Journal of Physics:
Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: PM Bluyssen *et al* 2025 *J. Phys.: Conf. Ser.* **3140** 122005

Cross-modal effects of environmental factors on perception and bodily responses: a pilot study

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Abstract. During perception with our senses interactions of different environmental stressors (olfactory, auditory, visual and thermal stimuli) at brain level might occur. To test these cross-modal effects, a three-way factorial design was applied. In total, 60 students across six groups were each exposed to three randomized combinations of different environmental conditions: three sound conditions, three lighting conditions, and two ventilation modes, while sitting in a semi-lab environment. Heart rate and respiration rate were monitored using a smart watch; acceptability and experience were collected through a questionnaire to assess subjects' comfort perception. Results showed no statistical differences between the two ventilation modes and no effect of light type on the physiological indicators. A trend towards an interaction effect was found for sound*light on the acceptability of odour ($p=0.076$) and the perceived level of sound ($p=0.055$). For future studies, it is therefore important to first identify physiological indicators that can be affected by all the independent factors studied.

1. Introduction

We are exposed to a mix of stressors, that can change over time, and our responses (the coping and the effects) are influenced by genetics, previous exposures and interactions between those stressors at human level [1]. During perception with our senses interactions of different environmental stressors (olfactory, auditory, visual and thermal stimuli) at brain level (central nervous system) might occur, as demonstrated in previous studies [2-4]. There is a need for unravelling these cross-modal effects: it might help to explain why people have different preferences for comfort-related aspects, and why they differ in different contexts. Previous studies also show that next to asking people about their annoyance or acceptability, certain physiological indicators can be used to study the effect of exposures on our health and comfort [1]. For example, to follow the so-called anti-stress reaction (mechanism in your body to cope with (un)conscious annoyance) over time, heart rate and respiration rate have been applied in a study on the effect of relatively low environmental sound levels [5]. Therefore, in the underlying pilot study, we asked ourselves the following question 'Which cross-modal effects occur when exposed to different combinations of environmental conditions and how do these perceptions correlate with certain physiological indicators?'

2. Methods

2.1 Study design

To test these cross-modal effects, a three-way factorial design was applied. In total, 60 students (from the faculty of Architecture and the Built Environment at the TU Delft) across six groups were each exposed to three randomized combinations of different environmental conditions: three sound conditions (background, mechanical ventilation, traffic), three lighting conditions (warm, neutral, cold), and two ventilation modes (displacement, mixing), while sitting in a semi-lab environment of 6.1 (l) x 4.2 (b) x 2.7 (h) = 69.2 m^3 (the Experience room of the SenseLab [6]), on September 11, 2024 (see Table 1). In the Experience room, a classroom set-up was created with twelve tables and chairs (see Figure 1). A researcher sat in front to instruct the students. The ventilation rate was kept at 1000 m^3/h and the air temperature at 21°C. The relative humidity was around 50%.

Table 1. Test conditions, time, and subjects.

Group: subjects	Displacement ventilation Sound	Lighting	Time	Group: subjects	Mixing ventilation Sound	Lighting	Time
1: 6	Background	Warm	13.00-	4: 11	Ventilation system	Cold	15.15-
	Traffic	Neutral	13.20		Traffic	Neutral	15.35
	Ventilation system	Cold			Background	Warm	
2: 11	Traffic	Warm	13.45-	5: 12	Traffic	Cold	16.00-
	Background	Neutral	14.05		Background	Neutral	16.20
	Ventilation system	Warm			Ventilation system	Warm	
3: 10	Ventilation system	Neutral	14.30-	6: 10	Background	Cold	16.45-
	Background	Cold	14.50		Ventilation system	Neutral	17.05
	Traffic	Cold			Traffic	Warm	

