LISTENING TO THE WORLD AROUND US.

Simon Carlile,
School of Medical Sciences,
University of Sydney, NSW 2006

Our perception of auditory space depends on the integration of a number of acoustic cues to the locations of sound sources. The binaural cues to location arise as a consequence of the two ears being separated by an acoustically dense head which results in differences in the time of arrival and level of the sound at each ear. The outer ears also filter the sound in a directionally dependent manner providing the spectral cues to a sound's location. Real world listening involves separating out multiple concurrent sound sources and differences in their spatial locations provide a means by which auditory spatial attention can be focused on one sound of interest and other masking sounds are ignored. Recent work has demonstrated that spatial release from masking is more effective when the target and maskers are speech sounds and that this involves both bottom up perceptual processes and top-down cognitive processes. This work indicates that preservation of the spatial cues is essential for the effective use of hearing aids implicating both binaural and in-the-ear fitting strategies.

1. REAL WORLD LISTENING

Much of the time, listening in the real world is a very complex task. Rarely do sounds of interest occur on a background of silence. Rather, the world is a tumultuous mix of multiple sounds that overlap in frequency and time. Some sounds can represent threats or opportunities while others are simply distracters or maskers. In many listening situations reverberance and/or echoes further complicate the soundscape. All of these sounds arrive at the ear drum as a combined stream and jointly excite the inner ear. What is most remarkable is that the auditory system is able to sort out the many different streams of sound and provides the capacity to selectively focus our attention on one or another of these streams. The auditory system is quite unlike the senses of vision or touch in that the sensory epithelia codes frequency and not spatial location. Consequently, our perception of auditory space is based on a variety of acoustic cues that occur at each ear. This means that the acoustic cues to the different source locations also need to be deconvolved from the complex signal reaching the ears. Our capacity to focus attention on one sound of interest and to ignore distracting sounds is dependent, at least in part, on the differences in the locations of the different sound sources. This article reviews the acoustic cues that the auditory system uses to achieve this amazing feat of signal processing, how these cues lead to our perception of auditory space and how this contributes to the understanding of speech in complex acoustic environments.

The three principal dimensions of auditory spatial perception are direction, distance and spaciousness. In our qualitative descriptions of the location of objects in every day life we refer to horizontal direction, height above or below the audio-visual horizon and distance from the head. In addition to the perception of location, the extent or "spaciousness" of the space inhabited by the listener and the "width" or apparent size of the sound source are also important attributes. The sense of spaciousness also plays an important role in the generation of the sense of "presence" or "being there" enjoyed by the listener using a virtual auditory display (see [1]).

2. CUES FOR SPATIAL LISTENING

Our perception of auditory space is based on acoustic cues that arise at each ear. These cues result from an interaction of the sound with the auditory periphery which includes the two ears, the head and torso as well as with the reflecting surfaces in the immediate environment (for review [2]). As the two ears are separated by an acoustically dense head, the auditory system can simultaneously sample the sound field from two slightly different locations. This gives rise to the so-called binaural cues to the location of a sound source. For a source located off the midline, the path length difference from the source to each ear results in an interaural difference in the arrival times of the sound or a difference in the phases of the on-going component of the sound at each ear (Figure 1a). This is referred to as the interaural time difference (ITD) cue. As the auditory system only encodes the phase of a sound up to a few kilohertz, the interaural phase difference cue is limited to the lower frequency range of human hearing. However, the auditory system is also able to extract interaural time differences from the amplitude modulation envelopes of more complex sounds over the whole range of frequency sensitivity (e.g. [3] but see [4], recent review [5]). Psychophysical studies using headphone presented stimuli have demonstrated sensitivity to interaural time differences as small as 13 μs [6] for tones from 500 to 1000 Hz.

As the head is relatively large with respect to the wavelengths of mid to high frequency sounds to which the auditory system is sensitive, the ear furthest from the source will be acoustically shadowed giving rise to an interaural difference in the sound level at each ear. This is know as the interaural level (or intensity) difference (ILD) cue. Sensitivity to interaural level differences as small as 1 dB have been demonstrated for pure tone stimuli presented over headphone [7]. In summary, the ITD cues are believed to contribute principally at the low frequencies and the ILD cues at the mid to high frequencies – this is sometimes referred to as the duplex theory of localisation.

