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Title: Annoyance due to railway noise and vibration: comparison and testing of results from the literature

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Annoyance due to combined railway noise and vibration: comparison and testing of results from the literature

Abstract

In situ surveys report some interactions between railway noise annoyance and the level of railway vibration on one hand, and between railway vibration annoyance and the level of railway noise on the other hand. Few studies have been conducted to investigate these interaction phenomena under laboratory conditions and their results are contradictory. During a laboratory experiment, recordings of noise and vibration from two train passages (1 freight train and 1 passenger train) were presented in combination to participants at different noise and vibration levels. The influence of noise level on participants' annoyance due to vibration, as well as the influence of vibration level on participants' noise annoyance was assessed in order to investigate two potential explanations for the contradictory results from the literature. Total annoyance responses due to combined noise and vibration were also analysed to further evaluate the influence of global noise and vibration levels on annoyance. No influence of vibration level on noise annoyance was detected. A weak influence of noise level on vibration annoyance was found, only when the vibration level was high ($L_{V_{eq}} = 116\text{dB}$). Several existing total annoyance models were tested. Among those, perceptual models showed good agreement with the laboratory data.

1 Introduction

Annoyance caused by railway noise has been widely studied, but it is still difficult to predict given the variability of results in the literature. Several studies have established dose-response relationships between sound energy-based indices and the percentage of people annoyed (%*LA*, %*A* or %*HA*; e. g. [1]). The European Commission recommends the use of such relationships for the estimation of annoyance due to railway noise although their predictive quality is quite low ([2]). In various socio-acoustic surveys, railway noise appears to be the least annoying transportation noise and as such receives a bonus in several regulations (e. g. in Germany, [3]). However, this observation is questioned by more recent studies which have shown that ignoring simultaneous vibration exposure limits the accuracy of dose-effect relationships for railway noise (cf. [4] for a review on the topic of combined noise sources). In particular, during *in situ* surveys, the level of vibration due to railway traffic seems to have an influence on noise annoyance (e. g. [5], [6]).

In order to study the influence of noise and vibration levels on annoyance, it is necessary to get insights into the perceptual mechanisms at stake in such combined exposure situations. To that end, few laboratory experiments have been conducted under controlled conditions during the past decades. Moreover, these investigations led to contradictory results.

Two laboratory experiments were conducted by Howarth and Griffin ([7]) and Paulsen and Kastka ([8]). Both used a similar protocol in which combinations of railway noise and vibration were presented to participants (24 participants for Howarth and Griffin and 16 participants for Paulsen and Kastka) at different levels. For each combination, participants were asked to evaluate (1) partial annoyance due to noise heard in the presence of vibration, (2) partial annoyance due to vibration felt in the presence of noise and (3) total annoyance due to combined noise and vibration.

The conclusions of the two studies differ as to the influence of vibration level on noise annoyance. Howarth and Griffin reported that no significant effect of vibration level on noise annoyance was detected while Paulsen and Kastka showed that low noise levels (below 33.4 dB(A)) were more annoying in the presence of strong vibration. Reciprocally, the influence of noise level on vibration annoyance was reported in different ways. According to [7], noise level tends to increase vibration annoyance when vibration level is high (synergistic effect) and to decrease it when vibration level is low (antagonistic effect). On the other hand, Paulsen and Kastka reported that low vibration levels (0.03 mm.s^{-1} and 0.05 mm.s^{-1}) were evaluated more annoying when combined with the highest noise levels (45.4 dB(A) and 59.9 dB(A)).

Comparisons between results of the two studies are difficult because of the differences in the measurement units used to express noise levels (A-weighted sound exposure level, SEL_A for [7] and A-weighted equivalent sound pressure level, L_{Aeq} , [8]) and vibration levels (W_b -weighted average rms acceleration, a_{rms} , and unweighted average rms velocity, v_{rms} , respectively). However, it seems that, for both noise and vibration, the levels used by Howarth and Griffin were higher than those experienced by participants in Paulsen and Kastka’s study (see table A.1 in appendix):

- The lowest noise level in [7] was 54dB(A), which corresponds to the second highest level in [8], taking into account the duration of the freight train passage (24s).
- The lowest vibration level in Paulsen and Kastka’s study was “just perceptible” while the first vibration level in Howarth and Griffin’s experiment (W_b -weighted $a_{rms} = 0.02 \text{ m.s}^{-2}$) was well above the perception threshold (unweighted $a_{rms} \approx 0.015 \text{ m.s}^{-2}$).

A final difference between the two studies is the source of the excitation (freight train in one case, tramway in the other one), which leads to signals with very different frequency contents.

Two initial hypotheses can therefore be put forward to explain the different results obtained by [7] and [8]:

Hypothesis H_1 : The results depend on the ranges of the selected noise and vibration levels. Indeed, stimuli used in [7] and [8] had very different level ranges.

Hypothesis H_2 : The different types of trains used as stimuli (freight train for [7] and tramway for [8]) had an influence on the obtained results. In particular, the spectral content of the vibration signal associated with the freight train ranged between 30Hz and 45Hz while the spectral content of the vibration signal associated with the tramway was wider band (between 16Hz and 60Hz).

