condition, $p < .001$, and higher in the Masker Normal condition, $p = .003$, than in the Co-located condition. The improvement in performance of the individuals with UHL produced by moving the masker from the front to the side of the impaired ear can be described as a “spatial advantage”, but as will be argued in the Discussion, it is no greater than what would be expected given the change in T/M ratio at the normal-hearing ear (i.e., the head shadow effect) and as such does not imply a perceptual effect or processing of spatial cues by these participants. The decrement in performance in the Masker Normal condition as compared to the Co-located condition can be explained in a similar way.

Experiment 3: Localization of Noise on the Horizontal Plane

Experiment 3 examined the ability of participants with UHL and those with normal hearing to localize wideband noise bursts on the horizontal plane. The absence of the ability of the listeners with UHL to use spatial cues may be related to poor localization skills. Therefore, the objective of Experiment 3 was to measure localization performance.

Method

Stimuli—Stimuli for the localization task were 250-msec Gaussian white noise bursts, bandpass filtered between 200 Hz and 16 kHz and shaped by 20-msec cosine-squared on/off ramps. The advantage of using a wide-band noise in this experiment was that it gave listeners access to high-frequency pinna cues, which have been shown to be valuable for monaural localization (Wightman & Kistler, 1997). Independent noise samples were generated on each trial. The noise signals were output at a 48 kHz sampling rate by Digital Audio Labs Card Deluxe 24-bit sound card. The level of the stimulus on each trial was random (uniform distribution) over a 10 dB range (i.e., ± 5 dB) with a mean level of 65 dB SPL. The purpose of the intensity rove, which has been employed by previous studies examining monaural localization (Slattery & Middlebrooks, 1994; Van Wanrooij & Van Opstal, 2004, 2007; Wightman & Kistler, 1997), was to prevent the listeners with UHL from using the relative intensity of the stimuli at the normal-hearing ear as a localization cue. Single noise bursts were presented either to a single loudspeaker (Cambridge Sound Works) or, at half power, to two adjacent loudspeakers in order to simulate a position between the two loudspeakers. The frequency response of each loudspeaker was digitally flattened using inverse filtering techniques.

Procedure—Localization testing was conducted in the same semi-anechoic room as was described in Experiment 2. Seven loudspeakers were positioned at ear-level and were spaced 30° apart from -90° to $+90^\circ$ degree azimuth. Participants were seated in the center of the array of speakers, facing the speaker positioned at 0° azimuth, and were asked to maintain an upright and frontal orientation throughout testing. The speaker-head distance was 1.2 m. The seven loudspeakers were labeled with numbers in increments of 10, ranging from 0 to 60. On each trial, a brief 1000 Hz “warning” tone was presented from a loudspeaker located above the listener’s head 1 second before the onset of the stimulus. The target noise was then presented randomly either from one of the 7 loudspeakers or from one of the 6 simulated positions at the midpoint of two adjacent speakers. Following the presentation of the noise signals, the participant was asked to respond verbally with an integer between 0–60 that best identified the location where he/or she perceived the noise to have originated.

Responses were picked-up by a microphone. Listeners were told that the noise could originate from any position, either at the loudspeaker positions or anywhere in between. An experimenter in an adjacent room recorded responses and assured that the listener maintained a frontal orientation during the presentation of the stimuli. A camera placed in the testing chamber allowed the examiner to monitor the orientation of the listener.

All participants were given at least 65 practice trials to familiarize them with the localization task. Following the practice trials, participants completed a minimum of 195 experimental trials (range: 195–585 trials). No feedback was given to participants regarding the accuracy of their responses.

Data Analysis—Performance on the localization task was evaluated by examining stimulus/response plots and by calculating root mean squared (RMS) error between the target and response angles. Mean signed error was also computed in order to evaluate response bias.

