Influence of congruent audio tones on pleasantness ratings for vertical whole-body vibration on an aircraft seat bench

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Introduction

Among other factors, noise and vibration are two major physical factors that can reduce the perceived comfort of passengers in an aircraft during flight [1, 2]. In order to improve the comfort, it is therefore important to understand the influence of sound and vibration to prioritize the modality with the highest importance. Recent studies addressed interaction effects of sound pressure level and vibration level on the perceived discomfort in turboprop driven aircraft, commercial vehicles and helicopters. Aggarwal et al. [3] showed that the discomfort ratings of combined sound and vibration using synthesized noise and vibration of a turboprop aircraft increase with increasing sound pressure level as well as with vibration level. Therefore, they proposed an additive linear prediction model based on sound level and vibration magnitude without an interaction term. In a study on annoyance ratings in commercial vehicles, Maravich and Altinsoy [4] proposed a prediction model based on sound pressure level and vibration level differences including a multiplicative interaction term between the two. Delcor et al. [5] proposed a prediction model for vibro-acoustic discomfort in helicopters with an interaction term, penalizing the discomfort when one modality is dominant.

Besides the level of vibration, and thus the perceived intensity, the vibration frequency might also have an impact on the perception and assessment because different vibration frequencies were shown to be associated with quite different sensations [6]. Similarly, a change in the sound character by adding a prominent tonal component can increase the annoyance or unpleasantness of a sound [7, 8]. Therefore, this study investigates pleasantness and tolerability ratings for sinusoidal whole-body vibrations in the vertical direction in the presence of an acoustic stimulus, consisting of a synthetic broadband aircraft cabin noise either with an additional acoustic tone at the same frequency as the vibration signal or without. The relationship between pleasantness and tolerability ratings was explored to see whether the two concepts differ in their meaning when rated in the laboratory.

Methods

Experimental setup

The experiments were performed in the vibration laboratory of the Carl von Ossietzky University in Oldenburg. A vibration platform with a typical economy class aircraft seat bench mounted onto it was used to produce sinusoidal vibration in the vertical direction (Figure 1). The backrest and seat surface of the seat were padded and covered with fabric. The armrests are made of rather solid plastic. Since the study was designed to specifically investigate the influence of the aircraft cabin seat on the perception of whole-body vibration, foam was placed on the platform grid to minimize the direct vibration transmission via the feet.

Figure 1: Vibration platform with the economy class seat bench.

The vibration signals were synthesized using MATLAB R2019a (MathWorks) and played back over an audio interface (RME, Fireface UC). The analog line level signals were amplified with a DC-capable power amplifier (Tira, BA500), which was driving an electrodynamic shaker (Tira, TV52120) placed underneath the vibration platform. The vibration signals were measured using an accelerometer (PCB, Type 356A15) mounted at the seat rail behind the right leg. To ensure that each subject was exposed to the same acceleration levels in the vertical direction, an individual calibration was performed before the rating experiment was carried out for all used

Frequency (Hz)	L_{eq} (dB)	$L_{A,eq}$ (dB(A))	Loudness (sone)
no tone	81.4	73.5	33.6
35	88.0	74.0	34.2
42	87.0	74.0	34.4
50	86.5	74.0	34.9
75	82.0	74.0	35.6

Table 1: Sound pressure levels, loudness (ISO 532-1) values for the different configurations without and with tones having the same frequency like the vibration signal embedded in the audio stimuli.

vibration signals. The audio signals in the experiments were also generated in MATLAB and played back using the headphone output of the audio interface and open headphones (Sennheiser, HD 650).

Stimuli

The vibro-acoustic stimuli consisted of sinusoidal whole-body vibrations in the vertical direction and an acoustic signal, consisting of a synthetic broadband aircraft cabin noise either with an acoustic tone at the congruent frequency or without the tone.

The vibration signals were chosen from one out of four frequencies (35, 42, 50, 75 Hz) and two different vibration levels (102 and 114 dB(vib), re. $1\mu m/s^2$) measured at the seat rail. Both vibration levels were well above the perception threshold for whole-body vibrations on that seat, which were determined in a prior study [9].

The acoustic signal was based on a synthetic broadband noise signal that was presented dichotically. It was derived from a typical cabin noise spectrum without prominent tones. When a congruent tone was included, then the tone-to-noise ratio was always 15 dB in the corresponding third octave band, which rendered the tone clearly audible. The overall level of the acoustic stimulus was always kept constant at 74±0.5 dB(A). The addition of a tone barely affected the overall A-weighted level and calculated loudness of the audio signals listed in Table 1. The stimuli had a duration of 15 s including a 1 s long fade-in and fade-out for the vibration signal and a 0.5 s fade-in and fade-out for the acoustic signal.

