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Mitigation of informational masking in individuals with single-sided deafness by integrated bone conduction hearing aids

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Abstract

Objectives—To confirm an increased susceptibility to informational masking among individuals with single-sided deafness (SSD). To demonstrate a reduction in informational masking when SSD is treated with an integrated bone conduction hearing aid (IBC). To identify the acoustic cues that contribute to IBC-aided masking release. To determine the effects of device experience on the IBC advantage.

Design—Informational masking was evaluated with the coordinate-response measure. Participants performed the task by reporting color and number coordinates that changed randomly within target sentences. The target sentences were presented in free field accompanied by 0 – 3 distracting sentences. Target and distracting sentences were spoken by different talkers and originated from different source locations, creating two sources of information for auditory streaming. Susceptibility to informational masking was inferred from the error rates of unaided SSD patients relative to normal controls. These baseline measures were derived by testing inexperienced IBC users without the device on the day of their initial fitting. The benefits of IBC-aided listening were assessed by measuring the aided performance of users who had at least three months device experience. The acoustic basis of the listening advantage was isolated by correlating response errors with the voice pitch and location of distracting sentences. The effects of learning on cue effectiveness were evaluated by comparing the error rates of experienced and inexperienced users.

Results—Unaided SSD participants (inexperienced users) performed as well as normal controls when tested without distracting sentences but produced significantly higher error rates when tested with distracting sentences. Most errors involved responding with coordinates that were contained in distracting sentences. This increased susceptibility to informational masking was significantly reduced when experienced IBC users were tested with the device. The listening advantage was most strongly correlated with the availability of voice pitch cues, although performance was also influenced by the location of distracting sentences. Directional asymmetries appear to be dictated

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by location-dependent cues that are derived from the distinctive transmission characteristics of IBC stimulation. Experienced users made better use of these cues than inexperienced users.

Conclusions—These results suggest that informational masking is a significant source of communication impairment among individuals with SSD. Despite the lateralization of auditory function, unaided SSD subjects experience informational masking when distractors occur in either the deaf or normal spatial hemifield. Restoration of aural sensitivity in the deaf hemifield with an IBC enhances speech intelligibility under complex listening conditions, presumably by providing additional sound segregation cues that are derived from voice pitch and spatial location. The optimal utilization of these cues is not immediate, but a significant listening advantage is observed after three months of unstructured use.

Introduction

Natural environments continuously broadcast multiple channels of sensory stimulation. These competing signals must be separated into discrete perceptual objects to accommodate the extraction of information with direct bearing on the survival of an organism (Hill et al. 2012; Luther et al. 2009; Ryan 1986). Auditory streaming, such as selectively listening to a conversational partner in a background of multiple talkers, is a complex acoustic problem that is solved with apparent ease by listeners with normal perceptual capabilities.

The acoustic basis of auditory streaming has been extensively studied in individuals with normal hearing (Allen et al. 2008; Mackersie 2003). When the sound of interest involves human speech, the formation of auditory objects is strongly influenced by the availability of acoustic cues that are related to the fundamental frequency of the talker's voice and spatial location (Allen et al. 2008; De Sanctis et al. 2008; McLachlan et al. 2010). Consequently, selective attention is enhanced when target and distracting voices are uttered by talkers with distinctive voice pitch characteristics or originate from separable source locations.

The concept of informational masking has been advanced to describe the confounding effects of complex listening environments on the formation of auditory objects (Brungart 2001; Wilson et al. 2012). In the context of informational masking, the listener's inability to separate the meaningful acoustic elements of an attended signal from a competing sound reduces intelligibility without necessarily changing detectability. Unlike traditional energetic masking, informational masking is derived from the shared perceptual attributes of signals and maskers and not necessarily their respective magnitudes (Leek et al. 1991). Where energetic masking is directly related to target-to-masker ratio (TMR), informational masking may persist when a distractor with shared attributes is presented at relatively low sound levels (Drullman et al. 2004; Summers et al. 2004).

