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Considering the perception of combined railway noise and vibration as a multidimensional phenomenon

Calum SHARP[1]; James WOODCOCK[2]; David WADDINGTON[3]

[1,2,3] University of Salford, United Kingdom

ABSTRACT

Classical models for predicting annoyance due to combined noise and vibration have typically taken the form of a summation of the magnitudes of the individual stimuli. In this paper, the perception of combined railway noise and vibration will be investigated as a complex multidimensional phenomenon. In a laboratory study, 30 subjects were exposed to 10 combined railway noise and vibration stimuli and asked to make paired comparison judgements of annoyance and judgements of pairwise dissimilarity. A multidimensional scaling analysis on the results revealed a perceptual space of 4 dimensions. Correlations between these perceptual dimensions and objective parameters of the noise and vibration signals were then tested in an attempt to find which, if any, noise and vibration parameters may be related to these perceptual dimensions. Once correlating parameters were found, a multiple regression model was developed to predict total annoyance due to combined railway noise and vibration as a function of these parameters. The final multidimensional regression model has a very strong and significant correlation coefficient (0.99, significant at the 0.001 level) and is able to accurately predict total annoyance as a function of spectral characteristics of the noise and vibration stimuli and the duration of the combined stimulus.

Keywords: Railway, Noise, Vibration I-INCE Classification of Subjects Number(s): 13.4.1, 49.1, 52.4

1. INTRODUCTION

Previous research has shown a disparity in the human response to freight and passenger railway vibration (1). Different relationships, or a source penalty for freight exposures, are required to estimate the human response to freight and passenger railway vibration when the independent variable is a measure of the vibration magnitude alone (i.e. vibration dose value or root mean square acceleration). It is possible that other objective features of the vibration signals from freight and passenger trains contribute to the overall human response to these sources and could help to explain the difference in the response relationships. Identifying these factors, and subsequently including them in a relationship to describe the human response to vibration from freight and passenger railway traffic, could allow the prediction of the human response to railway vibration, without the need to identify the vibration source or apply a source penalty to freight railway vibration exposure.

In addition, environmental vibration very often exists in concert with environmental noise from the same source. When investigating the response relationship to environmental vibration, therefore, it is also important to give consideration to the effects of combined noise and vibration. The perception of noise or sound has widely been accepted as a complex and multidimensional phenomenon. That is, the perception of noise is a function of several perceptual dimensions which relate to objective parameters of the noise (2, 3, 4). This has also been shown to be the case for environmental railway vibration (5). Several laboratory studies have shown that the perception of combined noise and vibration is complex, and that annoyance due to noise is affected by the presence of vibration and vice versa (6, 7, 8, 9), however, no attempt has yet been made to investigate the perception of combined noise and vibration as a multidimensional phenomena. Considering the perception of combined railway noise and vibration as a multidimensional phenomena, may allow the identification of objective features of the noise and vibration signals that can be used to predict the human response with a greater degree of accuracy than those which only take into account the magnitude of noise and vibration exposure.

In order to investigate the perception of combined railway noise and vibration, a subjective laboratory test

[1] c.sharp@edu.salford.ac.uk
[2] j.s.woodcock@salford.ac.uk
[3] d.c.waddington@salford.ac.uk

was designed. The design and methodology of the subjective test will be presented in this paper, followed by an analysis of the perceptual results using multidimensional scaling.

2. SUBJECTIVE TEST DESIGN AND METHODOLOGY

2.1 Measurement methodology

The subjective test involved exposing subjects to combined railway noise and vibration signals in a controlled setting. Since the test required stimuli of noise and vibration in combination, it was necessary to perform new field measurements. These field measurements of noise and vibration were performed over a period of two days in June of 2014 at a location that had previously been identified as a good location for measurements due to the lack of other noise and vibration sources in the area. The measurement location was on the West Coast Mainline in the United Kingdom. Noise was recorded using two AKG C214 microphones, with a sensitivity of 20 mV/Pa and a signal to noise ratio of 81 dB(A), configured in a stereo pair. Vibration was recorded using a Guralp CMG-5TD tri-axial strong motion accelerometer with a sampling rate of 200 Hz and a 100 Hz low pass filter. Both the stereo microphone configuration and the Guralp were positioned 10 m from the near-side rail and 20 m from the far-side rail. Noise and vibration was recorded continuously for several hours, with a note taken of the time and details of each train pass-by so that the signals could later be identified, extracted and labelled from the recordings.

