Sound Localization of mechanical equipment/ mobile plants in median and vertical plane during environmental noise survey

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ABSTRACT

Human sound localization relies on binaural difference cues for sound-source azimuth and pinna-related spectral shape cues for sound elevation as well as changes in all these cues during head motion. The interaural time difference (ITD) and interaural intensity difference (IID) cues are weighted to produce a perception of sound azimuth in the lateral plane. Sound source on the median plane is equidistant from both ears, IID and ITD cues are therefore invariant. Consequently, directional filtering by the external ears and scattering by listener's shoulders and upper torso provides the sole localization cues for sources in median plane. Localization distortion refers to the incorrect localization of the sound source due to various psychoacoustic phenomenon. This paper discusses the localization distortion for mechanical equipment and mobile plants on median and lateral plane during an environmental noise survey based on a frequency analysis.

INTRODUCTION

It has previously been established that sound localization is based on interaural time differences (ITD) at low frequency and interaural intensity differences (IID) at high frequency. Also the ITD and the IID provide the primary cues for the horizontal localization of a sound source, whereas the monaural spectral modifications introduced by the ear pinna provide the primary cues for vertical localization.

Sound waves that arrive from various directions in space are dissimilarly scattered by the listener's outer ears, shoulders, and upper torso. The scattering leads to the acoustical filtering of the signals appearing at the left and right ears. The filtering can be described by a complex response function head-related transfer function (HRTF). Generally there are peak-and-valley structures in the frequency spectra that tend to drift to higher frequencies as the elevation of the source increases from below to above the head (Hartmann, W.M, 1999). For example the peak near 7 kHz is thought to be a particular cue for a source overhead (explained later in this paper). The direction-dependent filtering by the anatomy, used by listeners to resolve front-back confusion and to determine elevation, is also a necessary component of localization. A problem with the application of HRTF is that there is very less evidence for the brain to comprehend if a spectrally prominent feature comes from direction-dependent filtering or whether is it part of the original source spectrum. For instance, a signal with a strong peak near 7 kHz may not necessarily come from above – it might come from a source that happens to have sound energy near 7 kHz. Binaural sound localization in an azimuth plane (an imaginary plane perpendicular to median plane and parallel to the ground) makes use of two important techniques, IID and ITD explained later.

Sound localization during a typical environmental noise survey can be challenging based on numerous sources (such as mobile plants, construction equipment, insects, traffic, etc.) occurring simultaneously. The example being discussed is a night time scenario near an operational coal mining. Noise monitoring was carried out at the boundary of a residence. The noise environment consisted of:

- Low frequency distant hum from coal mine operations;
- Traffic noise emission with similar frequency content as coal mine operating originating from a similar location on the horizontal plane;
- Aeroplane noise (hidden behind clouds) as a moving noise source on a median plane;
- Narrow band high frequency insect noise with comparative higher energy level than other noises existing on that site.

All the noise sources were concealed because of poor light and topographical conditions with intermittent wind constantly changing the levels and direction of noise reaching the receiver location. Localization of specific noise sources become demanding and inaccurate when presented simultaneously in an environmental setting.

This study investigates the auditory vertical and horizontal localization of broadband sound from typical noise sources encountered during an environmental noise survey. This study also examines the relation of image elevation and azimuth based on its fundamental frequency and its interaction between energy peaks at different frequency bands.

BACKGROUND

Interaural Intensity Difference (IID)

The standard comparison between intensities in the left and right ears is known as the interaural intensity difference (IID). The human head acts as noise barrier for frequencies above 2 kHz while others are diffracted very easily around the head and display very low IID. At a frequency of 500 Hz, the wavelength of sound is 0.69 m, four times that of the diameter of the average human head. The IID is therefore insignificant for frequencies below 500 Hz. The scattering by the head increases rapidly with increasing frequency, and at 4 kHz the head act as a noise barrier.

Interaural Time Difference (ITD)

For a pure tone, a difference in phase is equivalent to a difference in arrival times of waveform features at the two ears (Interaural time difference). The formula for diffraction by a sphere gives the interaural time difference Δt as a function of the azimuth (left-right) angle θ:

$$\Delta t = (3a/c)\sin\theta \tag{1}$$

where a is the radius of the head approx. 0.0875 m and c is the speed of sound, 344 m/s, therefore $3a/c$ = 763 µs. Listeners are sensitive to differences $\Delta\theta$ as small as 1-2º. A 1º difference in azimuth corresponds to an ITD of only 13 µs.

Median plane

The sound source on the median plane (an imaginary plane that bisects the body vertically through the navel, dividing the body exactly in left and right site) is equidistant from both ears, IID and ITD cues are therefore invariant in these situations. Consequently, directional filtering by the external ears and scattering by listener's head, shoulders and upper torso provides the sole localization cues for sources in median plane.

