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# Modelling of the contribution of noise, vibration and thermal stimuli to discomfort for aircraft passengers

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## ABSTRACT

Future aircraft designs will more sustainable and reduce environmental emissions. Turboprop aircraft can be 60% more fuel efficient in comparison to jet aircrafts but have high vibration and noisier cabins, thus affecting the comfort perception of aircraft passengers. The nature of the noise and vibration is highly tonal and therefore different to that previously studied.

This paper presents the development of a multifactorial model of the human comfort in response to noise, vibration, and thermal stimuli. Data were obtained through a laboratory study where the temperature, noise and vibration were adjusted. A model is generated that allows for mapping of the relative importance of the modalities.

## KEYWORDS

Model, Optimization, Cabin, Turboprop, Sustainability

### Introduction

The aircraft industry has shown advancements in technology to improve human comfort and to reduce environmental emissions. Worldwide approximately half of air travel is composed of short range flights many of which could be served with a turboprop. In ideal conditions turboprops emit less $CO_2$ and are more fuel efficient in comparison to jets (Kilic, 2023). However, the cabin noise and vibration in the cabin of turboprop aircraft are higher than jets, therefore reducing the human comfort perception (Vink, 2011). To enable acceptance of future propeller aircraft, noise and vibration environments must be improved.

Noise and vibration from propeller aircraft varies with design of aircraft and the flight phase. Manufacturers need to be able to predict the discomfort that would be experienced by passengers, to understand how acceptable the aircraft will be (Oborne, 1977). Previous studies have shown that subjective ratings of noise and vibration can be matched to generate a level of equivalence (Mansfield et al., 2007) although this has not been demonstrated for signals representative of the turboprop aircraft environment. However, studies using a turboprop showed that noise and vibration were high priority in context to human comfort in an aircraft cabin (Vink et al., 2022).

With the need to reduce emissions, future aircraft concepts are being actively pursued that include propeller propulsion. The vibration and noise experienced in turboprop aircraft is different to that experienced in jets (Bellman et al, 2004). Turboprops are dominated by tonal vibration relating to the blade pass frequency and turbulent wake interactions with the airframe. Jets have less tonality in the noise and vibration experienced in the passenger cabin. The temperature in an aircraft cabin can also vary due to the flight phase, time of day, and position in the aircraft. Whilst most current aircraft make use of hot bleed air from the jet engine for air conditioning systems, future electrically powered aircraft will not have opportunity to use this power source and therefore will need dedicated heating systems adding weight. To optimize the design of future propeller aircraft, an improved understanding of passenger perceptions of aircraft comfort is necessary.

## Methods

Laboratory experiments occurred in the environmental chamber, Department of Engineering, Nottingham Trent University. An aircraft cabin environment was replicated by synthesised noise and vibration from a turboprop aircraft presented via a vibration simulator and loudspeakers. Whilst seated on a BAE146 passenger seat, participants were presented with each combination of 10s samples of noise and vibration, after a calibration and familiarisation procedure (Figure 1). Noise was presented at each of 78, 82, 86 and 90 dB(A); vibration was presented at each of 0.75, 1.5, 2.25, 3.00 m/s² r.m.s. comprising a multi-tonal signal. This procedure was repeated at four different temperatures between 19˚C to 32 ˚C.

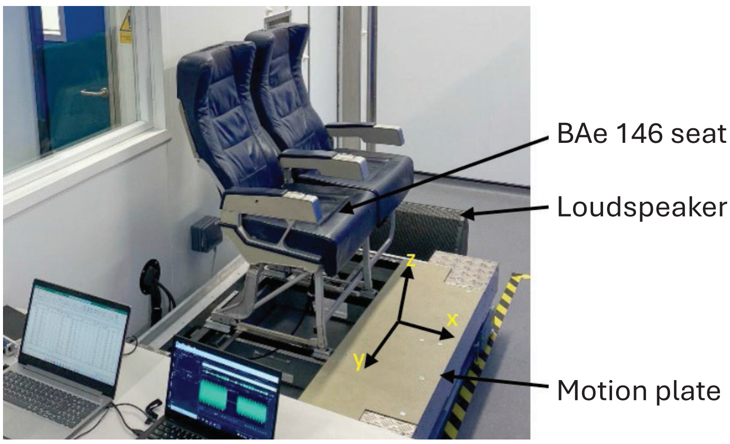

Figure 1. Experimental set up

After each combination participants were asked to give the subjective ratings of comfort based on noise, vibration, and thermal discomfort using scales adapted from ISO2631-1 and ISO 7730 (Figure 1). Overall discomfort was assessed using an adapted 100-point Borg CR-100 scale with verbal anchors Participants were also required to select whether they would prefer to change the temperature or reduce the noise or the vibration to improve comfort. This question used a forced choice protocol. Data were analyzed using MATLAB R2020a and SPSS. 20 volunteers aged between 19-52years participated in the experiment. The study was approved by NTU research committee.