Results

Figure 5 illustrates the localization performance in the horizontal plane of each of the 12 participants with normal hearing and Figure 6 shows the performance of the 12 participants with UHL. The panels in both figures are organized according to participant age (i.e., youngest to oldest). The scatter plots show the response angles as a function of target angle. Participants' judgments, which ranged from 0 to 60, were converted to angular judgments for the purpose of analysis. Prior to graphing the data points were "jittered" slightly by adding a uniform random deviate $\pm 2.5^\circ$ to the coordinates to eliminate the overlap resulting from duplicate responses to a given target (Cleveland, 1993). The average RMS error between response and target angles is shown in the upper left of each panel. As seen in Figure 5, the performance of the participants with normal hearing was quite good, as evidenced both by the small RMS errors and the cluster of responses around the major diagonal (response angle = target angle).

In contrast to the normal-hearing participants, there were large individual differences in performance among the participants with UHL, as seen in Figure 6, with RMS errors ranging from 16° to 68° . Some participants (UHL02 and UHL03) performed only slightly poorer than the normal-hearing individuals, while others (UHL09, UHL10, and UHL12) showed little or no ability to localize the stimuli. Table 4 displays mean signed error and RMS error of the listeners with UHL on the side of the impaired ear and the side of the normal-hearing ear. As seen in the table, most participants showed better performance (and a response shift or bias) on the side of their normal-hearing ear. One participant (UHL12) had better performance on the side of her impaired ear. Two participants (UHL02 and UHL10) showed equivalent performance on their impaired and normal-hearing sides.

One of the aims of the localization experiment was to compare the localization abilities of participants with UHL to their ability to receive spatial benefit on a speech task (Experiment 2). To this end, Pearson Product Moment correlation coefficients were calculated between RMS error on the localization task (Experiment 3) and threshold differences from the speech task (Experiment 2). Threshold differences on the speech task were defined as the difference in thresholds between the Co-located condition and the Masker Impaired condition (0° – 90° impaired Δ) and the difference in thresholds between the Co-located condition and the Masker Normal condition (0° – 90° normal Δ). Localization performance (RMS error) was not significantly correlated with 0° – 90° impaired Δ ($r=0.09$, $p=.781$) or 0° – 90° normal Δ ($r=0.45$, $p=.151$), suggesting that there was no relationship between localization performance and the ability to use spatial cues on the speech task among the listeners with UHL. It seems clear that even for those participants with UHL who demonstrated near-

normal ability to localize (e.g., UHL02 and UHL03), spatial separation of the target and masker on the speech recognition task provided only a modest performance advantage (about 4 dB for both participants) over the co-located condition. In addition, the spatial advantages on the speech task obtained by these participants in the speech task were no greater than that obtained by participants who demonstrated no ability to localize.

Discussion

In multi-source listening environments, individuals with normal hearing exploit binaural cues for understanding speech and localizing sound sources (e.g., Arbogast et al., 2002, 2005; Bronkhorst & Plomp, 1989; Freyman et al., 2001; Freyman et al., 1999; Ihlefeld & Shinn-Cunningham, 2008a, 2008b). In contrast, individuals with UHL are not afforded such binaural benefits and consequently show perceptual deficits in environments in which normal-hearing listeners rely on spatial cues (e.g., Bess, Tharpe, et al., 1986; Linstrom et al., 2009; Ruscetta et al., 2005; Sargent et al., 2001; Welsh et al., 2004). However, previous research has not systematically explored the listening performance of individuals with UHL in ways that can delineate the specific nature of their perceptual deficit. The current study sought to better define listening skills in individuals with UHL by evaluating performance on spatial and non-spatial listening tasks. Specifically, speech recognition on an informational masking task was measured in conditions in which the target and masker were presented monaurally (via headphones) and in the sound field in a condition with target and masker co-located and in conditions with 90° of spatial separation between target and masker. In addition, localization performance was measured to investigate whether or not localization skills are related to the ability to achieve a spatial release from informational masking on a speech perception task in listeners with UHL.

Regarding monaural listening performance, our findings revealed no difference between the performance of normal-hearing adults and those with UHL. Specifically, when the target and masker were presented monaurally over headphones to the normal-hearing ear (Experiment 1) the performance of the listeners with UHL was comparable to the monaural performance of normal-hearing listeners who were assessed in the current study and in previous studies (Brungart, 2001; Wightman & Kistler, 2005; Wightman et al., 2006). This was true both when the masker was a single talker (informational masker) and when it was a modulated noise (energetic masker).