Hearing loss degrades the neural representation of the acoustic cues that support auditory streaming (Harkrider et al. 2009; Le Prell et al. 1996; Miller et al. 1999). As a result, hearing-impaired listeners show an increased susceptibility to informational masking (Hornsby et al. 2006). These perceptual deficits are exacerbated in individuals with single-sided deafness (SSD) who lack critical binaural cues for the formation of location-based auditory objects (Arbogast et al. 2005; Rothpletz et al. 2012).

Over the past decade, osseointegrated bone conductors (IBCs) have become an increasingly important clinical intervention for the treatment of SSD (Hol et al. 2005; Stewart et al. 2011). The devices transform air-borne sounds into vibroacoustic stimuli that propagate to the functioning ear through bone conduction. The restoration of aural awareness in the deaf spatial hemifield improves speech comprehension in background noise, presumably by alleviating the attenuation effects (i.e., head shadow) that are incurred when auditory signals must propagate around the head and upper torso to reach the functioning ear (Kompis et al.

2007; Lin et al. 2006). These listening advantages are derived from changes in the TMR relationships that dictate energetic masking.

Beyond simple awareness of sound on the side of the deaf hemifield, a more pervasive clinical objective would be achieved by hearing aids that reduce informational masking through improvements in the bilateral directional hearing of SSD patients (Lin et al. 2006). Prior studies of this important patient population have paid little attention to the specific effects of IBCs on informational masking. In the absence of empirical evidence, two hypotheses can be advanced, each carrying opposite clinical implications. The device may improve perceptual streaming by enhancing segregation cues that exist in the spatial hemifield of the deaf ear, or the device may increase the listener's susceptibility to informational masking by confounding cues in the spatial hemifield of the normal ear.

The present study used the coordinate-response measure to explore the effects of informational masking on speech recognition in SSD patients. When target speech sentences were embedded in multi-talker babble, experienced IBC users performed significantly better than unaided SSD patients. Acoustic manipulations indicated that the performance advantage was derived from the enhanced processing of the voice pitch differences that distinguished target and distracting sentences, thus offsetting monaural disadvantages. The aided performance of experienced users was significantly better than inexperienced users, suggesting that IBC-dependent segregation cues are learned during the initial months of unstructured device exposure.

Methods

Participants

Participants were recruited from SSD patients who were fitted with IBC devices in the Department of Otolaryngology-Head and Neck Surgery at The Johns Hopkins University School of Medicine (Baltimore MD) or the Department of Otorhinolaryngology at Hartford Hospital (Hartford CT). Tests were arranged to coincide with scheduled clinical visits. Participants were not compensated.

Experienced users ($n = 11$) were defined as individuals who had used the device routinely for at least 3 months prior to testing. Inexperienced users ($n = 6$) were tested on the day of their initial device activation (day 0). Variations in age and the duration of deafness showed considerable overlap between the two groups and presumably did not contribute to performance differences (Table 1).

The hearing thresholds and speech recognition scores of SSD participants also showed similar variation among experienced and inexperienced IBC users (Table 2). Pure tone audiograms are summarized by the average threshold in dB HL for frequencies between 0.5 – 4 kHz. Both groups showed hearing asymmetries that were greater than 65 dB. Similar asymmetries were noted for speech recognition scores (percentage of correct responses), which were evaluated by asking the subject to repeat 25 single syllable words from a CNC (consonant – vowel nucleus – consonant) word list. The words were spoken by the audiologist at a conversational level inside the quiet testing booth.

To demonstrate an increased susceptibility to informational masking among SSD participants, the normal baselines of binaural subjects were established by testing adults with no reported hearing asymmetries ($n = 5$, median age 28 years). These control subjects were recruited from audiology staff at the participating institutions.

Design

IBC users were tested sequentially in two 15-minute sessions during the same clinical visit. One session was conducted with active input from the device, the other without the device. The order of testing was counter-balanced across participants. Consequently, a subset of inexperienced users were not strictly naïve because they were briefly tested with the device before they were tested without the device. The performance of inexperienced users was not affected by the order of testing. Control subjects with binaural hearing were tested in one 15-minute session.