Across the two days of recordings, 9 freight train and 53 passenger train pass-bys were recorded. Due to the nature of the subjective test, the choice of the number of stimuli selected for use in the test was strict. The subjective test took the form of a paired comparison test, which can result in extremely long tests when the number of stimuli is large, or the stimuli are of long duration. Since the nature of the research requires that some of the stimuli will be freight train pass-bys, which typically are of longer duration than passenger trains, it was necessary to significantly reduce the number of stimuli. This was achieved by rejecting any contaminated noise signals and by performing a principle component analysis on the remaining signals in order to obtain a varied stimulus set. The final stimuli set was composed of 7 passenger and 3 freight combined noise and vibration signals.

2.2 Subjective test design

The subjective test took place in the University of Salford's Listening Room, a room which has been specifically designed for subjective testing. It meets the stringent requirements for the subjective assessment of small impairments in audio systems laid out in ITU-R BS 1116-2 (10) as well as the requirements for listening tests on loudspeakers specified by BS 6840-13 IEC 60268-13 (11). The room dimensions are 6.6 m $\times$ 5.8 m $\times$ 2.8 m and the background noise level is 5.7 dB(A).

The noise and vibration reproduction and the user interface for the subjective test were controlled using the Max visual programming language. Stimuli were reproduced as three data channels - stereo audio plus a third channel for the vibration data. Channel data was passed from a Macbook Pro to an RME ADI-8 DS ADAT/TDIF AD/DA converter via an M-Audio Profire Lightbridge interface. Stereo audio was passed directly from the ADAT converter to a pair of bi-amplified loudspeakers (Genelec 8030A). Vibration data was passed to a tactile transducer (BK-LFE-KIT) rigidly mounted to the underside of a chair via a 1000 W amplifier (BKA1000-N). The listener and loudspeakers were positioned to comply with the recommendations of ITU-R BS 1116-2 (10) and EBU 3276 (12). The loudspeakers and listener formed an equilateral triangle with the distance between the two speakers and the distance between the listener and each speaker equal to 2 m. The loudspeakers were placed at a height of 1.2 m and the distance between each loudspeaker and the closest wall was 1.3 m.

The reproduced noise was recorded using a 01 dB Symphonie measurement system combined with an MCE212 microphone with a sensitivity of 50 mV/Pa and a frequency range of 6.3 Hz to 20 kHz. The reproduced vibration was measured using a Svantek SV38 seat pad accelerometer with a sensitivity of 100 mV/(m s^{-2}) and a frequency range of 0.1 to 100 Hz, paired with a Svantek SVAN 957 sound and vibration analyser. Objective descriptors of the 10 noise and vibration stimuli, as reproduced and measured using the subjective test setup, are presented in Table 1, where L_{Aeq} is the A-weighted equivalent continuous sound pressure level, SEL_A is the A-weighted sound exposure level, VDV_b is the W_b weighted vibration dose value and rms_k is the W_k weighted root mean square vibration acceleration. The noise and vibration stimuli were reproduced at levels that are comfortable for the subject, realistic for levels experienced at residential environments within 100 m of a railway line, and commensurate with levels used in previous subjective tests of combined railway noise and vibration (6, 7, 9).

Table 1 – Objective descriptors of the noise and vibration stimuli as reproduced and measured in the subjective test

Stimulus	L_{Aeq} (dBA)	SEL_A (dBA)	VDV_b (m s$^{-1.75}$)	rms_k (m s^{-2})	Duration (s)
1	51.6	62.6	0.0843	0.0305	11.3
2	50.7	59.8	0.0522	0.0217	10.1
3	57.6	68.3	0.0514	0.0219	8.8
4	52.8	62.9	0.0694	0.0288	6.2
5	60.0	70.6	0.0611	0.0258	9.6
6	53.2	64.4	0.0511	0.0202	7.2
7	57.1	68.0	0.0664	0.0258	12.4
8	58.7	72.4	0.0954	0.0226	53.3
9	58.2	74.2	0.0685	0.0140	38.7
10	62.5	75.0	0.0723	0.0230	22.1
Mean	56.2	67.8	0.0672	0.0234	18.0
Standard Deviation	3.9	5.3	0.0145	0.0047	15.8