In contrast to monaural listening performance under headphones, performance in the sound field conditions (Experiment 2) revealed significant differences between listeners with and without UHL, even when there was no spatial separation between target and masker. Although the co-located condition of Experiment 2 should not offer any benefit from binaural listening, given that the target and the masker were not spatially separated (and thus do not produce different patterns of interaural differences), there was a significant difference of about 4.5 dB between the average threshold of participants with UHL and participants with normal hearing, favoring the performance of the normal-hearing group. The source of this difference is unknown and will remain a topic for future study. However, this finding appears consistent with a handful of studies that have shown superior performance in diotic vs. monaural listening conditions by normal-hearing listeners on co-modulating masking release tasks (Schooneveldt & Moore, 1989), detection tasks (Langhans & Kohlrausch, 1992; Zwicker & Henning, 1985), and speech perception tasks (Bronkhorst & Plomp, 1988; Davis, Haggard, & Bell, 1990; Gallun et al., 2005). Some investigators attribute the superior diotic performance to a statistical advantage of having two independent observations vs. a single observation of the stimuli (Schooneveldt & Moore, 1989; Zwicker & Henning, 1985), while other investigators have suggested that the monaural-diotic performance difference

relates to efferent interaction between the right and left auditory pathways (Langhans & Kohlrausch, 1992).

In the condition in which the target and masker were spatially separated in Experiment 2, the normal-hearing participants used binaural spatial cues to attend selectively to the target and ignore the masker. The data (Figure 3 and Table 2) showed as much as a 27 dB release from masking in this condition. This result was consistent with several other studies of informational masking by showing large benefits in normal hearing listeners from spatial separation between the target and masker that exceed the benefits that can be attributed to head shadow effects or binaural interaction. (Arbogast et al., 2002, 2005; Kidd, Arbogast, et al., 2005; Shinn-Cunningham, Ihlefeld, Satyavarta, & Larson, 2005).

In contrast to the normal-hearing participants, participants with UHL did not demonstrate the use of spatial cues to achieve better performance when the target and masker were spatially separated. Compared the Co-located condition, when the masker was presented on the side of the impaired ear, listeners with UHL showed an average threshold improvement of approximately 4 dB. When the masker was presented on the side of the normal-hearing ear, listeners with UHL showed an average threshold decrement of approximately 2.5 dB compared to the Co-located condition. These threshold changes are nearly identical to the threshold changes predicted by a model proposed by Zurek (1993) that takes into account the changes in T/M ratio and consequent changes in the Articulation Index (French & Steinberg, 1947; Kryter, 1962) at the normal-hearing ear. This model was designed to predict speech intelligibility in monaural and binaural conditions based on the directionality of a target and a single-source masker. Specifically, in monaural conditions using high-context speech material and a speech spectrum noise masker, Zurek's model predicts an improvement of about 4 dB when the noise is on the side of an occluded ear and a decrement of about 3 dB when the noise is on the side of the normal-hearing ear. These changes in performance reflect head shadow effects. Thus, the changes in performance (i.e., benefits and decrements) of the participants with UHL produced by spatial separation of target and informational masker appear to be predictable based on differences in T/M ratio at the normal-hearing ear. This is in contrast to the large perceptual benefits of spatial separation in normal hearing listeners that are commonly described as spatial release from informational masking. Even the participants with mild or moderate degrees of UHL appeared to be unable to achieve a true spatial release from informational masking.

The inability of listeners with UHL to achieve a spatial release from informational masking is consistent with results from a study of normal-hearing listeners by Marrone et al. (2008) who measured performance on the CRM in binaural and monaurally occluded (i.e., plugged) conditions. In this study, the spatially separated conditions employed noise on both sides of the listener (i.e., at $\pm 45^\circ$ or $\pm 90^\circ$), thus there was no "better ear" in terms of target/masker ratio. In the binaural condition the listeners achieved a sizable spatial release from informational masking, which was effectively eliminated in the monaural occluded condition. Thus, similar to results from the current study, this study suggested that monaural listeners fail to exhibit spatial benefits when head shadow cues are discounted.

