# SPATIAL RELEASE FROM MASKING

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## Spatial release from masking in adults

In complex auditory environments multiple sounds occur, such as people uttering speech that is of interest, as well as speech sounds with uninteresting content. Additionally, humans spend a great deal of their awake hours in social, work-related and learning environments that contain maskers: background noise, music and various other environmental sounds, all of which can vary in direction, amplitude and familiarity to the listener, and have the potential to interfere with information transmitted by the speech signal. To communicate using spoken language, listeners must be able to use auditory cues to attend to the speech source of interest and ignore other sounds. When you next find yourself in a "cocktail party" environment, imagine what incredible processes the auditory system has to segregate speech from noise.

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The ability to segregate speech from maskers is determined by a complex set of auditory computations. This problem was named the "cocktail party effect" 60 years ago (Cherry, 1953; Pollack and Pickett, 1958) and has been the topic of dozens of studies since, in normal hearing adults and also in children. This topic has also become a focal point for populations of hearing impaired individuals, who often experience difficulty when hearing speech in noisy situations. These populations include listeners with hearing loss who are fitted with hearing aids, and also individuals who are deaf and undergo surgical procedures to receive cochlear implants to be able to hear.

Regarding the analysis of acoustic inputs, the auditory mechanisms involved in source segregation either process information from each ear separately (monaural) or compare the information arriving from two ears and use the inter-aural (between-the-ear) differences (binaural). In addition, in the process of segregating signal target speech from competing sounds, the human brain engages in higher-order processes such as auditory attention and memory.

Concerning the acoustic cues in a normally functioning auditory system, when sounds reach the ears from a particular location in space, the spherical shape of the head renders an important set of acoustic cues. Figure 1 provides a schematic of the directionally dependent cues that would be potentially available to listeners in the horizontal plane for a brief signal such as a click. In the horizontal plane, sources presented from directly in front or behind reach the ears at the same time and with the same intensity. Sources that are displaced to the side will reach the near ear before reaching the far ear. Thus, a binaural cue known as inter-aural time difference (ITD) varies with spatial location; however, the auditory system is particularly sensitive to ITD at frequencies below 1,500 Hz. For amplitude-modulated signals such as speech, ITD cues are also available from differences in the timing of the envelopes (slowly varying amplitude) of the stimuli. Inter-aural level difference (ILD) is a second binaural cue that results from the fact that the head creates an acoustic "shadow" so that the near ear receives a greater intensity than the far ear. ILDs are particularly robust at high frequencies and can be negligible at frequencies as low as 500 Hz.

When listening to speech in noise, spatial cues play an important role in improving speech understanding. The improvement arises when one compares conditions in which the signal and masker are co-located (for example both at 0 degrees in front of the listener) compared with a situation in which they are spatially separated (i.e., the target speech is at 0 degrees in front and the masker is at 90 degrees to the right). This example is illustrated in the schematic in Fig. 2.

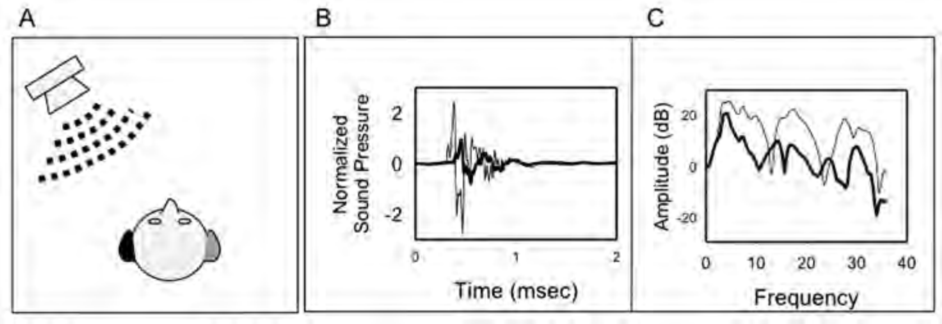

*Fig. 1. In panel A, a schematic of a sound source presented at 45° to the left of the listener is depicted. Panel B shows the time waveforms of impulse responses recorded in the left (thick line) and right (thin line) ear canals, for that sound source. Panel C shows the amplitude spectra for the same source, also recorded in the left (thick line) and right (thin line) ear canals. The left ear response occurs sooner than the right ear response (see B), hence the interaural time difference (ITD). In addition, the left-ear response has greater amplitude (see C), hence the interaural level difference (ILD).*