Changes in speech intelligibility, the operational definition of informational masking, were assessed by measuring the effects of distracting sentences on a listener's ability to extract color-number coordinates from simple sentences (Eddins et al. 2012). The corpus of sentences was taken from libraries for the coordinate-response measure (Bolia et al. 2000).

An increased susceptibility to informational masking among SSD patient populations was verified by measuring the unaided performance of SSD participants. Because long-term exposure to the IBC may alter unaided performance relative to untreated patient populations, the analysis was limited to individuals who were tested on the day of device activation (inexperienced users).

The benefits of IBC-aided listening were assessed by measuring the aided performance of SSD participants. Because optimum performance may be derived from learned listening strategies, a separate analysis was performed on individuals who were tested on the day of device activation (inexperienced users) or at least three months after device activation (experienced users). Learning effects were confirmed by comparing the aided performance of experienced and inexperienced users.

The acoustic basis of the IBC listening advantage was investigated by varying the voice pitch (fundamental frequency) and spatial location of distracting sentences in relation to the identifying characteristics of target sentences. Speech recognition errors were then correlated with the pitch and location of distracting sentences to isolate the relative importance of these cues in the perceptual streaming of target sentences.

Procedure

Data acquisition was automated using custom software that was implemented in a MATLAB programming environment (MathWorks). The participant was seated inside an audiological booth facing eight speakers that were placed at azimuths of -36° , -18° , -9° , 0° , 9° , 18° , 27° , and 36° at an elevation of 0° relative to the inter-aural axis. The participant was instructed to maintain a fixed head orientation relative to the center speaker. Participants confirmed their compliance at the completion of the testing session.

Speech sentences for the coordinate-response measure were spoken by eight professional male and female voice actors (Bolia et al. 2000), who were instructed to maintain a uniform cadence and loudness for all sentences. The average fundamental frequency of each talker's voice is shown in Table 3. For convenience, the individual talkers are categorized as same male (91.3 Hz), other male (101.5 – 113.0 Hz), or female voice pitches (196.3 – 226 Hz).

Each sentence contained a call sign and a color-number coordinate pair. Target sentences were always identified by the call sign *Arrow*. Distracting sentences began with one of the seven remaining call signs (*Baron*, *Charley*, *Eagle*, *Hopper*, *Laker*, *Ringo*, *Tiger*). Coordinates were randomly selected combinations of colors (*red*, *white*, *blue*, *green*) and numbers (1 – 4). In the example, “Ready, Arrow, go to green 2 now” the call sign *Arrow*

indicates that it is the target sentence. The participant responds correctly by pressing the green color key and numerical 2 key on a custom keypad.

Target sentences were always presented from the speaker directly in front of the participant (0° azimuth, 0° elevation), and were always spoken by the same male voice (talker 0). Distracting sentences were delivered from the remaining speaker locations using the same male voice (talker 0), other male voices (talkers 1, 2, and 3), or female voices (talkers 4, 5, 6, and 7). The number, location, and pitch category of distracting sentences were selected at random. The number of distracting sentences ranged from 0 – 3. Trials without a distracting sentence were used to monitor the audibility of target sentences and the attentional focus of the subject. All subjects produced error rates near 0% for these probe trials.

Sound energy in the target sentence reached the participant's head at an approximate peak free-field level of 82.5 ± 0.8 dBA. Target and distracting sentences were presented at the same peak voltage. Presentation levels were not altered to compensate for the number of distracting sentences on each trial. Consequently, TMR varied with distractor number. These effects were not simply additive because the signals were not coherent. Empirical free-field measures indicated that the total masking level increased on average by 0.9 and 1.4 dB for two and three distractors, respectively. Thus, TMR ranged from 0 dB for one distracting sentence to -1.4 dB for three distracting sentences.

