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The influence of binaural incoherence on annoyance reported for unpleasant low frequency sound

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ABSTRACT

The annoyance caused by unpleasant low-frequency sound is known to be influenced by many factors, but studies of the influence of differences in such signals reaching a listener's two separate ears are not common. This is despite the fact that when such sound intrudes into indoor environments, the received binaurally incoherent low-frequency sound can exhibit values of Interaural Cross Correlation (IACC) that are reduced well below that measured in the free field, and are associated with clearly audible differences relative to similar signals that are more binaurally coherent. In this study, a selection of three unpleasant low-frequency sounds were submitted to chaotic amplitude modulation with three different peak modulation rates (2 Hz, 5 Hz and 10 Hz), and were presented as both coherent and incoherent signals via a laterally positioned pair of subwoofers. The results clearly revealed that binaural incoherence influences the unpleasantness of low frequency sound perceived by human listeners. The study also revealed that of the three peak modulation rates tested, the lowest rate (2 Hz) was associated with greater reported annoyance than that reported at the higher rates (5 Hz and 10 Hz).

1 INTRODUCTION

Much of the intent behind the current study was drawn from the low frequency sound and modulation rates of wind farms and machinery. Better understanding of the way human listeners perceive unpleasantness in the low frequency range (below 250 Hz) is important in understanding how environmental and building acoustic design should focus on user comfort beyond an A weighted sound pressure level. Australian and International standards and legislative documents focusses on sound pressure levels using the A weighted curve; this metric, although useful in identifying low frequency for human hearing, neglects the adverse perceived effects of low frequency by rolling it off in the weighted curve. The current study explores how human perception of low frequencies can contribute to the overall perception of sound beyond loudness and tonality.

This study explored the effect of modulation rate and signal coherence for low frequency stimuli on a listener's perception of annoyance and unpleasantness. The notion of uncomfortable sensations from low frequency stereo content (e.g., when reproduced out of phase) is noted in Rumsey's (2001) book *Spatial Audio*. Morimoto and Maekawa (1988) found that spaciousness was increased particularly when incoherent components between 100 and 200 Hz were presented. Similarly, Griesinger (1999) highlighted the importance of idiosyncratic low frequency behaviour below 300 Hz in the perception of spaciousness and envelopment in multichannel stereo reproductions. With drivers positioned at either side of a listener, he found that lateral separation was perceptually influential down to frequencies as low as 60Hz. Further research on the effect of low frequencies by Martens, et al. (2004) suggested that clearly detectable incoherence in the 31.5-Hz to 125-Hz octave-bands operate to provided listeners with a greater sense of envelopment. These studies have helped inform the current study in deriving appropriate test stimuli, consisting of homogenous signals below 250 Hz, presented at varied amplitude modulation rates and coherence.

A prior study by the authors looked at mid frequency spectra stimuli and the factors associated with perceived unpleasantness (Stevens and Martens, 2016). Studies by Boyd (1959) and Halpern, et al. (1986) also demonstrated the mid and high frequency range contributed to adverse reactions and notable annoyance when studying auditory irritants and chilling sounds respectively. Interestingly, Halpern, et al. (1986) also stated that the low frequency component of these unpleasant sounds contributed to the discomfort associated when listening. The authors' prior study (Stevens and Martens, 2016) showed that spectral content of grinding, scraping and screeching sounds below 500 Hz was not perceived as offensive as the those with spectral content above 500 Hz for the samples used in the study. Because those samples were specifically selected for the presence of mid-frequency content, the current study has instead focussed on stimuli with a strong spectral content below 250 Hz to explore factors influencing annoyance and unpleasantness within this lower frequency range.

2 STIMULUS SELECTION

A study by Boueri ,et al (2004) suggests that listeners find localisation of stereo decorrelated signals more difficult to discriminate from a distinct source position, and instead perceive the sound coming from a wider, more general space between the loudspeakers. Coupling the difficulties in localisation from signal decorrelation, with the ambiguity in spatial awareness of an expanded auditory image for low frequency (Terrace 1962) was considered to have potential to create a sense of discomfort to participants. To further enhance the effect of the decorrelated low frequency, listeners for this study were position directly between 2 subwoofers for maximum interaural differences between the left and right ears.