An experiment is proposed to test these two hypotheses. Two train recordings (a freight train and a passenger train) whose generated vibrations showed differences in spectral content were presented to a panel of participants. The noise and vibration associated with each passage were presented in combination, at 5 different noise levels and 5 different vibration levels (25 possible combinations for each type of train), so as to cover as much as possible the ranges of noise and vibration levels involved in the two previously mentioned studies (resp. [7] and [8]). Responses of noise annoyance, vibration annoyance and total annoyance were obtained for each combination. Furthermore, the experimental data were also used to evaluate several existing models of total annoyance due to railway noise and vibration and to build a relationship of subjective equivalence between noise annoyance and vibration annoyance.

2 Method

2.1 Participants

Forty adults (23 males, 17 females; mean age = 33.3 years, standard deviation = 14.3 years) participated in the experiment. They were naive concerning the goal of the study and their hearing was evaluated before the experiment by means of an audiogram. All participant had normal hearing abilities. Finally, participants' written consent was required before the experiment began and compensation was paid at the end of the experiment.

2.2 Apparatus

Vibration was generated in the vertical direction by an electrodynamic shaker LDS-V650 (B&K, Nærum, Denmark, www.bksv.com). Noise was reproduced using two Tapco S5 speakers.

Participants sat on a rigid stool attached to the vibration test bench which consisted in a platform secured to the shaker by means of a clamping screw. A guardrail was present around the platform as a precautionary measure for participants to avoid any risk of falling. Participants were instructed not to lean against the guardrail and to keep their backs straight during the experiment. The speakers were placed so that they formed an equilateral triangle with the participant's head, once the participant sat on the stool. Each loudspeaker was 2.25m away from the participant's head. A touch screen was placed in front of the participant to display instructions.

The experiment was carried out in a semi-anechoic chamber. The background noise in the chamber did not exceed 30dB(A) and was mainly due to the cooling system of the vibration test bench power supply.

The frequency response of the vibration test bench was compensated by filtering the vibration signals before their reproduction.

2.3 Stimuli

The noise and vibration due to train passages were recorded simultaneously inside a house located near a railway track in Caluire-et-Cuire (France).

The equipment used for recording vibration signals was provided by Acouphen (Lyon, France, www.acouphen.fr). Measurements were made in the vertical direction using a Piezotronics 393B12 accelerometer (PCB Piezotronics, Depew, NY, www.pcb.com) valid over the frequency range of interest (i.e., between 1Hz and 80Hz for whole body vibration). The noise recordings were made according to the ORTF technique, using a pair of cardioid microphones spaced 17cm apart and oriented to form a 110° angle. This technique allows a stereophonic capture of the train passages to be used with a stereophonic sound reproduction, as it has been done previously in [9] and by other researchers for sound sequences with moving sound sources, considering its good representation and overall quality of reproduction ([10]).

For the experiment presented in this paper, noise and vibration recordings from two train passages were used. Several modifications were applied to the acoustic and vibration signals in order to avoid any potential influence of parameters such as stimulus duration on the results.

2.3.1 Selection of stimuli

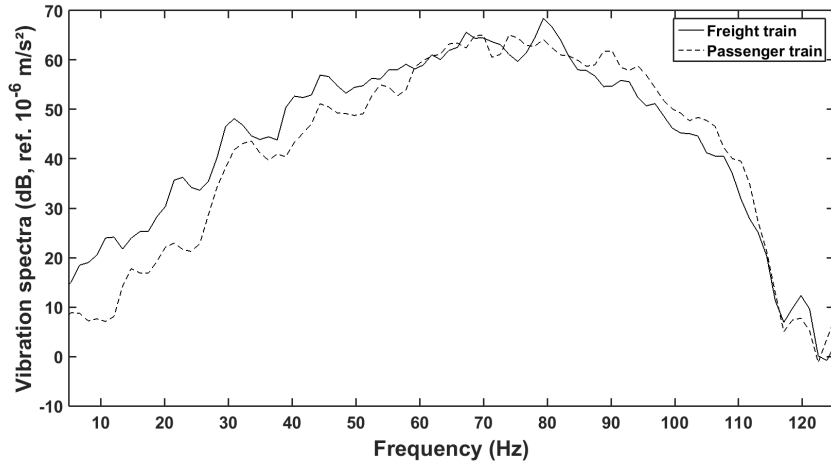


Figure 2.1: Frequency spectra of the selected vibration signals (sampling frequency 512Hz, 512 points Hanning window, overlap 50%).

The H_2 hypothesis was that the frequency content of the vibration signals influenced the results obtained by Howarth and Griffin ([7]) and Paulsen and Kastka ([8]).

In order to test this hypothesis, two vibration signals were selected among 20 recorded passages. The two train passages for which frequency content differences were greatest were a freight train passage and a passenger train passage (see figure 2.1).

This choice of stimuli was relevant due to the nature of the trains. Indeed, Sharp and his colleagues showed that there were significant differences between annoyances caused by vibration generated by freight trains and by passenger train ([11]). The authors explained this result by the differences in average duration between the two types of trains and also by the higher low frequency content in the case of freight trains.

