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Investigating the acute effects of combined exposure to heat and noise on human brain waves and perceived workload

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Abstract

Objectives: The prevalence of multiple health hazards in various industries is on the rise, with noise and heat being common harmful factors in industrial environments in Iran. This study aimed to examine the immediate effects of simultaneous exposure to thermal stress and noise on human brain waves and perceived workload.

Methods: Seventy-two students (36 men and 36 women) participated voluntarily in this study. Participants were subjected to varying levels of noise exposure, including four noise levels and heat stress (three levels of Wet Bulb Globe Temperature) for 30 minutes each. EEG recordings were conducted for 10 minutes, with participants allowed a 30-minute rest period between each test condition.

Results: The combined exposure to noise and heat at two high levels (SPL95+WBGT34 and SPL95+WBGT29) resulted in a significant increase in perceived mental workload compared to the baseline state ($P<0.05$). EEG analysis indicated a decrease in absolute alpha power in the two high-level conditions compared to the baseline ($t<0$), while absolute beta power showed a significant increase in the two high-level conditions compared to the baseline mode (SPL45+WBGT22).

Conclusion: The study demonstrated that simultaneous exposure to noise and heat, leading to an elevated perceived mental workload, was associated with decreased absolute alpha power and increased absolute beta power in the frontal and occipital regions. These findings suggest that these changes serve as reliable indicators of cognitive and physiological performance.

Keywords: Cognitive Performance, EEG, Brain Activity, Noise, Heat Stress.

Introduction

Noise and heat stress are crucial physical parameters in the work environment, playing a significant role in either enhancing or impeding employees' performance.[1,2] Exposure to high temperatures and hot atmospheres poses a risk for heat stress among employees, potentially resulting in heat-related illnesses and fatalities.[3] Uncontrolled heat stress in the workplace can lead to complications such as elevated heart rate, core body temperature, and increased fatigue.[4,5] Environmental factors, including heat, have a substantial impact on cognitive functions such as attention, concentration, and response times.[7,8] Sustained attention and reaction time are critical cognitive functions that play a vital role in preventing occupational accidents.[9] Rastegar et al.'s study[10] demonstrated that heat stress diminishes working memory performance, while Masuda et al.'s research indicated that heat exposure can lead to a decline in cognitive performance even under favorable working conditions.[11]

Another significant stressor in the workplace is noise, which, when combined with other stressors, can contribute to or exacerbate mental disorders.[12] Noise can impair cognitive function and induce oxidative stress in the brain, serving as a risk factor for functional impairments like attention and reaction times.[13,14] While numerous studies have explored the individual effects of noise and heat on humans,[8,14] contemporary environments, both occupational and non-occupational, often involve combined exposure to these stressors.[15] Chen et al.,'s study[16] revealed that simultaneous exposure to noise and heat can lead to cognitive impairment. Therefore, there is a pressing need for research to investigate the combined effects of noise and heat on human performance.

Mental and cognitive performance encompass various aspects such as reaction time, attention, intelligence, and concentration. Changes in cognitive performance can lead to human errors and increase the likelihood of accidents.[17] Attention, defined as the active cognitive selection process, plays a crucial role in emotional responses and cognitive performance.[18,19] Research has shown that exposure to external stimuli, such as noise and heat, can induce stress reactions in living tissues and cells, which may weaken over time but can be quantitatively measured bioelectrically.[20]

Numerous studies have explored the impact of noise and heat on cognitive performance, yielding conflicting results. Some studies have reported a negative effect of noise and heat on cognitive performance,[21-25] while others have suggested improvements.[26-29] Additionally, some studies have found no significant impact of noise and heat on cognitive performance.[30-32] The discrepancies in findings may be attributed to the diversity of evaluation tools used. In recent years, a variety of mental assessment tools, including questionnaires and cognitive tests, have been utilized to measure cognitive performance.[33] However, most behavioral performance assessments have focused on simple cognitive tasks, necessitating more comprehensive studies on the effects of noise and heat on human cognitive performance.