2.3 Subjective test methodology

Thirty subjects participated in the subjective tests described in this paper. The majority of subjects were members of the Acoustics Research Centre at the University of Salford, and had experience in taking part in various subjective tests. Prior to the start of the test, each subject was provided with written and verbal instructions of how the test would proceed, and were asked to sign a consent form agreeing to take part in the test. The subjects were encouraged to imagine that they were at home, living in the vicinity of a railway line, and that the noise and vibration stimuli would be something that they would experience on a day to day basis. An opportunity was provided for the subjects to ask any questions that they may have and were then asked to sit comfortably on the chair on top of the seat pad accelerometer. Once the subjects had made themselves comfortable, they were encouraged to keep their posture consistent as much as possible throughout the test. The 10 noise and vibration stimuli were then played in order to allow the subjects to familiarise themselves to the stimuli playback and to give them a feel for the levels that they would experience throughout the test. Subjects were then allowed to familiarise themselves with the test user interface with two trial pairs of noise and vibration stimuli. Following these processes of familiarisation and practice, the subjects then embarked on the paired comparison test of 45 pairs, comprised of all possible pairs of the 10 stimuli.

The touch screen user interface was presented on an iPad held by the subject and paired to the Macbook Pro using an ad-hoc wireless network. The subjects were allowed to play stimulus A or B from a pair by touching the respective buttons, and control playback using a play/stop button. The ordering of the pairs was randomised for each subject according to a Ross series (13) which ensures the greatest separation of pairs with common stimuli (14). For each pair, subjects were asked to make two paired comparison judgements:

1. Which of the pair would bother, annoy or disturb you most if you experienced them in your own home?
2. How similar do you perceive the pair to be?

Each subject marked their response to both of these questions via continuous 101 point sliders, which were coded between -0.5 to 0.5 for question 1 and 0 to 100 for question 2.

3. SUBJECTIVE TEST RESULTS

3.1 Single figure perceived annoyance

The data collected during the subjective test allows multiple forms of analyses to be performed. The paired comparison annoyance data can be used to determine single figure perceived annoyance ratings for each railway stimulus and the dissimilarity ratings can be used, through multidimensional scaling, to determine the perceptual dimensions associated with combined noise and vibration. A perceived annoyance model can then be determined by relating the perceived annoyance ratings to the positioning of each stimulus within the perceptual dimensions. A widely used model for the estimation of single figure scores is Thurstone's Case V model. Thurstone's model (15) pioneered psychometrics by utilising Gaussian distributions to analyse paired comparisons. Thurstone's Case V single figure annoyance can be determined by maximising the following log likelihood function (16):

$$LL(\mu|C) = \sum_{i,j} C_{ij} \ln(\Phi(\mu_i - \mu_j)) \quad (1)$$

where μ_i is the estimated single figure annoyance of stimulus i, C_{ij} is a count matrix determined by counting, across all subjects, the number of times stimulus i is chosen as more annoying than stimulus j and Φ is the standard normal cumulative distribution function. Figure 1 shows the single figure perceived annoyance scores as determined by fitting Thurstone's Case V model using maximum likelihood. Although a high annoyance score denotes a relatively high degree of annoyance, the absolute magnitude of annoyance of each stimuli cannot be known. However, it can be stated that, for example, stimulus 8 is more annoying than stimulus 2.

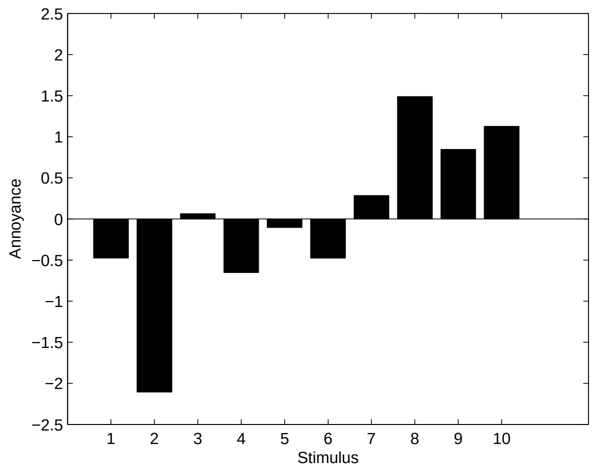

Figure 1 – Single figure perceived annoyance scores for the 10 combined noise and vibration stimuli as determined by Thurstone's Case V model

Referring to Table 1, some preliminary judgements can be made about which types of trains cause relatively higher annoyance. Clearly, the freight trains (stimuli 8, 9 and 10) cause significantly higher annoyance than the passenger train stimuli. This may be due to their extended duration and their above average noise levels (in terms of L_{Aeq} and SEL_A) and vibration levels (in terms of VDV_b). This is in line with the exposure-response relationships developed in previous research, which showed that the annoyance response due to exposure to freight railway vibration is higher than that due to exposure to passenger railway vibration (1).