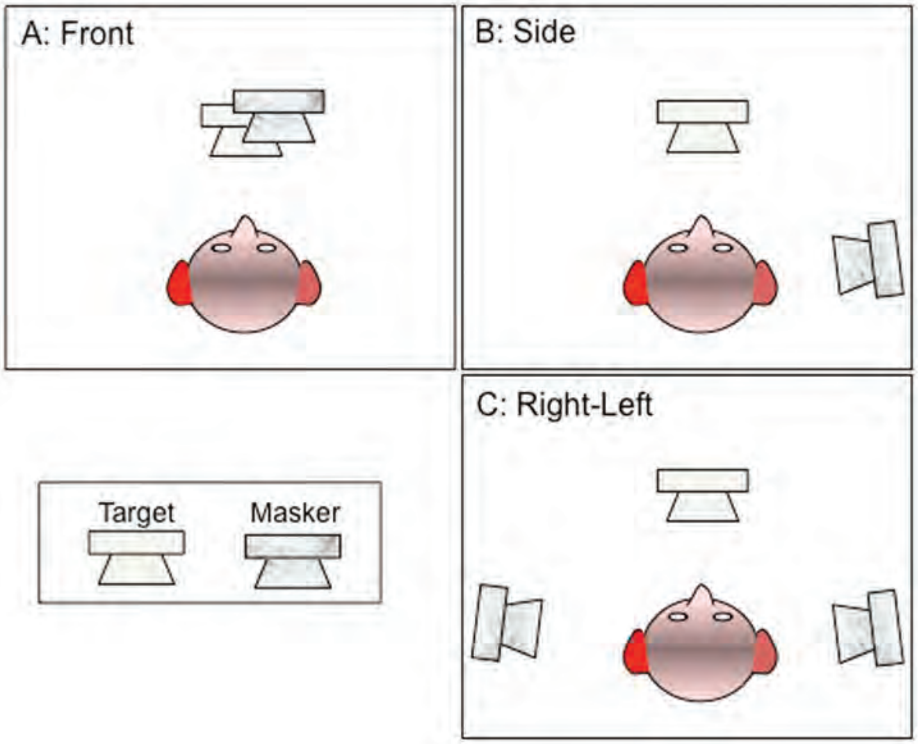

*Fig. 2. Schematic diagram illustrating configurations for stimuli used to study spatial release from masking (SRM). The listener is facing front, with target speech (shaded speaker) in front. Panel A: the masker (white speaker) is also in front, hence the co-located condition. Panel B: masker is on the side, thus the monaural head shadow in the ear on the opposite side of the head is partially protected from the masker. Panel C: two maskers occur, one on each side, reducing or eliminating the head shadow.*

Many studies to date have shown that the configuration in Fig. 2B can result in robust improvement in the percent correct for word identification compared with Fig. 2A (Plomp and Mimpen, 1981; Hawley *et al.*, 1999, 2004; Arbogast *et al.*, 2002; Drullman and Bronkhorst, 2002; Litovsky, 2005). This phenomenon is often referred to as *spatial release from masking* (SRM), because the interference, or masking that occurs in the presence of the masker(s) on the side (Fig. 2A) is reduced (released) when spatial cues are available. Studies on SRM in humans typically use speech materials such as words or sentences that are equalized across conditions for difficulty and frequency within the language, but across the various existing test materials, these variables can differ. SRM is typically quantified in one of two ways. In one paradigm we measure the percent correct ([P(C)]) when the signal-to-noise ratio (SNR) for the target and maskers is set to various intensity levels, and [P(C)] is obtained for each condition at each SNR, and computed as [$P(C)_{side}$-$P(C)_{front}$]; positive values would indicate improved performance. In a second paradigm we vary the SNR adaptively, and find the speech reception threshold (SRT), defined as the SNR at which listeners reach a predefined criterion, such as 50% or 75% correct. SRM is then computed as: [$SRT_{front}$-$SRT_{side}$]; positive values would indicate improved performance.