Previous studies

An effect of tone frequency on image elevation was first observed in 1930 (Pratt 1930) for five octave-related pure tones (256 Hz to 4.056 kHz), presented in the median plane. His experiment used a set of five tones reproduced by a movable telephone receiver behind a screen with a 2.5 m vertical scale. Results showed systematic vertical spatial ordering of these tones based on their frequency; for example, the 256 Hz tone had an average perceived elevation of 0.7 m, compared with the 4.096 kHz tone's 2 m perceived elevation. Similar experiments by Trimble (1934) and Roffler and Butler (1968a) also showed image elevation of pure tones to correlate positively to their centre frequency of 1/3 octave band, being independent to the source elevation.

Pratt's effect is frequency band phenomenon (Blauert, J, 1969/70) for sources located on the median plane, which concludes that the perceived location of few narrow band frequencies tend to be localized in the front, rear or overhead irrespective of their actual position. In summary 1/3 octave frequency band noise between 2.5 kHz, 6.3 kHz is localized in front, 8 kHz noise is localized above, noise bands between 10 – 12.5 kHz are localised behind and 16 kHz noise is localized in front. The reason behind the localization distortion is caused by a concept of boosted bands (Butler, R.A, and Helwig, C.C, 1983; Rogers, M.E, and Butler, R.A, 1992). The perceived location of the narrow band frequency is influenced by the direction that has the highest transfer function for that narrow band frequency. Also spectral cues influenced by ear pinnae tend to increase in frequency as the actual location of the sound source increases in elevation (Bothe, S.J and Elfner, L.F, 1972 and Gardner, M.B, 1973). For a low frequency narrow band sound with large wavelengths, ear pinnae because of its comparative small size is unable to provide any spectral cues, thereby inheriting a default image location (Vliegen, J and Van Opstal, J, 2004).

Relation between notch frequency and perceive source elevation on median plane was demonstrated by laboratory experiments (Hebrank, J, and Wright, D, 1974). Perceived sound localization in the front hemisphere of human head is caused by the notch frequency centered from 5 to 11 kHz. The notch in the frequency spectrum is caused by the interference of direct and concha reflected noise entering the external auditory canal in the ear. The profile of the concha (shown in Figure 1) plays an important part in shaping the spectral cues, which influence the perceived localization of the sound source in vertical and azimuth plane. The acoustics of the noise entering the pinna canal are a complex combination of diffractions, resonances and reflections. The reflection of a sound from the posterior concha ear wall interfering with the direct sound entering in the external auditory canal causes perception of source frontal elevation. The interference of direct and reflected sound caused phase shift from 120° and 240° which can cause attenuation of 6 dB or greater. As seen in Figure 1, for higher source location, the reflected noise path is shorter and therefore the notch is formed in the higher frequency band.

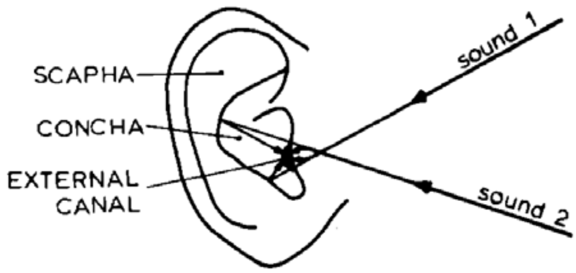


Figure 1. Schematic diagram of the external ear (Hebrank, J, and Wright, D, 1974)

To confirm the reflection hypothesis, the actual path lengths of concha reflections can be compared with the frequencies of notches in the external ear response. For example, the distance d from the external auditory canal to the posterior concha wall, at a MP sound incidence $Ø$, is related to the time delay τ of the reflected sound by

$$\tau\,(Ø) = 2d\,(Ø)/c \tag{2}$$

so the predicted notch in a sound' spectrum sound be centred at frequency f:

$$f\,(Ø) = ½\,\tau\,(Ø) = c/4d\,(Ø) \tag{3}$$

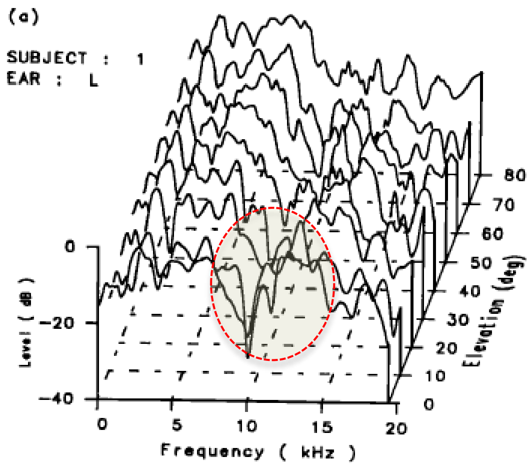
Previous model suggested the distance from the canal to concha wall is roughly 12.7 mm (½ inch) for -30ºMP sound incidence, 9.52 mm (3/8 inch) for 0º incidence, and 6.35 mm (¼ inch) for +30º incidence. These path lengths would cause delays of 76, 57, and 38µsec, predicting notch centre frequencies of 6.6, 8.8 and 13.2 kHz, respectively. The centre frequencies of the ear are 6.5, 9.5, and 10.5 kHz for -30º, 0º, and +30º elevations, respectively. The agreement of the notches predicted from the physical dimensions and the notches in the frequency response data supports the hypothesis that concha geometry is responsible for the production of elevation cues by the variable path-length reflections that occur of the posterior wall.

Sound localization on the horizontal plane through spectral cues caused by ear pinnae was investigated through series of experiments conducted by Musicant, A.D and Butler, R.A, 1984. The results of the experiment suggested that sound localization with high frequency sound (above 4 kHz) was more accurate compared to sound consisting of low frequency (1 kHz – 4 kHz). Similar trend was observed for front-rear reversals (noise source in front perceived as behind and visa-versa) where lower front-rear reversals was apparent with sound containing high frequencies (above 1 kHz).

Analysis of HRTF's reveals the existence of elevation-dependant features at low frequency for sources present in the median plane (Ralph Algazi, V, et al, 2001). The physical origin of the low frequency features is attributed primarily to head diffraction and torso reflections. Ear pinnae have a major effect on the spectrum above 3 kHz, but relatively little effect below 3 kHz. Upper body torso reflections act as comb filters, introducing bilaterally periodic notches in the frequency spectrum, which relate to the delays introduced by torso, thus producing patterns which varies with source elevation and generate cues for low frequency (<3 kHz) localization.

Ferguson, Cabrera, (2005) researched the effects of vertical localization of synchronous and asynchronous bands of noise. The result showed that low frequencies are localized below their physical positions whereas high-frequency sources are localized at their true positions. They also demonstrated that low frequency sources are not localized well when presented in exact synchrony with high-frequency sources, or when they only include energy below 500 Hz.

The role of spectral cues in the sound source to ear transfer function in median plane sound localization was investigated (Asano et al 1990). Dependence of external ear transfer function on the elevation angle for one subject is shown in Figure 2 and summarised as follows: Below 4 - 5 kHz, there was little directional dependence, above 5 kHz there is a dip observed between 6 kHz and 10 kHz and around 11 - 14 kHz a peak can be observed for frontal incidence. As the sound source is elevated, the dip between 6 kHz and 10 kHz moves toward higher frequency and the peak around 11 kHz – 14 kHz decreases. Similar effects were noticed with a level difference of the transfer function between front and above sound source: when the sound source is located above, the power of 6 kHz -10 kHz increases and that of 10 kHz - 15 kHz (including even higher frequency regions in several cases) decreases in comparison with the other frequency regions. In brief, the sound power at around 500 Hz and 3 kHz -5 kHz increases for frontal incidence, 1 kHz -2 kHz components increase for rear incidence and components above 13 kHz increase for frontal incidence.



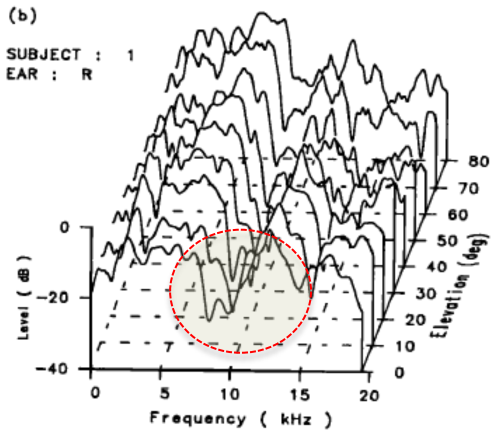


Figure 2. External ear transfer function at eight elevation angles of frontal incidence. Linear frequency axes are used in these figures to emphasize the variation of the transfer function at high frequency (Asano et al 1990)

Cabrera and Morimoto, (2007) presented further evidence on how Pratt's effect behaves especially for complex tone stimuli (considering that binaural difference cues are constant in the median plane and variable in the lateral plane). There is relative high evidence that spectral distortion caused by ear pinnae in the high frequency range above 5 kHz act as cues for localization in the median plane.

The next section presents the findings of an experiment conducted by the author (Lau 2008), which examines localization dependence of low frequency sound on the position of high frequency sound through multi-channel stereo speaker system for broadband noise spectrum presented in an anechoic chamber.

