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COMBINED EFFECT OF IAQ AND ACOUSTICS ON CALCULATION IN UNIVERSITY CLASSROOMS

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ABSTRACT

Literature studies have outlined that indoor environmental quality (IEQ) in educational environments can seriously impact students' learning and cognitive abilities. Research on the combined effects of IEQ domains on cognitive abilities is scarce, especially as regards acoustics and indoor air quality (IAQ). In this laboratory study, 29 university students were exposed to two IAQ conditions which were approximated by means of two CO2 concentrations: 800 ppm (good air quality) and 3000 ppm (poor air quality). For each of them four acoustic conditions, namely quiet, mechanical ventilation noise, babble noise, and birdsongs, were considered. Participants performed a simple calculation task; accuracy in the operations and the time needed for solution (response time) were collected. Data were analysed using generalised linear mixed-effects models by including the main effect of the environmental stressors and their interaction as independent variables. Accuracy was unaffected by environmental stressors, while response time revealed a combined effect of the two domains. Specifically, poor IAQ acted as a trigger, revealing faster responses in the babble noise case compared to quiet and mechanical ventilation. No discrepancies were found in good IAQ conditions. In conclusion, IAQ and acoustics should be considered in combination while investigating cognitive abilities.

Keywords: *Students, Cognition, Ventilation Sounds, IAQ.*

1. INTRODUCTION

Individuals spend approximately 90% of their day indoors [1]; therefore, it is essential that buildings exhibit a high level of indoor environmental quality (IEQ) to prevent adverse health effects and, in the case of educational buildings, negative impacts on cognitive abilities. While literature on the effects of individual IEQ domains on cognitive performance is relatively extensive, research examining the simultaneous influence of two or more domains (especially their "combined" effect, see [2]), is notably limited and this hold particularly for indoor air quality (IAQ) and acoustics.
The present study investigates the combined effect of ventilation noise and IAQ on the calculation abilities of university students.

2. METHODS

A group of 29 students (mean age 22.76 years, std 2.53 years, 31% female) from the Technical University of Denmark (DTU) participated in an experiment conducted in the DTU Sustain Indoor Environment Field Labs. The laboratory was furnished with two desks and two chairs, separated by a partition (Fig.1). Participants were required to perform a calculation task on a tablet while simultaneously being exposed to ventilation-related sounds

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and noises via headphones. All participants completed the test under both good and poor indoor air quality (IAQ) conditions.

The four acoustic conditions employed, mimicked both natural and mechanical ventilated classroom scenarios, that is: a quiet reference, babble noise, mechanical ventilation noise, and birdsong. All sounds were recorded binaurally; the natural ventilation sounds were recorded with one ear oriented towards an open window and the mechanical ventilation noise was sampled in a laboratory. All stimuli were reproduced at 47 dBA, corresponding to their actual recorded sound levels.

Figure 1. Laboratory settings and participants performing the experiment.

Regarding indoor air quality, two concentrations of bio-effluents were used, measured in terms of CO_2 concentration: 800 ppm for good IAQ and 3000 ppm for poor IAQ. For the cognitive task, participants had to indicate whether the equations presented on the screen were correct or incorrect. Both accuracy and response time were recorded. In total, 24 equations were presented for each acoustic condition. The equations, taken from Caviola et al. [3], consisted of addition or subtraction problems with a provided result. Two levels of difficulty were included, namely with and without carrying/borrowing. Testers had to judge whether the provided result was correct or not. The order of equations within each acoustic condition was randomised, as was the assignment of equation lists to acoustic conditions. All participants first completed all auditory conditions at one CO_2 concentration before repeating the test under the other concentration. At the end of the second section, the students completed the short version of the Weinstein Noise Sensitivity Test. [4]. The auditory and CO_2 conditions were counterbalanced using a Latin square design. Overall, each participant was engaged for two hours and was remunerated with a voucher equivalent to 300 DKK (approximately €40). Noise sensitivity data were analysed as described by Senese et al. [4]. Accuracy and response time data instead were analysed using generalised linear mixed models. Specifically, accuracy was examined as a function of test difficulty, CO_2 concentration, listening conditions, and the respective two-way interactions among these three factors. The model included noise sensitivity, gender and the order of listening conditions (from 1 to 4) as covariates, along with the interactions between noise sensitivity and listening conditions, and between order and CO_2 concentration. Participants were included as a random factor, and a binomial distribution was specified for the model. For response time, the same analysis as for accuracy was implemented; the only difference was that a logarithmic gamma distribution was employed in this case in the modelling phase. All analyses were performed using R (version 4.4.2) and the lme4 package (version 1.1-36).

3. RESULTS

Regarding the accuracy model, the only significant effect was that of difficulty ($\chi^2(1)=45.6$, $p<0.001$), with more challenging equations resulting in lower accuracy. For response time, significant effects were observed for difficulty ($\chi^2(1)=1063$, $p<0.001$), the order of execution ($\chi^2(4)=10.72$, $p=0.01$), and the interaction between CO_2 concentration and auditory conditions ($\chi^2(3)=10.92$, $p=0.01$). In this study, we chose to focus exclusively on the latter interaction, as our aim was to investigate the combined effects of sound conditions and IAQ. First, an effect of CO_2 concentration on the quiet listening condition was found ($z=2.74$, $p=0.03$), whereby the response time increases in the presence of poor indoor air quality (IAQ). Secondly, the effect of listening conditions under poor air quality was identified. Specifically, a slowing down of response time was observed in the babble noise stimuli compared to both quiet ($z=3.03$, $p=0.02$) and mechanical ventilation noise ($z=3.64$, $p=0.004$). The results are plotted in Fig. 2.