The binaural cues alone provide an ambiguous cue to the spatial location of a source because any particular interaural interval specifies the surface of a cone centred on the interaural axis - the so called "cone of confusion" (Figure 1b).

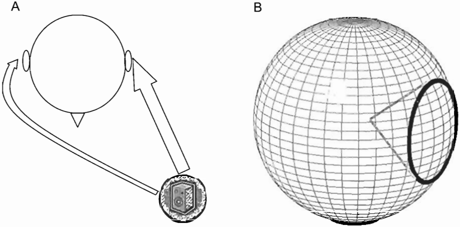


Figure 1: (A) When a sound source is located off the midline the separation of the two ear by the head results in differences in the path lengths between the sound source and each ear (length of arrows). This results in a difference in the time of arrival of the sound to each ear by up to 800 μs or more. The ear furthest from the sound source will be in the acoustic shadow cast by the head which leads to an interaural level difference (width of arrows). (B) The cone of confusion is shown for a particular interaural time and level difference corresponding to a location 60° from the midline.

The outer ear, the pinna and concha, is an asymmetrical and highly convoluted structure that filters sound in a manner that is dependent on the direction of the wave front (e.g. [8, 9]; Figure 2). This gives rise to the spectral (or monaural) cues to location. Reflections from the shoulder and torso may also contribute to the filtering in the lower frequency range where the wavelengths are long compared to the dimensions of the outer ear (see [2] for review). These location dependent filter functions can be measured by inserting small microphones into the ear canals and are referred to as the head related transfer functions (HRTF) [9, 10]. The spectral cues provide the basis for resolving the cone-of-confusion (Figure 1 and Figure 2) and, together with the head shadow [11], also explain the residual sound localisation capability observed in monaurally deaf individuals [12].

In summary, accurate determination of the direction of a sound source is dependent on the integration of the binaural and spectral cues to it's location (see [13];). The relative roles of the ITD and ILD are determined in part by the frequency content and the depth of amplitude modulation of the envelope of the sound [14]. The spectral cues from each ear are weighted according to the lateral angle of the source; the ipsilateral ear dominates for locations close to the interaural axis but there is an increase in the weighting of the contralateral cues as the sound location approaches the midline [15]. Interestingly, the interaural spectral difference per se is unable to support normal localisation at any lateral angle [16]. The sound level and duration of the stimuli also play an important role. At low (< 40 dB) and high (> 60 dB) sound levels, localisation accuracy on the cone of confusion decreases. In the latter case this has been attributed to saturation [17, 18] and/or compression [19] of the cochlear excitation patterns leading to distortion of the encoded spectra. The poor performance at low sound levels could result from level dependent non-linear amplification of the cochlea and subsequent distortion of the spectral profile or a poor signal to noise ratio leading to noisy analysis of the cue [19]. Localisation performance on the cone-of confusion has also been reported to deteriorate for stimuli less than 30 ms in duration suggesting that this may represent a minimum time window for spectral integration [18, 19]. A range of physiological studies have also demonstrated that neural representations of auditory space in the superior colliculus in mammalian midbrain are dependent on the integration of these binaural and monaural cues (reviewed in [20]).

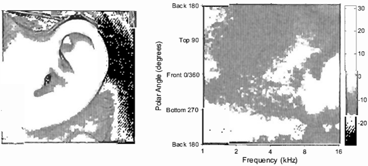


Figure 2: Left ear of a female subject and the head related transfer functions obtained for the mid-line cone of confusion. The scale bar indicates the variations in the level of the filter functions in dB.

While it is the interactions of the sound with the auditory periphery that provides the cues to source direction, it is the interactions between the sound and the listening environment that provide the four principal cues to source distance (for recent review see [21]). First, the intensity of a sound decreases with distance according to the inverse square law: this gives rise to a 6 dB decrease in level with a doubling of distance. Second, as a result of the transmission characteristics of the air the high frequencies (>4 kHz) are absorbed to a greater degree than low frequencies. This leads to a relative reduction of the high frequencies of around 1.6 dB per doubling of distance [22]. Notably for both of these cues there is a confounding of source characteristics (intensity and spectrum) with distance so they can only act as reliable cues for familiar sounds (speech is a particular case in point). The third cue is the ratio of the direct to reverberant energy [23]. The level of reverberation in a room is determined principally by the characteristics of the room and is basically constant throughout the room while the direct energy is subject to the inverse square law of distance. This is a particularly powerful distance cue but is dependent on the reverberant characteristics of the listening environment [24]. Recent work exploring distance perception for sound locations within arms reach (i.e. in the near field) has confirmed the very early observations of Hartley and Fry [25] that substantial changes in the interaural level differences can occur with variation in distance (see for instance [26]). The distance effect on interaural time difference appear to be less salient [27]. There are also distance related changes to the HRTFs in the near field because of the parallax change in the relative angle between the source and each ear with distance [28].

