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Exploring gender differences in acoustic-thermal comfort and performance in a simulated working environment

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ARTICLE

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This study investigated gender differences in acoustic-thermal comfort and cognitive performance in three workload levels in eight simulated work environments with two noise levels (55 and 75 dBA) and four air temperatures (18, 22, 26, and 30 °C). Subjective perceptions, including noise annoyance and fatigue, physiological measurements like Heart Rate Variability (HRV), respiration rate, and EEG variables (ALPHA, BETA, THETA) were used to assess comfort. In addition, the cognitive performance of men and women was evaluated on three levels: simple, medium, and complex. Women generally reported higher annoyance levels than men, especially at 75 dB noise level and increasing temperatures. Women experienced higher fatigue in warmer conditions than men. Women exhibited higher accuracy and lower reaction time than men at 18 °C and 22 °C with a quiet noise level (55 dBA) and simple and medium tasks. However, women acted accurately in complex tasks but had a higher reaction time. On the contrary, as the tasks are complicated and air temperature (26 °C and 30 °C) increases, men have higher accuracy and further reaction time than women. Accuracy and reaction time were diminished in both genders at 75 dBA noise level. Significant changes in the physiological parameters were observed at 18–22 °C for men and at 26–30 °C for women with the same noise level. Women had higher alpha and beta waves at 18–22 °C, indicating greater comfort and alertness, but these values decreased as air temperature rose. Overall, the study emphasizes the importance of considering gender differences when designing indoor work environments for optimal comfort and performance.

1. Introduction

Regulation of indoor work environment conditions based on gender has always been one of the challenges for environmental ergonomists [1]. Acoustic and thermal comfort are two main factors in maintaining the comfort and safety of employees in an indoor work environment [2]. Acoustic comfort refers to the sound level within a space considered pleasant or acceptable for occupants. Lack of acoustic comfort can lead to discomfort, annoyance, distractions, and stress [3]. Moreover, excessive noise levels can negatively impact concentration, communication, productivity, and overall well-being [4]. Thermal comfort also involves maintaining an optimal thermal environment where occupants feel neither hot nor cold [5]. Individual temperature preferences can vary based on gender, age, clothing, and metabolic rate [2,6,7]. Therefore, due to diverse experiences with thermal environments, differences in thermal and noise sensitivity, and individual traits, creating uniform acoustic and thermal conditions in a shared indoor workspace may not meet the needs of all individuals.

Employees' acoustic and thermal comfort in occupational environments involved in cognitive tasks such as office and control rooms are critical to creating a productive and pleasant indoor environment [8]. Creating acoustic and thermal comfort for employees in these environments depends on identifying individual differences. Gender is the most crucial individual difference among people, and it significantly impacts the definition of a favorable thermal environment and the development of workers' acoustic and thermal comfort [9,10]. Gender profoundly influences how we perceive and experience our surroundings [9]. Du revealed that women tend to experience more thermal discomfort than

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men. However, they reported that there are no significant differences between genders when it comes to preferred temperature [11]. Studies have found that there can be up to a 3 °C difference between men and women in terms of their preferred indoor temperature [1]. Indraganti noted that Asian women are 37.3 % more likely to be dissatisfied with their thermal environments than men [12]. Karjalainen's research suggests that women exhibit greater sensitivity than men towards variations from optimal temperatures. Nevertheless, most studies have not reported substantial differences in neutral temperatures between genders. Existing evidence generally points to lower thermal satisfaction among office women [10]. On the other hand, research indicates that gender differences also exist in sensitivity to noise. While some studies suggest that women are more tolerant of low-frequency noise than men, others highlight that women tend to experience greater annoyance when exposed to noise and are more sensitive to noise [13]. In general, research on acoustic comfort based on gender is quite scarce.