The *a priori* compensation for these modest changes in TMR is not trivial because distracting sentences not only varied randomly in content and location, but also were delivered acoustically or through bone conduction. For these reasons, a fixed presentation level was selected as the most viable testing strategy. The probability of random errors remained low regardless of the number of distracting sentences, suggesting that energetic masking effects were not augmented during trials with more distractors.

Statistical analyses

All statistical analyses were computed with the statistical toolbox of MATLAB. The minimum level of statistical significance was based on a criterion of $P < 0.05$. Higher levels of significance are reported where they were observed.

Differences in the magnitude of informational masking between device types were determined using an unbalanced, two-way ANOVA. The error rates were factored according to two levels of device experience (between-group factor: experienced and inexperienced) and four types of devices (within-group factor: Baha 3, Baha 3 power, Intenso, and Ponto). The calculations were performed in MATLAB using the function *anovan* (Fig. 2).

Differences in the magnitude of informational masking between aided SSD participants (experienced users), unaided SSD participants (inexperienced users), and binaural controls were determined with a mixed model, two-way ANOVA. The error rates were factored according to the three subject groups (between-group factor) and the number of distracting sentences (within-group factor). The calculations were performed with the function *mixed_between_within_anova* (Fig. 3).

Post hoc contrasts were performed to determine the significance of performance differences between individual groups. The ANOVA was performed with Bonferroni adjustments for multiple comparisons.

A profile analysis was constructed to identify the acoustic cues that separate target sentences from multi-talker babble. The importance of voice pitch was determined by grouping error rates according to distracting sentences that were spoken by the same male voice, other male

voices, or female voices (within-group factor, left column of Fig. 5). The importance of spatial location was determined by grouping error rates for distracting sentences in the deaf or normal hemifield (within-group factor, right column of Fig. 5).

Cue effectiveness was examined in isolation by analyzing trials with only 1 distracting sentence (upper row of Fig. 5), or in a more complex listening environment by combining data from all trials (bottom row of Fig. 5). For the latter analysis, the cue of interest was embedded in random combinations of pitch and location that were conveyed by the remaining simultaneous distractors.

Profile analysis is derived from a MANOVA statistical test, which is the multi-variate equivalent of the mixed model ANOVA. In the present study, errors in speech recognition were grouped by the independent variables same, male, and female distractors to evaluate the importance of pitch cues. The independent variables deaf and normal hemifield were used to evaluate location cues. The MANOVA was performed in MATLAB using the function *profana*.

Profile analysis generated groupwise plots of mean error rates as a function of cue. The graphical relationship between the error profiles supported three statistical interpretations, as illustrated in Fig. 1. Experienced users were expected to show on average lower error rates than our estimates of the unaided performance of SSD patients (inexperienced users who were tested without the device). The between-group effect is visualized as a vertical displacement between the two profiles (Fig. 1A). The statistical significance of the displacement is specified by the level probability (P_L).

Both groups were expected to rely on certain speech streaming cues. The within-group effect of the cue is visualized as sloped error profiles (Fig. 1B). The statistical significance of any departure from a slope of 0 is specified by the flatness probability (P_F).

It was also anticipated that experienced users would respond to sources of information that were not available to unaided SSD participants. The group $\times$ cue interaction is visualized as a departure from parallelism for the two profiles (Fig. 1C). The statistical significance of the interaction is indicated by the parallelism probability (P_P).

Error profiles were grouped by the status of the device (aided versus unaided listening) and length of exposure (experienced versus inexperienced users). The unaided error rates of inexperienced users related acoustic factors to the increased susceptibility to informational masking among SSD participants. The aided error rates of experienced users isolated the factors that contribute to the IBC listening advantage. The aided error rates of inexperienced users revealed how attentional biases are acquired during the initial months of device exposure.