The fact that the listeners with UHL in the current study did not show marked improvement in performance in what should have been the most advantageous condition for them (i.e., the condition in which the masker was on the side of their impaired ear) was consistent with a study by Best et al. (2005). This study measured listeners' abilities to identify finch song amidst energetic and informational maskers. The listeners achieved an average of 10 dB greater release from informational masking when the target and masker were spatially separated than when the better-ear signal was presented diotically. Thus, in conditions characterized by considerable informational masking, normal-hearing listeners receive

binaural listening advantages that exceed those gains obtained simply by having access to the better-ear signal. Arguably, normal-hearing listeners use central processes to obtain a release from informational masking by directing their attention toward a target signal and away from distracters. These same attentional processes used to obtain a spatial release from informational masking do not appear to be available to listeners with UHL.

The third objective of the current study was to measure localization performance in listeners with and without UHL and investigate whether or not spatial release from informational masking on a speech task was related to localization ability. Findings from the localization experiment (Experiment 3) were consistent with those of previous studies, in that there was considerable individual variability in performance among the listeners with UHL, listeners with UHL showed deficits in performance relative to listeners with normal hearing, and listeners with UHL tended to bias their responses toward the side of their normal-hearing ear (as seen in Table 4). Two participants (UHL02 and UHL03) in the current study were able to localize the sound sources with near-normal proficiency. However, these participants had only mild-moderate hearing loss in the impaired ear, and thus had the greatest amount of residual hearing. Unlike the participants with severe-profound UHL, it is possible that these two individuals with milder degrees of UHL were able to use interaural difference cues to assist their localization. This is consistent with results from a recent study by Agterberg et al. (2011) of listeners with mild-severe UHL that suggested that their listeners who showed relatively proficient localization abilities were able to use their limited binaural difference cues to perform the localization task. A related finding was reported by Wightman and Kistler (1997) in a study of the impact of artificial broadband interaural level differences on localization. Normal hearing listeners achieved surprisingly good localization performance, even with a 40 dB interaural level difference. In the current study, a few participants with profound UHL (i.e., UHK04 and UHL07) demonstrated localization performance that seemed better than what might be expected given their degree of UHL, but their performance was poorer than that of normal-hearing listeners.

As explained in the Introduction, previous investigators have suggested that many listeners with UHL use intensity cues provided by the head shadow on localization tasks (Agterberg et al., 2010, 2011; Slattery & Middlebrooks, 1994; Van Wanrooij & Van Opstal, 2004). That is, these listeners tend to localize low intensity stimuli closer to the impaired ear and higher intensity stimuli closer to the normal-hearing ear. Although these trial by trial variations in level at the functioning ear can be valuable cues for localizing stimuli on laboratory tasks that employ fixed-intensity paradigms, such level cues are not accessible in real word listening. In the current study we attempted to reduce the listeners' ability to rely on such intensity cues by roving the overall level of the stimuli over a 10 dB range. Although this level rove almost certainly lessened the participants' ability to utilize level cues on the localization task, it is possible that a 10 dB level rove was not large enough to prohibit some participants from using intensity cues to determine the approximate position of the sound source, as argued by Van Wanrooij and Van Opstal (2004).

Some listeners with UHL are thought to be able to capitalize on monaural spectral cues to localize sound sources (Newton, 1983; Slattery & Middlebrooks, 1994; Van Wanrooij & Van Opstal, 2004). Monaural spectral cues may assist in localization because the characteristics of pinna filtering change depending on the position of the sound source. The use of monaural spectral cues for localization relies on the listener's ability to extract pinna filtering characteristics from an incoming signal and associate those characteristics with the corresponding sound direction (Wightman & Kistler, 1997). Because the spectrum received at the ear is a combination of the source spectrum and the pinna characteristics, knowledge of the source spectrum is required in order to decode the pinna cues. However, some researchers suggest that after years of monaural listening experience, some individuals with