2.3.2 Duration of acoustic and vibration signals

Duration of vibration stimulus seems to influence vibration annoyance. Griffin and Whitham have shown that duration influences vibration annoyance due to sinusoidal vibration signals, up to a duration of 32s ([12]). Recently, Woodcock and his colleagues developed a model of vibration annoyance based on railway vibration recordings, in which the duration of the vibration stimulus is considered as a variable ([13]). Sharp and colleagues also used the duration of the vibration signal in a model of total annoyance due to railway noise and vibration ([14]).

In contrast, several studies have shown that annoyance due to various environmental noises was not influenced by duration (e. g. [15] for stimuli of short duration and [16] for stimuli up to 80s duration). Trollé and his colleagues also indicated that duration does not influence noise annoyance due to tramway recordings from 8s to 25.5s ([17]). Finally, Vallin et al. also found no correlation between noise annoyance responses and stimulus duration for train recordings from 6s up to 47s ([18]).

To avoid any potential influence of duration of the combined noise and vibration stimuli on annoyance, the signals were normalized to a 10s duration. The signal shortening process was performed using the free software Audacity® by truncating portions of the signals. To ensure realism, rise and decay were not deleted and a final check by ear was performed after modification of the signals.

2.3.3 Amplitude fluctuations

Amplitude fluctuations can have an influence on annoyance, at a fixed equivalent level. Indeed, indices such as the maximum A-weighted sound pressure level ($L_{A_{max}}$) or the sound pressure level exceeded during x% of the time (L_x) may be correlated with noise annoyance (e. g. [19], [14]). Similarly, the maximum vibration level has been used as an indicator in some studies (e. g. [20]).

In this study, the indicators used to quantify the energy of noise and vibration signals are the A-weighted equivalent sound pressure level ($L_{A_{eq}}$) and the average rms vibratory acceleration level ($L_{V_{eq}}$). The second step was therefore to limit the amplitude fluctuations in the acoustic and vibration signals so that their energy contents could be represented only by these indicators.

Two gain functions, $G_n(t)$ and $G_v(t)$, were applied to noise and vibration signals, respectively, in order to satisfy criteria related to noise and vibration level fluctuations over time. The criterion for vibration signals was that the median value of the short-term rms acceleration, $L_{V_{eq,125ms}}$, should fall within the interval $90\text{dB} \pm 1.5\text{dB}$. The criterion for noise signals was that the difference between the L_{10} and L_{50} indices should be inferior to the value of 2dB(A) . This step was performed using Matlab®.

2.3.4 Selection of noise and vibration levels

The H_1 hypothesis was that the ranges of variation of noise and vibration levels has an influence on the results obtained in [7] and [8].

To test this hypothesis, the noise and vibration stimuli were presented at 5 different levels:

- The A-weighted equivalent sound pressure levels, $L_{A_{eq}}$, of noise stimuli N_1, N_2, N_3, N_4 and N_5 were 42, 50, 58, 66 and 74dB(A).
- The unweighted vibration levels, $L_{V_{eq}}$, of vibration stimuli V_1, V_2, V_3, V_4 and V_5 were 72 (no vibration), 92, 100, 108 and 116dB. They respectively corresponded to the W_b -weighted vibration dose values, VDV_b , 0.004, 0.022, 0.046, 0.127 and $0.316 \text{ m}\cdot\text{s}^{-1.75}$.

As a result, 25 combinations $N_i V_j$ of noise and vibration could be formed ($i = 1 : 5, j = 1 : 5$) for each of the two selected train passages.

The two lowest sound pressure levels of the Paulsen and Kastka study (32.5 and 33.4dB(A)) were not selected, as they would not have emerged sufficiently from the background noise emitted by the experimental set-up. The equivalent sound pressure level of 74dB(A) may correspond to that of a train passage inside a dwelling with open windows or outside (e. g. terrace, balcony).

The range of variation of vibration levels was selected so as to cover as much as possible the ranges of vibration levels tested by [7] and [8].

2.4 Procedure

The participants' task was to evaluate, for different combinations of noise and vibration, partial noise annoyance, partial vibration annoyance and total annoyance (3 responses per combination). The experiment consisted of 3 sessions A, B and C, each containing:

- Session A: the 25 combinations N_iV_j formed from the noise and vibration signals corresponding to the freight train.
- Session B: the 25 combinations N_iV_j formed from the noise and vibration signals corresponding to the passenger train.
- Session C: the combinations N_3V_3 and N_4V_4 formed from the noise and vibration signals corresponding to the freight train and passenger train (4 combinations in total).

For each combination, participants were asked to provide their responses using three continuous annoyance scales ranging from 0 (“not annoying at all”) to 10 (“extremely annoying”), displayed on the touch screen in front of them. This methodology was validated in a previous laboratory study (cf. [9]).

The participants first performed sessions A and B (random order). Within each session, the order of stimuli was randomized. A training test was performed at the beginning of each of the two sessions. Four combinations of freight (resp. passenger) train noise and vibration were presented to participants during session A (resp. session B): a strong combination (N_5V_5), a weak combination (N_1V_1) and two intermediate combinations (N_1V_5 and N_5V_1).

Session C was conducted following sessions A and B. The purpose of this session was to evaluate the repeatability of the annoyance responses provided during the first two sessions in order to be able to make comparisons, if necessary, of these.