Besides comfort, men and women exhibit varying performance, particularly cognitive performance, contingent upon environmental conditions [14–16]. Extensive research has explored gender differences across various domains, including work, physical abilities, and cognitive performance [17]. Generally, men excel in visuospatial tasks and mathematical abilities, while women demonstrate strengths in perceptual speed, accuracy, and fine motor skills [18]. Studies suggest that cognitive function is better in females, whereas males exhibit higher grip strength [19]. The disparity in performance between genders can fluctuate based on the task, workload, and environmental factors like noise, temperature, humidity, and air quality [1]. Chang et al. believe that in office settings, women exhibit better cognitive performance in warmer environments, while men perform better in colder temperatures [16]. Additionally, previous research shows that men tend to perform more accurately in high-noise conditions and high-workload tasks [20].

Therefore, the results of previous studies regarding performance and acoustic-thermal comfort based on gender are inconsistent and uncertain. Exploring gender differences in performance and acoustic-thermal comfort considering workload level, particularly those involving cognitive tasks, is crucial for improving indoor environmental quality, enhancing health and productivity, and user satisfaction. By recognizing gender-specific differences regarding environmental factors such as noise and temperature, we can create inclusive and productive workplaces that promote health and well-being in work settings. It can also help better personnel selection, design and optimize work environments and task design based on gender, and productivity. Moreover, Insights into gender differences can guide policies related to building codes and standards, ensuring that indoor environments are conducive to the needs of all genders. Given the limited research on this topic, this study investigated gender differences in acoustic-thermal comfort and cognitive performance according to the workload level across various combined conditions of sound and temperature using subjective perceptions, cognitive skills, and physiological parameters to design a desirable work environment. Specifically, subjective questionnaires or rating scales are used to collect individuals' perceptions of the environment. Moreover, many studies have examined the individuals' electroencephalogram (EEG) features in indoor environments. Some have also addressed heart rate variability concerning thermal comfort. Ren et al. measured the electrocardiogram (ECG) and electroencephalogram signals to predict occupant's thermal comfort [21]. Moreover, Pan et al. believe EEG signals can be used as physiological indicators to screen the environment [22]. However, this study has tried to evaluate the comfort and performance in men and women based on subjective judgments, physiological changes, and cognitive performance.

2. Methods

2.1. Participants

A total of 32 healthy students participated in the study. Among them, 16 were females with an average age of 22.62 years (±SD: 1.06) and an average body mass index (BMI) of 23.14 (±SD: 3.67). The other 16 participants were males, with an average age of 23.81 years (±SD: 3.8) and an average BMI of 23.3 (±SD: 2.7). Eligibility criteria for participation included enjoying general health, normal hearing, non-smoking, no alcohol or drug use, sufficient and good-quality sleep. Initially, the participants underwent screening for overall health, hearing, and vision. Their general health was assessed using the General Health Questionnaire-28 (GHQ-28) [23], and their sensitivity to noise was measured using the Weinstein Noise Sensitivity [24]. Visual health was evaluated using the E chart. An audiologist measured the hearing threshold levels of the participants using a calibrated audiometer (MEVOX ASB15) across the frequency range of 125–8 kHz. Only participants with an average hearing threshold level of at least 20 dBA were included in the study. In the study, participants who had a history of neurological, cardiovascular, and hormonal diseases, metabolic syndrome, heat stroke, or were taking drugs that affect the nervous system were omitted. All participants were instructed to ensure they had sufficient sleep the night before the experiments. They were also advised to abstain from stimulating substances for 12 h before the study. Every participant received compensation to enhance their motivation for participating in the study. Involvement was voluntary, and all participants provided informed consent.