UHL may learn to use monaural spectral cues to determine the direction of sound on the horizontal plane (Newton, 1983; Slattery & Middlebrooks, 1994; Van Wanrooij & Van Opstal, 2004). These studies and others (i.e., Abel & Lam, 2008; King et al., 2001) suggest that the ability to use monaural spectral cues is not learned immediately following unilateral deafness or monaural occlusion, but is learned over a period of at least several months. However, another study by Shub et al. (2008) found no difference between listeners with UHL and those with normal hearing on a monaural localization task and suggested that the testing paradigm itself, rather than monaural listening experience, had greater influence on monaural performance of normal-hearing listeners. In the current study, all participants with UHL had their hearing loss for at least 4 years (most over 10 years), and there did not appear to be a relationship between duration of unilateral impairment and localization ability.

Regarding a possible relationship between spatial release from informational masking and localization ability in listeners with UHL, findings from the current study suggest that there is none. Correlational analyses showed no significant relationships between the small spatial effects on the informational masking task and performance on the localization task in listeners with UHL. Although there was considerable variability in the ability to localize by the listeners with UHL, there was little variability on the spatial speech task in that none of the listeners with UHL achieved a spatial release from informational masking beyond that which would be predicted from head shadow effects. A few of the participants demonstrated localization performance that was nearly comparable to that of normal-hearing participants, but they did not show substantial improvements in speech understanding when the target and masker messages were spatially separated. This was despite the fact that participants were informed of the location of the target and masker sources prior to each block of trials. This finding seems to be in contrast with previous studies that have suggested normal-hearing listeners use differences in the perceived location of a target to obtain a spatial release from masking in complex listening situations and that “knowing where to listen” improves performance (Ericson, Brungart, & Simpson, 2004; Kidd, Arbogast, et al., 2005). However, findings from the current study are consistent with other studies that have cast doubt on the relationship between localization and spatial release from informational masking. For example, these studies have suggested that listeners do not appear to use perceived location to obtain binaural release from informational masking (Gallun et al., 2008), and that spatial release from masking is not well predicted by localization ability (Drullman & Bronkhorst, 2000; Hawley et al., 1999).

Conclusion

This study explored selective listening skills and localization abilities in individuals with UHL. Findings lend themselves to the following conclusions:

1. The monaural listening performance of individuals with UHL is comparable to that of individuals with normal hearing.
2. Speech understanding in noise deficits of listeners with UHL appear to be most pronounced in environments in which normal-hearing listeners are able to benefit from spatial separation between the target and masker. Listeners with UHL appear to be unable to achieve spatial release from informational masking beyond that which may be attributed to the head shadow effect. The inability to achieve a spatial release from informational masking by listeners with UHL appears to occur even in those who have mild degrees of UHL and/or proficient localization abilities.
3. Listeners with UHL show great variability in localization skills. Some individuals with UHL exhibit localization ability that is nearly comparable to normal-hearing

listeners, while others show little or no ability to localize sounds. Localization performance tends to be poorest on the side of the unilateral impairment.

Acknowledgments

The authors gratefully acknowledge the assistance of Ms. Crystal Williamson with data collection and the assistance of Dr. Arun Gadre and Ms. Angie Buckingham with participant recruitment. Ms. Carissa Shafto and Mr. Derek Knisely kindly offered editorial feedback on earlier drafts of this manuscript. We would also like to thank the individuals who served as participants in this project for their time and involvement. Finally, we would like to express our appreciation to the Associate Editor (Dr. Beverly Wright) and two anonymous reviewers for their constructive feedback on previous drafts of this manuscript. This research was supported by a grant (FLW, PI) from the National Institutes of Health (NIDCD RO1-HD023333).

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Figure 1.

Psychometric functions for the speech-target condition (left panels) and for the modulated-noise condition (right panels) of Experiment 1. The top panels display individual psychometric functions of the participants with UHL, and the middle panels display individual psychometric functions of the participants with normal hearing. The bottom panels display mean performance as a function of target/masker ratio. The error bars represent 95% confidence intervals. Because of the substantial overlap of group means in the bottom panel, data from the participants with UHL were offset by -0.5 dB T/M and data from the participants with normal hearing were offset by $+0.5$ dB T/M.