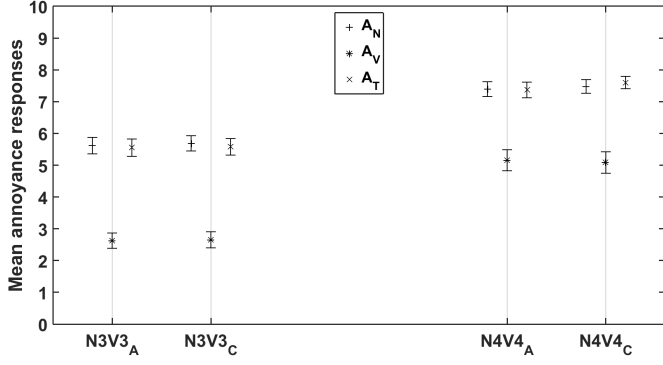
3 Results

3.1 Hypothesis testing

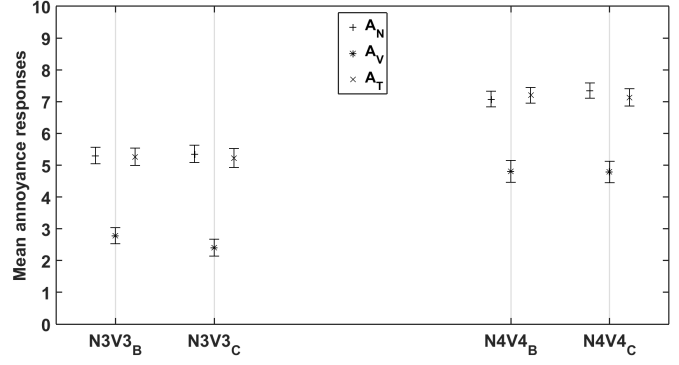
First, repeated-measures analysis of variance (RM-ANOVAs, [21]) were conducted on partial noise annoyance (A_N), partial vibration annoyance (A_V) and total annoyance (A_T).

Six 1-factor RM-ANOVAs were conducted on A_N , A_V and A_T due to the combinations N_3V_3 and N_4V_4 for freight and passenger train passages collected during sessions A and C respectively and during sessions B and C (see figure 3.1). The factor considered was the factor **session** (2 levels). The 6 RM-ANOVAs indicate that the effect of the factor **session** was not significant. The partial annoyance responses as well as the total annoyance responses due to noise and vibration of the freight train and passenger train could therefore be compared during the following analyses.

Three 3-factors RM-ANOVAs were then conducted to evaluate the influence of factors **noise and vibration** (5 levels per factor) as well as factor **train** (2 levels) on partial annoyance due to noise (A_N), partial annoyance due to vibration (A_V) and total annoyance (A_T).



(a)



(b)

Figure 3.1: Mean annoyance responses and associated standard errors due to combinations N_3V_3 and N_4V_4 , collected: (a) during sessions A and C (freight) and (b) during sessions B and C (passenger train).

Effect of noise and vibration levels on A_N

The effect of the **noise level** on A_N was significant [$F(4, 156) = 484.636, p < 0.001$]. The percentage of variance η^2 explained by the factor **noise level** was 66.1%, giving information about the great size of the effect. The effect of the **vibration level** on A_N was not significant [$F(4, 156) = 0.522, p > 0.71$]. No significant effect of the interaction between factors was observed.

Effect of noise and vibration levels on A_V

The effect of the **noise level** on A_V was not significant [$F(4, 156) = 0.791, p > 0.53$]. The effect of the **vibration level** on A_V was significant with a large effect [$F(4, 156) = 455.249, p < 0.001, \eta^2 = 70.0\%$]. The effect of the interaction between factors **noise and vibration** on A_V was significant, although the effect size was very small [$F(16, 624) = 3.134, p < 0.001, \eta^2 = 0.36\%$]. No effect of the interaction between other factors was detected.

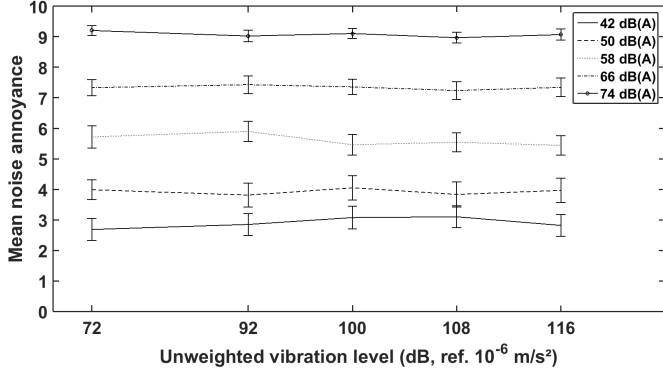
The mean noise annoyance responses (sessions A and B aggregated) as a function of vibration level, and mean vibration annoyance responses (sessions A and B aggregated) as a function of noise level, are presented in figure 3.2.