EXPERIMENT

Introduction

The experiment studies the vertical localization perception of music samples containing broadband frequencies in an anechoic environment compared with its actual location. The experiment aims to prove the dependence of low frequency sound vertical perception on high frequency sound.

Procedure

The experiment was conducted using 6 pairs of Tannoy stereo loudspeakers (only 4 pairs of loudspeakers were operational) positioned on a median plane connected to Macintosh computer with MaxMSP software (real-time digital audio programming environment) regulating the random output of portion of 4 songs with diverse frequency spectra (15 second broadband song extracts) through the 4 pairs of channel (total 8 channel output). Each song extract was divided in the frequency domain into 2 parts along 1 kHz (4^{th} order Butterworth crossover -24 dB slope) crossover frequency to achieve a steeper filter slope and fed randomly to 4 pairs of Tannoy speakers. 20 listeners were asked to localize low frequency (20 Hz - 1 kHz called as woofer) and high frequency (1 kHz - 20 kHz called as tweeter) portion for each song. Figure 3 shows the perspective view of the speaker arrangement inside the anechoic chamber.

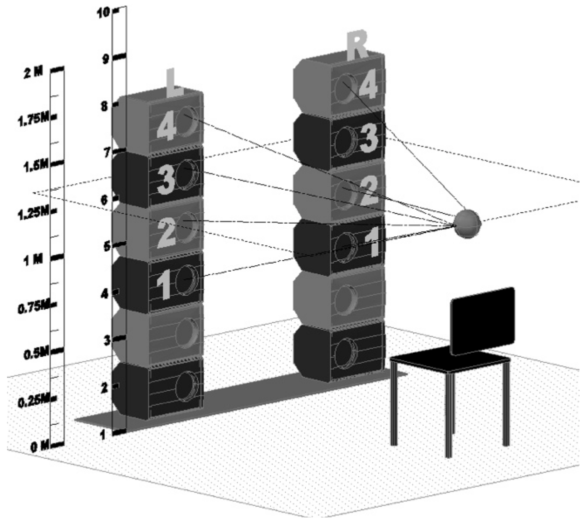


Figure 3. Perspective view showing 6 pairs of loudspeaker of which 4 pair (namely 1 – 4) were operating while bottom 2 pairs were non-operational.

Result

The outcome of the experiment complied with previous results concluded by Ferguson and Cabrera (2005). Figure 4 shows the two graphs of the localization test conducted on 20 participants. First graph shows the result of localization test for 4 song samples when the actual position (marked as 0.0 in the x-axis in the graph) of the tweeter was 1 and woofer was 4 (refer to Figure 3 for corresponding height of loudspeakers at position 1 and 4). Notice the deviation of woofer from the mean position compared to the tweeter position. Subjects perceived the location of woofer close to the tweeter position (closer to the ear height) because of lack of localization cues available for sounds below 1 kHz. Similar trend can be seen in the second graph in Figure 4 but with less deviation of woofer position compared to first graph because the actual woofer position (location 1) is closer to the ear height. Below is the summary of the results relevant to this paper:

- The location of the song's low frequency portion (woofer) were perceived closer to the mean position (horizontal plane aligning with the ear height) when the actual location of the low frequency portion was above or below the perceived location;
- The perceived low frequency portion's position was affected by its corresponding high frequency portion's position. It was observed that when high frequency portion was played through speakers placed above the mean position (keeping the low frequency portion fixed at mean position), the perceived low frequency portion's location showed positive deviation above the mean position. This observation reflects that low frequency localization is perceived closer to the high frequency position in the median plane irrespective of its actual position. This inference is similar to the results obtained by Cabrera and Ferguson (2005).

