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Analysing Tones in Industrial and Commercial Sound

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ABSTRACT

The significance of an adverse impact at a residential receiver due to a commercial sound source can be affected by certain acoustic features. British Standard 4142:2014 allows for a correction for these features when assessing the significance of the impact, one of which is a correction for tonality. The standard provides an objective method for determining a graded correction from 0 to 6dB based on the tone audibility. However, the prescribed method uses an amplitude spectrum that is time-averaged over "at least 1 min", making the method potentially inappropriate for time-variant sounds that are commonly assessed using the standard. A study has been carried out comparing the method adopted in the standard with other available methods for evaluating tone audibility in both stationary and time-variant sounds.

Keywords: BS 4142, Tonality, Commercial, Industrial, Assessment
I-INCE Classification of Subject Number: 69

1. INTRODUCTION

British Standard 4142 includes the second version of the Joint Nordic Method ("JNMv2") for assessing the audibility of tones in industrial and commercial sound. [1] This method ratios the sound pressure level of the tone within a very narrow band of sound to the sound pressure level of the masking sound within a critical band centred on the tone being analysed. Where the tonal sound being analysed contains a stationary and prominent tone, the evaluation procedure is robust, which leads to repeatable and reproducible results. However, when the sound contains tones that are time-varying, the method asks the user to reduce the length of the time-series being analysed whilst offering no additional guidance on how to do this without compromising the required frequency resolution.

Industrial and commercial sound frequently includes tones that are time-varying. Examples of this are intermittent processes, mobile plant and variable speed machinery. Implementing JNMv2 faithfully for such sources requires a level of signal processing knowledge not offered in the standard and not necessarily possessed by the user.

This paper discusses how a new psychoacoustic tonality metric, Hearing Model Tonality ("HMT"), can evaluate tonal content in industrial and commercial sounds that wouldn't be captured by JNMv2 without any additional user defined parameters.

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2. BACKGROUND

BS 4142 was first published half a century ago in 1967 and, since its original publication, has sought to assess the impact of industrial sound on residential receivers. The guidance contained in the standard has always been based on accumulated experience rather than substantial research; but the document has evolved, largely tracking the changes to the ISO 1996 series of standards.

BS 4142 is used to determine the significance of an industrial or commercial noise impact on residential receivers using the principle of noise intrusion. This is done by taking the difference between the rating level (the specific sound level corrected for the character of the sound) and the background sound level measured using L_{A90}.

It was with the introduction of L_{Aeq} in the 1990 revision to quantify the specific sound that tonal sound character was first considered as part of the assessment. [2] Identification of sounds containing *"a distinguishable, discrete, continuous note (whine, hiss, screech, hum, etc,..."* would attract a 5dB character correction and relied on a subjective impression of the noise as described in BS 4142:1990.[2]

It was identified during a comprehensive review of this standard that the omission of an objective procedure for evaluating the tonality of industrial sound resulted in problems applying BS 4142. [3] This was made more significant by the digital approach to applying the 5dB correction; misapplying a 5dB character correction could easily make a critical difference to the assessment outcome, which may have financial or social implications.

The treatment of tonality was subtly changed in the 1997 revision of the standard [4] with discussion of "acoustic features" rather than noise "characteristics" [5]; but despite the outcomes of the comprehensive review, no objective means of assessing tonality was incorporated into the standard because a suitable means of doing so was not available at the time of its publication.

The 2014 edition was a significant revision of the standard with greater provision for the treatment of noise "character", the word now having been reintroduced interchangeably with the term "acoustic feature". The standard now includes three means of assessing the prominence of tone in the sound, with provision for a graded correction: a subjective method, an objective method and JNMv2 used as a reference method.

The inclusion of the reference method in particular addresses the implementation problems that were highlighted as early as 1990; however, the subjective method of assessment remains part of the standard. The continued presence of the subjective method has inevitably led to a slow uptake of the new objective methods, a problem exacerbated by the fact that the new reference method requires Fourier analysis, which is not commonly implemented by environmental acoustics practitioners in the UK.