3.2 Regression models for predicting annoyance due to combined noise and vibration magnitude

Several previous studies have looked at the effects of combined railway noise and vibration on annoyance. In two studies, Howarth and Griffin (6, 7) investigated the effects of combined railway noise and vibration, finding that the overall annoyance response depends on the magnitude of both stimuli, and that a reasonable approximation of the total annoyance caused can be determined from a summation of the effects of the individual stimuli. A study by Paulsen and Kastka (9) found that, though assessment of combined noise and vibration stimuli from a passing tram and a hammermill was dominated by noise, it was also influenced by simultaneously perceivable vibration. To investigate the effects of combined noise and vibration on overall annoyance, multiple linear regression analyses were performed in a similar manner to that employed in the studies mentioned above.

Regression analyses were performed with the Thurstone's Case V single figure annoyance as the dependent variable, and the magnitude of noise alone, the magnitude of vibration alone and the magnitude of noise and vibration combined as the independent variables. The vibration magnitude is quantified by the W_b weighted vibration dose value (VDV_b) and the noise magnitude is quantified by the A-weighted equivalent continuous sound pressure level (L_{Aeq}). The results of these regression analyses are presented in Table 2. Though the relationship between noise magnitude and annoyance has a reasonable correlation, the correlation for the regression model with vibration magnitude alone is poor and the correlation is substantially higher for the regression model with noise and vibration magnitude combined.

The relationship between the measured single figure annoyance and the single figure annoyance predicted by the regression model with combined noise and vibration magnitudes is shown in Figure 2. Though some

Table 2 – Regression models for annoyance predictions based on noise alone, vibration alone and combined noise and vibration

Model	Regression Equation	R^2	p-value
Noise Only	$0.214L_{Aeq} - 12.0$	0.665	< 0.010
Vibration Only	$41.1VDV_b - 2.76$	0.333	*n.s*
Noise & Vibration	$0.191L_{Aeq} + 30.7VDV_b - 12.8$	0.843	< 0.010

scatter is apparent, the relationship shows that a reasonable approximation of total annoyance. caused by combined noise and vibration can be determined from a linear summation of the magnitudes of the individual stimuli. The standardised regression coefficients for the noise and vibration parameters are 0.729 and 0.431 respectively, showing that, for this set of stimuli, variations in noise magnitude have a stronger effect on the total annoyance than variations in vibration magnitude.

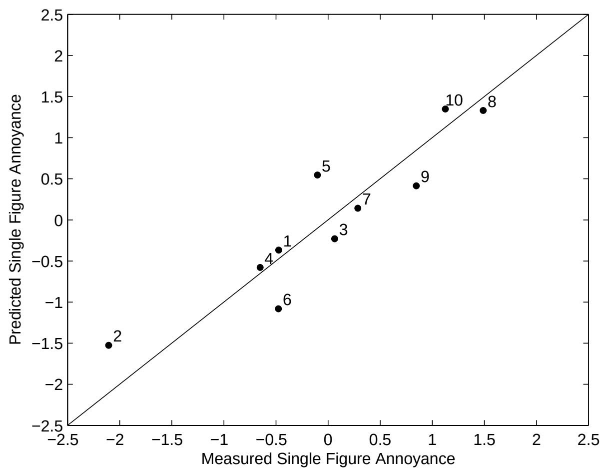

Figure 2 – Comparison of single figure annoyance scores measured during the subjective test and those predicted using the regression model with combined noise and vibration magnitudes ($R^2 = 0.843$, $p < 0.010$)