SRM tends to be largest when the speech and masker can be easily confused, and when listeners are unsure as to what aspects of the masker to ignore. Confusability can arise when the target/masker voices are similar; for example, consider a case in which the target speech and masker are both male voices with similar fundamental frequency ($f_0$), vs. a case in which the target has an $f_0$ of 125 Hz and the masker is a woman's voice with $f_0$ of 250 Hz. Confusability can also arise when the target/masker have similar content, such as speech materials that can be inter-changeable or that carry similar meaning. These aforementioned examples elicit what has become known as "informational masking," which is the default term used to describe masking that goes beyond "energetic masking," or masking that is accounted for by processes in the peripheral auditory system (Durlach *et al.*, 2003). Spatial separation of maskers from the target is an effective way to counteract informational masking (Kidd *et al.*, 1998; Freyman *et al.*, 1999, 2001). As a result, the magnitude of SRM with informational maskers can be quite large relative energetic maskers (Durlach *et al.*, 2003; Jones and Litovsky, 2008, 2011).

As mentioned above, acoustic cues can also affect the magnitude of SRM, and the effects can be divided into binaural and monaural components (Hawley *et al.*, 1999, 2004; Jones and Litovsky, 2011; Bronkhorst, 2000; Loizou *et al.*, 2009; Garadat *et al.*, 2010). When target speech and masker are spatially separated, half of the binaural advantage comes from the "better ear effect" (also known as the "monaural head shadow effect"), where the SNR is increased in one ear due to attenuation of the noise from the listener's head (Zurek, 2003). Another advantage, the binaural squelch effect, depends on the ability of the auditory system to utilize binaural aspects of the signal, including differences in the ITDs and ILDs of the target speech and the masker (Bronkhorst, 2000; Culling *et al.*, 2004; Litovsky *et al.*, 2012). A third effect is that of "binaural summation" whereby the activation of both ears renders a sound that is presented from a location in front easier to hear due to summation of the signals at the two ears. Finally, for amplitude-modulated signals such as speech, ITD cues are also available from differences in the timing of the envelopes (slowly varying amplitude) of the stimuli.

The binaural cues that are thought to be important for segregation of speech and noise can be studied selectively over headphones by imposing either similar binaural cues on the speech and masker, the co-located condition, or by varying the binaural cues, such that the target and masker are perceived to be at different intracranial (inside the head) locations, the separated condition. For speech separation, the binaural intelligibility level difference (BILD), the difference in speech intelligibility threshold between the co-located and separated conditions, can be as large as 12 dB in adults, depending on the condition (Blauert, 1997; Hawley *et al.*, 2004; Litovsky *et al.*, 2012). A simpler version of the BILD is the binaural masking level difference (BMLD), where a target signal such as a tone or narrow-band noise is detected in the presence of a masking noise. BMLD can be measured, for example, by comparing threshold for tone detection when: both the noise and tone are in-phase at the two ears—the $N_0S_0$ condition—and to that when the noise is in-phase at the two ears, but the tone signal is out-of-phase at the two ears—the $N_0S_\pi$ condition. Presumably, the tone and noise are perceived as co-located intracranially in the $N_0S_0$ condition, while they are perceived as spatially separated in the $N_0S_\pi$. The difference in threshold between $N_0S_\pi$ and $N_0S_0$ ranges from 8 to 30 dB, depending on the specific condition.

The BMLD, headphone-based paradigm, in which ITD is manipulated to produce source segregation, has been instructive in thinking about the benefit that listeners get in spatially separated conditions in free field. Unmasking occurs in these paradigms, because in the separated condition the acoustic characteristics of the signals in two ears are highly dissimilar (Gabriel and Colburn, 1981; Bernstein and Trahiotis, 1992; Culling and Summerfield, 1995). Thus, the task becomes one in which listeners detect "incoherence" between the separated and co-located conditions. Note that these conditions, in which one cue is varied (e.g., ITD) do not provide listeners with all the cues available in a realistic listening situation. Because of the interest in understanding SRM under conditions that mimic the real world, many studies have implemented the testing paradigm illustrated in Fig. 2, where monaural and binaural cues are mixed and both contribute to SRM (Hawley *et al.*, 1999, 2004; Bronkhorst, 2000; Culling *et al.*, 2004; Litovsky *et al.*, 2012).