In this context, evaluating human neurophysiology under noise and heat exposure using techniques like electroencephalogram (EEG) analysis is crucial. Unlike subjective evaluations such as questionnaires, EEG analysis provides an objective measurement of human neurophysiological responses to various stressors over time, minimizing the impact of personal biases and external factors on the data.[34,35] EEG is considered one of the most effective brain imaging methods for processing workplace stressors due to its non-invasiveness, cost-effectiveness, accuracy, safety, and convenience.[36] The analysis of multiple frequency bands in EEG signals, such as the alpha and beta bands, can offer valuable insights into the effects of stressors like heat and noise on cognitive performance.[37]

The alpha band, with a frequency range of 8-13 Hz, reflects a calm state with minimal mental processing, while the beta band (13-30 Hz) dominates during complex mental activities like concentration and emotional stability.[38,39] Studies have shown that fluctuations in alpha and beta bands correlate with cognitive performance, with increased alpha frequency and decreased beta frequency indicating improved cognitive function.[40,41] By examining these frequency bands in EEG signals, researchers can effectively diagnose and assess the effects of stressors like heat and noise on cognitive performance.[42]

Objectives

This study aims to investigate the acute effects of combined exposure to heat and noise on human brain waves and perceived workload using EEG analysis.

Methods

This experimental study (before and after) involved 72 students with an average age of 27 years who voluntarily participated. In order to ensure reliable results, the inclusion criteria required participants to have normal hearing, no history of cardiovascular disorders, no prescription drug use, no alcohol or caffeine consumption within 12 hours before the test, no high sensitivity to sound, a body mass index (BMI) within the range of 18 to 28, and no general health disorders. Individuals with any of the mentioned disorders or diseases, as well as those who did not wish to continue participating due to the time-consuming nature of the study, were excluded. All participants completed an Ethical Consent Form.

The participants were randomly assigned to one of four groups based on the experimental design. Each group was exposed to different levels of noise and heat conditions. There was no pattern or repetition of exposure, and each individual experienced four different conditions. One of these conditions served as the background condition (SPL45+WBGT22), against which the results of the other three conditions were compared [Figure 1].

Participants received training on how to perform the tests. Each group underwent different tests in four steps according to the test plan, lasting 30 minutes under noise and heat exposure, with a half-hour break between each step. Brain wave recordings were conducted during exposure to noise and heat according to the study procedure, and mental workload assessments were performed at the end of each phase [Figure 2]. Participants were acknowledged at the end of the experiment with a reward.

The experimental environment comprised two adjacent rooms. One room housed heat and humidity control equipment, noise speakers, and brain wave recording facilities for conducting tests, while the other room served as the researcher's station. The researcher utilized a computer connected to a Closed-circuit television (CCTV) system and an internal communication device to interact with subjects and monitor laboratory conditions.

For noise exposure, recorded industrial noise was used, and a Pulse multi-analyzer system type 3560 recorded the noise. A B&K sound level meter type 2238 (Brüel & Kjær, Denmark) was employed to analyze the noise recorded in the laboratory. Gold Wave software version 4.26 was utilized to correct and maintain constant noise levels, which were played through two Genius HF 2020 speakers.

The Wet-Bulb Globe Temperature (WBGT) index was chosen to evaluate heat stress in the workplace.[43,44] To create the necessary heat conditions for the experiment, two Iranian-made electric fan heaters, model EFHA 2200, were utilized. These heaters were positioned on the left and right sides of the subjects behind them on the ground, maintaining a distance of at least 3 meters. Additionally, two German-made Beurer LB60 humidifiers were used to regulate the required relative humidity in the laboratory, which was maintained at 50% in all conditions.