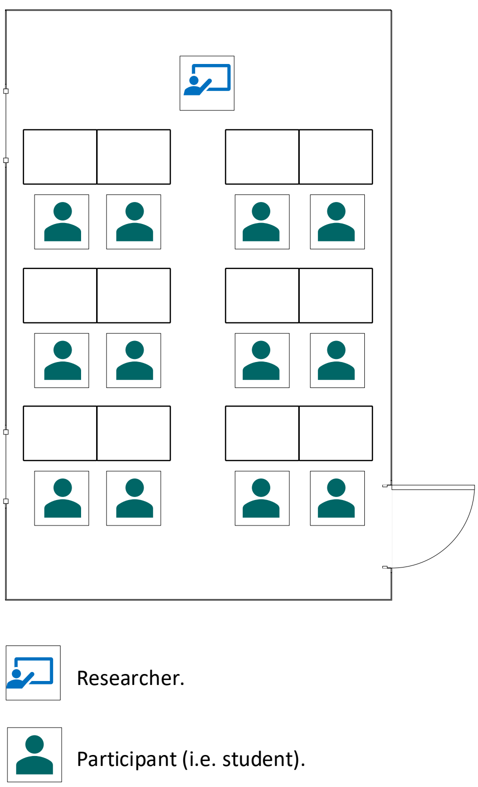

Figure 1. Test set-up in the Experience room.

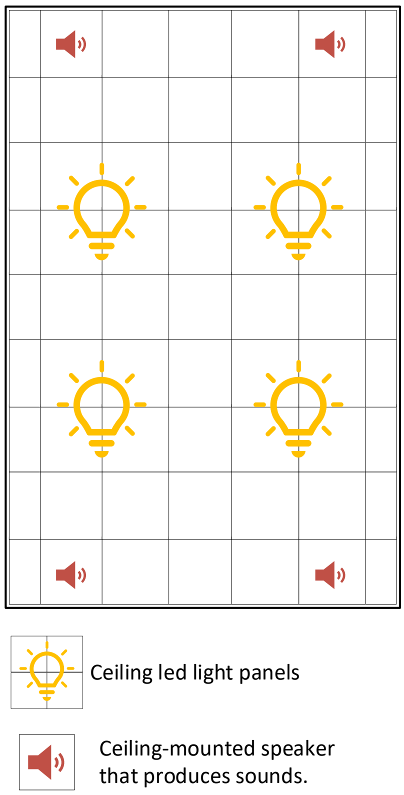

Figure 2. Speakers and LED light panels in ceiling.

The sound levels of the traffic and mechanical ventilation, measured in the middle of the Experience room with a Norsonic Nor 140 sound level meter, were set at 40 dB(A) and the background sound level was 32 dB(A). Sounds were produced by a sound system in the ceiling of the Experience room, including four ceiling mounted speakers (Figure 2) and a subwoofer connected to an audio interface and a computer outside the Experience room [6].

The lighting conditions are created by 16 LED light panels in the ceiling, of which the intensity as well as the colour temperature are individually controllable via an interface in the ceiling connected to a computer outside the Experience room (Figure 2). The light intensity for each of the lighting conditions was measured with a HOBO-Analog Data Logger (MX1104): 818, 843, and 813 lux for warm, neutral, and cold light, respectively. The correlated colour temperatures in Kelvin (K) were determined using a chromameter: 2700, 3000, and 6000 K for warm, neutral, and cold light, respectively.

Heart rate and respiration rate were monitored using a Vivosmart 5 smartwatch by Garmin. A one-page questionnaire was used to assess the acceptability and perceived level of sound, temperature, odour, and light for each of the conditions the students were exposed to on a continuous scale [4]. Additionally, each student completed a questionnaire with personal information.

2.2 Procedure

The students were sent an email with the information letter and a copy of the consent letter one week before the test day. A subject could always decide not to continue and stop with the test. The TU Delft Human Research Ethics Committee approved the study on November 15, 2023.

Upon the arrival of the students, they were informed about the test procedure, completed the consent form, and received the smartwatch. Then they were asked to enter the Experience room. In the Experience room the students were invited to take a seat at the organized positions (Figure 1), instructed on how to complete the one-page questionnaire, and then on how the experiment would take place. It was explained to them that they would experience three different conditions lasting two minutes each, with a two-minute interval, which they would have to assess each time using the appropriate questionnaire. The two-minute exposure time was chosen because no differences in physiological measurements were identified between the two- and four-minute exposure time during the pilot testing, where it was also concluded that 2 minutes was enough to recover, as reported in [5] and [7].