The decision to include JNMv2 in BS 4142 followed an extensive review carried out to identify objective methods for identifying acoustic features in industrial sound, which was completed in 2005.[6] In total, 20 different methods were identified for evaluating the tonal content in sound. Each of these methods was examined for: how sophisticated/complex they were, how representative they were of the human auditory system and whether or not they estimated the extent of the adverse response (i.e. what correction to be applied). The lineage of each method was traced as part of a literature review, which illustrated how many had evolved from others, and the methods tended to fall within three broad camps:

- Tone-to-Noise Ratio ("TNR")
- Prominence Ration ("PR")
- Psychoacoustic

Subsequent to this original review TNR [7, 8], PR and psychoacoustic methods [9] for evaluating tonal content in sound have been developed and further standardised. All of these methods are readily implementable in modern PC software and handheld analysers.

2.1. TNR and PR

The TNR family of methods, of which JNMv2 is one, ratios the sound pressure contained within a narrow band of sound considered to be the tone to the sound pressure in adjacent bands. At its most simple level, this takes the form of comparing the sound pressure in the 1/3rd octave band containing a tone to that in the two adjacent bands. TNR is more commonly implemented using spectral estimation, comparing the sound pressure within the half or quarter-power bandwidths of the tone to the remaining energy within the critical band. The idea of the critical band is a psychoacoustic concept so, in this respect, the more sophisticated TNR methods can be considered to be partially psychoacoustic.

Prominent tones are generally created with broadband noise for real sources. The part of the noise within the critical band mask the tone, with the width of the critical band being a function of frequency. A prominent tone is considered to be just audible in the presence of noise when the sound pressure level of the tone is between 2 and 6dB below the sound pressure level of the masking noise.

TNR can underestimate the prominence of a tone where the masking noise forms a sloped spectra. It will also fail to detect tonality that is not caused by prominent tones, important examples of this in industrial and commercial sound are: resonances (acoustic and structural) and edge tones caused by sudden changes in the spectrum.

The PR family of methods ratio the energy contained within a critical band to the energy contained in the adjacent critical bands. This makes the method suitable for tonality caused by sounds containing more than one pure tone; however, the method could be limited where the adjacent critical bands also contain tones.

Both TNR and PR require high frequency resolution, which for industrial and commercial sounds can be challenging. During a field survey of industrial and commercial sound, obtaining a 1-minute time-series of the source continuously operating can be challenging from a remote receiver location. This is particularly the case for mobile plant, equipment operating at varying speed and intermittent machinery.

2.2. Psychoacoustic Tonality

Full psychoacoustic tonality takes account of the physical characteristics of the human auditory system. During the original 2005 review, previously mentioned, psychoacoustic metrics were restricted to the Aures method, which was not implementable with the type of equipment commonly used by environmental acoustics practitioners. The results of the Aures method are also potentially less useful than PR and TNR as it provides only a ratio of the tonal to non-tonal loudness. [10] Without spectral information, the scope of the method is limited as it could not be used to identify the most dominant tonal features from a variety of industrial or commercial sources.

HMT has been included in the 15th edition of ECMA 74. The method is based on Zwicker specific loudness and a hearing model is used to separate the loudness caused by tonal and non-tonal components, which has a number of advantages. Most importantly, elevated bands of sound proximate to tones are differentiated from other masking sound and, because the method is based on a hearing model, the relative loudness and threshold of hearing are intrinsic.

By implementing many overlapped ½ critical bandwidth filters, the frequency resolution ranges from 3Hz at lower frequencies to 24Hz at the highest frequency, whilst maintaining a time resolution of between 40 and 5ms respectively. [11] This can provide the time and frequency resolution required to identify time-varying tones that are synonymous with industrial and commercial sound. It also resolves the periodic signature of beating tones within a critical band, which would allow these additional features to be identified and considered in any assessment.

A distinct advantage of using HMT for assessment of industrial or commercial sound is that it captures all of the features with a single set of input parameters, making it fully automated. This is important because planning applications in the densely populated UK often hinge on the outcome of environmental noise assessments. A robust, repeatable and reproducible evaluation procedure is essential for the avoidance of doubt and possible debate in a planning enquiry. This is important because the aim of the existing reference method is to be absolute: something it can currently only be for stationary and prominent tones.

3. EXPERIMENTAL STUDY

As part of the original review carried out in the UK, sound recordings which had previously been used by W. Pompetzki in Germany, [12] were presented to a panel of listeners at an acoustics trade conference. [13] The listeners were asked to rate the recordings to what degree they contained "…droning, whining, singing, screeching and whistling..." on a scale from 0 (no tonal components) to 5 (clearly heard). These ratings corresponded to an acoustic feature correction applied during the numerical assessment from BS4142 in dB.