The NASA Task Load Index (NASA-TLX) questionnaire was employed to assess mental workload in this study. Developed over three years at the NASA research center and tested in over 40 laboratory simulations, this tool has been utilized in more than 550 research studies.[45] Qurbani et al.,[46] and Mohammadi et al.,[47] have validated the reliability and validity of this index, which has a Cronbach's alpha coefficient of 0.83. The evaluation model for mental workload consists of three dimensions: physical, mental, and time requirements, along with factors related to work performance outcomes such as personal efficiency, level of effort, and level of frustration.

Brain waves were recorded using a 16-channel portable E-wave device equipped with Ag/AgCl electrodes mounted in an elastic cap. The amplifier bandpass was set to 1–40 Hz with a sampling rate of 250 Hz, following the international 10-20 standard for electrode placement. Impedance was maintained below 10 KΩ during the trial. Absolute power was measured in two frequency bands, alpha (8-12.5 Hz) and beta (12.5-30 Hz), based on their power spectral density using MATLAB software version 2017b.

The continuous variables were expressed as the mean±SD, and the categorical variables were presented as a percentage and frequency. All statistical analyses were performed with SPSS (version 16.0, SPSS Inc, Chicago, IL, USA). A “P-value” less than 0.05 was considered significant.

The study was conducted in accordance with the Declaration of Helsinki. Institutional Review Board approval (code: IR.SBMU.PHNS.1396.63) was obtained. The present study did not interfere with the process of diagnosis and treatment of patients and all participants signed an informed consent form.

Results

In this study, 72 participants, comprising 36 men and 36 women, were included. The total average and standard deviation of weight, age, BMI, and height were 72.81±9.08, 26.75±2.32, 23.54±1.82, and 173.55±8.20, respectively.

The findings indicated that exposure to high levels of combined heat and noise significantly increased the perceived mental workload compared to the background state. Table 1 revealed that only the combined exposure modes (SPL95+WBGT34 and SPL95+WBGT29) led to a notable rise in perceived mental workload compared to the background mode. However, minor and significant effects were observed in the other four combined exposures (P>0.05). The statistical analysis using generalized estimation equations demonstrated that the difference in average scores of perceived mental workloads between the exposure modes SPL95+WBGT34 and SPL95+WBGT29 was not statistically significant. No significant changes were observed in mental workload scores for the combined exposures of SPL85+WBGT29 and SPL85+WBGT34. Conversely, a decrease in mental workload score was noted in the combined exposures of SPL75+WBGT29 and SPL75+WBGT34. This suggests that mental workload increases at noise and heat levels above the permissible exposure limit but decreases at levels below it.

Table 1. The perceived mental workload score of people in the face of noise and heat and its comparison coefficients with the value of the background state (SPL45+WBGT22)

Modes of exposure	M	SD	Mox	Min	B	P value
SPL_{95}+$WBGT_{34}$	58.27	6.24	70	48	3.83	0.009
SPL_{95}+$WBGT_{29}$	56.66	4.77	66	50	2.22	0.04
SPL_{85}+$WBGT_{34}$	54.83	4.43	67	48	0.38	0.71
SPL_{85}+$WBGT_{29}$	54.88	4.48	66	49	0.44	0.70
SPL_{75}+$WBGT_{34}$	53.22	4.57	65	47	-1.22	0.31
SPL_{75}+$WBGT_{29}$	52.88	5.67	64	45	-1.55	0.28
SPL_{45}+$WBGT_{22}$	54.44	4.75	70	48	-	-

Based on the Kolmogorov-Smirnov test results, the EEG data followed a normal distribution. To analyze brain signals during exposure to varying levels of heat and noise, the absolute power of frequency bands was examined. Table 2 presents the statistical coefficients comparing the absolute power changes of the alpha band during combined exposure to noise and heat compared to the background state (SPL45+WBGT22). The results indicated that in two exposure modes (SPL95+WBGT34) and (SPL95+WBGT29), the absolute alpha power decreased compared to the background mode (t<0). This decrease in alpha power was more pronounced in the first exposure state than in the subsequent one. Notably, at a heat level of 34°C, the most significant decrease in absolute alpha power was observed in the exposure mode of SPL95+WBGT3 compared to the background in brain channel F7 (t=-3.30), which was statistically significant (P<0.05). Similarly, at a heat value of 29$^{\circ C}$, the highest absolute alpha power reduction was observed in channel C4 (t=-3.99), also statistically significant (P<0.05).