The perception of auditory spaciousness has been characterized by "apparent source width" which is related to the extent of early lateral reflections in a listening space and the relative sound level of the low frequencies (e.g: [29, 30]). A second aspect of spaciousness is "listener envelopment" which is related more to the overall reverberant sound field and is particularly salient with relatively high levels arriving later than 80 ms after the direct sound (see [31]).

An important but almost unstudied issue in auditory spatial perception is the extent to which a sound is heard externalized away from the head. When normally listening over headphones, the percept generated is of a sound source located within the head. By manipulating the ITD or ILD the phantom source can be lateralized towards one or the other side of the head but remains within the head. However, if the sound is first filtered with the head related transfer functions (HRTFs) for a particular location in space and then played back over headphones, the apparent source of the sound is heard externalized to the spatial location corresponding to the HRTFs used. On the one hand, this should not be surprising because if the headphone transfer functions are properly compensated for, then the pattern of sound waves at the ear drums should be identical to that produced by the sound actually out in space. On the other hand, this also demonstrates the important role the HRTFs play in enabling this sense of externalization. This manipulation of the sound is the basis of virtual auditory displays or so-called auditory virtual reality systems using headphone delivery. An important issue for virtual auditory displays is the match between the set of head related transfer functions (HRTFs) used to render the virtual auditory environment and the actual HRTFs of the listener. Even relatively small differences between the sets of HRTFs can degrade the accuracy with which sound sources can be rendered at specific locations in virtual space. There are also a range of other factors involved in generating or enhancing the percept of externalization. For instance, the reverberant characteristics of the sound and active head movement within the listening environment can both contribute to the sense of externalization and "presence" in the virtual auditory world [32].

3. LOCALISATION PERFORMANCE – DIRECTION AND DISTANCE

There are quite a number of studies of the accuracy and resolution of human auditory spatial perception (for reviews see [2, 33]). Absolute localisation accuracy has been assessed by allowing subjects to indicate the perceived direction of a sound source whose spatial location is randomly varied (e.g. [34-36]). Subject's perception of location has been measured using both continuous (e.g. [35, 36]) and quantized methods (e.g. [37, 38]) of indicating the perceived location. Knowledge about the potential locations of stimuli has also been shown to influence the subjects' responses in a non-sensory manner [39].

In general these experiments demonstrate two classes of localisation errors: (i) Large "front-back" or "cone of confusion" errors where the perceived location is in a quadrant different from the source but roughly on the same cone of confusion; (ii) Local errors where the location is perceived to be in the vicinity of the actual target. Average localisation errors are generally only a few degrees for targets directly in front of the subject (SD ± 6° - 7°). Absolute errors and the response variability around the mean, gradually increase for locations towards the posterior midline and for elevations away from the audio-visual horizon. For broadband noise stimuli the front-back error rates range from 3% to 6% of the of trials. However, localisation performance is also strongly related to the characteristics of the stimulus. Narrowband stimuli [13], particularly high or low sound levels (e.g. [19]) or reverberant listening conditions [40] can all significantly degrade performance.

A different approach to understanding auditory spatial performance is to examine the resolution or acuity of auditory perception. In these studies, subjects are required to detect a change in the location of a single source (e.g. [41]). This is referred to as a minimum audible angle (MAA). This approach provides insight into the just noticeable differences in the acoustic cues to spatial location. Consistent with the absolute accuracy studies, MAA studies have demonstrated that resolution is highly dependent on both the type of stimulus and the spatial location about which the change in location is measured (see [41, 42]). The smallest MAA (1-2°) is found for broadband sounds located around the anterior midline and the MAA increase significantly for locations away from the anterior median plane. The MMA is also much higher for narrow band stimuli. More recent work has also examined the ability of subjects to discriminate concurrent sounds as originating from different locations [43]. In this case, the ability to parse the locations of two concurrent stimuli with identical spectral characteristics is dependent on interaural differences rather than the spectral cues.