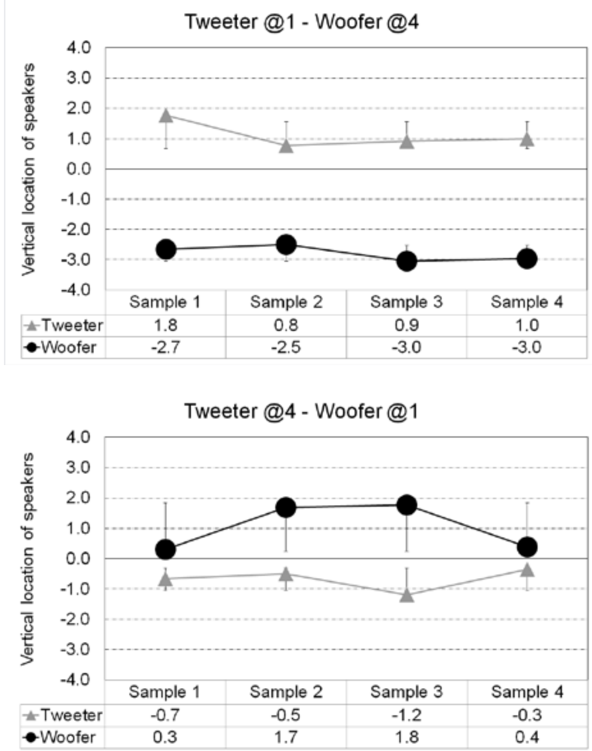


Figure 4. Result of the localization test shows graphs with deviation of perceived tweeter (1 kHz – 20 kHz) and woofer (20 Hz – 1 kHz) position from their respective mean positions (0.0 in the x-axis). Mean position is the actual location of tweeter or woofer.

ENVIRONMENTAL NOISE ASSESSMENT

For ease of simplifying results noise data of two typical noise source types are examined in this section namely mechanical equipment and insects which are widely found in any rural/ suburban environment during a typical noise survey.

Mechanical equipment

Noise data for various mechanical equipment sources is available based on previously carried out environmental noise surveys conducted at a wide variety of locations. Some typical noise monitoring sites included coal mining sites (e.g. NCIG, Wandoan Coal Mine), ash repository sites near power stations (e.g. Wallerawang Power Plant), and defence activity sites. (e.g. RAAF, NT). Sound Pressure Levels (octave-band frequency) of mechanical plant typically encountered during an environmental noise survey was investigated as shown in Table 1. All noise data has been standardized to 7 m distance from the mobile equipment excluding power plant cooling towers (CT) which are measured at a distance of 110 m.

Table 1. A-weighted octave band Sound Pressure Levels for typical mechanical equipment

Noise source	Octave band centre frequency							
	63	125	250	500	1k	2k	4k	8k
Power Plant CT	47	51	57	59	61	59	52	43
Tractor	53	63	70	76	79	80	76	60
Ejector Truck	56	62	65	70	72	70	66	55
Excavator	59	66	69	72	74	72	72	69
Water truck	55	61	64	70	71	70	64	55

Figure 5 and Figure 6 shows the frequency spectrum of typical mechanical plant and cooling towers for a thermal coal power station at a distance of 7 m and 110 m respectively.

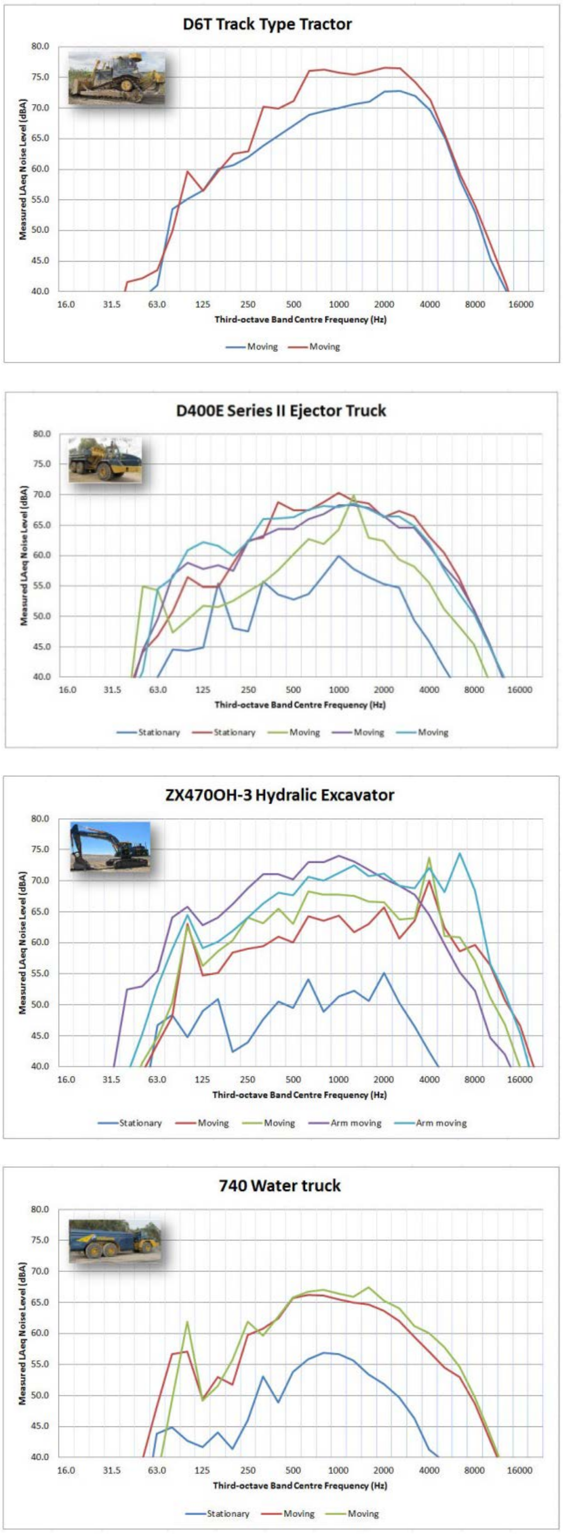


Figure 5. A-weighted frequency spectrum of typical representative mechanical plant measured at 7 m.