Effect of noise and vibration levels on A_T

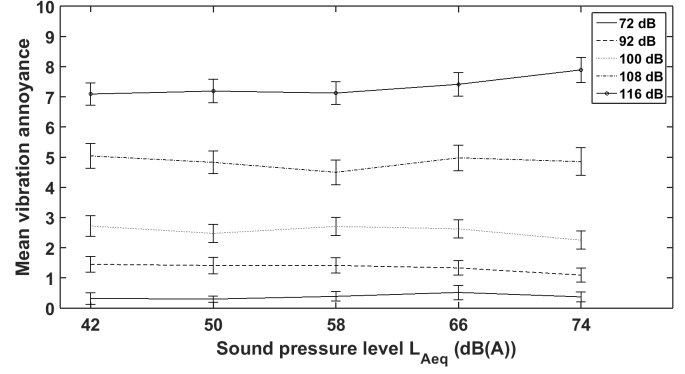
The effect of the **noise level** on A_T was significant with a large effect [$F(4, 156) = 297.128, p < 0.001, \eta^2 = 40.1\%$]. The effect of the **vibration level** on A_T was significant with a smaller effect [$F(4, 156) = 98.898, p < 0.001, \eta^2 = 11.1\%$]. The effect of the interaction between the factors **noise and vibration** on A_T was significant [$F(4, 156) = 22.339, p < 0.001, \eta^2 = 3.4\%$]. No effect of the interaction between other factors was detected.

Effect of the train type on annoyance

The effect of the factor **train** on A_N, A_V and A_T was not significant: [$F(1.39) = 3.913, p > 0.055$], [$F(1.39) = 1.011, p > 0.32$] and [$F(1.39) = 3.847, p > 0.056$] respectively.



(a)



(b)

Figure 3.2: Mean partial annoyance responses and associated standard errors due to (a) noise as a function of vibration level, (b) vibration as a function of noise level.

3.2 Predictive quality of total annoyance models

The literature provides several models of total annoyance due to railway noise and vibration that need to be evaluated in terms of predictive quality. These models are of two kinds: in psychophysical models the independent variables are the global noise and vibration levels whereas in perceptual models the variables are the partial annoyances due to noise and vibration.

Psychophysical models

The first model was proposed by Howarth and Griffin ([22]) and was based on the use of Stevens' power law for both modalities:

$$\psi = 22.7 + 243 \cdot \phi_v^{1.18} + 0.265 \cdot \phi_s^{0.036} \quad (1)$$

where the variable ϕ_v corresponds to the W_b -weighted vibration dose value (VDV_b) and where $\log_{10}(\phi_s)$ is assimilated to the A-weighted Sound Exposure Level or SEL_A .

Later on, the same authors proposed a second model ([7]) in which coefficients were relatively close to the previous ones:

$$\psi = 15.9 + 260 \cdot \phi_v^{1.04} + 0.167 \cdot \phi_s^{0.039} \quad (2)$$

In these two studies, it was specified that the addition of an interaction term $\phi_v^{n_v} \cdot \phi_s^{n_s}$ did not significantly improve the correlation coefficient.

Paulsen and Kastka ([8]) proposed a third model, based on the mean rms vibration velocity, v_{rms} , and on the equivalent sound pressure level, L_{Aeq} , in which the total annoyance was calculated by a multiple linear regression, and is expressed:

$$y = -0.15 + 1.58 \cdot \log_{10}(v_{rms}) + 0.11 \cdot L_{Aeq} \quad (3)$$

Finally, Sharp ([23]) proposed a fourth model in which the independent variables were the W_b -weighted VDV index and the L_{Aeq} index. The model obtained by means of a multiple linear regression is as follows:

$$A_T = -12.8 + 30.7 \cdot VDV_b + 0.19 \cdot L_{Aeq} \quad (4)$$

Perceptual models

Lee and Griffin ([24]) established two perceptual models, based on the perceptual models from the literature dealing with total annoyance due to combined noise sources. In the first model, called the independent effects model, the contributions of partial noise annoyance (A_N) and partial vibration annoyance (A_V) are summed:

$$A_T = 2.742 + 0.25 \cdot A_V + 0.54 \cdot A_N \quad (5)$$

In the second model, called the dominance model or strongest component model, only the most important partial annoyance is considered as the independent variable:

$$A_T = 2.179 + 0.78 \cdot A_D \quad (6)$$

where $A_D = \max(A_N, A_V)$.

The predictive quality of the above-mentioned models was evaluated using the data of the current study. Total annoyance, A_T , was predicted using each model and the correlation coefficients between this predicted annoyance and the measured one are presented in table 3.1.

Table 3.1: Values of correlation coefficient $r_{Pearson}$ corresponding to the linear regressions between the values of A_T predicted by the models from the literature and the values of A_T measured during the experiment. * : $p < 0.001$.

	Model	$r_{Pearson}$
Psychophysical models	Howarth and Griffin [22]	0.76*
	Howarth and Griffin [7]	0.80*
	Paulsen and Kastka [8]	0.91*
	Sharp [23]	0.82*
Perceptual models	Lee and Griffin [24] (independent effects)	0.96*
	Lee and Griffin [24] (dominance model)	0.98*

3.3 Subjective equivalence relationship determination

Based on the partial noise and vibration annoyance responses collected during the experiment, one can establish a subjective equivalence relationship between noise levels and vibration levels resulting in equivalent annoyance.

For stimuli of various kinds, Stevens' law links the perceived intensity of a stimulus, ψ , to its physical intensity, ϕ , by the following relationship:

$$\psi = k \cdot \phi^n \quad (7)$$

where k and n are constants ([25]).