The Pompetzki recordings have been reprised to investigate the effectiveness of HMT compared to the use of JNMv2 when assessing the tonal content of industrial and commercial sound. Partly because the correction scale now spans from 0-6dB and partly because the original breakdown of subjective responses has been lost, the subjective tests have been repeated to provide a dataset for the comparison.

3.1. Objective Analysis

The recordings were analysed using JNMv2 as it is implemented at noise.co.uk Ltd for environmental noise assessments. The autospectra on which the analysis was based implement a Hanning window and are presented in dB(A) referenced to 20μPa. A frequency resolution of 1Hz has been used and the tone seek criterion used to identify noise pauses was set at 1dB. The method is automated in Matlab and has been validated against RION AS-70, a commercially available software package.

An example analysis of one of the audio recordings is given in Figure 1.

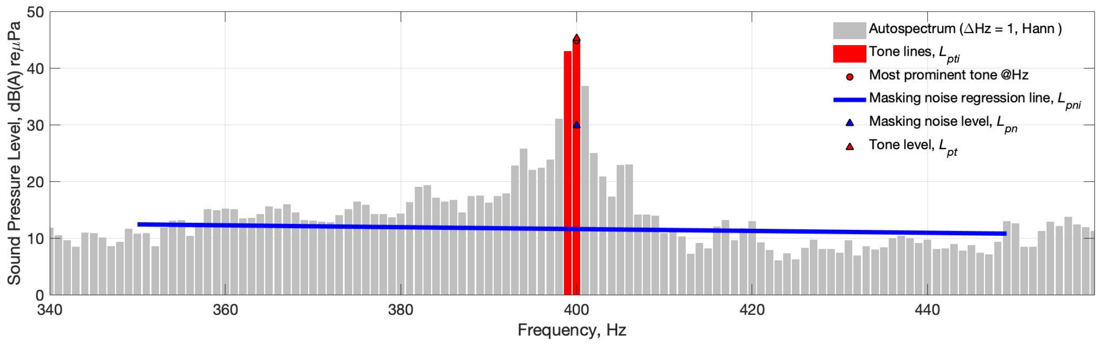

Figure 1 – Example showing the evaluation of tone prominence using JNMv2 in one of the recordings used by Pompetzki containing the sound from a hydraulic pump

The audio recording analysed in Figure 1 contained sound from a hydraulic pump, which generated prominent tones that were stationary for the duration of the recording. These sources are easily identified by JNMv2 and the resulting tone audibility and acoustic feature correction are likely to be reproduced easily by other parties, given the same recordings.

Where the audio recordings contain tones that are not stationary, JNMv2 is less able to quantify their tonal content without additional user manipulation of the autospectrum. A strong example of this is the audio recording containing sound from a ventilation exhaust, the analysis for which is illustrated in Figure 2.

(a) (b)

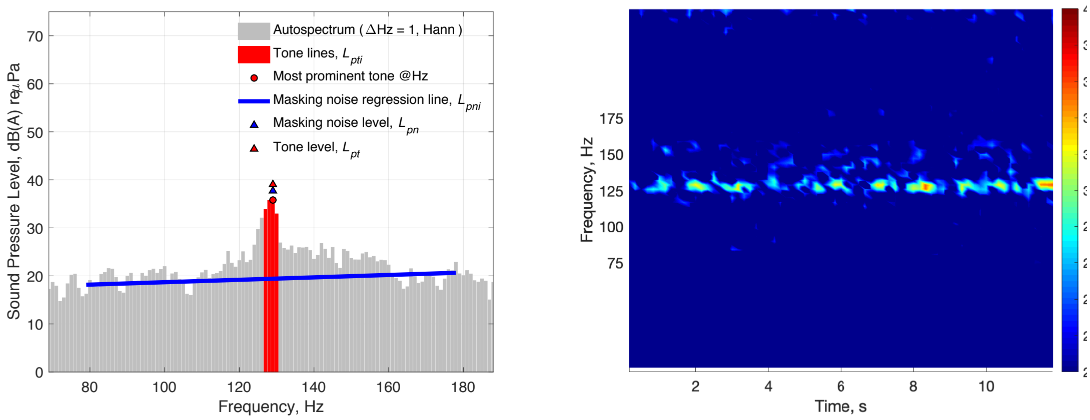

Figure 2 – (a) Example showing the evaluation of tone prominence using JNMv2 in one of the recordings used by Pompetzki containing sound from a ventilation exhaust