4. DISCUSSIONS

The observed findings may be interpreted in light of the arousal theory, commonly referred to as the Yerkes-Dodson law [5]. According to this theory, performance is a function of an individual's level of arousal, following an inverted U-shaped curve. Optimal performance is achieved at moderate arousal levels, whereas both lower and higher levels result in diminished performance. Moreover, the literature indicates that both air quality and sound can elevate arousal levels [6,7]. In the present study, although the arousal levels of the participants were not directly measured, it can be speculated that a CO_2 concentration of 3000 ppm may have induced an over-aroused state, thereby prolonging response times under quiet conditions. However, this hypothesis appears to contradict the findings from the second part of the interaction, where performance was superior under babble noise compared to quiet conditions and mechanical ventilation. According to the aforementioned theory, one might have expected that the addition of sound would further increase arousal and consequently impair performance. An alternative explanation is that CO_2 may have influenced the perceived task difficulty. Sorensen et al. [8] suggest that the perceived difficulty of a task can alter the shape of the Yerkes-Dodson curve; for simpler tasks, the curve is steeper with a plateau at higher arousal levels, whereas for more challenging tasks, the curve is more defined, resulting in an overall decline in performance. This perspective may account for the differences observed between the listening conditions at the higher CO_2 concentration. In contrast, at 800 ppm, the listening conditions likely fell within the plateau phase. Nonetheless, the disparity between the two CO_2 concentrations under quiet conditions remains evident.

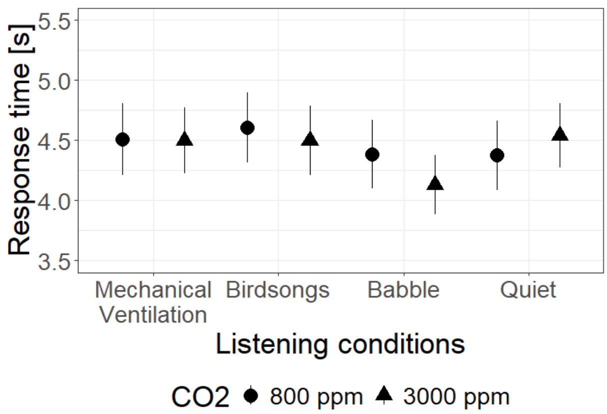

Figure 2. Response time mean values and standard deviations for each listening condition and CO_2 concentration

5. CONCLUSIONS AND LIMITATIONS

The work is an initial attempt to identify whether there a combined effects of acoustics and IAQ on calculation tasks performed by university students might occur. Response times were sensitive to the modulation of the experimental variables. In fact, an increase in response times (worsening) was observed when exposed to poor IAQ in quiet conditions, and a reduction (improvement) in response times was observed when exposed to babble noise, compared to quiet and mechanical ventilation, under higher CO_2 concentrations. These effects can be explained by an increase in arousal due to exposure to the different conditions. However, direct measurements of both physiological and subjective arousal were not undertaken to support this theory.

Given the limitations of this single experiment, it is difficult to determine the optimal ventilation solution. The proposed arousal theory is not substantiated by direct measurements in the present study, additionally, only acute exposures were investigated. It is therefore plausible that more prolonged exposures, especially to CO_2 concentrations, could have different effects on cognitive performance. One clear finding from this study is that a more variable sound environment, such as that produced by natural ventilation, appears to be beneficial.

Future research could verify the arousal hypothesis by incorporating direct measurements of arousal. Furthermore, investigating different sound stimuli, employing alternative cognitive tests, and examining the effects of prolonged CO_2 exposure could lead to new insights.

A more detailed account of the research can be found in [9].

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] European Comission. European Comission Indoor Air Pollution: "New EU Research Reveals Higher Risks than Previously Thought", European Comission: Brussels, Belgium, 2003.

[2] G. Chinazzo, R. K. Andersen, …, S. Wei: "Quality criteria for multi-domain studies in the indoor environment: Critical review towards research guidelines and recommendations", *Building and Environment,* vol 226, 2022.

[3] S. Caviola, C. Visentin, E. Borella, I. Mammarella, N. Prodi: "Out of the noise: Effects of sound environment

on maths performance in middle-school students", *Journal of Environmental Psychology,* vol. 73, 2021

[4] V. P. Senese, F. Ruotolo, G. Ruggiero and T. Iachini:"The Italian version of the Weinstein Noise Sensitivity Scale: Measurement invariance across age, sex, and context", *European Journal of Psychological Assessment, 28*(2), pp. 118–124, 2012

[5] R. M. Yerkes, J. D. Dodson: "The relation of strength of stimulus to rapidity of habit-formation", *Journal of Comparative Neurology and Psychology*, vol. 18, no. 5, pp. 459-482, 1908

[6] B. Du, M.C. Tandoc, M.L. Mack, J.A. Siegel, "Indoor CO2 concentrations and cognitive function: A critical review", *Indoor Air, vol* 30, pp 1067–1082, 2020

[7] A. Alvar, A.L. Francis, "Effects of background noise on autonomic arousal (skin conductance level)", *JASA Express Lett. Vol* 4,2024

[8] L.K.A. Sörensen, S.M. Bohté, H.A. Slagter, H.S. Scholte, "Arousal state affects perceptual decision making by modulating hierarchical sensory processing in a large-scale visual system model", *PLoS Comput Biol* vol 18, 2022.

[9] Pellegatti et al. "Combined and cross-modal effect of acoustics and air quality on university students", *Under preparation for Building and environment*.