2.2. Experiment design

This was an experimental study. Eight simulated combined experimental conditions were designed including two levels of noise (55 and 75 dBA) and four levels of air temperature (18 °C, 22 °C, 26 °C, and 30 °C) in the lab. Each participant took part in eight consecutive sessions in the morning. The sessions were conducted randomly, each lasting 1 h. The experiments took place in a climate-controlled room measuring 3.7 × 2.4 × 2.7 m, allowing temperature and relative humidity adjustments. Two LED lights provided illumination, emitting a light intensity of 500 lux. The room's walls were clad in polyurethane foam, and the floor was carpeted. The average noise reduction coefficient (NRC) for low-frequencies in the room was measured at 0.2. A desk, chair, and computer were also set up for administering cognitive tests. This room has an adjustable electric panel for controlling temperature and humidity. The electrical control board connected to outlet valves in the room's roof and walls regulates air temperature and humidity. Throughout all sessions, the relative humidity was consistently maintained at 50 %. The noise in the room was generated by 10-W speakers flanking the monitor to ensure uniform noise exposure, accompanied by an 8-W subwoofer. The equivalent sound pressure level was continuously measured during the test using an SVAN 971 sound level meter. The origin of the noise stemmed from typical office sounds, encompassing both conversations and the operation of office equipment. These machines, including printers, photocopiers, and phones, produce background noise that can impact comfort and productivity. We recorded psychophysiological responses using the NeXus-4 device and evaluated cognitive performance during each session. Fig. 1 depicts the room's interior and exterior space, the electrical panel for controlling temperature and humidity, the equipment used for cognitive tasks, and the NeXus-4 device for EEG and ECG recording.

2.3. Study procedure

In this study, the acoustic and thermal comfort experienced by both men and women was examined based on subjective judgment (noise annoyance and fatigue) and measurement of physiological parameters, including Heart rate variability (HRV), LF/HF ratio (low frequency (LF) to high frequency (HF)), and the respiration rate (RR), and three variables of electroencephalogram (EEG) include ALPHA, BETA, and THETA. In addition, the cognitive performance was assessed across eight simulated work conditions. Initially, participants underwent theoretical