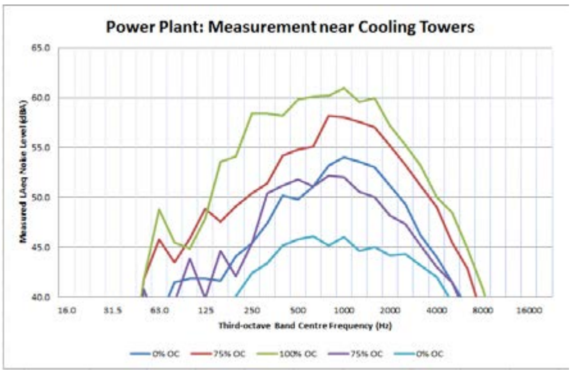


Figure 6. A-weighted 1/3 octave frequency spectrum graph of noise measured near cooling towers at various operating capacities for a thermal coal power station at 110 m.

This section aims to investigate the attenuation of noise from the mechanical plant in the frequencies above 1 kHz due to the ground and air absorption over distance. Data shown above (Figure 5 and Figure 6) displays that the A-weighted energy of the mechanical equipment lies in the mid frequency region of 500 Hz to 2 kHz with energy steeply declining above 4 kHz.

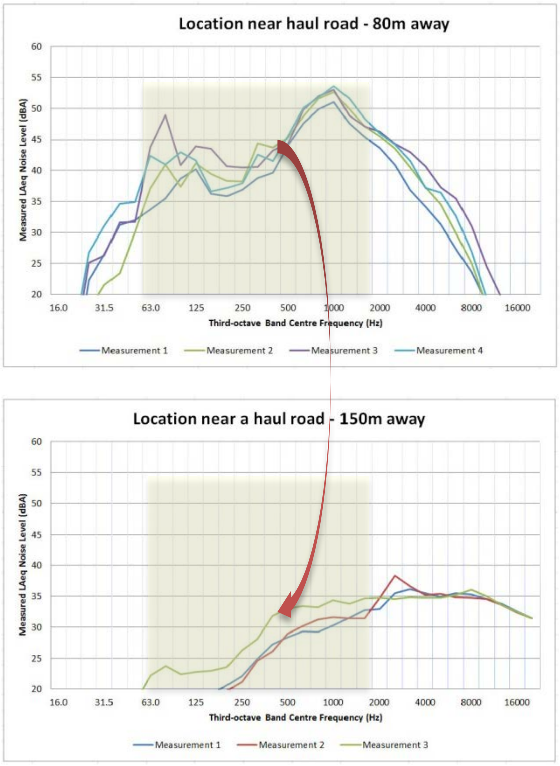


Figure 7. A-weighted frequency spectrum graph of noise from dump trucks moving on haul road showing attenuation of lower to mid frequencies over distance.

Figure 7 provides a comparison between two measurements (at 80 m and 150 m away from haul road respectively) conducted near a haul road with regular dump truck operation during the entire measurement period. Although the two sets of measurements were conducted at a different times of the day, the graph focusses on the attenuation of lower to mid frequencies (63 Hz – 2 kHz) due to distance, air absorption, barrier attenuation from buildings, scattering by vegetation and other factors. ISO 9613-2:1996 provides detailed information on noise attenuation over the one-third octave frequency band over a wide range of temperatures and relative humidity. As a result of absorption of lower to mid frequencies, the noise reaching the measurement location possesses peak values in the narrow region of 3 kHz.

Insects

Insect's noise emissions contain totally different frequency spectrum components compared to mechanical plant sources. Extensive studies in the field of noise measurements for insects have been conducted over the past decade. This study takes an example of few very common insects found during a typical environmental noise survey in a rural or suburban region of NSW, namely Cicadas, Katydids, mantis, etc.

Singing males (Cicadas species *Okanagana rimosa*) usually sit on woody parts of a plant, including smaller branches. Males produce the airborne calling song using their timbals, and it functions in long range signalling. Laboratory experiments were conducted (Stolting, H, 2002) to investigate the frequency range of the airborne noise from the songs of cicadas. These induced airborne sound had a spectral content from 2 kHz - 12 kHz and that its energy peaks at around 7 kHz - 10 kHz as shown in Figure 8.