Table 2. Statistical coefficients comparing the absolute power changes of the alpha band in the combined exposure to sound and heat compared to the background state (SPL45+WBGT22)

Combined exposure modes	**SPL$_{95}$+WBGT$_{29}$**		**SPL$_{95}$+WBGT$_{34}$**	
Channel	**t-value**	**P value**	**t-value**	**P value**
Fp_1	-0.4311	0.6717	-2.3898	0.0287
Fp_2	-2.7066	0.0149	-2.3106	0.0336
F_3	-1.6463	0.1180	-2.6930	0.0153
F_4	-2.5604	0.0220	-1.7345	0.1009
F_7	-2.7621	0.0133	-3.3003	0.0042
F_8	-0.2940	0.7722	-0.9539	0.3534
T_3	-0.5380	0.5975	-2.6611	0.0164
T_4	0.6018	0.5552	-2.1555	0.0457
C_3	-2.8207	0.0117	-1.4536	0.1642
C_4	-3.9987	0.0088	-2.7429	0.0138
P_3	-1.7912	0.0910	-1.7106	0.1053
P_4	0.0517	0.9593	-1.3713	0.1880
O_1	-0.9079	0.3766	-2.8976	0.0100
O_2	1.3486	0.1953	-2.1429	0.0468
Cz	-0.1810	0.8584	0.0036	0.9974
Pz	0.5564	0.5851	-3.2023	0.0052

The results regarding changes in absolute beta power at different levels of heat and noise mirrored those of absolute alpha power. Out of the six exposure modes combining sound and heat, only two exposure modes (SPL95+WBGT34 and SPL95+WBGT29) had a significant effect on the absolute power of the beta band, with no significant change detected in the remaining exposure modes (P>0.05). As shown in Table 3, these two states demonstrated an increase in absolute beta power across all 16 brain channels compared to the background state (SPL45+WBGT22) (t>0). This increase was significant in several brain channels (P<0.05). Contrary to the decrease observed in absolute alpha power under sound and heat exposure compared to the background state, the absolute power of beta increased. The most significant increase in absolute beta power compared to the background condition was observed at a heat level of 34°C in channel F3 (t=2.87) and at a heat level of 29°C in channel F8 (t=2.51).

Table 3. Statistical coefficients comparing the changes in the absolute power of the beta band in the combined exposure to sound and heat compared to the background state (SPL45+WBGT22)

Combined exposure modes	**SPL$_{95}$+WBGT$_{29}$**		**SPL$_{95}$+WBGT$_{34}$**	
channel	**t-value**	**P value**	**t-value**	**P value**
Fp_1	2.3588	0.0305	2.1943	0.0423
Fp_2	1.2184	0.2395	1.1384	0.2707
F_3	2.6000	0.0186	2.8725	0.0105
F_4	1.0279	0.3183	1.04447	0.3107
F_7	1.5708	0.1346	1.6187	0.1239
F_8	2.5183	0.0221	2.3554	0.0307
T_3	1.8138	0.0874	1.9442	0.0886
T_4	1.0129	0.3254	1.0224	0/3208
C_3	1.9393	0.0692	2.1697	0.0444
C_4	1.6391	0.1194	0.2432	0.0589
P_3	1.9773	0.0644	2.2720	0.0364
P_4	2.0500	0.0561	2.2743	0.0361
O_1	2.0103	0.0605	2.3105	0.0336
O_2	1.5784	0.1328	1.6608	0.1150
Cz	1.4296	0.1709	1.3375	0.1986
Pz	1.1278	0.2750	1.1533	0.2647