For noise and vibration stimuli, one can then write $\psi_s = k_s \cdot \phi_s^{n_s}$ and $\psi_v = k_v \cdot \phi_v^{n_v}$.

If one assumes that the annoyance due to noise (resp. vibration) is directly related to the perceived intensity of the noise (resp. vibration) stimulus, the two following equations can be obtained:

$$\log_{10}(A_N) = a_s + b_s \cdot L_{A_{eq}} \quad (8)$$

$$\log_{10}(A_V) = a_v + b_v \cdot L_{V_{eq}} \quad (9)$$

where $a_s = \log_{10}(k_s)$, $a_v = \log_{10}(k_v)$, $b_s = \frac{n_s}{20}$ and $b_v = \frac{n_v}{20}$, and where $L_{A_{eq}} = 20 \cdot \log_{10}(\phi_s)$ and $L_{V_{eq}} = 20 \cdot \log_{10}(\phi_v)$.

Assuming that the perceived intensity of the noise and vibration stimuli is equal, a relationship between noise and vibration levels is given by:

$$L_{A_{eq}} = a + \frac{n_v}{n_s} \cdot L_{V_{eq}} \quad (10)$$

where a is a constant.

To experimentally determine the subjective equivalence relationship corresponding to the data collected during the experiment, linear regressions were performed between the independent variable $L_{V_{eq}}$ and the mean values of the dependent variable $\log_{10}(A_V)$, obtained from the vibration annoyance responses given by participants exposed to each of the 5 noise levels.

Table 3.2 presents the mean A_V responses obtained for each combination of noise and vibration levels. The results of the linear regressions are presented in Table 3.3.

Table 3.2: Mean vibration annoyance responses A_V collected for each combination $N_i V_j$.

	A_V				
	$V_1 = 72$	$V_2 = 92$	$V_3 = 100$	$V_4 = 108$	$V_5 = 116\text{dB}$
$N_1 = 42$	0.32	1.45	2.72	5.04	7.09
$N_2 = 50$	0.3	1.41	2.48	4.83	7.19
$N_3 = 58$	0.39	1.41	2.7	4.5	7.12
$N_4 = 66$	0.52	1.33	2.63	4.98	7.41
$N_5 = 74 \text{ dB(A)}$	0.37	1.09	2.25	4.85	7.89

For each of the 5 noise levels, the vibration level giving rise to a vibration annoyance equivalent to the specific noise annoyance due to the noise level alone was calculated. From equation (9), it was obtained as:

$$L_{V_{eq,estim}} = \frac{\log_{10}(A_{N_i V_1}) - a_v}{b_v} \quad (11)$$

where $A_{N_i V_1}$ represents the specific noise annoyance due to the noise level N_i without the presence of vibration (vibration level V_1).

Table 3.3 shows the equivalent vibration levels calculated from the measured data.

According to the equation (10), a linear regression between the independent variable $L_{V_{eq,estim}}$ and the dependent variable $L_{A_{eq}}$ leads to the following subjective equivalence relationship ($r = 0.99$, $p = 0.001$):

$$L_{A_{eq}} = -134.5 + 1.7 \cdot L_{V_{eq,estim}} \quad (12)$$

Table 3.3: Coefficients a_v and b_v of the linear regressions between $\log_{10}(A_V)$ and $L_{V_{eq}}$ yielding the vibration level $L_{V_{eq,estim}}$ equivalent in terms of annoyance to each noise level $L_{A_{eq}}$. * : $p < 0.001$.

		A_V				
$L_{A_{eq}}$	$A_{N_{N_i}V_1}$	Intercept	Slope	$r_{Pearson}$	$L_{V_{eq,estim}} = \frac{\log_{10}(A_{N_{N_i}V_1}) - a_v}{b_v}$	(dB)
(dB(A))		(a_v)	(b_v)			
42	2.7	-2.73*	0.031*	0.99*		100.8
50	4	-2.80*	0.032*	0.99*		106.7
58	5.7	-2.50*	0.029*	0.99*		112.05
66	7.3	-2.28*	0.027*	0.99*		116.0
74	9.2	-2.72*	0.031*	0.99*		118.7

4 Discussion

4.1 Verification of H_1 hypothesis

The studies conducted by Howarth and Griffin ([7]) and by Paulsen and Kastka ([8]) both examined the influence of the global level on railway noise and vibration annoyances. But noise and vibration levels used in these two studies were significantly different, with the levels involved in Paulsen and Kastka's experiment being lower than those involved in Howarth and Griffin's study.

The H_1 hypothesis was that these experimental choices explained the different results between the two studies.

During the experiment presented in this paper, the ranges of noise and vibration levels approximated the ranges covered by the two studies. If the H_1 hypothesis was verified, then the results of Howarth and Griffin and those of Paulsen and Kastka should have been found, at high levels for the first study and at low and moderate levels for the second one.