Results

SSD participants wore four types of IBC devices. Most were fitted with Baha 3 (Cochlear) or Ponto (Oticon) processors. Three participants with higher amplification needs were fitted with Baha 3 power (Cochlear) or Intenso (Cochlear) processors. The aided error rates of individual subjects are plotted in Fig. 2. Alphanumeric symbols indicate the type of device that was worn during aided testing. For the comparison, error rates are derived from all trials that contained 1 – 3 distracting sentences. The participants have been separated into two groups based on their previous experience with the device. Error rates were significantly different between experienced and inexperienced users (ANOVA, $P < 0.01$), but no device was associated with significantly higher or lower error rates within the two groups (ANOVA, $P > 0.05$). Consequently, the following results are combined across device types.

The effects of the number of distracting sentences on speech recognition are shown in Fig. 3. When target sentences were presented in isolation (0 distractors), all participants achieved near-perfect performance. These results confirmed the general audibility of the corpus of stimuli. When inexperienced IBC users were tested without the device to estimate the performance of untreated SSD patients, the addition of one distracting sentence significantly elevated error rates (40.8%, SE = 5.6). One distractor had negligible effect on the error rates of binaural control subjects (2.3%, SE = 1.0). The dichotomy between unaided SSD participants and binaural controls expanded when the number of distracting sentences was increased.

Optimum performance with the IBC was assessed by measuring the aided performance of experienced users. These individuals showed significantly less informational masking than unaided SSD participants. One distracting sentence produced error rates of only 24.2% (SE = 3.0). A listening advantage of similar magnitude was noted for 2 and 3 distractors.

The between-group factor (binaural controls, unaided inexperienced SSD participants, and aided experienced users) and within-group factor (0 – 3 distracting sentences) showed highly significant statistical differences ($P < 0.001$). A *post hoc* analysis of the between-group factor confirmed significantly lower error rates in binaural controls than in the aided and unaided SSD groups ($P < 0.05$). Aided experienced users demonstrated a significant advantage relative to the unaided performance of SSD participants with no device history ($P < 0.05$).

An analysis of error type can reveal whether the psychometric relationships in Fig. 3 are determined by energetic or informational masking effects (Ihlefeld et al. 2008). When incorrect responses are dictated by informational masking, subjects attend to coordinates that are contained in the distracting sentence rather than the target sentence. The subject may report both coordinates from a distracting sentence (switch error), or may mix one coordinate from a target sentence with one coordinate from a distracting sentence (mixture error). When incorrect responses are dictated by energetic masking, the subject reports random coordinates that are not contained in the target or distracting sentences (random error).

The type of errors committed by aided SSD participants (experienced users) and unaided SSD participants (inexperienced users) are compared in Fig. 4. Results from binaural controls are not included because they generated too few errors to support the analysis. Both groups of SSD participants showed similar error patterns. Single errors involving one coordinate were twice as likely as double errors involving both coordinates (Fig. 4A). Single errors of both groups were slightly skewed toward color coordinates.

When subjects produced double errors, they were likely to involve switch errors (Fig. 4B). The majority of single errors involved mixture errors (Fig. 4C). Random errors were relatively rare, confirming the dominant role of informational masking in the CRM task.

Profile analyses of the error rates of aided (experienced users) and unaided SSD participants (inexperienced users) are shown in Fig. 5. In the presence of one distracting sentence (top row of Fig. 5), aided participants produced on average fewer errors. This result was previously noted in Fig. 3. Here, the same group effects are restated as significant level difference statistics for the paired pitch and location profiles ($P_L < 0.01$).

Error profiles based on pitch in Fig. 5A also indicated a significant departure from parallelism ($P_P < 0.05$). This statistic reveals the presence of a group $\times$ cue interaction; that is, the two groups did not make equal use of voice pitch segregation cues. The error rates of aided SSD participants showed a monotonic decline as the magnitude of the disparity in

fundamental frequency increased relative to the male target voice (same < male < female). Unaided SSD participants showed no systematic relationship.

Error profiles based on location in Fig. 5B are parallel ($P_P > 0.05$) but not flat ($P_F < 0.05$). These statistics indicate a common correlation between error and distractor location within the two groups. Both groups produced fewer errors when distractors originated in the deaf hemifield.