During the tests, one researcher remained sitting in the Experience room to inform the subjects when to start and stop completing the questionnaire for each condition: one minute after each condition started, they were asked to start completing the questionnaire, and one minute later to stop, as the condition ended.

2.3 Data management and analysis

All questionnaire data were manually typed and stored in an Excel database. The smartwatch data were downloaded from the appropriate sensor management software and reported according to the temporal sequence of the conditions analysed for each participant. Unfortunately, during the tests with the first group of students, for which only six students arrived on time, the setting of the background sound of the mechanical ventilation system of the building was not turned off, which increased the background level by 2 dB(A). Therefore, all data of group 1 were removed from the analysis, resulting in a total sample size of 54. The remaining data were first checked with Q-Q plots, which showed that they were all normally distributed. Then, for each test condition, the minimum, maximum, mean and standard deviation values were calculated. For the physiological data, the percentages of variation in each environmental condition compared to the baseline value, were also calculated. Because of the uneven sample sizes between the two ventilation modes resulted from the exclusion of group 1, first, independent samples t-tests were made for the perceptual assessments and bodily responses between displacement ventilation and mixing ventilation (Table 2). The outcome showed no statistical differences between the two ventilation modes, and therefore, ventilation type was no longer taken as a variable in the analysis.

Consequently, this led to two independent indoor environmental factors remaining, namely sound and light, each with three conditions. For perceptual assessments, there were eight dependent variables: both acceptability and perceived level of the four IEQ aspects, and for physiological indicators, there were two: heart rate and respiration rate. Hence, for both perceptual assessments and physiological indicators, a two-way MANOVA (multivariate analysis of variance) test was performed to identify the main effect of sound and light types, as well as the interaction effect of sound and light. The statistical significance level was set to be 0.05.

Table 2. Comparison of perceptual assessments and bodily responses between displacement ventilation and mixing ventilation using independent samples t-tests.

		Displacement ventilation n=63	Mixing ventilation n=99	t	p
Perceptual assessment: mean (standard deviation)					
Type	IEQ aspect				
Acceptability	Sound	0.3 (0.5)	0.4 (0.5)	-0.69	0.50
	Temperature	0.6 (0.3)	0.5 (0.4)	1.32	0.19
	Odour	0.7 (0.3)	0.7 (0.4)	0.14	0.90
	Light	0.4 (0.4)	0.4 (0.4)	0.64	0.52
Perceived level	Sound	2.4 (0.8)	2.2 (0.8)	1.00	0.32
	Temperature	0.0 (0.2)	0.0 (0.2)	-0.19	0.85
	Odour	1.7 (0.6)	1.6 (0.7)	1.06	0.29
	Light	0.3 (0.4)	0.3 (0.3)	1.22	0.23
Physiological indicator: mean (standard deviation)					
Heart rate change (%)		-0.1 (4.9)	-0.8 (5.7)	0.04	0.90
Respiration rate change (%)		0.3 (5.5)	-0.5 (6.7)	0.78	0.50

The statistical power was calculated using G*Power version 3.1.9.7. For both perceptual assessments and physiological indicators, the effect with the lowest effect size (0.399 and 0.074, respectively), namely the interaction effect, was used for calculating the statistical power, with α level of 0.05 and a sample size of 54. Consequently, the statistical power for perceptual assessments and physiological indicators were 0.87 and 0.39.

3. Results and discussion

3.1 Descriptive analysis

Figures 3 shows the mean perceptual votes for sound, temperature, odour and light when exposed to different conditions. For sound, the acceptability was noticeably higher under background sound than mechanical ventilation sound and traffic sound, with a perceived level much lower under background sound than the other two. Overall, the subjects reported the highest sound acceptability and lowest perceived level under the combination of background sound*warm light, with the lowest sound acceptability and highest perceived level under traffic sound*warm light. For temperature, the perceptual assessment was rather similar across different conditions, showing moderate acceptability and neutral perception, with the acceptability slightly higher under mechanical ventilation sound*cold light. For odour, the acceptability was in general high, especially under background sound*cold light and mechanical ventilation sound*neutral light, while the perceived level was slightly higher under traffic sound. For light, warm light showed the lowest acceptability alongside lowest perceived brightness level. While cold light showed the highest perceived brightness, the neutral light was voted to be mostly acceptable.