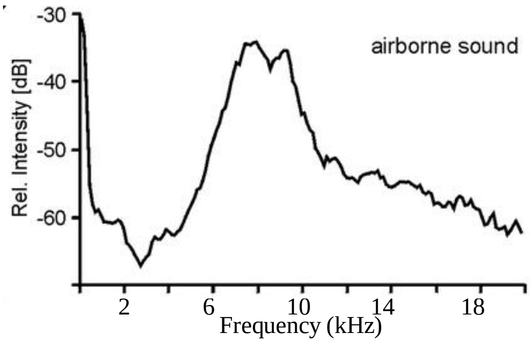


Figure 8. Graph of the frequency spectrum of the airborne sound produced by an electrically-stimulated cicada species *Okanagana rimosa (Stolting, H, 2002)*

Frequency analysis in katydids (species *Mygalopsis marki*) concludes that its song has a broad spectrum of 8 kHz to 30 kHz in close proximity to the source. As the higher frequencies get attenuated due to absorption from plants, air, etc. frequencies above 12 kHz lose most of its energy.

Crickets (species *Teleogryllus oceanicus*) generate songs in the narrow frequency band usually in the dominant frequency of 4.5 kHz. Figure 9 shows the frequency range of some of the typical representatives of major orthoptera group (*Orthopteran species*). As evident, most the spectral content lies in the higher frequency range above 10 kHz, while frequencies extending into ultrasound range (30 kHz) containing highest energy levels.

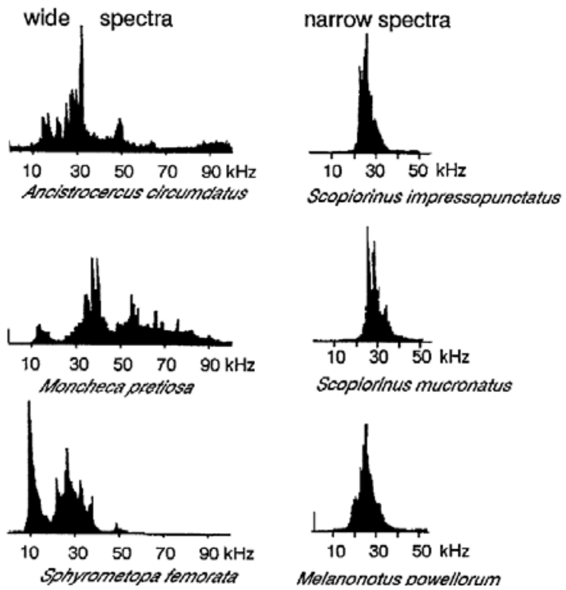


Figure 9. Graph of the frequency spectrum of typical representatives of major orthoptera groups. Species on the left are characterised by wide frequency spectra extending into ultrasound region, while species on the right exhibit narrow band frequency spectrum (Stolting, H, 2002)

DISCUSSION

The analysis of the above study shows a combination of sound source elevation and broadband sound's fundamental frequency affecting image elevation influences, which depends on various factors including the spectral content of the environmental noise and psychoacoustic phenomenon. For broadband sounds deficient in high frequency sound, image elevation is mainly affected by the fundamental frequency consistent with Pratt's effect. The effect of frequency spectra on vertical localization is consistent with the concept that spectral cues above 5 kHz are of prime importance which is supported by many other studies.

A typical environmental noise survey could present sources such as mechanical plant having fundamental frequency in the region of 63 Hz & below and insects having energy predominantly in the frequency region of 3 kHz and above. Location of multiple noise sources in typical environment such as insects and mechanical equipment could differ in terms of distance from the measurement location, elevation from the mean position and angular displacement. Figure 10 shows the A-weighted 1/3 octave band frequency spectrum graphs of noise measured at three separate locations in NSW near an existing haul road (80 m and 150 m away) and power plant (300 m away) respectively. Peak noise was measured around 3 kHz from insect calling in the second graph and a peak around 50/80 Hz from the mechanical equipment and power plant hum in the first and third graphs respectively. First graph exhibits the situation where mid frequency (1 kHz) and low frequency (63 Hz) are presented simultaneously for that receiver location.