The majority of localisation performance studies have been carried out in anechoic environments. Localisation in real world environments will of course include environments with some level of reverberation. Interestingly, localisation in rooms does not appear to be as robust as in anechoic space [40] but it does appear to be better than what might be expected based on how reverberation degrades the acoustic cues to location. For instance, reverberation will tend to de-correlate the waveforms at each ear because of the differences in the patterns of reverberation that combine with the direct wave front at each ear [44]. This will tend to disrupt the extraction of ongoing ITD although the auditory system may be able to obtain a reasonably reliable estimate of the ITD by integrating across a much longer time window. Likewise, the addition of delayed copies of the direct sound will lead to comb filtering of the sound that will tend to fill in the notches and flatten out the peaks in the monaural spectral cues and decrease the overall ILD cue. These changes will also be highly dependent on the relative locations of the sound sources, the reflecting sources and the listener (see review [45]).

4. THE COCKTAIL PARTY PROBLEM

In the course of most human communication, the speech we are attending to occurs against a background of other talkers and non-speech sounds. This is referred to as the cocktail party problem: that is, how the auditory system segregates and streams the talker of interest from multiple concurrent talkers and other sounds [46, 47]. In signal processing terms, the concurrent sounds are composed of different and relatively sparse spectral components that are changing dynamically over time. It is also likely that some spectral components will transiently overlap in different frequency regions. The first puzzle is how the auditory system groups together the spectro-temporal components and associates them with different sources (auditory objects). Secondly, how are these grouped elements connected over time into coherent and segregated streams of information? The overall process is referred to as auditory scene analysis [48] and two basic and complementary processes are conceived to be operating:

Primitive grouping: The notion of primitive grouping is based on the Gestalt principals of *proximity, similarity, common fate, set, continuity, symmetry and closure*. A number of processes have been identified psychophysically. One processes exploits harmonicity – that is, the energy in many natural sounds (including speech) is distributed harmonically across frequency and concurrent sounds will almost always have instantaneous differences in the fundamental frequency (F0). The associated spectral components can then be grouped on the basis of their respective harmonic relationships to the fundamental frequencies of the different sources. Spectral components are also grouped on the basis of common onset and/or offsets and common amplitude modulation (for review see [49]). These process are thought to be bottom-up and automatic. Once grouped together according to these rules the relevant spectro-temporal components are connected up over time into separate streams of information that are associated with different auditory objects (see [50] for review).

Schema based processes: With multiple concurrent sounds there will inevitably be intermittent spectro-temporal overlap and at various instances the louder sound will mask the presence or absence of energy from other sounds. This is an example of simple energetic masking which can interfere with the primitive grouping and compromise the integrity of the information in the streams. Therefore, the auditory system has to fill in the gaps in the streams and correct flawed groupings. In this classical view, when the sound of interest is a talker, schema based processes relying on the semantic and linguistic context can be used to help fill the gaps in the attended stream. This is generally conceived of as a knowledge based, cognitive and/or top-down process.

5. INFORMATIONAL AND ENERGETIC MASKING AND SPATIAL RELEASE FROM MASKING

The amount of energetic masking of a talker in the proximity of (or co-located with) other masking sounds can be reduced by spatially separating the target from the maskers. In the first instance, this spatial release from masking can be explained by an improvement in the signal to noise ratio in one or other of the ears (Figure 3). However, the work of Freyman [51, 52] and others (e.g. [53, 54]) has demonstrated that the spatial release from masking of speech produced by a concurrent talker (as opposed to a non-speech masker) is greater than that predicted by a simple energetic model of the interactions of the sounds at each ear. This additional masking is referred to as informational masking.