Studies of wind turbine noise and its annoying attributes show that amplitude modulation is an important factor in the degree of perceived annoyance. Ioannidou's (2016) study showed that persistent modulated noise, particularly at a modulation frequency of 2Hz was rated more annoying than intermittent or lower modulation frequencies. It has also been noted that for large modern wind turbines for a blade passing frequency of 1 Hz, 2 Hz would be considered the second harmonic frequency. Taking from this study, a 2 Hz amplitude modulation was implemented in the processing of low frequency stimuli and presented to test subjects. For comparison, sound samples 5 and 10 Hz modulation rates were also presented to listeners with the prediction that 2 Hz would be rated as more annoying.

Stimuli sounds used for the study were created using stringed instruments in an anechoic chamber, heavily bowed below the bridge and then processed to present frequencies below 250 Hz. Further processing of the anechoic recordings including jitter, overlapping and adding in matlab, created sound that could be described as a rumbling or low frequency whirling sound not dissimilar to machine motors. Participants were asked to assess their level of annoyance or perceived unpleasantness based on the stimuli presented to them in while situated between a pair of subwoofers in anechoic conditions so that results were influenced only by the direct sound from the loudspeakers. A graphic user internface was used in matlab to present and collect data of the each pairwise comparison with participants slecting the A or B stimuli that they felt more unpleasant when tasked with listening to. Breifing of participants explained these samples are short, however consider listening to them for a longer duration and how annoy or uncomfortable they were likely to feel, selecting only the simili of each presented pair that they would consider more annoying or unpleasant to endure for a longer period of time.

3 METHODS

3.1 Preparing the stimuli

A total of 27 different stimuli were generated, based upon three distinct types of sound, which were identified herein as types A, B, and C. Each of the three raw sound types were processed and presented in nine versions within separate pairwise comparison sessions. The nine versions represented a 3-by-3 factorial combination of modulation conditions and coherence conditions. Three modulation rates (2, 5, and 10 Hz) were crossed with three coherence presentations and presented to listeners positioned between 2 subwoofers in anechoic conditions. Note that in two of the coherence conditions, an identical signal was presented from both of the lateralised subwoofers. In only one of the three 'coherence-condition' presentations were incoherent pairs of signals presented from the lateralised subwoofers. The two modulation signals that were presented via both subwoofers, referred to in this study as ‘Coherent’, were subsequently used as the two ‘Incoherent’ modulation signals that were applied independently to each subwoofer. Figure 1 illustrates the 3 instances of coherency presented for each of the sound types (A, B and C) and modulation rates.

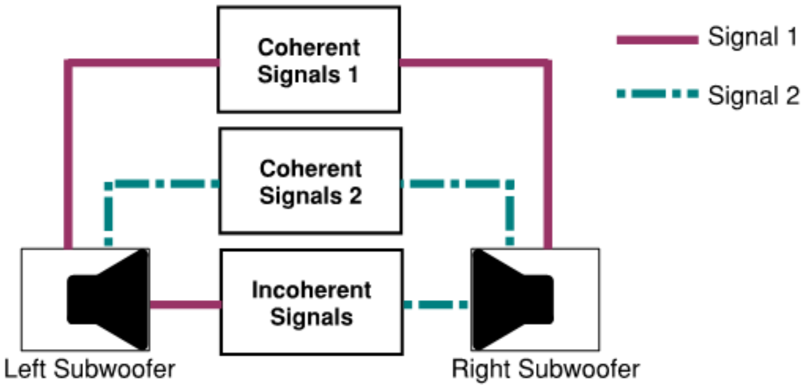

Figure 1: Diagram showing the signal flow for each of the three stimulus conditions that differed in presence or absence of binaural coherence. The solid lines connecting the **‘Coherent Signals 1**’ box to both of the subwoofers indicates the first of the two coherent signal presentations. The solid line and the dashed line connecting the ‘**Incoherent Signals**’ box to each of the subwoofers indicates that the incoherent signal presentations utilised signals from each of the two source boxes. Note that three types of sound samples (identified in the text as type A, B and C) were presented to participants according to the shown signal at 3 different modulation rates, making for an overall total of 27 stimulus presentations in the current study.