The relatively low frequency tone identified by JNMv2 does not appear to result in a particularly audible tone when analysed as an averaged spectrum, as shown in Figure 2(a). However, when the audio recording is analysed with smaller time steps it is clear that the tone is intermittent: this is illustrated in Figure 2(b). The intermittency of the tone reduces to the overall energy when analysed as an averaged spectra, potentially underestimating its audibility within the masking sound.

JNMv2 prescribes reducing the long-term averages into shorter time-averages for such situations; however, this requires knowledge of signal processing that may not be possessed by the person reviewing the recordings and may also require long recordings from which to extract shorter-time averages that contain the tones.

HMT was implemented using HEAD Acoustics commercial ArtemiS Suite software according to the method contained in ECMA-74. The Psychoacoustic loudness of the signal is determined and divided into tonal and broadband components by means of an autocorrelation function. The measurement unit of HMT is "Tonality Units according to The Hearing Model by Sottek", shortened to Tu_{HMS}. By way of reference >0.1 Tu_{HMS} is generally considered to be the threshold where sounds can be considered tonal, sounds >0.4 Tu_{HMS} would be considered to contain prominent tones and sounds >0.8 Tu_{HMS} would be considered to have very highly prominent tones. [14]

The analysis of the audio recordings has been presented in Figure 3, the results have been presented as Tu_{HMS} vs. Time.