Figure 4 shows the mean % of change in heart rate and respiration rate compared to the baseline. The heart rate decreased under the combination of the three light types and the ventilation sound system. Similarly, it also decreased during the traffic sound combined with cold and warm light. In contrast, a slight increase was observed under the background sound condition combined with warm and neutral light. Regarding respiration rate, a decrease occurred only during the traffic sound combined with neutral light, whereas a slight increase was observed under the background sound combined with neutral light.

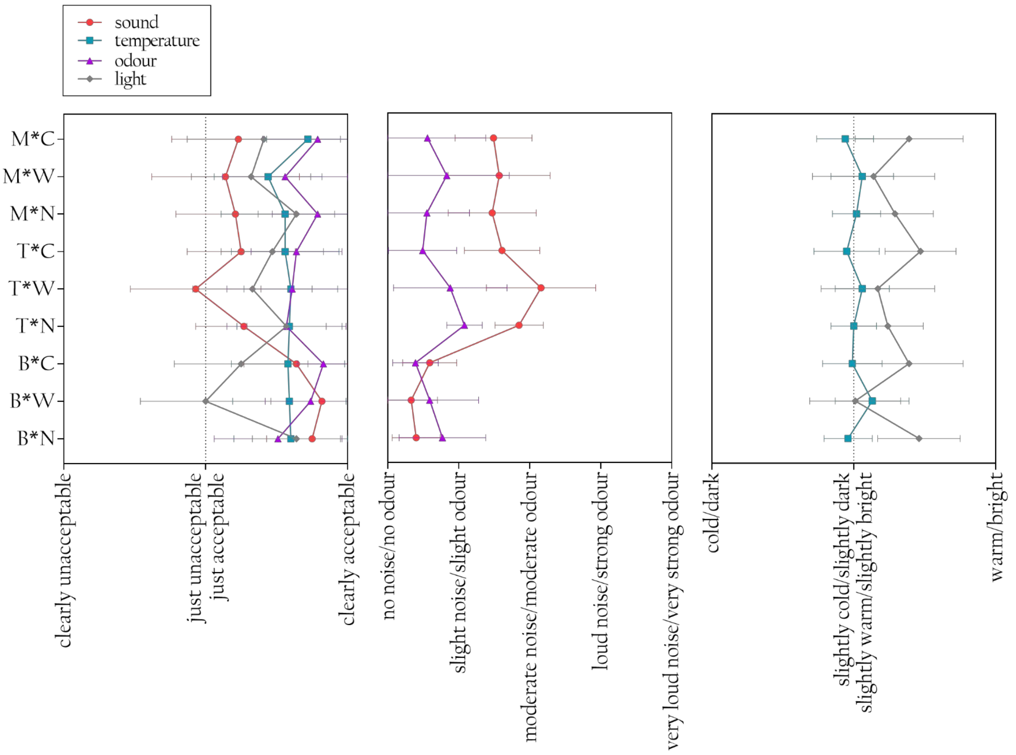

Figure 3. Mean and standard deviation of the perceptual votes for sound, temperature, odour, and light under different combinations of conditions. Note: the conditions are denoted as sound*lighting. For sound conditions, B = background, T = traffic, M = mechanical ventilation. For lighting conditions, N = neutral, W = warm, C = cold.