Another area of growing interest regarding unmasking of speech is that of non-sensory processes involved in source segregation. These could potentially include cognition, attention, memory, emotion and other similarly "top-down" processes. One model for considering these processes is that of "object formation" (Shinn-Cunningham, 2008), whereby there is an attempt to explain how attention influences perceptual abilities. It has been suggested that attentional mechanisms, which are invoked in a "cocktail party" situation to segregate speech from maskers, share aspects of the neural mechanisms controlling attention in the visual field. In addition, the role of visual cues in directing auditory attention turns out to be important in segregating speech from maskers and enhancing SRM (Best *et al.*, 2007; Varghese *et al.*, 2012).

## Spatial release from masking in children

Thus far, the discussion has focused on mechanisms by which the auditory system of adult listeners teases apart co-occurring sounds and facilitates speech understanding in noisy environments. A number of studies by Litovsky and colleagues have simulated aspects of the auditory environment that might be encountered in a "classroom party effect." Litovsky (2005) first demonstrated SRM in children aged 4-7 years with target and maskers and compared with those found in adults. The testing paradigm is different from that which is typically implemented with adults, since young children have a more limited vocabulary and ability to provide a reliable response on the task. Thus, a novel method for testing children was devised. Children engaged in a listening "game" with a four-alternative forced-choice (4AFC) task, whereby children pointed to pictures matching the heard words. Prior to testing, children are familiarized with target spondaic words, selected such that they could each be represented with a visual icon (e.g., ice-cream, cow-boy, bird-nest), and that were within the vocabulary of 4-year-old children. Maskers consist of sentences strung together that do not overlap in content with the target speech. In this study, SRM was computed from SRTs measured in the co-located and separated conditions, and averaged 5.2 dB and 7.4 dB, in conditions with one or two maskers, respectively. Thus, children were able to benefit from differences in spatial cues between target speech and masker, with larger effects if two-talker maskers were used. It is worth noting that in this study the target-masker configurations resulted in SRM due to a combination of binaural and monaural cues. More recently we (Misurelli and Litovsky, 2012) found that children aged 4-7 years also demonstrate SRM when head shadow cues are minimal (see Fig 2C). In the right-left condition, the maskers are displaced towards both sides of the head, thus resulting in a condition with minimal or absent "better ear." SRM is computed either by comparing percent correct $[P(C)_{\text{right-left}}\text{-}P(C)_{\text{front}}]$ or thresholds $[SRT_{\text{front}}\text{-}SRT_{\text{right-left}}]$. It is noteworthy that right-left SRM was smaller than side SRM, when both head shadow and binaural cues were present. Similar findings have been reported in adults as well (Marrone *et al.*, 2008; Jones and Litovsky, 2011.