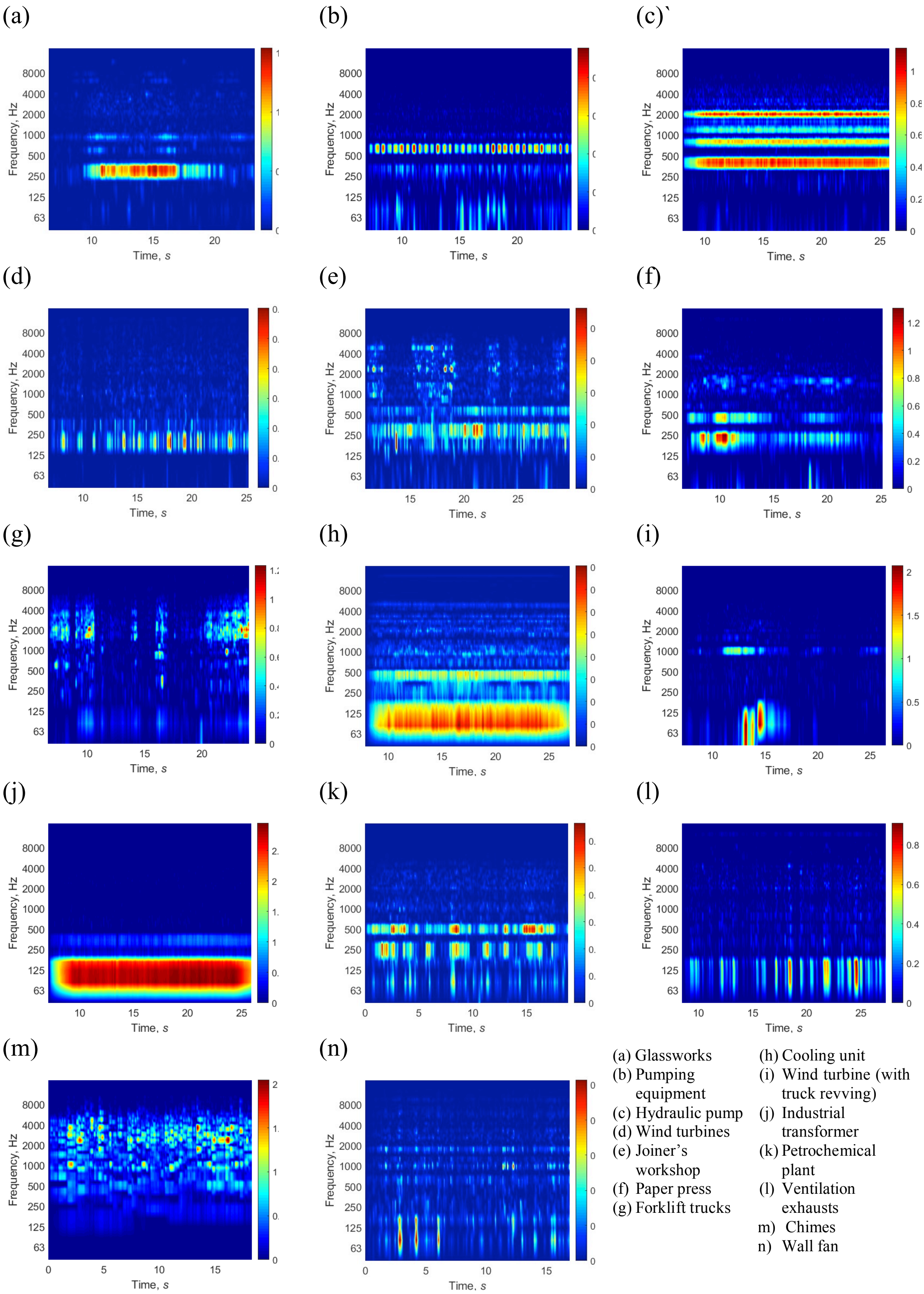

Figure 3 – Tonality spectrograms for the analysed recordings. Tonality presented in Tu_{HMS}

Subjective Tests

The 14 audio recordings were presented to 25 subjects via a computer and headphones designed to make the acquisition of the subject's responses quick. The use of the computer interface allowed the audio files to be presented in a different randomised order to each subject, which helped to mitigate some of the effects of subject training. A screenshot of the main test screen is presented in Figure 4.

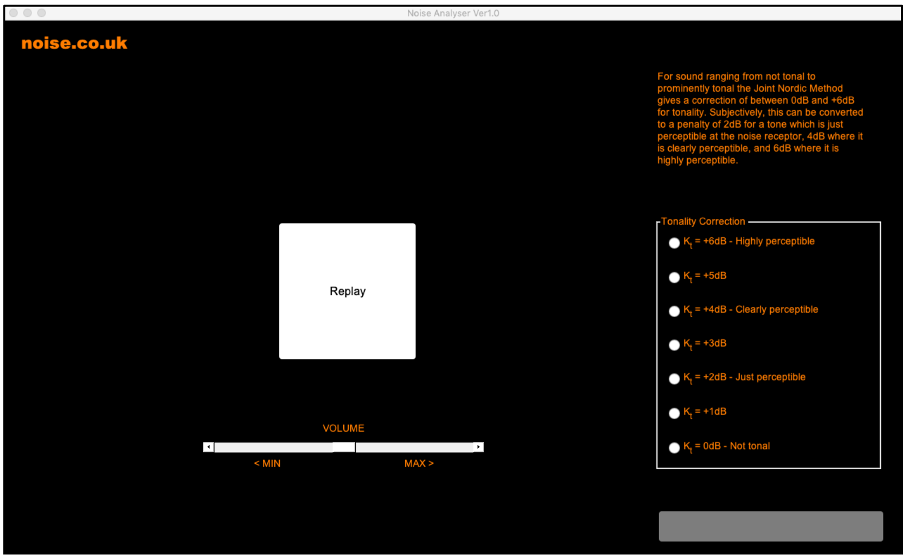

Figure 4 – Screenshot of the test screen presented to the users.

Each audio file automatically started after the 'continue' button from the previous audio file was pressed. The subject was offered the seven possible corrections for not tonal (0dB), 'just perceptible' (2dB), 'clearly perceptible' (4dB) and 'highly perceptible' (6dB) including the intermediate steps. The subject could not advance until one had been selected. The subjects were presented with the recordings at the same gain and could replay the recordings as many times as they liked, being able to change the gain by ±6dB. The options remained greyed out until they had listened to the entire audio recording at least once, and the subjects were not able to return to samples once they had made their selection.

The subjects that took part in the study were all environmental acoustics practitioners that would normally be expected to offer their subjective opinion of tone audibility in the context of a BS 4142 assessment. This included two environmental health officers and 23 noise consultants.