4. A MULTIDIMENSIONAL MODEL FOR THE PERCEPTION OF COMBINED RAILWAY NOISE AND VIBRATION

4.1 Motivation for the use of multidimensional scaling

Though a reasonable approximation of the total annoyance caused by combined railway noise and vibration can be determined from classic models of annoyance prediction involving summations of the noise and vibration magnitudes, there is still a substantial amount of scatter when comparing measured and predicted single figure annoyance scores. Several studies have shown that the perception of noise is a multidimensional phenomenon that can be explained by multiple objective parameters that make up a perceptual space, using a technique known as multidimensional scaling (2, 3, 4). Likewise, a study by Woodcock *et al.* (5) found that the perception of vibration can be explained by a multidimensional perceptual space using multidimensional scaling. However, no research has yet been performed on the perception of combined noise and vibration using multidimensional scaling. Therefore, in this paper, a multidimensional scaling analysis is performed on the results of the subjective test described above, in the hope of determining the perceptual dimensions that underlay the perception of combined noise and vibration. This knowledge can then be used to develop models that are able to predict overall annoyance as a function of these perceptual dimensions, potentially with a greater degree of accuracy than models based on a summation of the magnitudes of the noise and vibration stimuli alone.

4.2 Multidimensional scaling: theory and application

Multidimensional scaling (MDS) is a method by which measurements of similarity (or dissimilarity) among pairs of objects are represented as distances between coordinates in a multidimensional space. In this paper, MDS will be used as a tool to determine the perceptual dimensions upon which subjects make their judgements of similarity for combined railway noise and vibration stimuli. These dimensions will then be related to objective properties of the noise and vibration stimuli and utilised to develop a perceptual model that explains judgements of dissimilarity and perceived annoyance.

The methods of MDS rely on the related concepts of psychological similarities and psychological distances which are widely used in the field of cognitive psychology. Coomb's theory of data (17) suggests that when subjects are presented with pairs of stimuli and asked to judge how similar they perceive the pair to be, the resulting judgement will take the form of a proximity relation. The quantity of similarity therefore represents a "distance" between two sets of coordinates in a psychological space. When judgements are made between all possible pairings of a set of stimuli, the resulting proximities between stimuli relate to coordinates in a multidimensional psychological space which describes the response of a subject to a set of stimuli. Analysing this multidimensional psychological space can therefore allow the understanding of the structure and dimensions of the psychological space upon which perceptual judgements are made.

MDS is an exploratory technique that can be used to investigate these psychological dimensions that underlie the perception of a set of stimuli. It develops a configuration of a set of stimuli in an m-dimensional space to provide a representation of pairwise (dis)similarities and hence psychological distances between the stimuli. In a paired comparison subjective test, where subjects are presented with every possible pairing (i, j) of n stimuli and asked to judge how dissimilar they perceive the pair to be, a matrix of pairwise dissimilarities, δ_{ij}, can be constructed. This dissimilarity matrix can then be analysed using MDS methods to find the optimum representation of the stimuli in an m-dimensional space, with a large distance, d_{ij}, between stimuli in this space representing a large judged dissimilarity, δ_{ij}. Studying the configuration of the stimulus coordinates in the space, and the dimensions along which they lie, allows the identification of perceptual attributes used by subjects to make their judgements.

4.3 Multidimensional scaling of the subjective test dissimilarity judgements

In the subjective test, as well as being asked to make annoyance comparisons, subjects were asked for each pair of stimuli: "How similar do you perceive the pair to be?". The subject's responses were recorded on a 101 point scale ranging from 0, "Very Similar", to 100, "Very Different". These similarity judgements can be used to determine the perceptual dimensions used by the subject group to make their similarity judgements using the methods of MDS. The MDS models considered in this paper were developed and analysed using the PROXSCAL program in SPSS. The weighted Euclidean individual scaling model was used to preserve inter-subject variability. Since the measured distance data are of the ordinal form, ordinal proximity transformations were applied. For more information on the algorithms used in multidimensional scaling, see (18).

4.4 Considering dimensionality

When building an MDS model it is important to consider the number of dimensions that will make up the MDS configuration. Increasing the dimensionality of an MDS configuration reduces its stress at the cost of increased complexity. A convenient way to determine a reasonable number of dimensions is to create a visual representation of stress as a function of dimensionality in what is known as a "scree" plot. Figure 3 shows such a relationship for the MDS configurations in this paper. Kruskal (19) suggests a reasonable choice of dimensionality is one such that the stress is acceptably small and for which a further increase in dimensionality does not significantly reduce stress. In some cases, an "elbow" in the data representing such a phenomenon can be visually identified. Such an elbow can possibly be identified in Figure 3 when the dimensionality is 4. Certainly the criteria that the stress is acceptably small is met with 4 dimensions, with a stress of 0.020, a value of fit which is quantified by Kruskal (19) as "excellent". In addition, previous research on the multidimensional perception of noise and vibration have utilised models with dimensionality of 3 and 4, giving further confidence that 4 perceptual dimensions is a sensible choice for the MDS configuration (2, 3, 5).