The results of the 3-factor RM-ANOVA conducted on noise annoyance responses did not report any effect of the **vibration level** on noise annoyance. These results are consistent with those obtained by Howarth and Griffin ([7]). Similar results were also observed in a previous investigation where the tested noise levels ranged from 44 to 62 dB(A) and the tested vibration levels from 90 to 100 dB (ref. $10^{-6} m.s^{-2}$ [9]). Yet, several studies have reported an effect of vibration level on railway noise annoyance. In laboratory, Morihara and Matsumoto ([20]) also found that vibration level influences noise annoyance felt during a thinking or a reading activity for maximum noise levels, $L_{A_{max}}$, ranging from 50 to 70 dB(A) and for vibration levels ranging from 65 to 75 dB (ref. $10^{-5} m.s^{-2}$).

However, it seems that this effect only occurs when the noise level is low. In particular, Paulsen and Kastka reported that vibration level influenced noise annoyance for noise levels less than or equal to 33.4 dB(A). As the background noise level during their experiment was close to this value ($L_{A_{eq}} = 32.5$ dB(A)), a question may arise whether this equipment noise level may affect annoyance responses due to low levels of railway noise. In the current study, choice was made to test higher levels of railway noise in order to mask the noise from the cooling system due to the vibration test bench power supply.

The results of the 3-factor RM-ANOVA conducted on vibration annoyance responses did not report any effect of the **noise level** on A_V . On the other hand, a significant effect of the interaction between noise and vibration levels was detected.

A t-test conducted between A_V due to the combination N_1V_5 and A_V due to the combination N_5V_5 yields a significant difference ($p < 0.01$). At high vibration level ($L_{V_{eq}} = 116\text{dB}$), the average response of A_V goes from 7.1 when the noise level is low ($L_{A_{eq}} = 42\text{dB(A)}$) to 7.9 when the noise level is high ($L_{A_{eq}} = 74\text{dB(A)}$) (see figure 3.2)).

Cohen's d is an estimate of the effect size shown by a t-test. According to this estimation, the effect of the noise level on annoyance due to the fifth vibration level V_5 is relatively small: $d = 0.42$. Indeed, Cohen specifies that an effect is considered weak when $d = 0.2$ and that it can be considered as average from $d = 0.5$ ([26]).

The result of the t-test is consistent with results presented in [7]. This study showed that a synergistic effect of noise level on annoyance due to railway vibration may occur when the vibration level is high. This result is supported by the significant effect of the interaction of noise and vibration levels on A_V , which could be related to the occurrence of a noise level effect above a certain vibration level.

There is a lack of consensus in the literature regarding the effect of vibration level on noise perception (and in particular on noise annoyance). On the other hand, the effect of noise level on vibration perception is more widely accepted (e. g. [6] and [27], *in situ*). In the laboratory, Parizet and Marpe ([28]) showed that the perceived intensity of a sinusoidal vibration signal (28Hz) was significantly influenced by the presence of a tonal sound signal (28Hz).

4.2 Verification of H_2 hypothesis

Howarth and Griffin ([7]) and Paulsen and Kastka ([8]) studied the influence of the global level on A_V , A_N and A_T due to train passage recordings. The stimuli involved in these two studies were very different in nature: a freight train passage was presented to participants in the first case, and a tramway passage in the second one. In addition, the vibration associated with the two cases had very different frequency contents. The energy for the freight train vibration was mainly contained in the range [30Hz : 40Hz]. In the case of the tramway, the vibration spectrum was wider band ([16Hz : 60Hz]) with several energy peaks at 16Hz, 32Hz and 50Hz. The H_2 hypothesis was that these differences in frequency content influenced the results, explaining the differences between the two studies.

During the experiment presented in this paper, two passages of different natures and frequency contents were presented to the participants. Both stimuli had a wide band vibration spectrum (between 10Hz and 120Hz), but in the case of the freight train, the energy contained in the low frequencies (between 16Hz and 30Hz) was higher than in the case of the passenger train (about 10dB difference, see figure 2.1). If the H_2 hypothesis was verified, then the participants' responses should have been affected by the stimulus presented to them.

The results obtained in the case of the freight train and the passenger train are similar. The H_2 hypothesis is therefore not verified.

One explanation may be that the vibration spectra did not show enough differences, compared to those found between the vibration stimuli used by [7] and [8], to generate a difference in the results. Indeed, the stimuli used in this study were both extracted from recordings carried out inside the same dwelling. Although differences exist between the spectral contents of the freight train and passenger train vibration, both signals contained energy over a common range [16Hz : 120Hz].

Using measurements carried out at several sites, Sharp and his colleagues have shown that vibration emitted by a freight train are generally perceived as more annoying than those emitted by a passenger train, at equivalent average rms acceleration ([11]). This result was explained by differences in average duration (freight trains being generally longer) but also in frequency content (freight trains being generally heavier and therefore showing more energy at lower frequencies according to the authors).

4.3 Total annoyance models

Four psychophysical models and two perceptual models from the literature were evaluated in terms of predictive quality, using annoyance responses from the experiment.

For psychophysical models, the model providing the best predictive quality was the one established by Paulsen and Kastka ([8]) based on the average rms vibration velocity index.

Both perceptual models proved to be equally accurate. Other studies on noise annoyance due to combined noise sources have reported highest quality of perceptual models compared to psychophysical models, in terms of model fit with *in situ* data (e. g. [29], [30]) and in terms of predictive quality for models tested using *in situ* data (e. g. [31]).

4.4 Subjective equivalence relationship

A relationship of subjective equivalence between noise annoyance and vibration annoyance was built in order to compare our results to those of other similar experiments.