The importance of voice pitch and location cues in more complex listening environments was evaluated by performing the same profile analysis on trials in which 1 – 3 distractors were presented (bottom row of Fig. 5). Again, as noted in Fig. 3, aided participants produced fewer errors on average than unaided participants (between-group effect, $P_L < 0.01$).

The effects of cue on error rates were similar to results obtained with 1 distractor, but the profiles were less modulated. The group $\times$ cue interaction of the voice pitch profile in Fig. 5C failed to reach statistical significance ($P_P > 0.05$), as did the within-group effect of location in Fig. 5D ($P_F > 0.05$). These results suggest that pitch and location cues are less effective in more complex acoustic environments. Despite the challenge, aided participants maintained a general performance advantage over their unaided counterparts.

The effects of learning on the IBC advantage are summarized by the error profiles in Fig. 6. Because SSD participants did not receive longitudinal audiological assessments in the present study, acquired listening strategies were estimated by comparing the aided performance of experienced and inexperienced users. These were the same two groups of subjects that produced the error profiles in Fig. 5, but in this case inexperienced users were tested with the device.

Inexperienced users showed a sensitivity to voice pitch cues that was not evident during testing without the device. When 1 distractor was presented (Fig. 6A), neither within-group nor interaction effects were statistically significant ($P_L > 0.05$, $P_P > 0.05$). The effect of voice pitch across groups was significant ($P_F < 0.005$). These results suggest that inexperienced users immediately adopted the voice pitch processing strategy of experienced users. The two groups also displayed equivalent performance for distractors that were located in the normal spatial hemifield, which is not surprising given the dominant position of the functioning ear. An exception to this parallelism was the increased sensitivity of inexperienced users to distractors in the deaf hemifield.

Inexperienced users were especially prone to informational masking when tested with multiple distracting sentences (bottom row of Fig. 6). Differences between experienced and inexperienced users were highly significant regardless of the type of segregation cue ($P_L < 0.001$). As shown in Fig. 6C, both groups made effective use of voice pitch cues ($P_F < 0.05$), but experienced users produced error profiles that were better correlated with cue strength ($P_P < 0.05$). As shown in Fig. 6D, error profiles based on location failed to show cue ($P_F > 0.05$) or interaction effects ($P_P > 0.05$).

Discussion

Previous hearing in noise tests have reported significant masking release in unilateral IBC users (Pfiffner et al. 2011). These benefits have been attributed to the enhanced TMR that is achieved when the attenuating effects of the head and upper torso selectively impede the propagation of masking noise (Lin et al. 2006; Rothpletz et al. 2012). In most instances, an individual with SSD can reduce energetic masking without an IBC by establishing a favorable spatial orientation with a conversational partner (i.e., placing the attended talker on the side of the functioning ear).

The results of the present study suggest that the effects of informational masking on speech recognition are profound and pervasive among unaided SSD participants. One concurrent source of distraction increased speech recognition errors by over 40%. In addition, error rates were not significantly reduced when distracting sentences were delivered from sources in the deaf spatial hemifield. This lack of laterality implies that informational masking is resistant to moderate changes in the audibility of competing speech streams. Previous studies of speech recognition in hearing impaired listeners have reported similar findings (Drullman and Bronkhorst 2004; Summers and Molis 2004). Therefore, only modest perceptual benefits are likely to be gained by unaided listening strategies, such as attempting to optimize the spatial arrangement of target and distractor.

The IBC listening advantage was correlated with the availability of voice pitch cues, and to a lesser extent, location cues. Experienced users produced fewer errors when male target sentences were paired with other male or female distracting sentences. Unaided SSD patients generated a less modulated profile. The statistically significant interaction between group and voice pitch suggests that the unusual transmission characteristics of an IBC do not degrade cues that are derived from the fundamental frequency of the talker's voice. In fact, based on these data, the device appears to create supplemental cues that benefit experienced users.