Procedure

The subjects rated the pleasantness (in German "Angenehmheit") and tolerability (in German "Erträglichkeit") of the perceived vibration in separate experiments on different days. For each experiment, a single participant sat in the middle seat of the seat bench, wearing headphones, and was requested to imagine a two hour long economy class flight for the ratings. The range of the stimuli was introduced to the participants in an orientation phase before the ratings started. The ratings took place on a verbally anchored 9-point scale with five labeled categories, shown as English translations in the results figure 2, and four unlabeled intermediate categories. The results presented here were part of a larger study and stimulus set with further configurations including intermediate and lower vibration levels and other frequencies.

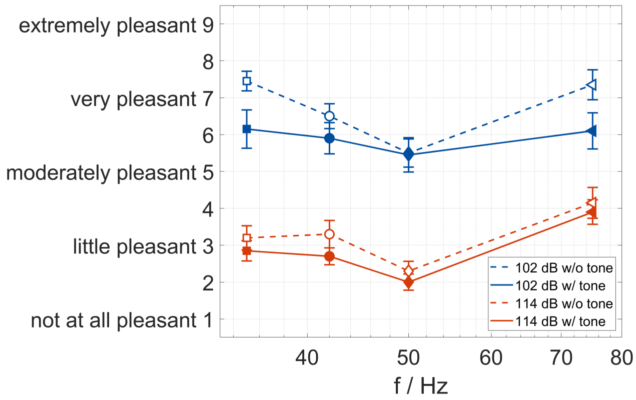

Figure 2: Average pleasantness ratings plotted over the frequency of the vibration signal. Error bars indicate standard errors. Vibration levels are indicated by color. Dashed lines link ratings without (w/o) congruent tones, continuous lines connect ratings with (w/) congruent tones.

Subjects

Twenty volunteers (ten female and ten male), aged between 19 and 41, participated in the experiments. The weight of the participants was between 50.9 kg and 108.3 kg (mean weight 74.1 kg) and the body height was between 1.60 m and 1.92 m (mean size 1.74 m). The volunteers received a compensation of 10 €/hour. The Research Ethics Committee of the University of Oldenburg had no objections regarding the study (Drs.EK/2020/011).

Results

Influence of congruent audio tones on pleasantness ratings

Figure 2 shows the average pleasantness ratings plotted over the frequency of the vibration signal and the within-subjects effects of a repeated measures ANOVA are listed in Table 2. All effects are reported as significant at $p <$ .05.

There was a significant main effect of the the vibration level on the pleasantness ratings, $F(1, 19) = 164.99$, $p <$ .001. All conditions with the higher vibration level of 114 dB(vib)(in red color in Fig. 2) were less pleasant than those with a lower vibration level of 102 dB(vib) (in blue color) by 2 to 4 scale units.

There was also a significant main effect of the signal frequency on the pleasantness ratings, $F(3, 57) = 20.85$, $p < .001$. The 50-Hz condition was always the least preferred configuration. Lower as well as higher vibration frequencies got higher pleasantness ratings for each of the two tested vibration levels, with or without a tone. The underlying reason for this frequency dependence might be the transfer function of the seat between seat rail and

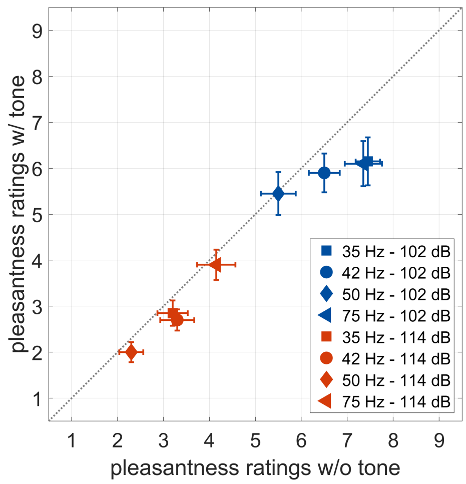

Figure 3: Average pleasantness ratings with a tone (y-axis) congruent to the vibration frequency plotted over those without a tone (x-axis) for all vibro-acoustic stimuli configurations.

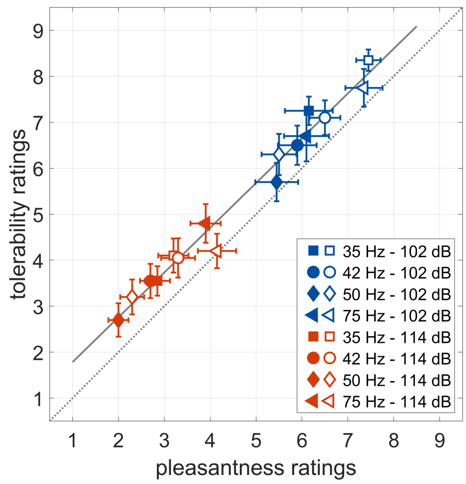

Figure 4: Tolerability ratings plotted over pleasantness ratings for all configurations with (filled symbols) or without a congruent audio tone (open symbols). Solid grey line indicates a linear regression with a slope of 0.97 and an offset of 0.81 scale units.