The subjects were not screened in any other way and they were not asked about the state of their hearing. The decision not to do this was taken based on the time available to carry out the user tests but also because the subjects make these judgements about tonality in the course of their job, regardless of the state of their hearing, and none of them stated that they had refrained from making these assessments due to their hearing.

The tests were delivered at the places of work of the test subjects and in most instances a meeting area was provided. In the context of carrying out a BS 4142 type assessment it would be expected that a desktop review of audio recordings would take place in a variety of environments and this variability is considered acceptable for the purposes of this study.

4. RESULTS & DISCUSSION

A comparison of the results from JNMv2 and HMT with the subjective responses has been presented graphically in Figure 5 and Table 1. It should be noted that audio recording (j) of the industrial transformer has been treated as an outlier because of its extreme tonality and has not been included in the regression analysis.

(a) (b)

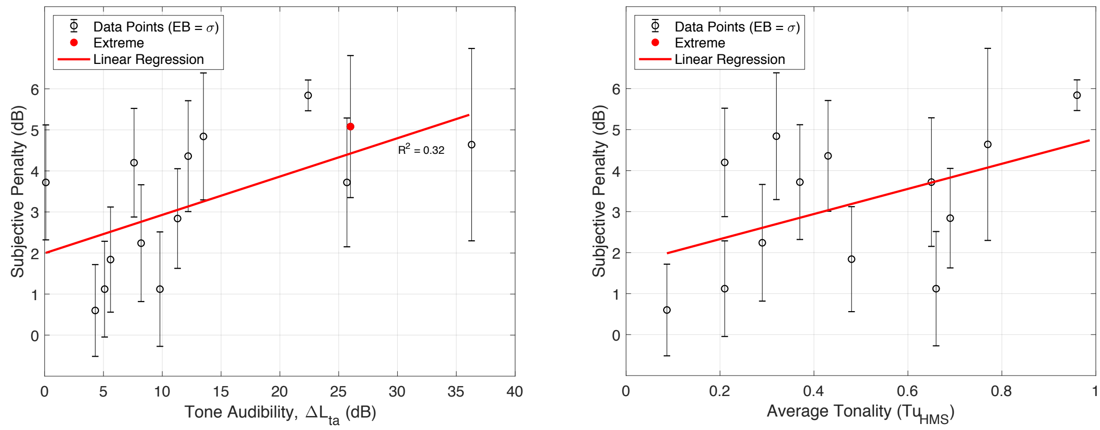

Figure 5: Comparison of the results from JNMv2 and HMT with subjective Responses

It is clear from Figure 5 that the tone audibility analysed to JNMv2 does not agree with the values published by Berry et al. [15] However, the same values were reproduceable by adjusting the frequency resolution of the autospectra individually. This is an example of how two independent assessments of the same sound could obtain different results using JNMv2.

Based on the superficial regression analysis it would appear that JNMv2 provides a slightly better correlation with subjective response than HMT. This is surprising given the level of detail provided by HMT, which is demonstrated in Figure 3 for each recording. Upon reviewing the audio recordings with the aid of sound pressure level and Tu_{HMS} spectrograms, it is easy to convince oneself that HMT is providing a true representation of tonal elements within the industrial sound.

JNMv2 loses detail where tonalities exist for very brief periods of time and where tones are accompanied by elevated levels of proximate narrowband sound. This was clear from audio recording (b) of the pumping equipment, which exhibited beating effects. This resulted in the sound not being considered to be perceptible by JNMv2 despite being deemed clearly perceptible by the subjects and identified as prominent by HMT.

Retrospective reviews make it difficult to understand how all subjects did not give recording (m) of the chimes a maximum +6dB correction for tonality and this strongly indicates that, to some extent, some of the subjects were rating the *pleasantness* of the sound, rather than clinically focusing on *tone audibility*.

HMT detected brief periods of tonality in many recordings that JNMv2 did not. A very good example of this is the truck manoeuvre that briefly features in audio recording (i) of the wind turbine. There is little doubt after reviewing this audio recording that the engine orders of the truck cause the most prominent tonality; however, the lower rating provided by the subjects clearly indicate that this transient feature in the recording was either not considered to be part of the assessment or its transience somehow reduced its subjective prominence.