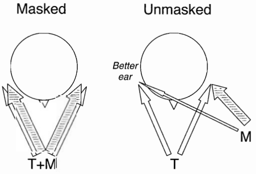


Figure 3: Spatial release from masking for non speech maskers can be understood in terms of the changes in signal to noise ratio at the "Better" or shadowed ear. T target talker of interest; M masker

Informational masking can be related to the similarity between the masker(s) and the target which leads to confusion about the assignment of different words to different streams [54]. The spectral components are correctly grouped and the information correctly identified but streaming fails because of confusion relating to higher level components in the information. An example is the confusion that can occur when two concurrent talkers have similar sounding voices.

Informational masking is also associated with stimulus uncertainty: i.e. when a stimulus is highly variable and the listener does not know what to expect (for discussion see [55]). Linguistic and semantic context are seen as important in helping to correct these sorts of errors as the information in the stream unfolds. The role of semantic analysis indicates the involvement of high level cognitive or schema based processes. Most interestingly, however, there is some data that suggests that the maskers do not have to be intelligible to produce informational masking. Freyman et. al. [52] demonstrated that almost the same amount of informational masking occurred when the masker talker was speaking in a language not understood by the listener compared to one that was understood by the listener. In addition, time reversed masker speech could also produce substantial informational masking. These two findings are problematic for an account of informational masking that relies on a top-down, semantic model as, although these stimuli are recognisable as human speech, they are clearly unintelligible.

In the context of spatial hearing, a most important finding is that perceived differences in the locations of target and masker talkers gives rise to a larger spatial release from masking than that observed with talkers masked by a purely energetic masker like speech shaped noise (see for review [56]). This indicates that when the target and maskers are co-localised there is interference in the schema based processes (informational masking) that is over and above the energetic masking. However, the differences in the locations are utilised by the auditory system to allow the listener to focus their spatial attention on the target talker and/or to disattend to the masker talkers [53] in a way that decreases the informational interference between the target and the masker. The differences in location appears to help to keep separate the informational streams associated with each talker. In the case of noise maskers, the spatial release from masking is governed by the reduction in the energetic masking when the masker is moved away from the target talker. With this type of masker there is no informational masking and nearly all of the spatial unmasking can be explained in terms of the signal to noise ratio at the better ear (Figure 3). The residual unmasking is probably related to binaural processing [53] and will be dependent on the nature of the sounds and the acoustic environment [57].

The ability to focus attention on a particular talker and indeed to switch attention between talkers plays a key role in solving the cocktail party problem. Although primitive grouping provides very effective means to separate concurrent talkers and other sounds, much human spoken communication is actually carried out under quite adverse listening conditions (the pub or the cocktail party are the case in point). Under such conditions, a talker will generally raise the level of his or her voice so that the signal to noise ratio is around 0 dB at the listener [58]. Under such conditions, where there is also the potential for substantial informational masking, the spatial separation of the target and maskers plays an important role in supporting good speech intelligibility under real world listening conditions.

6. HEARING IMPAIRMENT

Hearing impaired listeners are also able to capitalize on the differences in the locations of talkers to reduce the amount of masking. However, the spatial release from informational masking is reduced by 5 dB in listeners with even mild hearing impairment compared to normally hearing listeners under the same conditions [59]. Many studies have demonstrated that speech intelligibility falls off relatively quickly as a function of signal to noise ratio and a loss of 5 dB spatial unmasking results in a very significant reduction in the percentage of words understood in a noisy listening environment. These findings have an important implication. The hearing deficit will undoubtedly have degraded the quality of the cues to spatial location. It is important, therefore, to provide hearing aids that support the encoding of the acoustic cues to spatial location.

In the first instance this could be as simple as providing binaural aids that are properly calibrated to preserve the normal ITD and ILD cues. The more challenging question however, is how to preserve the information in the spectral cues. Certainly the development of relatively powerful digital hearing aids small enough to fit inside the auditory canal provides a means of preserving the normal spectral cues to location. However, the hearing impairment is also characterized by a significant reduction in sensitivity to the mid to high frequency range of hearing and it is over this range that the majority of location dependent spectral cues are generated (see [9, 60]. Recently, it has been suggested that transposing the spectral cues into a lower frequency range could provide the opportunity for the auditory system to relearn to use these new spectral cues ([61] see also [62]).