SRM can be found in children as young as 3 years of age (Garadat and Litovsky, 2007), again using age-appropriate speech and computerized listening games. In this case the speech corpus was chosen to be within the receptive language and vocabulary of children at ages 2.5 to 3.0 years. As in Litovsky (2005), the child selected a visual icon to match the heard word on each trial. By age 3 years children had SRM values that were similar to those of 4-5 year olds, suggesting that the ability to benefit from spatial separation between target and maskers developed at this young age. Furthermore, children who demonstrated the greatest SRM were those with high speech reception thresholds (SRTs) in the front condition where the target and maskers were co-located. In the Litovsky (2005) study SRM was shown to be larger when two-masker speech stimuli were used than when one-masker was used, suggesting that, when the listening environment is more complex, spatial cues play an increasingly more important role in assisting the listener with source segregation. Follow-up studies have been conducted in which other aspects of the auditory environment have been manipulated, such as the type of masker (Johnstone, 2006; Johnstone and Litovsky, 2006), with evidence to suggest SRM in children is greatest when target-masker similarity is high (i.e., when both the target and masker were produced by a male talker), similar to what has been seen in adults (Bronkhorst, 2000; Brungart *et al.*, 2001). This effect has been attributed to the fact that target-masker similarity renders speech segregation extremely difficult, making spatial cues the most salient cues that listeners can use to segregate target from maskers. By comparison, SRM is smaller with different-sex and non-speech maskers, because cues resulting from differences in the spectra of the signals can be useful for source segregation. A somewhat different variation on the target-masker similarity can be introduced with a reversed-speech masker, which contains the same temporal amplitude fluctuations and long-term spectrum as speech. In children, this masker produced SRM that was similar to that with the speech masker from which it was created, even though it carried no linguistic content (Johnstone and Litovsky 2006), a finding that is consistent with observations in adults (Hawley *et al.*, 2004). Children provided anecdotal reports that the masker had a novel feature with some resemblance to a person speaking in a foreign language. This may have added to the interference that would have been produced simply by a modulated speech-shaped noise masker that bears similarity in the spectral and amplitude-modulation domain, but carries no resemblance to spoken language.

## Spatial release from masking in special populations

A growing number of adults and children with hearing impairment have been receiving stimulation in both ears in an effort to provide them with perceptual benefits on auditory tasks that are known to rely on having inputs in both ears. For many years, the standard of care in acoustic amplification has been to provide bilateral hearing aids to people with bilateral hearing loss (Litovsky and Madell, 2009). Another population of patients with hearing loss who cannot benefit from amplification is a population of people with severe-to-profound hearing loss. These patients are often candidates for receiving electrical stimulation through cochlear implants (CIs). These devices have been clinically available for the past few decades, and can provide auditory input by electrically stimulating the auditory nerve, bypassing the damaged sensory organ of hearing, known as the cochlea.

For many patients, electrical input through a CI is sufficient for attainment of speech perception and production within the normal range, allowing aural-verbal communication. The standard of care for many years was considered to be provision of adequate speech perception and language acquisition through the use of a monaural CI. Deciding which ear to implant has been a complex decision, one which has undergone a series of changes throughout the years. In considering this choice, it is important to note that many patients do not have symmetrical hearing loss in the two ears, thus the ear chosen for implantation has depended on numerous factors, including the etiology of the hearing impairment and various clinical considerations. In some cases, patients with residual acoustic hearing in one ear but not the other receive the implant in the "worse" ear to preserve the residual hearing, which can otherwise be destroyed with insertion of the CI. Alternatively, consider a patient with long-term hearing loss in at least one ear; thus, the ear with residual hearing may also be the ear that has had less auditory deprivation and thus responds best to stimulation with the CI.

Either way, many patients or parents of children who are eligible for CIs have reported that monaural hearing can be challenging, with poor speech comprehension in complex noisy environments, and poor sound localization. Clinical care has undergone a transformation, whereby many patients, or parents of young patients, are electing bilateral CIs (one in each ear), with the goal of providing an improved ability to segregate speech from background noise and to localize sounds (e.g., van Hoesel, 2004, 2011; Litovsky *et al.*, 2009; Litovsky, 2011). Sometimes the surgical procedures are simultaneous, and other times they are sequential, with months or years between procedures. Research to date has shown that the vast majority of adults who became deaf post-lingually and were implanted bilaterally show significant improvement on the desired abilities when their performance is compared in bilateral vs. monaural conditions (van Hoesel and Tyler, 2003; Litovsky *et al.*, 2009). Typically, adults who are post-lingually deaf will have had exposure to acoustic hearing for many years prior to becoming deaf, and the activation of bilateral CIs most likely re-activates some aspects of their previously established spatial-hearing abilities. In children the issues are quite different, because most of them are congenitally deaf and will not have been exposed to acoustic input prior to becoming deaf.