Spectral content of the low frequency sound samples in the previous study had little power between 100 and 200 Hz. As previously noted, these frequencies have been attributed with influence on envelopment. Figure 2 shows the low frequency spectrum used for both the previous study and the current. It can be seen that not only do the sound samples in the current study have greater levels at low frequencies, but there is also a boost between 100 to 200 Hz. It is also noted that the current study low pass roll off is at 250 Hz with some energy slightly above 250 Hz compared to frequencies up to 500 Hz that were included in the previous study’s stimuli

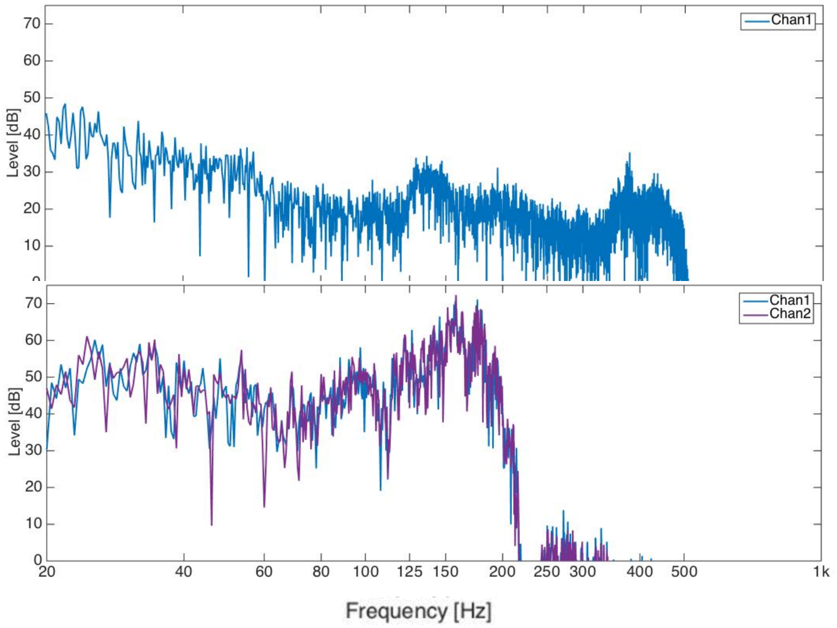

Figure 2: Low Frequency Spectrum of 2016 study stimuli (top) and 2018 study stimuli (bottom)

3.2 Characterising the Stimuli

To assure that reproduction levels of all stimuli were always matched, levels were compared with playback of a pink-noise reference signal that was set at 81.6 dB (Z-weighted) at the centre point (for each subwoofer individually, and at each instance that the test was run). Note that the low frequency limit of the BM12S subwoofers is a nominal 18 Hz with 250 Hz upper limitation. Now with respect to the characterisation of the relative incoherence of the signals, the classical means for measuring two-ear correlation in the statistical sound fields of rooms used spaced omnidirectional microphones. However, Lindevald & Benade (1986) showed that including head diffraction gives substantial reduction in a the value of the two-ear correlation function at low frequencies, moving the decoupling frequency down to 500 Hz, less than half the free field (no-head) value. For the current study, a rigid spherical receiver mounted with binaurally-positioned omnidirectional microphones was placed in the listening position, and was used to record each of the 27 sound samples for subsequent parameter measurements. This sort of receiver works well in examining interaural cross correlation (IACC) at low frequencies, which was selected here to be used in predicting the subjective responses to low frequency noise and the changes in annoyance that such stimuli varying in IACC might cause for the human listener.