REFERENCES

1. Durlach, N., "Auditory localization in teleoperator and virtual environment systems: Ideas, issues and problems", Perception. 20, 543-554, (1991).
2. Carlile, S., "The physical and psychophysical basis of sound localization", in Virtual auditory space: Generation and applications, S. Carlile, Editor. Landes: Austin. p. Ch 2, (1996).
3. Henning, G.B., "Detectability of interaural delay in high-frequency complex waveforms", J Acoust Soc Am. 55, 84-90, (1974).
4. Eberle, G., et al., "Localization of amplitude-modulated high-frequency noise", Journal of the Acoustical Society of America. 107 (6), 3568-3571, (2000).
5. Bernstein, L.R., "Auditory processing of interaural timing information: New insights", Journal of Neuroscience Research. 66 (6), 1035-1046, (2001).
6. Zwislocki, J. and R.S. Feldman, "Just noticeable differences in dichotic phase", J Acoust Soc Am. 28, 860-864, (1956).
7. Mills, A.W., "Lateralization of high-frequency tones", J Acoust Soc Am. 32, 132-134, (1960).
8. Mehrgardt, S. and V. Mellert, "Transformation characteristics of the external human ear", J Acoust Soc Am. 61 (6), 1567-1576, (1977).
9. Carlile, S. and D. Pralong, "The location-dependent nature of perceptually salient features of the human head-related transfer function", J Acoust Soc Am. 95 (6), 3445-3459, (1994).
10. Pralong, D. and S. Carlile, "Measuring the human head-related transfer functions: A novel method for the construction and calibration of a miniature "in-ear" recording system", J Acoust Soc Am. 95 (6), 3435-3444, (1994).