Referring to the above-mentioned spatial cues (monaural head shadow and binaural), studies have been conducted (Litovsky *et al.*, 2006a, 2009) in which SRTs or percent correct measures are obtained with various spatial distributions of target and maskers. Rather than measuring SRM *per se*, the focus in many studies has been to measure *bilateral benefit*, i.e., improvement in speech understanding when patients are using bilateral vs. monaural CIs. As for studies described above with normal-hearing listeners, studies with bilateral CI users have compared performance for conditions with target speech in front, and masker(s) either were co-located with the target or spatially separated. Because one of the two CIs can be turned off, rendering the patient monaurally deaf, the spatial configuration of the target and maskers must be considered along with the active/inactive ear. A schematic diagram of the three different masker configurations (right, left, or front) combined with each of the three listening modes (right CI only, left CI only, or bilateral) is shown in Fig. 3.

Results from the vast majority of patients to date (Schleich *et al.*, 2004; Litovsky *et al.*, 2006a, 2009) suggest that the primary benefit from bilateral CIs can be attributed to the

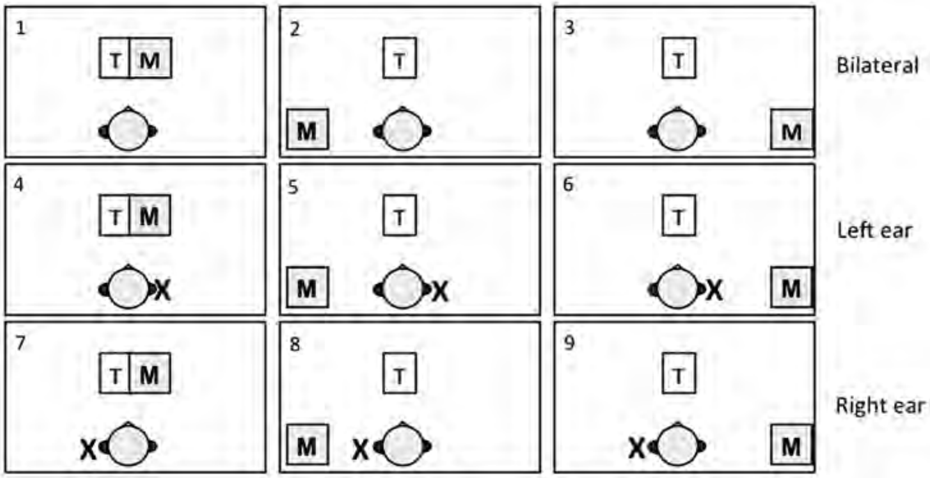

*Fig. 3. Schematic diagram of the nine possible conditions (3 masker configurations x 3 listening modes). Binaural listening conditions (1,2,3) are in the top row, Left-ear conditions (4,5,6) in the middle row, and Right-ear listening conditions (7,8,9) in the bottom row. Target (T)-Masker (M) in front occurs in the three conditions in the left column (1,4,7). Masker on the left is shown in the conditions in the middle column (2,5,8) and masker on the right is shown in the three conditions in the right column (3,6,9).*

monaural "better ear" or "monaural head shadow" cue, which arises when the monaural condition has an ear with a poor SNR, and a contralateral ear with a better SNR is added (activated) to create the bilateral listening mode. This benefit would occur by comparing speech intelligibility in conditions 5 and 2 or 9 and 3 (see Fig. 3). A smaller effect is also seen when the monaural condition has the ear with the better SNR and the ear with the poorer SNR added to create the bilateral listening condition (known as the squelch effect). This benefit would occur by comparing speech intelligibility in conditions 8 and 2 and 3 and 6. A third effect known as binaural "summation" is also observed, when both target and interferer are in front, and unilateral vs. bilateral listening conditions are compared; the addition of the second ear improves speech reception thresholds. This benefit would occur by comparing speech intelligibility in conditions 1 and 4 or 1 and 7.