For two omnidirectional microphones separated by the distance between human ears (~15 cm), the free-field coherence for spherically isotropic (3-D, diffuse) noise is frequently measured using magnitude squared coherence (MSC), which asymptotes to a value of 1.0 as frequency is decreased towards zero. In contrast, when a rigid sphere is placed into a reverberant environment, the signals captured by two omnidirectional microphones separated by a headwidth asymptotes to a lower values as frequency is decreased, and is substantially lower in value relative to that measured in the free field for all frequencies below 500 Hz (Jeub, et al., 2011). For characterising the non-stationary signals presented in the current study, a conventional IACC measure was employed that utilised the routine named IACC_music.m found within AARAE, (Audio and Acoustical Response Analysis Environment) an open source acoustic analyser that runs under Matlab (Cabrera, et al, 2014).

Figure 3 shows the results of measurement of interaural cross correlation (IACC) for all samples from 25 – 250 Hz. The result makes sense since as the higher the frequency increases, an increasingly greater effect of head diffraction should be observed in the signals received by the two ears. Not surprisingly, the IACC for incoherent signals at all rates of modulation had the greatest differential from 100 – 250 Hz where the IACC dropped from 0.9 to 0.5 or lower. The rate of modulation had little effect on the IACC, showing no notable trend. The measured data suggests that the critical range for spatial ambiguity on the horizontal plane may be greatest in the 100 – 250 Hz range, and therefore, based on the binaural response to such incoherent signals, it is suggested that presence of two or more signals in this range could start to trigger an unpleasant sensation giving rise to annoyance.