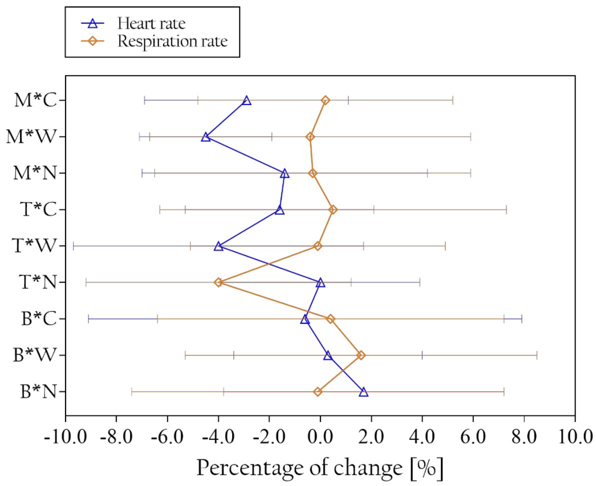

Figure 4. Mean % of change in heart rate and respiration rate compared to the baseline condition before the tested combination of conditions. Note: the conditions are denoted as sound*lighting. For sound conditions, B = background, T = traffic, M = mechanical ventilation. For lighting conditions, N = neutral, W = warm, C = cold.

3.2. Interaction analysis

The results of the two-way MANOVA are presented in Table 3. For perceptual analysis, although no interaction effect was found to be statistically significant, there is a trend towards interaction effects of sound*light on the acceptability of odour and the perceived level of sound, given the p values of 0.076 and 0.055, respectively. Furthermore, for the main effect of the individual factors, it is shown that sound type had a significant effect on sound acceptability and perceived sound level, while light type had a significant effect on light acceptability and the perceived level of temperature, odour, and light. Such results observed for lighting conditions leads to further interests on investigating how it can affect occupants' perceptions of different IEQ aspects.

Heart rate and respiration rate showed no significant differences in response to changes in sound type, light type, or their combination (sound*light). However, heart rate exhibited a more significant difference with sound type (p value of 0.08), as previous studies showed that sound type and its level have an effect on heart rate [8,9]. These results suggest that light type does not affect these two physiological indicators. Future studies could explore other physiological measures, such as brain waves [10], to investigate the interaction between light type and bodily responses.

Table 3. Results of the main effects, and two-way interactions "sound*light" on perceptual assessments of sound, temperature, odour, and light, and on physiological responses (% of change in heart rate and respiration rate) using two-way MANOVA.

		p	p of sound type	p of light type
Perceptual assessment				
Type	IEQ aspect			
Acceptability	Sound	0.119	**< 0.001**	0.370
	Temperature	0.498	0.977	0.646
	Odour	0.076	0.371	0.171
	Light	0.319	0.064	**< 0.001**
Perceived level	Sound	0.055	**< 0.001**	0.469
	Temperature	0.708	0.806	**0.011**
	Odour	0.375	0.213	**0.041**
	Light	0.196	0.949	**< 0.001**
Physiological indicator				
Heart rate (%)		0.08	0.08	0.2
Respiration rate (%)		0.6	0.4	0.2

4. Conclusions

The underlying study was a pilot study to investigate which cross-modal effects occur when exposed to different combinations of environmental conditions and how do these perceptions correlate with certain physiological indicators. First, we determined how many subjects we need to test interaction effects of perceptual assessments and physiological measures, for a study design with three independent factors and 2x3x3 levels. The power analysis showed a good statistical power (0.87) and a large effect size (0.40) for the perceptual assessments for the applied study design (two independent factors, 3x3 levels, excluding ventilation mode). To achieve a statistical power of 0.9, with the same study design 58 subjects would be required for the perceptual analysis, while assuming a study design with three independent factors and 2x3x3 levels (original study design) with an assumed medium effect size (0.15), would have required 72 subjects.

For the physiological measures, the power analysis showed a low statistical power (0.39) for the interaction effect (small effect size is 0.074), which can be related to the fact that light type does not affect the physiological indicators heart rate and respiration rate. For future studies, it is therefore important to first identify physiological indicators that can be affected by all the independent factors studied. Moreover, the exposure time for each combination of conditions will need to be optimised for all independent factors.

Acknowledgements

We thank AnneMarie Eijkelenboom, Arghyanir Giri, Nadine Hobeika, Shivani Dolas, and Hsing-Yu (Meg) Ou for their support at the experimental day.

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