Figure 2.
Magnitude spectra of a sample target (grey) and masker (black) sentence in Experiment 2.

Figure 3.

Psychometric functions from three representative normal-hearing participants in Experiment 2. The 51% threshold estimates are indicated by “x”s and the error bars indicate the 95% confidence intervals for the estimated thresholds.

Figure 4.

Psychometric functions and threshold estimates for three representative subjects with UHL in the Co-located, Masker Normal, and Masker Impaired conditions of Experiment 2. The 51% threshold estimates are indicated by “x”s and the error bars indicate the 95% confidence intervals for the estimated thresholds.

Figure 5.

Localization performance of the 12 participants with normal hearing in Experiment 3 organized left to right, top to bottom by age. The scatter plots show participants' response angles (i.e., the azimuth at which the participant judged that the stimuli originated) as a function of target angle (i.e., the azimuth at which the stimuli was presented). Prior to graphing the data points were "jittered" slightly by adding a uniform random deviate $\pm 2.5^\circ$ to the coordinates to eliminate the overlap resulting from duplicate responses to a given target. The value in the upper left corner of each panel represents the participants' root-mean-square (RMS) error across all target angles. The title of each panel indicates the participant's identification code and his/her age (in parentheses).

Figure 6.

Same as Figure 5 except data show localization performance 12 participants with UHL. The title of each panel indicates the participant's identification code, his/her age (in parentheses), his/her side of impairment (i.e., "R"=right and "L"=left) and his/her degree of UHL (e.g., "mild", "moderate", "severe", etc.).

Table 1

Demographic and audiologic information of participants with UHL

Participant ID	Age (Years)	Side of UHL	PTA (dB)	Age of Identification (Years)	Etiology of Hearing Loss
UHL01	18	Right	96.7	14	Idiopathic
UHL02	18	Right	50	Birth	Aural Atresia
UHL03	19	Right	33.3	Birth	Ossicular Malformation
UHL04	21	Left	110	Birth	Idiopathic
UHL05	22	Right	120+	Birth	Idiopathic
UHL06	22	Right	81.7	3	Idiopathic
UHL07	25	Right	105	14	Idiopathic
UHL08	46	Right	55	21	Idiopathic
UHL09	54	Right	78.3	37	Idiopathic
UHL10	55	Right	120+	41	Viral Infection
UHL11	59	Left	93.3	49	Acoustic Neuroma
UHL12	64	Left	81.7	60	Idiopathic

Note. Pure tone Average (PTA) represents the average audiometric threshold of the impaired ear at 500, 1000, and 2000 Hz.

Table 2

Individual T/M thresholds in dB (with 95% Confidence Limits) and threshold differences (Δ) in dB of the participants with normal hearing

Participant ID	0°	90° Left	0°–90° Left Δ
NH02	–4.0 [–6.9, –1.9]	–19.0 [–22.5, –16.5]	15.0
NH04	–2.2 [–3.8, –0.7]	–13.6 [–15.4, –11.9]	11.4
NH05	–1.1 [–3.0, 0.7]	–27.7 [–35.4, –20.5]	26.6
NH06	–6.4 [–8.5, –4.7]	–16.2 [–18.6, –14.4]	9.8
NH09	–0.2 [–1.7, 1.1]	–21.0 [–24.2, –18.8]	20.8
NH10	–10.0 [–13.8, –7.4]	–28.1 [–32.4, –25.0]	18.1
NH12	–5.4 [–7.4, –3.9]	–18.5 [–21.3, –16.5]	13.1
NH18	–7.5 [–9.3, –5.7]	–19.0 [–21.3, –17.0]	11.5
NH20	–1.2 [–3.1, 0.5]	–20.2 [–24.7, –17.2]	19.0
NH21	–7.4 [–9.9, –5.3]	–20.8 [–23.1, –19.2]	13.4
NH22	–11.4 [–13.6, –9.4]	–21.7 [–24.2, –19.8]	10.3
NH23	–4.9 [–6.8, –3.4]	–19.6 [–23.4, –17.0]	14.6
Mean (SD)	–5.1 (3.6)	–20.5 (4.1)	15.3 (4.1)

Note. Thresholds are given for the co-located (0°) condition and the condition in which the masker was presented 90° to the left of the target (90° Left). Differences between the thresholds in the 0° and –90° (0°–90° Δ) provide an index of the effect of spatial separation of target and masker on performance.