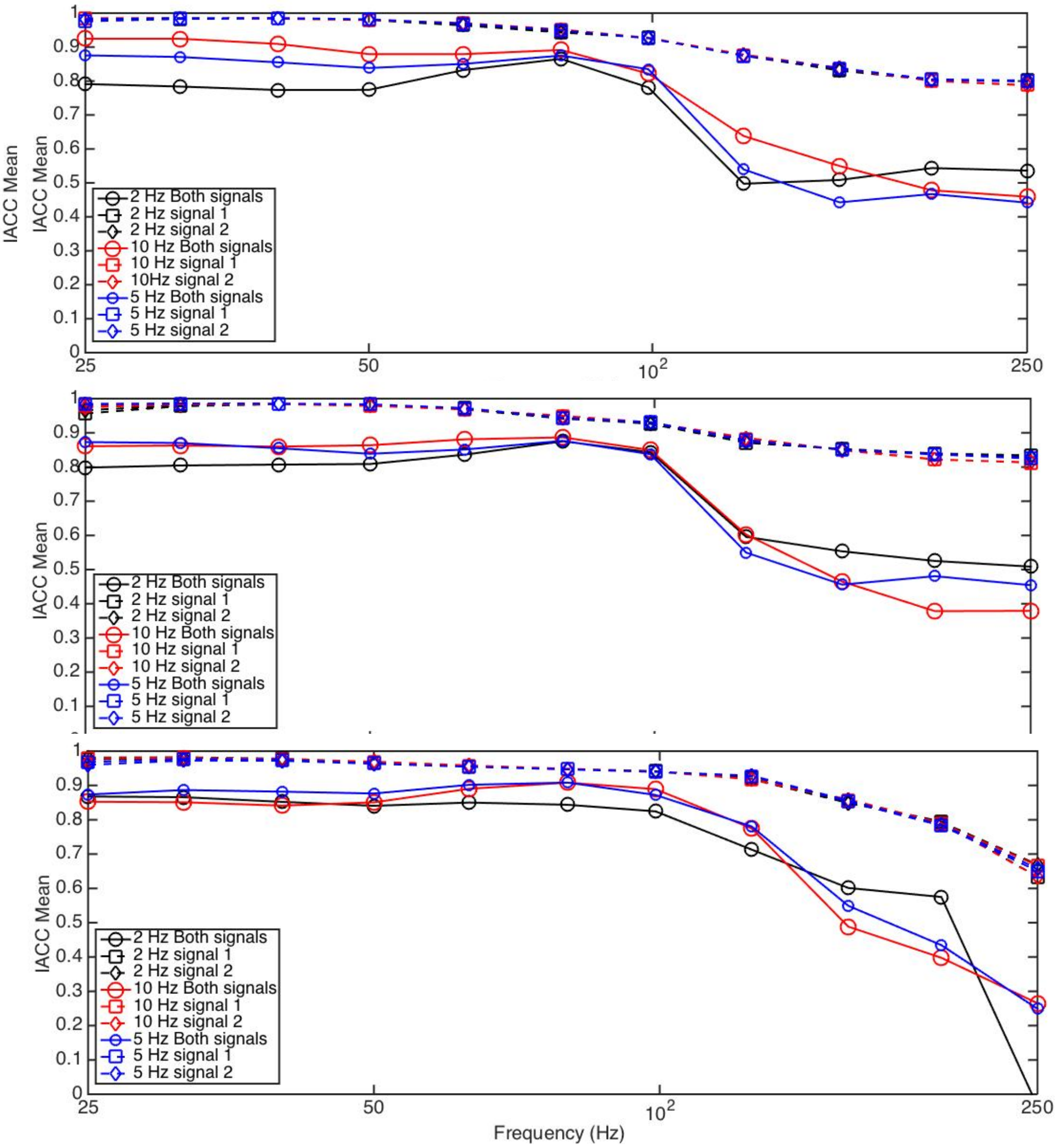

Figure 3: Mean IACC as a function of frequency for sound types A (top) B (middle) and C (bottom) for each of the 9 stimulus conditions. The entire-duration signals were analysed using the routine named IACC_music.m found within AARAE (Audio and Acoustical Response Analysis Environment), an open source acoustic analyser that runs under Matlab (Cabrera, et al, 2014).

3.3 Conducting the Study

A total of 21 participants with reported normal hearing took place in the study in which each listener was seated alone in an anechoic chamber located at the University of Sydney, NSW, Australia. A pair of Dynaudio BM12S subwoofers were located at the ear-level of the listener, with the front faces of the 12" subwoofer enclosures positioned at 1 meter from the centre of the listener's head (or from the centre of the rigid spherical receiver utilised for the physical measurements). Figure 4 illustrates the set-up of the experiment.

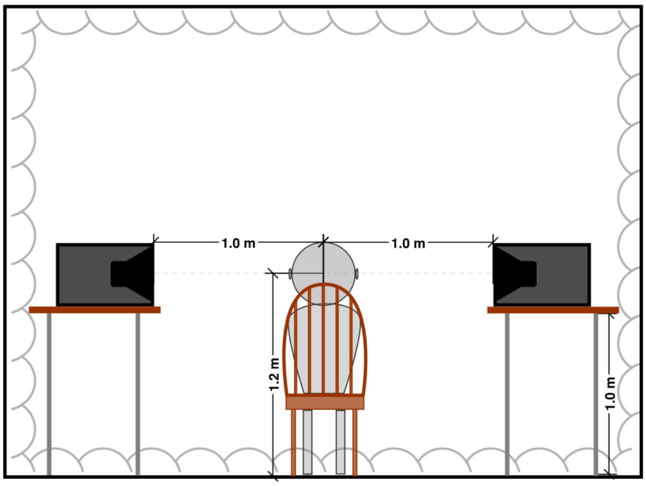

Figure 4: Positioning of 2 subwoofers in the anechoic chamber with the listener situated 1m from the centre of the head to the subwoofer enclosure surface.

Listeners each took part in three sessions, one for each sound sample type A, B and C. Within each session, the sound-type sample was presented at each of the three modulation rates, and as either a coherent or incoherent signal pair. Two presentations utilising coherent signals were included in each set of stimuli in order to ensure that idiosyncratic details of each particular modulation would not confound the comparisons between the nine versions of each type of sound. Not only did this inclusion control for the potential influence of idiosyncratic modulation details, but also enabled a comparison of annoyance levels for two particular ‘coherent’ stimuli with the annoyance associated with an ‘incoherent’ stimulus that shared idiosyncratic modulation details with each of the two ‘coherent’ stimuli (with all three of those cases sharing the same underlying subjective scale, as quantified via the common derived annoyance scale).