Effects	df		F-value	p-value	part. η^2
Level (L)	1	19	164.99	<.01	0.90
Freq (F)	3	57	20.85	<.01	0.52
Tone (T)	1	19	13.78	<.01	0.42
L*F	3	57	1.43	.24	0.07
L*T	1	19	1.94	.17	0.09
F*T	3	57	1.65	.19	0.08
L*F*T	3	57	2.05	.12	0.10

Table 2: Results of the repeated measures ANOVA

seat surface, because the vibration levels reported here were measured at the seat rail. The transfer function of the tested seat had a maximum in the transmission at 50 Hz [9, 10].

In general, the addition of a congruent tone reduced the pleasantness ratings for all conditions, $F(1, 19) = 13.78$, $p < .001$. However, the A-weighted sound pressure level and the calculated loudness of the acoustic stimuli did barely differ when the tones were added. The variability was only about 0.5 dB in terms the A-weighted sound pressure level and less than 10% in terms of calculated loudness values (in Tab. 1). Thus, the change in sound character rather than the perceived intensity seems to be responsible for the differences in the pleasantness ratings.

The effect size for the vibration level, part. $\eta^2 = 0.90$, is largest compared to all other effects. The effect size of the additional audio tone (part. η^2=0.42) is only slightly smaller compared to the effects size of the frequency (part. η^2=0.52), indicating a similar importance of these two factors for the chosen stimulus parameter values.

Fig. 3 shows the relationship between the average ratings of the conditions with the additional audio tone and those without the audio tone. All data points are below the diagonal line. Although the interaction effects were statistically not significant, the deviations compared to the diagonal line are slightly different for the different vibration levels. For the stimulus configurations with a higher vibration level of 114 dB(vib), the differences are smaller than half a scale unit and similar for all tested frequencies. Here, the vibration might be dominating the judgment and the change in sound character by embedding a tone does add only little to the unpleasantness if at all. For the stimuli with a lower vibration level of 102 dB(vib), the effect is negligible for the 50 Hz condition, which was already rather unpleasant compared to the other tested frequencies. For those conditions with lower vibration levels, which were rather pleasant without the tone and more towards the right hand side on the x-axis, the addition of a congruent tone reduces the pleasantness ratings by up to more than one scale unit for the 35 Hz and 70 Hz condition. Thus, it might be concluded that the observed main effect of the embedded audio tones results mainly from these stimulus conditions.

Relationship between pleasantness and tolerability ratings

Figure 4 shows the relationship between the pleasantness and the tolerability ratings for the stimulus conditions with and without congruent tones. The correlation coefficient between the ratings on the two scales is $r = 0.99$, indicating a very close link between the concepts of pleasantness and tolerability when measured under laboratory conditions. A linear regression indicated by the grey line in Fig. 4 has a slope of 0.97. Nevertheless, a clear offset compared to a one-on-one agreement (dotted line in that figure) is apparent and the tolerability ratings are on average 0.81 scale units higher than the pleasantness ratings across all tested stimulus conditions. This indicates that, despite the close link between the tolerability and and the pleasantness ratings, the participants did in fact use different rating criteria and distinguished the two concepts. However, this relationship might be different when assessed in situ over a longer time span during a real flight.

Discussion

The present results indicate an influence of the vibration level on the pleasantness ratings. An increase in vibration level reduces the pleasantness ratings which is in overall agreement with results from other studies [3, 4, 5] although they partially covered different level ranges and other application contexts. Due to a constant A-weighted sound pressure level and very similar calculated loudness values for the acoustic stimuli in the present study, a comparison with the different proposed discomfort and annoyance models and their structures regarding the interaction of sound and vibration is not directly possible.

The present study also showed a clear influence of the vibration frequency which might be explained by the accelerometer position at the seat rail and the frequency dependent auditory and vibration perception. The transfer function of the tested seat bench has a maximum at 50 Hz which might explain the lower pleasantness ratings for the 50 Hz condition [9, 10]. Additional measurements of the vibration exposure directly at the seat surface might enable a broader interpretation of the present results and comparability with other studies.

The main effect of congruent frequency audio tones on the pleasantness ratings for whole-body vibration indicates that the sound character of the audio signal plays a role in the assessment of the pleasantness, especially when comparing stimulus configurations with audio signals having equal intensity of the sound in terms of A-weighted sound pressure level or loudness values. Such an effect might have been inhibited in other studies which explicitly varied the sound pressure level over a large dynamic range and at rather high overall levels. Although the data from the present study is very limited, the interaction of sound and vibration characteristics seem to be important for the development of multi-modal models aiming at a more holistic prediction of discomfort in vehicles. This conclusion is also supported by other studies which found a reverse cross-modal effect of whole-body vibration on auditory roughness perception and pleasantness ratings in the context of automobiles [11].

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