Table 3

Individual psychometric T/M thresholds in dB (with 95% Confidence Limits) and threshold differences (Δ) in dB of participants with UHL.

Participant ID	0°	90° Impaired	90° Normal	0°–90° Impaired Δ	0°–90° Normal Δ
UHL01	1.3 [0.1, 2.6]	–0.7 [–2.2, .9]	3.4 [2.2, 4.7]	2.0	–2.1
UHL02	–0.4 [–2.2, 1.6]	–3.9 [–5.8, –2.1]	5.3 [3.6, 6.9]	3.5	–5.7
UHL03	–12.4 [–14.1, –10.6]	–17.0 [–18.9, –15.4]	–10.6 [–11.9, –9.3]	4.6	–1.8
UHL04	–3.0 [–5.1, –1.3]	–9.0 [–11.1, –7.4]	–2.5 [–5.2, –0.4]	6.0	–0.5
UHL05	1.7 [0.0, 3.2]	–1.6 [–3.1, –0.2]	4.6 [2.9, 6.5]	3.3	–2.9
UHL06	–0.2 [–2.0, 1.5]	–5.2 [–7.2, –3.6]	1.7 [–0.3, 3.5]	5.0	–1.9
UHL07	0.2 [–1.5, 2.1]	–1.9 [–3.5, –0.3]	5.4 [3.8, 7.2]	2.1	–4.9
UHL08	–0.4 [–1.6, 0.8]	–4.6 [–5.9, –3.4]	2.2 [1, 3.3]	4.2	–2.6
UHL09	2.2 [1.0, 3.4]	–2.3 [–3.4, –1.0]	0.7 [–1.0, 2.1]	4.5	1.5
UHL10	0.9 [–0.6, 2.4]	–2.9 [–4.6, –1.3]	5.8 [4.3, 7.2]	3.8	–4.9
UHL11	2.5 [0.4, 4.2]	1.0 [–1.2, 2.7]	4.7 [3.1, 6.3]	1.5	–2.2
UHL12	1.0 [–0.9, 2.9]	–4.9 [–6.7, –3.2]	3.1 [1.5, 4.6]	5.9	–2.1
Mean (SD)	–0.6 (4.0)	–4.4 (4.7)	2.0 (4.6)	3.9 (1.5)	–2.5 (2.0)

Note: Thresholds are given for the co-located (0°), Masker Impaired (90° Impaired), and Masker-Normal (90° Normal) conditions. Differences between the thresholds in the Co-located and Masker Impaired condition (0°–90° Impaired Δ) and the Co-located and Masker Normal condition (0°–90° Normal Δ) provide indices of the effect of spatial separation of target and masker on performance.

Table 4

Mean error and mean RMS error by side in participants with UHL

Participant ID	Ear of Impairment	Side of Impaired Ear		Side of Normal Ear	
		Mean Signed Error	Mean RMS Error	Mean Signed Error	Mean RMS Error
UHL01	Right	-11.3	46.1	-2.2	32.0
UHL02	Right	2.0	15.7	0.3	19.7
UHL03	Right	-13.3	22.6	1.3	11.5
UHL04	Left	15.2	32.6	-6.4	21.7
UHL05	Right	-36.1	48.8	-3.7	22.5
UHL06	Right	-44.3	52.5	-11.7	21.1
UHL07	Right	-20.4	29.9	-10.9	20.0
UHL08	Right	-36.1	45.0	-7.9	16.0
UHL09	Right	-52.5	87.5	-9.7	23.7
UHL10	Right	-15.3	64.7	16.6	47.6
UHL11	Left	37.2	48.8	-4.6	30.2
UHL12	Left	1.6	38.0	-25.6	62.5