Listeners were presented with a total of (9x8)/2 = 36 stimulus pairs in each session, and asked to listen to them one after another using a Matlab-based GUI, on each trial selecting which was more annoying between the two sounds presented. Selecting the more annoying sound would trigger the next pair to play until all nine stimuli had been compared to one another, according to a randomised order of presentation to guard against systematic sequential dependencies. This process was completed separately or each of the three sound types. So that results were not influenced by a participant’s fatigue or variation in compliance, each listener had a randomised rotation in the order in which they completed the sessions, starting at either session A, B or C. This control for sequential response dependencies also reduced the likelihood that listeners’ biases developing throughout their participation might influence particular stimuli differentially, based on experience in previous sessions.

According to the hypothesis underlying the paired-comparison data analysis, the tallied choice proportions may be analysed to yield a coordinate for each of the nine stimuli along a linear perceptual scale following Thurstone’s (1927) classic indirect scaling method. The first step was to convert the choice proportion data into the Z-Score values for each comparison, which Z-Scores are then taken to indicate the magnitude of the underlying perceptual differences between each pair of stimuli. The final step is to take the sum of the values in each column of the paired-comparison matrix, which constitute the scale value determined for each stimulus in a manner consistent with Thurstone’s Case IV. The values on this derived scale are effectively normalized so that the nine values will sum to zero, with the negative values balancing the positive values assigned to stimuli on the scale.

4 RESULTS

The standardised annoyance derived for three distinct types of sound are shown in Figure 5. Results from the subjective tests show the standardised annoyance for each of the 3 sound types. This analysis results were derived from separate choice datasets for each sound type (choice of which sound in each pair as more or less annoying than the other). A scale of ‘Standardised Annoyance’ was created from the combined data for the 21 participants taken together.

As predicted, in all cases, the incoherent signals were perceived as having greater annoyance than those of the same signal presented coherently. Sound type A had more adverse response in the incoherent cases overall, followed by B and then C. Another prediction was that the 2 Hz modulation rate would be considered especially annoying (based on results of research with wind farm noise). This was supported for the incoherent stimuli, although not all of the coherent samples showed greatest annoyance at the 2 Hz modulation rate. Sound type A presented coherently seems to have been heard as more annoying at the 5 Hz modulation rate.

Coherent signals were perceived as considerably less annoying than those incoherent for the same sound type. The 10 Hz modulation rate was rated the least annoying for all sound types, followed by less conclusive results for 2 Hz and 5Hz. Of the total 18 stimuli presented coherently, only four showed positive standardised annoyance. A broad observation in the variation in coherent signal perception is that stimuli at 2 and 5 Hz varied between moderate and not very annoying, while stimuli at the higher modulation rate of 10 Hz was overall much less annoying.