The coefficient 1.7 obtained in equation (12) is quite close to what could be expected from existing data. Indeed, the exponent of Stevens' power law for loudness is known to be close to 0.6 (when physical intensity is expressed in Pascal, [32]).

In the meantime, the exponent for subjective intensity of whole-body vertical vibration is often reported as close to 1 (e. g. [33], [34]).

Therefore the ratio $\frac{n_v}{n_s}$ is equal to $\frac{1}{0.6} \approx 1.67$ which is very close to the value appearing in equation (12).

In order to compare the constructed subjective equivalence relationship with those obtained in the literature, it was necessary to establish a linear regression between the variable $L_{A_{eq}}$ and the estimated equivalent vibration levels expressed in terms of W_b -weighted vibration dose value (VDV_b) (see table A.2 in appendix).

This regression ($r = 0.99$, $p = 0.001$) yielded the following subjective equivalence relationship:

$$L_{A_{eq}} = 89.7 + 40.4 \cdot \log_{10}(VDV_{b,estim}) \quad (13)$$

Huang and Griffin ([35]) conducted a study to determine the effects of noise and vibration levels on noise and vibration annoyances, resulting in the following subjective equivalence relationship ($r = 0.99$, $p < 0.001$):

$$L_{A_{eq}} = 84.4 + 32.6 \cdot \log_{10}(VDV_b) \quad (14)$$

The authors also presented the relationships obtained by different studies which used various acoustic and vibration signals (not only railway traffic recordings):

- The values of the intercept range from 51.9 ([8]) to 93.6 ([36]).
- The values of the slope vary between 14.4 ([8]) and 40.0 ([37]).

The coefficients of the relationship (13) are therefore consistent with those from the literature.

5 Conclusion

The objective of this work was first of all to study the influence of the global level (expressed by $L_{A_{eq}}$ for noise and $L_{V_{eq}}$ for vibration) on partial noise annoyance (A_N), partial vibration annoyance (A_V) and total annoyance (A_T). The purpose of the experiment was also to get clues about the origins of the differences between the findings of two studies from the literature that previously addressed the same topic.

Two different train passages (1 freight train and 1 passenger train) were presented to participants in the form of combinations of noise and vibration at different levels. These passages have been selected from a set of recordings in order to maximize the differences in vibration frequency content. A similar modulation frequency for the two vibration signals was also a selection criterion.

Regardless of the train passage considered, it seems that participants assessed the annoyance due to the noise without taking care of the level of vibration. Partial vibration annoyance responses were slightly influenced by noise level, only when the vibration level was at least equal to 116dB. These results were also found by Howarth and Griffin ([7]) but not by Paulsen and Kastka ([8]).

From the current study, it seems that the different ranges of noise and vibration levels used by Howarth and Griffin and by Paulsen and Kastka can explain the differences observed between their results. The use of different trains and in particular the differences of vibration frequency content associated with the train passages, does not seem to have been the cause of the different results in their studies. Nevertheless, further laboratory experiments should be carried out to test the influence of vibration frequency on annoyance, using vibration recordings with more variability.

In the context of the signals used in the current work, noise was generally the most annoying component. Indeed, the variance of the total annoyance responses explained by noise was 40.1% compared to only 11.1% explained by vibration. The strongest component model (or dominance model) proposed in the literature allowed a good prediction of total annoyance due to combined railway noise and vibration.

A Appendix

Table A.1: Noise and vibration levels tested by Howarth and Griffin ([7]) and by Paulsen and Kastka ([8]), background noise levels and stimulus duration for both studies.

	Index	Howarth and Griffin	Index	Paulsen and Kastka
Stimulus duration		24 seconds		16 seconds
Tested noise levels	SEL_A	54, 59, 64, 69, 74 and 79 dB(A)	$L_{A_{eq}}$	32.5, 33.4, 45.4 and 59.9 dB(A)
Tested vibration levels	a_{rms} (W_b weighting)	0.02, 0.03, 0.04, 0.06 and 0.09 $m.s^{-2}$	v_{rms} (no weighting)	0.03, 0.05, 0.12 and 0.31 $mm.s^{-1}$
Background noise level	SEL_A	42 dB(A)	$L_{A_{eq}}$	32.5 dB(A)

Table A.2: Coefficients a_v and b_v of the linear regressions between $\log_{10}(A_V)$ and $\log_{10}(VDV_b)$ yielding the vibration level $\log_{10}(VDV_{b,estim})$ equivalent in terms of annoyance to each noise level $L_{A_{eq}}$. * : $p < 0.001$.

A_V					
$L_{A_{eq}}$	$A_{N_{N_i V_1}}$	Intercept	Slope	$r_{Pearson}$	$\log_{10}(VDV_{b,estim}) = \frac{\log_{10}(A_{N_{N_i V_1}}) - a_v}{b_v}$ (dB)
(dB(A))		(a_v)	(b_v)		
42	2.7	1.31*	0.72*	0.99*	-1.22
50	4	1.31*	0.73*	0.99*	-0.96
58	5.7	1.24*	0.67*	0.99*	-0.73
66	7.3	1.22*	0.63*	0.99*	-0.56
74	9.2	1.29*	0.72*	0.99*	-0.45

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