The aided performance of experienced users were strongly modulated by location cues only when distractors were presented in isolation. The steep slope of the error profile in Fig. 5B reflects the low error rates that were generated by distractors in the deaf spatial hemifield. This outcome is somewhat surprising given the potentiating effects of the device on energetic masking. Clearly, in the context of informational masking, errors in speech recognition appear to be dictated by the improved quality of streaming cues not the concomitant increase in distractor level.

The parallelism of location profiles suggests that experienced IBC users and unaided SSD participants respond to the same directional cues. If that interpretation is correct, the listening advantage must arise from an increased sensitivity to those cues. Previous studies, however, have found no improvement in the directional acuity of IBC users (Wazen et al. 2005). Although the perceptual processing of monaural spectral cues may be enhanced in SSD patients, several lines of evidence suggest that this information source is less important in the CRM task. The strong directional filtering effects of the human head-related transfer function occur at frequencies above 8 kHz (Middlebrooks et al. 1989). Conversely, the spectral energy of human speech declines sharply as frequencies approach 8 kHz (Pittman et al. 2003). The speech waveform is further biased toward low frequencies by the gain characteristics of the IBC transducer and the transmission characteristics of transcranial vibroacoustic stimulation (Stenfelt 2012).

An alternative explanation for a lateralized listening advantage is that the error rates for distractors in the deaf spatial hemifield were reduced by an independent source of non-directional information. IBC users may produce fewer errors than unaided SSD participants because the device delivers supplemental segregation cues to the functional ear via bone conduction. Implicit in this explanation is the concept of "pseudo-binaurality." Under normal circumstances, the binaural brain creates the spatial identities of multiple auditory objects by computing the time and level disparities of inputs from the left and right ears. A similar analysis may be accomplished by comparing sounds that are delivered to the same functioning ear via acoustic (normal hemifield) and vibroacoustic stimulation (deaf hemifield). In this situation, the brain may create a spatial identity from disparities in the two transmission modalities, which are biased by the location of the sound source. The source of

the disparities may lie in any time, level, or pitch disparities that are unambiguously associated with IBC stimulation.

Errors in speech recognition increased in proportion to the number of simultaneous distracting sentences. For both voice pitch and location cues, the mix of 1 – 3 distractors elicited error rates that were approximately 20% higher than those of a single, isolated distractor. The loss of cue effectiveness was reflected in the decreased slope of error profiles. Although both groups of participants were negatively affected, the dichotomy between the aided performance of experienced IBC users and unaided SSD participants was magnified in more complex listening environments.

Typically, IBC users are implanted with a percutaneous titanium abutment, and then return after a period of osseointegration to be fitted with the aid (Arnold et al. 2011; Mylanus et al. 1994). When inexperienced users were tested during their initial fitting (day 0), the device increased their rate of speech recognition errors. Nevertheless, a profile analysis of the errors revealed meaningful pitch relationships that were not present during their unaided performance. Like experienced users, inexperienced users generated fewer errors when target sentences were paired with a single distractor that was spoken by other male or female voices.

In contrast with experienced users, inexperienced users tended to make more errors when a single distractor was presented from a source in the deaf spatial hemifield. This result suggests that the hypothesized association between spatial location and currently unknown IBC disparity cues (i.e., pseudo-binaurality) is acquired during the initial three-month period of unstructured device use.

The performance deficits of inexperienced users were exacerbated by increasing the number of distracting sentences. As previously noted for the unaided performance of these same individuals, error profiles were not significantly modulated by voice pitch or location cues. In particular, the voice pitch profile of inexperienced users failed to indicate the most basic segregation of male and female voices.

The most dramatic experience-dependent enhancements appear to be linked to the formation of target identities that are derived from learned IBC cues. The present study has not addressed how IBC-dependent segregation cues are acquired during the initial months of device exposure. Although unstructured listening environments were sufficient to promote a listening advantage, it is possible that structured training programs may further optimize cue effectiveness, increase the efficiency of learning, and reduce the persistent confounding effect of complex listening environments. Given the relatively low impact of directional cues on the error profiles of experienced users, training programs can be conveniently delivered to new users under closed-field conditions without the need for speaker arrays and audiological booths.