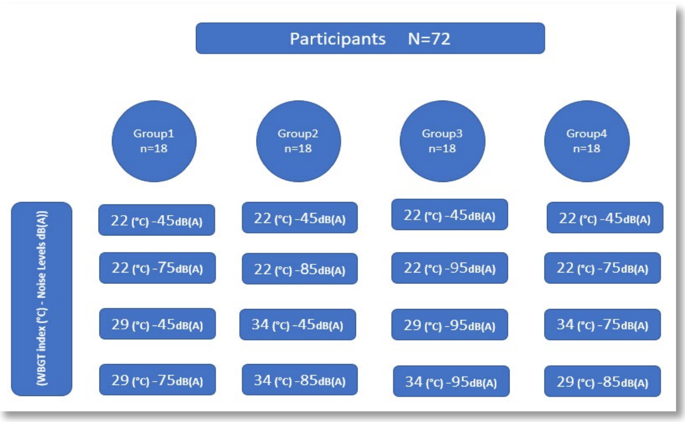

Figure 1. Test conditions

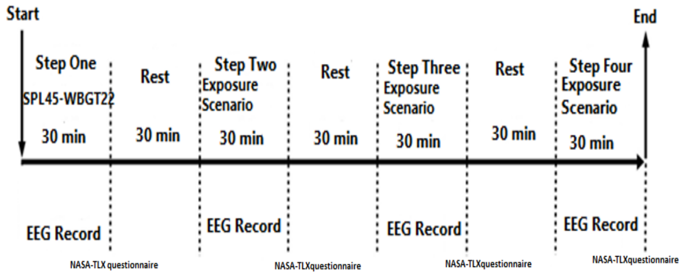

Figure 2. Study protocol

Discussion

The findings of this study revealed that the effect of gender on perceived mental workload parameters under combined conditions of varying heat and noise levels did not exhibit significant changes (P>0.05). This lack of significance may be attributed to the careful consideration and control of confounding factors in participant selection across both genders. Notably, only exposure to high levels of combined noise and heat (SPL95+WBGT34 and SPL95+WBGT29) resulted in a significant increase (P<0.05) in perceived mental workload compared to the background state, while lower levels led to a decrease in mental workload. These results align with previous studies by Ke et al., which demonstrated that higher noise levels increased mental workload, whereas moderate noise levels had a negative impact on workload and cognitive performance.[48] Additionally, Jafari et al.,'s study indicated that exposure to a noise level of 95 decibels reduced mental workload and cognitive performance in individuals.[49]

Furthermore, Wang et al.'s research titled "Investigating the Effect of Indoor Thermal Environment on Occupants' Mental Workload and Task Performance using Electroencephalogram" highlighted that slightly warm environments induced higher mental workloads.[8] Consistent with the inverted U theory, Pilcher et al.'s findings suggested that as arousal from environmental stressors increases, cognitive performance and mental workload improve. They also noted that human performance is less affected within a WBGT range of 21.11 to 26.61 degrees Celsius. In our study, a significant decline in cognitive and behavioral performance was observed at 34 degrees Celsius, supporting the inverted U theory and findings by Pilcher et al.[50]

In Table 2, the statistical coefficients comparing the absolute power changes of the alpha band during combined exposure to heat and noise compared to the background state are presented. The results indicated that in these two exposure conditions, the absolute alpha power decreased compared to the background state (t<0), and this decrease was statistically significant (P<0.05). However, the decrease in absolute alpha power was more pronounced in the exposure mode (SPL95+WBGT34) compared to the exposure mode (SPL95+WBGT29). Abbasi et al.'s study titled "Combined Effects of Noise and Air Temperature on Human Neurophysiological Responses in a Simulated Indoor Environment" demonstrated that alpha indices decreased with increasing air temperature.[35] Considering that the WBGT index evaluates environmental heat stress and an increase in environmental temperature contributes to increased heat stress, it can lead to a decrease in the absolute alpha band. Additionally, an increase in WBGT is linked to a decrease in the absolute alpha band, which can elevate individuals' mental workload.[51]