4.5 Relative annoyance model as a function of the perceptual dimensions

With the perceptual dimensions defined by the four-dimensional MDS configuration, an annoyance model representing the single figure annoyance scores as a function of the perceptual dimensions can be derived using multiple linear regression. The result of the multiple linear regression with Thurstone's Case V single figure annoyance scores as the response variable and the coordinates of the combined noise and vibration stimuli on the perceptual dimensions, revealed through the multidimensional scaling, as the predictor variables is shown in Equation 2, where A_p is the predicted single figure annoyance score and D_m is the position of the combined noise and vibration stimulus on the mth dimension.

$$A_p = 0.56D_1 + 0.10D_2 - 0.56D_3 + 0.29D_4 \tag{2}$$

Equation 2 provides a good agreement ($R^2 = 0.831$, $p < 0.050$) between the measured single figure annoyance scores and those predicted using the perceptual dimensions derived from the multidimensional

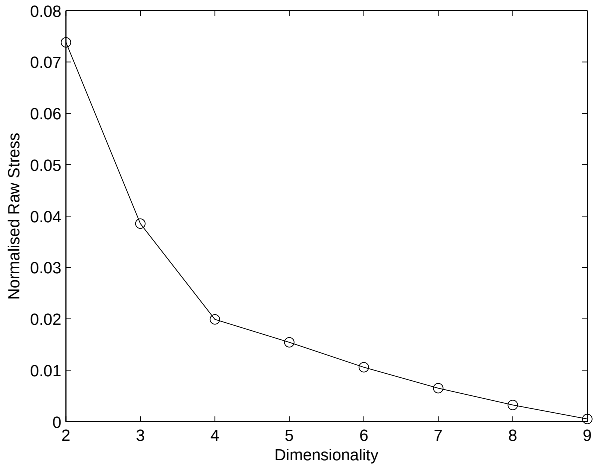

Figure 3 – Normalised raw stress as a function of dimensionality

scaling model. This is an important result of the MDS analysis as it shows that the perceptual dimensions of noise and vibration can be related to the overall annoyance caused by these stimuli. With the perception of noise and vibration described by this small number of perceptual dimensions, it will be possible to find objective parameters of noise and vibration that relate to these perceptual dimensions. If objective parameters can be found which correlate with these perceptual dimensions, a model can then be derived to predict self reported annoyance due to noise and whole body vibration exposure based on objective features of the noise and vibration stimuli.

4.6 Interpretations of the perceptual space

An investigation into correlations between objective descriptors of the noise and vibration stimuli and the perceptual dimensions used to predict self reported annoyance should allow the development of a model that can predict annoyance due to objective parameters of the noise and vibration stimuli. The first step into such an investigation is to calculate objective features of each stimuli. Since MDS is an exploratory technique, no restriction was imposed on the objective features to be calculated and as such a wide range of features which quantify the energy, psychoacoustic, statistical, spectral and temporal characteristics of the noise and vibration stimuli are considered.

Calculated measures of the energy of the noise signal include the peak level (L_{max}), the root mean square (*rms*) pressure, the equivalent continuous sound pressure level (L_{eq}), the sound exposure level (SEL) and the sound pressure level exceeded for 10% of the signal duration (L_{10}). These properties were calculated on both the un-weighted and A-weighted noise signal. Calculated psychoacoustic parameters include the overall specific loudness, the peak specific loudness, the overall sharpness, the peak sharpness, the fluctuation strength, and the roughness. Statistical parameters of the noise signal include the skewness, the kurtosis and the crest factor. Spectral parameters of the noise signal include the spectral centroid and the dominant frequency of the power spectral density (f_{max}). Parameters relating to the duration of the signal include the duration defined by the 3 dB and 10 dB downpoints of the signal, and the duration exceeded by the top 1/5th, 2/5ths, 3/5ths and 4/5ths of the signal's dynamic range. Additionally, two parameters which were found by Trollé *et al.* (4) to correlate with instantaneous annoyance of tram noise were calculated, namely the variance of time-varying A-weighted pressure normalised by root mean square A-weighted pressure (VAP) and a new psychoacoustic index, the total energy of the tonal components within critical bands from 12 to 24 Barks ($TETC$).