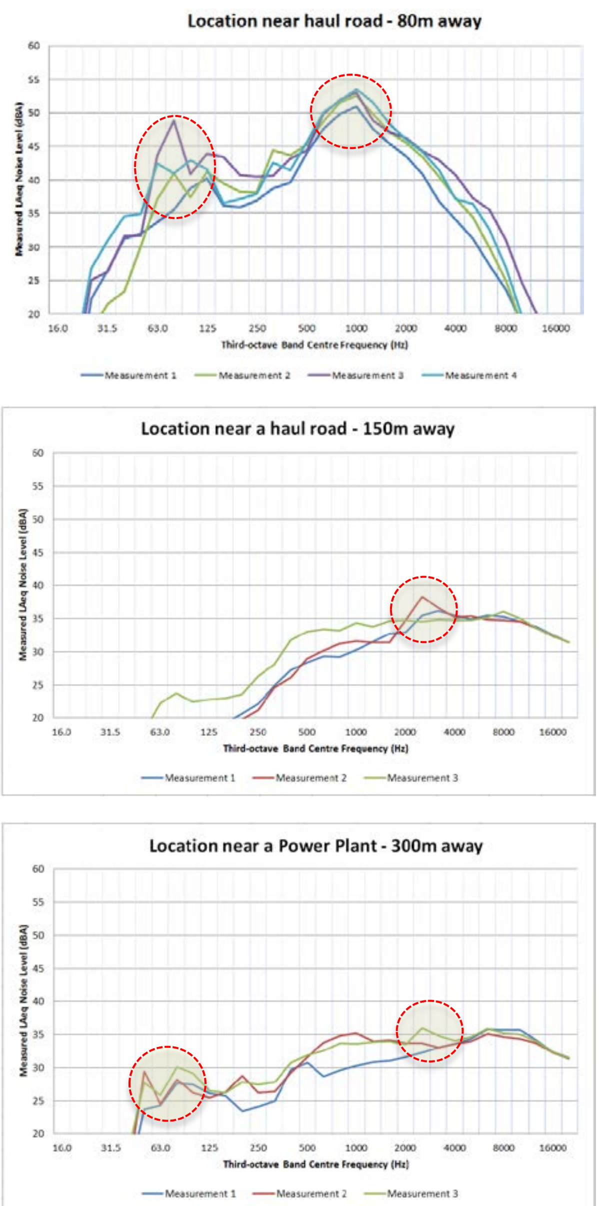


Figure 10. A-weighted 1/3 octave frequency spectrum graph of noise measured at three locations near a haul road and power station with peak around 3 kHz from insect calling in the second graph and a peak around 50/80 Hz from the power plant hum in the first and third graph.

The result of the previous studies indicate that both the source elevation and the fundamental frequency of broadband sound can systematically affect the vertical elevation and horizontal displacement of auditory images, and the strengths of these influences depend on the spectral attributes of the sound. Presence of low frequency tones from mechanical equipment (below 63 Hz) in conjuncture with high frequency tones from insects (above 8 kHz - 10 kHz) can provide analytical confusion for brain to process. Localization cues from ear pinnae are used to locate high frequency tones while cues aided by noise scattering via head, upper torso and shoulders are used to localize low frequency tones. As the noise sources in real case scenario (mechanical equipment emitting low frequency tones and insects emitting high frequency sound waves simultaneously) are usually located at different distances and azimuth angle (θ), low frequency tones localization will be affected (low frequency sounds are perceived closer to high frequency tone) by the location of high frequency tones consistent with the results from the laboratory experiment. Also, insect "calls" are intermittent, which infers that during a 15 minute attended noise monitoring the insects noise might intermittently stop thereby affecting the localization of the low frequency source image periodically with every onset of insect noise.

In the case of absence of high frequency sounds (above 1 kHz) during a noise measurement (i.e. presence of noise sources such as mechanical equipment which contains low frequency sounds) localization accuracy of low frequency sound will decline (Musicant, A.D and Butler, R.A, 1984). Noise containing frequency spectra below 1 kHz could also give rise to front-rear reversals especially for noise located in the median plane.

Noise from insects (which predominantly peaks around 10 kHz) will be localized in front of the head irrespective of the source actual location (Asano et al 1990). This anomaly in the localization of high frequency source image can subsequently affect the perceived location of low frequency tones (for instance mechanical equipment) when occur simultaneously with the high frequency tones (Ferguson, S and Cabrera, D, 2005).

CONCLUSION

While there has been much research carried out on sound localization in clinical settings, there has been limited research on localization in practical environmental settings. Noise spectra from realistic noise measurements were utilized to analyse the frequency content that may cause localization misrepresentation during the survey. This paper has outlined influences and justifications that can cause localization distortion during a typical environmental noise survey which acoustic consultants might not be aware of. Inaccurate localization of noise sources can further lead to imprecise computation and incorrect identification of noise contribution from noise sources. This paper attempts to equip acousticians carrying out environmental noise surveys with knowledge of localization errors that can occur during measurements. This paper also lays the foundation for any further investigation that can be conducted on dangers of use of subjective impression to identify (localize) offensive noise sources during an environmental survey.

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