Bohria et al.'s study revealed that exposure to 90 dB noise resulted in a decrease in alpha band power compared to a silent environment, aligning with the findings of the current study.[52] Kim et al.,'s study showed a strong correlation between noise exposure and EEG data of alpha and beta frequency bands, consistent with the present study.[53] According to Table 3, the results indicated that in both conditions (SPL95+WBGT34 and SPL95+WBGT29), the absolute beta power increased in all 16 brain channels compared to the background condition (t>0), and this increase was statistically significant (P<0.05). Therefore, contrary to the decrease in absolute alpha power under exposure to heat and noise compared to the background state, the absolute power of beta increased, indicating a direct positive relationship with mental workload.

Fan et al.,'s study titled "Effects of Noise Exposure and Mental Workload on Physiological Responses during Task Execution" demonstrated that the beta band increased with rising mental workload, consistent with the current study.[14] Cho et al., investigated the effect of noise at three frequencies (low, medium, and high) on beta frequency band power, showing that exposure to high and low-frequency noise led to an increase in beta band power compared to no noise, aligning with previous research.[54] Another study by Cho et al., indicated that mosquito and ambulance noises increased beta band power compared to piano and sea wave sounds, suggesting that industrial noise played in the laboratory could be considered uncomfortable for participants, similar to Cho et al.,'s findings.[55] Therefore, this study's results suggest that exposure to stressful factors such as noise and heat in the work environment can lead to an increase in perceived mental workload, reflected by changes in absolute alpha and beta power in specific brain regions, serving as suitable indicators for cognitive and physiological performance alterations.

Conclusions

The results of this study indicate that the effect of gender on perceived mental workload parameters under combined conditions of varying levels of heat and noise did not show significant changes. This lack of significance may be attributed to the careful selection and control of intermediary factors in both genders among the participants. It was observed that combined exposure to high levels of heat and noise led to a significant increase in perceived mental workload compared to the background condition. Conversely, at lower levels, a decrease in mental workload was noted, with a notable decline in cognitive and behavioral performance observed at 34 degrees Celsius.

The EEG results revealed that in the two high-level exposure modes, the absolute alpha power decreased compared to the background state, correlating with an increase in mental workload. In contrast, in these high-level modes, the absolute beta power showed a significant increase compared to the background condition, indicating a positive direct relationship with mental load.

Given the prevalence of combined stress factors (such as heat and noise) in both occupational and non-occupational environments, it is crucial to consider occupational exposure standards. Currently, many occupational exposure standards and permissible limits established by the Health and Work Environment Center of Iran are based on individual exposures to harmful factors rather than combinations. Therefore, the findings of this study contribute to the identification of appropriate outcomes and brain indices that can help develop effective control solutions to mitigate the adverse effects of combined harmful factors like noise and heat.

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Competing interests

The authors declare that they have no competing interests.

Abbreviations

Body mass index: BMI;
Closed-circuit television: CCTV;
Wet-Bulb Globe Temperature: WBGT;
NASA Task Load Index: NASA-TLX;
Electroencephalogram: EEG.

Authors' contributions

All authors read and approved the final manuscript. All authors take responsibility for the integrity of the data and the accuracy of the data analysis.

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Availability of data and materials

The data used in this study are available from the corresponding author on request.

Ethics approval and consent to participate

The study was conducted in accordance with the Declaration of Helsinki. Institutional Review Board approval (code: IR.SBMU.PHNS.1396.63) was obtained. The present study did not interfere with the process of diagnosis and treatment of patients and all participants signed an informed consent form.

Consent for publication

By submitting this document, the authors declare their consent for the final accepted version of the manuscript to be considered for publication.

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