Parameters which quantify the energy of the signal include the vibration dose value (VDV), the root mean square (*rms*) acceleration, the equivalent continuous vibration level (V_{eq}), the vibration exposure level (VEL) and the peak acceleration (V_{max}). The modulation depth is defined as the average difference between the maxima and minima of the signal envelope. Statistical parameters of the vibration signals include the skewness, the kurtosis and the crest factor. Spectral parameters of the vibration signals include the spectral centroid and the dominant frequency of the power spectral density (f_{max}) and the *rms* acceleration in the 4 Hz, 8 Hz, 16 Hz, 32 Hz and 64 Hz octave bands, expressed both as an absolute value and as a proportion of the overall *rms* acceleration in the signal. The modulation frequency is defined as the inverse of the average period between the maxima of the signal envelope. Temporal parameters of the vibration signals include the duration defined by the 3 dB and 10 dB downpoints of the signal and the duration exceeded by the top 1/5th, 2/5ths, 3/5ths and 4/5ths of the signal's dynamic range. These parameters were also determined for W_b and W_k weighted accelerations signals where appropriate.

To test which of these objective parameters of the noise and vibration signals may be related to the perceptual dimensions revealed by the MDS configuration, Pearson's correlation coefficients were calculated between each objective parameter determined from the 10 combined stimuli and the position of the stimuli on each of the four perceptual dimensions. The results of these correlation tests led to the following hypotheses:

1. The first perceptual dimension is related to aspects of the noise signal: its energy magnitude, psychoacoustic loudness, "peakiness" (quantified by the kurtosis and crest factor) and psychoacoustic properties of its irregular/continuous character (quantified by *VAP*) and high frequency content (quantified by $TETC$).
2. The second perceptual dimension is related to the duration of the combined stimulus, the energy magnitude and modulation frequency of the vibration signal as well as psychoacoustic parameters of roughness, sharpness and the spectral centroid of the noise signal.
3. The third perceptual dimension is related to aspects of the noise signal: its energy magnitude, duration and dominant frequency.
4. The fourth perceptual dimension is related to characteristics of the vibration signal: its energy magnitude, duration, "peakiness" and the frequency at which peaks occur (quantified by the modulation frequency).

These hypotheses suggests that subjects make their dissimilarity judgements based on separate aspects of the combined noise and vibration stimuli, and in particular that they make their judgements based not only on the energy magnitude of the stimuli but also on spectral and temporal characteristics of the stimuli.

4.7 A new model for predicting annoyance due to combined noise and vibration

In order to develop new annoyance models for combined railway noise and vibration, multiple linear regression models can be created based on what has been learned from the multidimensional scaling analysis and the above hypothesis. This can be achieved by deriving regression models with the Thurstone's Case V annoyance scores as the dependent variable, and all possible combinations of the parameters which exhibit a significant correlation with the perceptual dimensions as the independent variables. All possible combinations that result in a significant regression model ($p < 0.050$) have R^2 values ranging between 0.806 and 0.993. The model with the highest R^2 value is presented in the following equation:

$$A_p = -69.7 + 4.16TETC + 0.054T_{4/5,v} + 0.316L_{10} - 0.273f_{mod} \quad (3)$$

where $TETC$ is the total energy of the tonal components within critical bands from 12 to 24 Barks (4), $T_{4/5,v}$ is the stimulus duration defined by the duration for which the vibration signal exceeds the top 4/5ths of its dynamic range, L_{10} is the sound pressure level of the noise signal exceeded for 10% of its duration and f_{mod} is the vibration modulation frequency. This model captures a greater degree of complexity of the combined stimulus than the model based on only on the combined magnitudes, since it takes into account the duration of the stimulus ($T_{4/5,v}$), the spectral distribution of the noise signal ($TETC$) and the frequency at which peaks occur in the vibration signal (f_{mod}) as well as a measure of the pressure magnitude of the noise signal (L_{10}). A previous MDS analysis of the perception of railway vibration by Woodcock *et al.* (5) found two parameters in common with this model, the vibration duration and vibration modulation frequency, to correlate with the perceptual dimensions discovered in their perceptual test. They also found these two parameters, combined with the *rms* acceleration in the 16 Hz and 32 Hz octave bands, to provide a successful annoyance prediction model. Though Woodcock *et al.* (5) defined the duration by the 10 dB downpoints of the vibration signal, this duration descriptor is very highly correlated with the duration defined by 4/5ths of the dynamic range. A comparison between the Thurstone's Case V single figure annoyance scores measured during the subjective test and those predicted using Equation 3 is shown in Figure 4. Details of the multiple linear regression model are presented in Table 3.