When performance is measured at fixed SNR (Agrawal, 2008; Litovsky *et al.*, 2012) and competitors are placed in the left-right configuration shown in Figure 2C, rendering the "head shadow" weak or absent, bilateral CI users show marked decline in performance compared with normal hearing subjects. Effectively, bilateral CI users need the SNR to be significantly more favorable than do normal hearing people to understand the target speech. This difference between the two populations suggests that, while the use of bilateral CIs provides a benefit over monaural CIs, as described above, in a listening situation with maskers presented from both the right and left, the ability of bilateral CI users to hear speech in noise is markedly worse than that of normal-hearing listeners. Finally, in terms of SRM measures *per se*, a recent study in bilateral CI users (Loizou *et al.*, 2009) controlled for monaural and binaural cues while still preserving spatial cues that occur in the free field. In this study, target and maskers were convolved through *head related transfer functions* that had been measured through the ear canals of a human-like manikin. Stimuli were provided to listeners via direct connect input to the auxiliary port of the CI in each ear. Results showed that SRM (quantified as $SRT_{front}$-$SRT_{side}$) due to binaural interaction was about 0 dB, in contrast with 6 dB in normal-hearing listeners. SRM due to monaural cues was about 4 dB in both groups of listeners, suggesting that when the CI microphones are bypassed at least the monaural head shadow cue observed in normal-hearing listeners is retained.

A small number of studies in children who receive bilateral CIs have also been conducted on this subject. Results suggest that the primary spatial cue used by these children is the monaural head shadow cue; either they do not have access to, or do not utilize binaural cues. The most illustrative example comes from a recent study by Misurelli and Litovsky (2012), in which maskers were placed in the three configurations shown in Figure 2 (A, B, and C). SRM was measured for both the front vs. side conditions and front vs. right-left conditions. First, it is noteworthy that children perform better when both CIs are used compare with monaural listening conditions (Litovsky *et al.*, 2006b, 2012). Second, children aged 4-9 years showed SRM with the latter conditions, but not the former. That is, when monaural head shadow was present, these children displayed SRM, albeit not as large as that seen in age-matched normal-hearing children. However, when maskers were placed towards both the right and left, greatly reducing or eliminating the head shadow cue, SRM was eliminated. Thus, children who are bilaterally implanted can use spatial cues to segregate target from maskers, however, this effect is dominated by their ability to benefit from having a good SNR in one ear, rather than from being able to integrate inputs arriving at the two ears. It is possible that the binaural integration ability is acquired with listening experience. However, it is important to review the fact that *bilateral* CIs are not very effective at preserving *binaural* cues. While the former consist of cues that are presented to the two ears, but not necessarily in a manner that preserves the synchronization of inputs to the two ears, the latter specifically refers to stimulation consisting of well-preserved and synchronized inputs in the right and left ears.

Outcomes in patients who use bilateral CIs are curtailed by the inherent limitation in the speech processors that are used in today's CIs. The hardware and signal processing in the implantable devices are far from ideal as far as providing binaural cues with fidelity. Bilateral CI users are essentially fit with two separate monaural systems. Speech processing strategies in clinical processors utilize pulsatile, non-simultaneous multi-channel stimulation, whereby a bank of band pass filters is used to filter the incoming signal into numerous frequency bands (ranging from 12 to 22), and to send specific frequency ranges to individual electrodes. The envelope of the signal is extracted from the output of each band and is used to set stimulation levels for each frequency band; thus, fine-structure is discarded. Although ITDs in the envelopes may be present, because the processors have independent switch-on times, the ITD can vary dynamically and unreliably (van Hoesel, 2004, 2011). In addition, the microphones are not placed in the ear in a manner that maximizes the capture of directional cues such as spectrum and level cues. Microphone characteristics, independent automatic gain control and compression settings distort the monaural and interaural level directional cues that would otherwise be present in the horizontal plane. In an ideal situation, speech processors would provide bilateral CI users with binaural cues, similar to those available to normal-hearing listeners.

In summary, this paper focuses on the ability of humans to understand speech in complex noisy environments, and to benefit from spatial separation of maskers from target speech. Both binaural and monaural cues play a role in providing this benefit. The effect size can depend on the extent to which listeners "need" spatial cues for source segregation. That is, when other auditory cues are unavailable, such as when target/masker similarity is high, spatial cues are especially relevant, thus SRM can be large. SRM also varies, depending on the population of listeners being tested, and the integrity of their binaural auditory system. While monaural cues are generally seen in all listeners, when head shadow is available, binaural cues are only useful when preserved and presented to the auditory system with fidelity.**AT**

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