11. Van Wanrooij, M. and J. Van Opstal, "Contribution of head shadow and pinna cues to chronic monaural sound localization", J Neuroscience. 24, 4163-4171, (2004).
12. Slattery, W.H. and J.C. Middlebrooks, "Monaural sound localization: Acute verses chronic unilateral impairment", Hear Res. 75, 38-46, (1994).
13. Middlebrooks, J.C., "Narrow-band sound localization related to external ear acoustics", J Acoust Soc Am. 92 (5), 2607-2624, (1992).
14. Macpherson, E.A. and J.C. Middlebrooks, "Listener weighting of cues for lateral angle: The duplex theory of sound localization revisited", J Acoust Soc Am. 111 (5 Pt 1), 2219-2236, (2002).
15. Hofman, P.M. and A.J. Van Opstal, "Binaural weighting of pinna cues in human sound localization", Experimental Brain Research. 148 (4), 458-470, (2003).
16. Jin, C., et al., "Contrasting monaural and interaural spectral cues for human sound localisation", J Acoust Soc Am. 115 (6), 3124-3141, (2004).
17. Hartmann, W.M. and B. Rakerd, "Auditory spectral discrimination and the localization of clicks in the sagittal plane", J Acoust Soc Am. 94 (4), 2083-2092, (1993).
18. Macpherson, E.A. and J.C. Middlebrooks, "Localization of brief sounds: Effects of level and background noise", J Acoust Soc Am. 108 (4), 1834-1849, (2000).
19. Vliegen, J. and A.J. Van Opstal, "The influence of duration and level on human sound localization", J Acoust Soc Am. 115 (4), 1705-1713, (2004).
20. King, A.J. and S. Carlile, "Neural coding for auditory space", in The cognitive neurosciences, M.S. Gazzaniga, Editor. MIT Press: Boston. p. 279-293, (1994).
21. Zahorik, P., D.S. Brungart, and A.W. Bronkhorst, "Auditory distance perception in humans: A summary of past and present research", Acta Acustica United with Acustica. 91 (3), 409-420, (2005).
22. Zahorik, P., "Assessing auditory distance perception using virtual acoustics", J Acoust Soc Am. 111 (4), 1832-1846, (2002).
23. Mershon, D.H. and L.E. King, "Intensity and reverberation as factors in the auditory perception of egocentric distance", Percept Psychophys. 18 (6), 409-415, (1975).
24. Mershon, D.H., et al., "Effects of room reflectance and background noise on perceived auditory distance", Perception. 18, 403-416, (1989).
25. Hartley, R.V.L. and T.C. Fry, "The binaural location of pure tones", Physics Rev. 18 (6), 431-442, (1921).
26. Shinn-Cunningham, B.G. "Distance cues for virtual auditory space", in IEEE 2000 International Symposium on Multimedia Information Processing. Sydney, Australia, (2000).
27. Brungart, D.S. and W.M. Rabinowitz, "Auditory localisation of nearby sources. Head related transfer functions", J Acoust Soc Am. 106, 1465-1479, (1999).
28. Brungart, D.S. "Auditory parallax effects in the hrtf for nearby sources", in 1999 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics,. New Paltz, New York, (1999).
29. Blauert, J. and W. Lindermann, "Auditory spaciousness: Some further psychoacoustic analyses", J Acoust Soc Am. 80 (2), 533-542, (1986).
30. Potter, J.M., J. Raatgever, and F.A. Bilsen, "Measures for spaciousness in room acoustics based on a binaural strategy", Acta Acustica. 3 (5), 429-443, (1995).
31. Okano, T., L.L. Beranek, and T. Hidaka, "Relations among interaural cross-correlation coefficient (iacc(e)), lateral fraction (lfe), and apparent source width (asw) in concert halls", Journal of the Acoustical Society of America. 104 (1), 255-265, (1998).
32. Durlach, N.I., et al., "On the externalization of auditory images", Presence. 1, 251-257, (1992).
33. Middlebrooks, J.C. and D.M. Green, "Sound localization by human listeners", Annu Rev Psychol. 42, 135-159, (1991).
34. Oldfield, S.R. and S.P.A. Parker, "Acuity of sound localization: A topography of auditory space i. Normal hearing conditions", Percept. 13, 581-600, (1984).
35. Makous, J. and J.C. Middlebrooks, "Two-dimensional sound localization by human listeners", J Acoust Soc Am. 87 (5), 2188-2200, (1990).
36. Carlile, S., P. Leong, and S. Hyams, "The nature and distribution of errors in the localization of sounds by humans." Hearing Res. 114, 179-196, (1997).
37. Butler, R.A., R.A. Humanski, and A.D. Musicant, "Binaural and monaural localization of sound in two- dimensional space." Percept. 19, 241-256, (1990).
38. Wightman, F.L. and D.J. Kistler, "Headphone simulation of free field listening. Ii: Psychophysical validation." J Acoust Soc Am. 85 (2), 868-878, (1989).
39. Perrett, S. and W. Noble, "Available response choices affect localization of sound", Perception and Psychophysics. 57 (2), 150-158, (1995).
40. Hartmann, W.M., "Localization of sound in rooms", J Acoust Soc Am. 74 (5), 1380-1391, (1983).
41. Mills, A.W., "On the minimum audible angle", J Acoust Soc Am. 30 (4), 237-246, (1958).
42. Grantham, D.W., "Spatial hearing and related phenomena", in Handbook of perception and cognition, B.C.J. Moore, Editor. Academic: San Diego, (1995).
43. Best, V., A.v. Schaik, and S. Carlile, "Separation of concurrent broadband sound sources by human listeners", J Acoust Soc Am. 115, 324-336, (2004).
44. Kopco, N. and B.G. Shinn-Cunningham. "Auditory localization in rooms: Acoustic analysis and behaviour", in 32 International Acoustical Conference. Slovakia, (2002).
45. Shinn-Cunningham, B.G. "Acoustics and perception of sound in everyday environments", in 3rd Int Workshop on Spatial Media. Aisu-Wakamatsu (Japan), (2003).
46. Cherry, E.C., "Some experiments on the recognition of speech with one and two ears", J Acoust Soc Am. 25, 975-979, (1953).
47. Bronkhorst, A.W., "The cocktail party phenomenon: A review of research on speech intelligibility in multiple-talker conditions", Acustica. 86, 117-128, (2000).
48. Bregman, A.S., "Auditory scene analysis : The perceptual organization of sound", Cambridge, Mass: MIT Press (1990).
49. Darwin, C.J. and R.P. Carlyon, "Auditory grouping", in Handbook of perception and cognition, volume 6: Hearing, B. Moore, Editor. Academic Press: Orlando, Florida. p. 387-424, (1995).
50. Moore, B.C.J. and H. Gockel, "Factors influencing sequential stream segregation", Acta Acustica United with Acustica. 88 (3), 320-333, (2002).
51. Freyman, R.L., et al., "The role of perceived spatial separation in the unmasking of speech", J Acoust Soc Am. 106 (6), 3578-3588, (1999).
52. Freyman, R.L., U. Balakrishnan, and K.S. Helfer, "Spatial release from informational masking in speech recognition", J Acoust Soc Am. 109 (5 Pt 1), 2112-2122, (2001).
53. Arbogast, T.L., C.R. Mason, and G. Kidd, "The effect of spatial separation on informational and energetic masking of speech", J Acoust Soc Am. 112, 2086-2098, (2002).
54. Brungart, D.S., et al., "Informational and energetic masking effects in the perception of multiple simultaneous talkers", J Acoust Soc Am. 110 (5 Pt 1), 2527-2538, (2001).