Comparing Figures 2 and 4, it can be seen that the optimal multiple linear regression model (Equation 3) provides a better agreement between the measured and predicted single figure annoyance scores. The R^2 value is higher, the model is significant to a higher level and each regression parameter is significant to a higher level. The new multidimensional model provides a substantial improvement in the accuracy of the prediction of perceived annoyance, accounting for approximately 15% more variance in annoyance scores. This suggests that the perception of combined noise and vibration is a complex multidimensional phenomenon that takes into account not only the energy magnitude of the stimuli but also the duration, frequency content and envelope modulation of the combined stimulus.

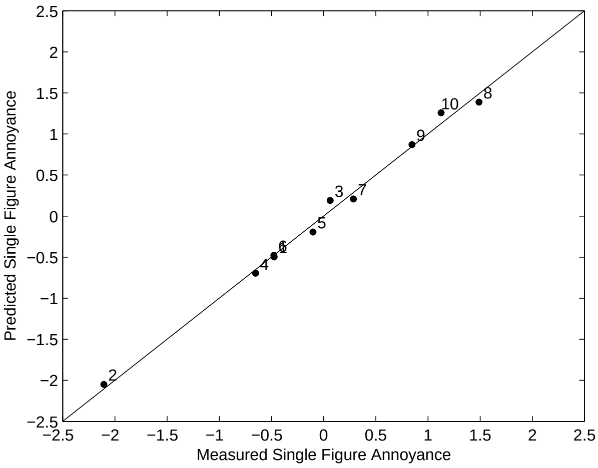

Figure 4 – Comparison of single figure annoyance scores measured during the subjective test and those predicted using Equation 3 ($R^2 = 0.993$, $p < 0.001$)

Table 3 – Parameter estimates and other details of the multiple linear regression model for single figure annoyance as a function of the objective parameters that provide the optimal multiple linear regression

Parameter	β Estimate	Standard Error	Standardised β Estimate	p-value	Overall Model	
Intercept	-69.7	4.36		< 0.001	N	10
$TETC$	4.16	0.464	0.427	< 0.001	p-value	< 0.001
$T_{4/5,v}$	0.054	0.006	0.490	< 0.001	R^2	0.993
L_{10}	0.316	0.032	0.501	< 0.001		
f_{mod}	-0.273	0.064	-0.221	< 0.010		

5. SUMMARY

This paper presents analysis of the results of a subjective test on annoyance caused by combined railway noise and vibration. Using the methods of multidimensional scaling, a multidimensional perceptual model was created from the perceived dissimilarity, measured during the subjective test, of a set of noise and vibration railway stimuli. This multidimensional scaling model revealed four perceptual dimensions upon which subjects made their judgements of dissimilarity, and which can be used to successfully predict the perceived single figure annoyance of the noise and vibration stimuli. These perceptual dimensions can be related to several objective properties of the noise and vibration stimuli which quantify the energy of the noise or vibration signal, the duration of the signal, the spectral distribution of the signal, aspects of the “peakiness” of the signal and psychoacoustic properties of the noise signal.

Multiple linear regression was used to model the predicted single figure annoyance as a function of the objective parameters of the noise and vibration signals that have been shown to correlate with the perceptual dimensions of the multidimensional scaling model. The model with the greatest accuracy of prediction of the perceived single figure annoyance is a function of the spectral distribution of the noise signal, the duration of the stimulus, the energy of the noise signal and the modulation frequency of the vibration signal envelope. This is a complex multidimensional model, suggesting that the perception of combined noise and vibration not only takes into account the magnitudes of the combined stimuli, but also spectral and temporal characteristics of the stimuli. This may explain why previous research has shown that the human response to freight and passenger railway vibration cannot be successfully predicted using a single model based on the magnitude of the vibration exposure alone (1). This new multidimensional model, which takes into account the signal duration, a property which varies significantly between freight and passenger railway signals, may therefore be able to better predict annoyance due to these two sources of environmental noise and vibration.

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