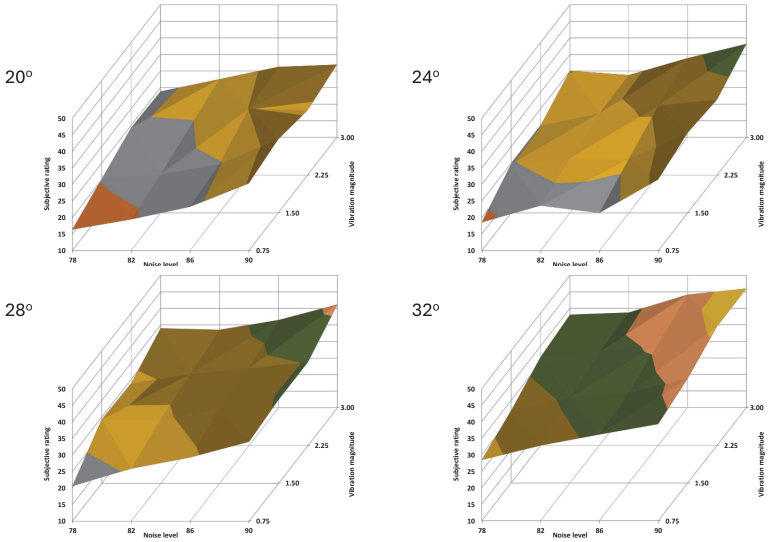


Figure 2. Measured overall discomfort.

## Results

As expected, mean ratings of noise increased with noise level and mean ratings of vibration increased with vibration ($p<0.0001$). There was no indication of a cross-modal effect; i.e. ratings of noise were not affected by the vibration and ratings of vibration were not affected by the noise (n.s. 2-way ANOVA). These effects were observed at each of the four temperatures. Overall discomfort increased with noise, with vibration, and with temperature (Figure 2).

Preferences for reducing noise or vibration shifted to those modalities as the intensity of the stimulus increased (Figure xx). Considering those modalities that were selected at the preference by more than 50% of participants (Figure xx), temperature was not a priority at 20 or 24 deg, but became dominant at 32 deg, apart from those stimuli where there were the highest magnitudes of noise and vibration. These data show that, even for short duration stimuli, noise and vibration can dominate subjective responses, under hot conditions.

Preferences for reducing noise or vibration shifted to those modalities as the intensity of the stimulus increased (Figure 3). Considering those modalities that were selected at the preference by more than 50% of participants (Figure 3), temperature was not a priority at 20 or 24 deg, but became dominant at 32 deg, apart from those stimuli where there were the highest magnitudes of noise and vibration. These data show that, even for short duration stimuli, noise and vibration can dominate subjective responses, under hot conditions.

20 deg C

| | 78 dB | 82 dB | 86 dB | 90 dB |
|---|---|---|---|---|
| 3.00 m/s² | V | V | N | N |
| 2.25 m/s² | V | V | N | N |
| 1.50 m/s² | V | N | N | N |
| 0.75 m/s² | N | N | N | N |

24 deg C

| | 78 dB | 82 dB | 86 dB | 90 dB |
|---|---|---|---|---|
| 3.00 m/s² | V | V | V | N |
| 2.25 m/s² | V | V | N | N |
| 1.50 m/s² | V | N | N | N |
| 0.75 m/s² | NP | N | N | N |

28 deg C

| | 78 dB | 82 dB | 86 dB | 90 dB |
|---|---|---|---|---|
| 3.00 m/s² | V | V | V | N |
| 2.25 m/s² | V | V | N | N |
| 1.50 m/s² | V | NP | N | N |
| 0.75 m/s² | T | NP | N | N |

32 deg C

| | 78 dB | 82 dB | 86 dB | 90 dB |
|---|---|---|---|---|
| 3.00 m/s² | V | V | V | N |
| 2.25 m/s² | T | T | NP | T |
| 1.50 m/s² | T | T | T | N |
| 0.75 m/s² | T | T | T | N |

Figure 3. Preference for changing modalities. V: vibration >50%, N: noise >50%, T : temperature >50%, NP : no preference (none reached 50%).

Polynomial digital models of the human were created for noise discomfort, vibration discomfort, and overall discomfort. Models were fitted to individual data points, whereas RMS error (%RMSE) was calculated to the mean data. For noise and vibration discomfort, RMS errors were less than 4% in all cases. Models followed patterns as expected in the data, showing increases in discomfort with noise and vibration.

For models that are designed to represent noise discomfort and vibration discomfort the polynomial model parameters were dominated by those addressing the modality of interest, indicating little cross-modal interaction. A linearized general model was developed using a machine learning algorithm. This method allowed for the prediction of the overall discomfort on the basis of 4 model parameters such as Noise, Vibration, Temperature and Overall. Testing the model on mean data from 20 participants showed an RMS error of 6.4%. The simulated cabin temperatures were designed to be in a range where discomfort would increase with temperature. However, if the temperature falls below 20 degrees, participants could feel discomfort due to cold.

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