Informational masking impacts the daily lives of individuals with many forms of hearing loss. Patients fitted with acoustic aids or cochlear implants are challenged by the same speech streaming problems as SSD patients. Acoustic cues must be found in the aided input that reliability separate meaningful signals from environmental backgrounds. The coordinate-response measure represents a basic approach for isolating the psychoacoustic factors that define informational masking in diverse patient populations. Understanding these unique perceptual limitations is a critical first step for the design of better assistive devices and more specialized rehabilitation procedures.

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Fig. 1.

Statistical interpretation of error profiles. A. A significant difference in level ($P_L < 0.05$) indicates that group A makes fewer errors than group B. B. A significant departure from flatness ($P_F < 0.05$) indicates that the error rates of both groups are correlated with stimulus value. C. A significant lack of parallelism ($P_P < 0.05$) indicates that the two groups respond differently to changes in stimulus value.

Fig. 2. Distribution of aided error rates among experienced and inexperienced users. Different symbols indicate the type of processor: Baha 3 (3), Baha 3 power (3p), Intenso (I), and Ponto (Po). Closely spaced symbols are shifted to the right for visual clarity.

Fig. 3.

Effects of the number of distracting sentences on performance in the coordinate-response task. Average error rates are compared for binaural controls, unaided SSD participants who were tested on the day of device activation, and aided SSD participants who were tested at least three months after device activation. Error bars indicate ± 1 SE.

Fig. 4.

Error patterns for aided and unaided SSD participants. A. Both groups tended to make single errors of color or number. B. When double errors were committed, subjects often responded with the coordinate pair of a distracting sentence (switch error). C. When single errors were committed, the incorrect coordinate was usually contained in a distracting sentence (mixture error).

Fig. 5.

Profile analysis of the acoustic cues that contribute to the IBC listening advantage. The aided performance of experienced users is contrasted with the unaided performance of inexperienced users. Mean error rates are grouped by the distractor's category of voice pitch (A, C) or spatial location (B, D). The cue was presented in isolation (top row) or with other distractors (bottom row).

Fig. 6.

Learning effects that contribute to the IBC listening advantage. IBC-aided performance is contrasted between experienced and inexperienced users. Error rates are grouped by the distractor's category of voice pitch (A, C) or spatial location (B, D). The cue was presented in isolation (*top row*) or with other distractors (*bottom row*).

Table 1

Biographical characteristics of participants

Group	Female	Male	Age (yrs)	Duration of SSD (yrs)	Duration of IBC use(mos)
Experienced	5	6	59 (39–81)	20 (1–50)	15 (3–61)
Inexperienced	4	2	68 (42–70)	21 (1–46)	0 (0)
Normal	3	2	28 (25–38)	—	—

Median and range (in parenthesis) for age, duration of SSD, and duration of IBC use. SSD, single-sided deafness.

Table 2
Hearing thresholds of experienced and inexperienced IBC users

Group	PTA normal ear (dB HL)	PTA deaf ear (dB HL)	Speech better ear (%)	Speech deaf ear (%)
Experienced	18 (15–34)	83 (55–BTL)	100(96–100)	0 (0–40)
Inexperienced	25 (12–54)	99 (66–BTL)	100(76–100)	0 (0–80)

Median and range (in parentheses).

PTA, mean threshold for frequencies between 0.5 – 4 kHz.

BTL, beyond testing level.

Speech, correct recognition of spoken CNC syllables in quiet.

Table 3
Fundamental frequency (F0), gender, and role of each talker in the speech corpus

Talker	F0(Hz)	Gender	Role
0	91.3	male	target
1	106.8	male	distractor
2	101.5	male	distractor
3	113.0	male	distractor
4	226.0	female	distractor
5	208.5	female	distractor
6	216.0	female	distractor
7	196.3	female	distractor