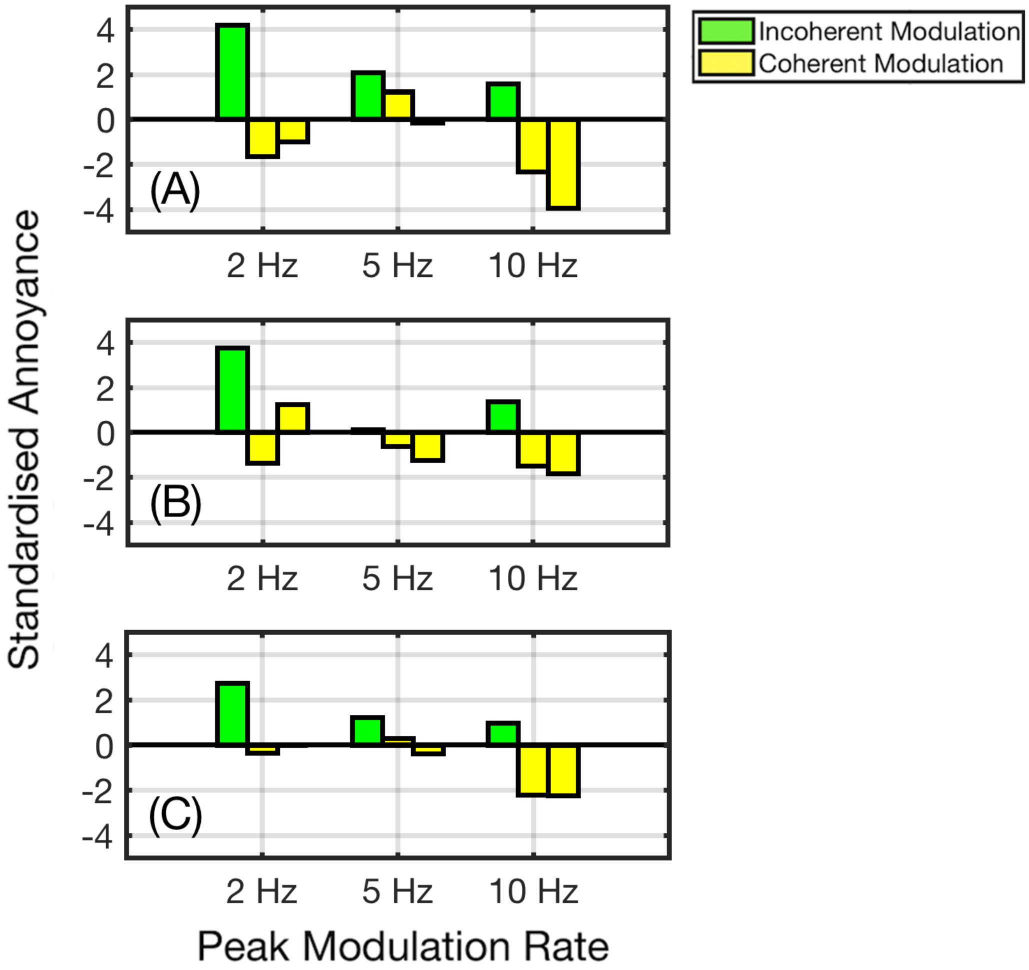

Figure 5: Panels A, B, and C show standardised annoyance derived for three distinct types of sound. In each panel, groups of bars are plotted for each of three modulation rates, and at each rate, results for an 'Incoherent' stimulus are contrasted with results for two related 'coherent' stimuli. Note that standardised annoyance scores plotted in each of the three panels are internally conditioned, and therefore each set of nine stimuli should theoretically share a common underlying subjective scale, as quantified via the annoyance scale values derived from the response proportions obtained for that sound type. The standardised annoyance scores in each of the three plots reference a different sample mean and standard deviation (local to the sampled responses to each set of nine stimuli), and therefore are not strictly on the same relative scale.

5 CONCLUSION

In conclusion, a series of subjective listening tests were conducted on a group of 21 individuals. The test stimuli was chosen to determine the characteristics that would make low frequency noise more annoying or unpleasant to the human listener. Results confirmed those of prior research that showed lower modulation rates (of 2 to 5 Hz) were more annoying than the higher rate of 10 Hz also tested in this study. Relative to the highly coherent signals tested, exposure to binaurally incoherent signals also increased the reported annoyance of participants. In a practical setting, this might explain why people may find machinery, fans and wind farm noise particularly annoying, as the low modulation rate couples with multiple sound sources reaching the ear at different times would be similar to the controlled stimuli presented in this laboratory study (i.e., under controlled environmental conditions). Australian and international standards are yet to take into consideration the effect of IACC on annoyance for the binaural human listener. In many cases, an overall A weighted curve is applied to criteria (although some modification factors do deal with low frequency or intermittent noise). Results from this study show that a non-stationary low-frequency noise, while not at a high volume, can indeed be annoying or unpleasant, and that that annoyance will generally increase with increasing binaural incoherence. Further research into the categorisation of annoying sounds could be done to identify potentially annoying sounds and to limit their exposure considering factors extending beyond a loudness measure.

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