Rec.	Content	Analysis	
		JNMv2	**HMT**
(a)	**Glassworks** Transient tone with a period of <10s	Tone detected at 299Hz and determined to be highly perceptible	The worst-case elements of the tonality are extracted, focussing on the same tone detected by JNMv2
(b)	**Pumping Equipment** Beating tones	Tone detected at 314Hz, broader beating tone at 630Hz not detected because it is too broad in the average spectra	Tone at 630Hz shown to contain most tonal energy. Output illustrates beating
(c)	**Hydraulic Pump** Continuous tones with strong harmonics	Most prominent tone detected at 400Hz, other higher frequency harmonics present	Same fundamental tone identified as the source of the strongest tonality as JNMv2
(d)	**Wind Turbines** Continuous tones with amplitude modulation	Continuous tone detected at 190Hz but not evaluated as just perceptible	Peaks in tonality detected at same frequency
(e)	**Joiner's Workshop** Continuous tones from plant and transient tones from grinder	Transient tone from grinder detected as most prominent but not considered clearly perceptible	Sound from the grinder dominates the results but is not evaluated as prominently tonal
(f)	**Paper Press** Transient tones from rotating equipment at start of recording.	Highly perceptible tone at 224Hz identified.	Extreme levels of tonality detected at 224Hz at start of recording. Reduces in remainder of recording
(g)	**Forklift Truck** Continuous background tone and varying tone from forklift	Dominant tone at 100Hz detected	Forklift tones between 1-4kHz dominate results
(h)	**Cooling Unit** Strong continuous tones	Dominant and clearly perceptible tone detected at 109Hz	Same dominant tone detected at 109Hz
(i)	**Wind Turbine** Continuous mechanical tone, truck movement in background	Tone at 1kHz detected as most prominent	Engine orders of truck manoeuvre identified as most prominent <200Hz
(j)	**Industrial Transformer** Continuous tone	Highly perceptible magnetostriction tone detected. Side bands not detected	Extreme tonality of entire acoustic feature detected
(k)	**Petrochemical Plant** Beating tones	Most prominent tone detected at 194Hz but not considered highly perceptible	Same tonal content detected but short periods of intensity also detected
(l)	**Ventilation Exhausts** Beating tones	Tone detected at 129Hz but not considered perceptible	Same tonal content detected but short periods of more prominent tonality identified
(m)	**Chimes** Variety of different tones	Multiple highly perceptible tones identified	Multiple prominent tones identified
(n)	**Wall Fan**	Highly perceptible tone identified at 147Hz	Same tonal content detected but short periods of more prominent tonality identified

Table 1 – Comparison of the results for each audio recording

In the audio recordings containing stationary and prominent tones JNMv2 and HMT both identified the same features as the most prominent tones. Good examples of this are audio recording (j) containing an industrial transformer with extreme levels of tonality and audio recording (c) of hydraulic pumps, which contained harmonics that were all identified by both methods.

5. CONCLUSIONS

Since the original decision to adopt JNMv2 as the reference method for BS4142, a new method for evaluating tonality, HMT, has been standardised that allows for full automation without any additional user defined settings. This is likely to have implementation benefits and improve repeatability and reproducibility.

The two methods have been compared using the original recordings used to validate the use of JNMv2 in the UK. Whilst the subjective study had only a very small sample, a superficial regression analysis showed that JNMv2 correlated better with the subjective judgement of a group of environmental. acoustics practitioners. However, it is clear that HMT is faithfully detecting tonality that was present in the audio recordings when they are reviewed with the aid of Tu_{HMS} spectrograms. The subjective responses indicated that the subject group as a whole tended to assess the general pleasantness of the sound and not just the perceived tone audibility. This finding indicates one of two things:

- Subjective evaluation by environmental acoustics practitioners is a poor gauge for tonal content in industrial and commercial sound; and/or,
- The response to tonal sounds is heavily influenced by the presence of other non-tonal elements of an industrial or commercial sound, such as intermittency or impulsivity.

HMT has been demonstrated to identify more tonal features in industrial and commercial sound than JNMv2 without the need individually process each time-signal to create a suitable autospectrum. However, the time and frequency resolution provided by HMT may be providing information that cannot be correlated with subjective responses without first learning more about how the number, duration, regularity and source of tonal industrial and commercial sounds affect human, and by extension, subjective response.

6. ACKNOWLEDGEMENTS

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