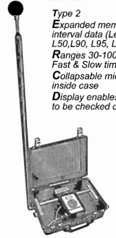
55. Durlach, N.I., et al., "Note on informational masking (I)", J Acoust Soc Am. 113 (6), 2984-2987, (2003).
56. Shinn-Cunningham, B.G. "Influences of spatial cues on grouping and understanding sound", in Proceedings of the Forum Acoustica, (2005).
57. Shinn-Cunningham, B.G., et al., "Spatial unmasking of nearby speech sources in a simulated anechoic environment", J Acoust Soc Am. 110 (2), 1118-1129, (2001).
58. Plomp, R., "Acoustical aspects of cocktail parties", Acustica. 38, 186-191, (1977).
59. Arbogast, T.L., C.R. Mason, and G. Kidd, "The effect of spatial separation on informational masking of speech in normal-hearing and hearing impaired listeners", J Acoust Soc Am. 117, 2169-2180, (2005).
60. Hofman, P.M. and A.J. Van Opstal, "Bayesian reconstruction of sound localization cues from responses to random spectra", Biological Cybernetics. 86 (4), 305-316, (2002).
61. Jin, C., et al. "Transposition of high frequency spectral information helps resolve the cocktail party problem in the mild to moderately hearing impaired listener", in Proceedings of the Australian Neuroscience Society. Sydney, (2006).
62. Hofman, P.M., J.G.A.V. Riswick, and A.J.V. Opstal, "Relearning sound localization with new ears", Nature Neurosci. 1 (5), 417 - 421, (1998).

Cronulla
PRINTING
COMPANY. PTY. LTD.

Specialists in
Scientific Printing
and Publishing

91-93 Parraweena Road, Caringbah NSW 2229
PO Box 2740 Taren Point NSW 2229
Phone: 9525 6588 **Fax:** 9524 8712
Email: printing@clp.com.au

A division of **Cliff Lewis Printing**



ENVIRONMENTAL NOISE LOGGER MODEL RTA02

Hire and Sales Check The Price !

Type 2
***E**xpanded memory - 4,400 sets of interval data (Leq,L0,L1,L5,L10, L50,L90, L95, L100)*
***R**anges 30-100dB(A) and 65-135dB(A) Fast & Slow time weighting*
***C**ollapsable microphone pole stacks inside case*
***D**isplay enables setup and calibration to be checked on site without computer*
***D**isplay enables single set of measurements to be read without computer*
***O**perates for up to 2 weeks using the supplied battery*
***W**eatherproof unit - complete new design*
***R**eal time clock*
***S**erial real time data streaming*

NATA ACCREDITED LABORATORY
NEW
NATA Calibration of:
***S**ound level meters*
***L**oggers*
***F**ilter Sets*
***C**alibrators*
***21** Point Detailed Checkup.*
Visit our website for samples
NATA
NATA Accredited Laboratory Number 14966

ENM
ENVIRONMENTAL NOISE MODEL

Noise Prediction Software

A computer program developed especially for government authorities acoustic & environmental consultants, industrial companies and any other groups involved with prediction of noise in the environment.

RTA TECHNOLOGY PTY LTD
Acoustic Hardware and Software Development
ABN 56 003 [illegible] 140
Email : rtatech@rtagroup.com.au www.rtagroup.com.au

Sydney (Head Office)
Level 9, 418A Elizabeth St,
Surry Hills NSW 2010
Ph : (02) 9281 2222
Fax : (02) 9281 2220

Melbourne
1/66 Curzon St,
North Melbourne VIC 30651
Ph: (03) 9329 5414
Fax: (03) 9329 5627

NATA
NATA Accredited Laboratory Number 14966