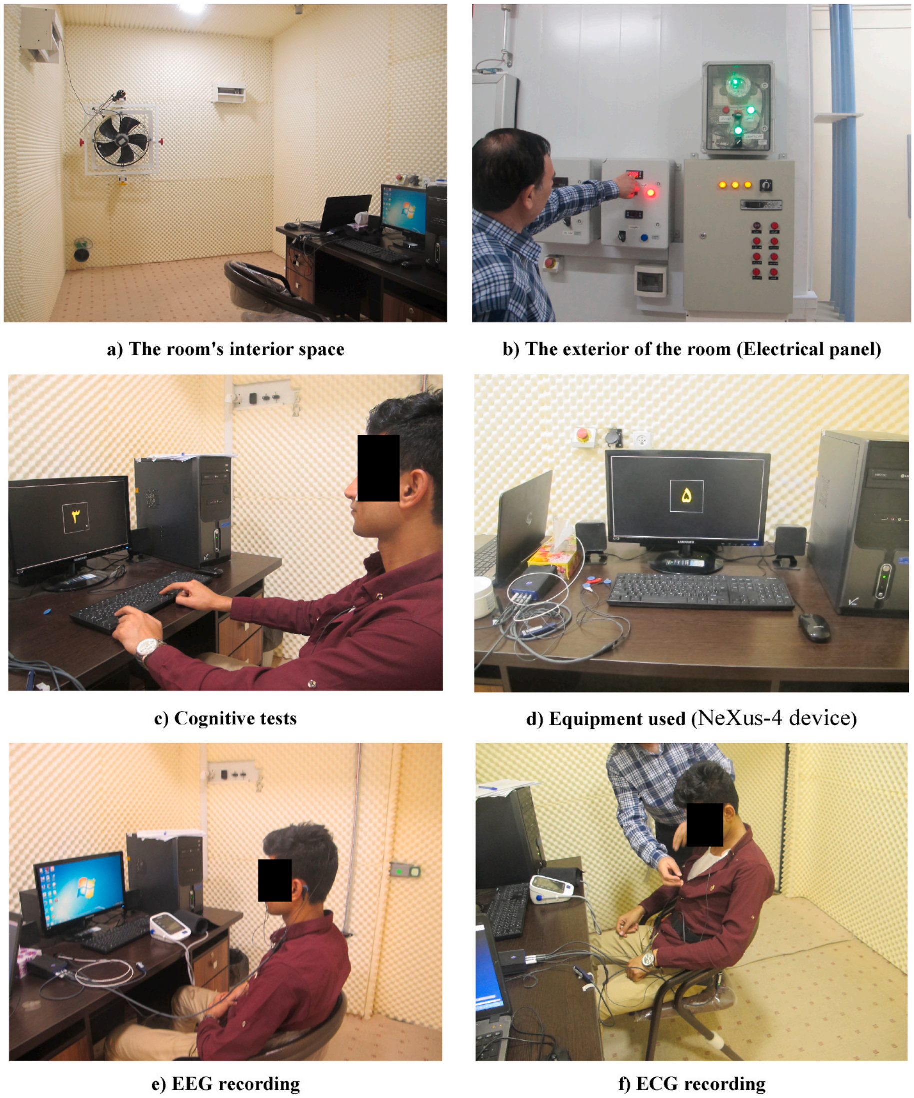

Fig. 1. The room's interior and exterior space, the electrical panel for controlling temperature and humidity, the equipment used for cognitive tasks, and the NeXus-4 device for EEG and ECG recording.

and practical sessions to acquaint themselves with the experiments' fundamental principles. Participants were directed to ensure adequate sleep and avoid caffeine or stimulating substances the night before each session. Before each session, they sat at their desks for about 15 min to adjust to the chamber's climate. Subsequently, ECG and EEG electrodes were attached to the participants' chest and head, and baseline values were documented for 5 min. Subsequently, we recorded the ECG throughout the experiment under combined noise and temperature conditions. Fifteen minutes after the start of the experiment, cognitive tests were conducted and the subject's cognitive skills were evaluated. These tests spanned three levels of workload: simple tasks, medium tasks, and complex tasks, with intervals of 5 min between each test. During the experiment, each test level lasted 5 min. We monitored the noise level and WBGT (Wet Bulb Globe Temperature) using a dosimeter (SV 104) and a WBGT meter (model HT30). We also recorded the LF/HF ratio and respiratory rate (RR) during the trial period. Immediately after the end of the 60 min of the experiment, EEG electrodes were attached to the participant's head, and EEG signals were recorded for 5 min.

At the end of each session, the subjects were asked to judge noise-induced annoyance and condition-induced subjective fatigue.

2.4. *Subjective perceptions*

The study assessed two subjective responses in participants at the end of each experiment session: annoyance and subjective fatigue. The standard scale developed by ISO 15666:2003 [25] was used to measure experienced noise annoyance. The visual analog rating scale (VAS) was also employed to evaluate subjective fatigue [26]. The Visual Analog Scale (VAS) used in the study featured a 10-cm line. The left end was labeled "0," while the right was labeled "10." Participants were instructed to mark the point on the line corresponding to their perceived annoyance and fatigue level. Moreover, the Weinstein Noise Sensitivity Scale (WNSS) was used to examine the noise sensitivity of men and women [25].

2.5. *Measurement of cognitive skills*

The working memory test of N-back was employed to gauge cognitive tasks. The N-back test assesses working memory by measuring the ability to remember and compare stimuli from previous trials. The higher the N (number of trials back), the more challenging the task becomes. Participants must balance accuracy and speed while maintaining information in their memory. In the 1-back task, participants are presented with a sequence of stimuli (such as letters or numbers) one by one. For each stimulus, they must decide if the current stimulus matches the one presented one trial ago. If the current stimulus is the same as the one presented in the previous trial, participants respond accordingly. The 1-back level (simple tasks) is relatively straightforward, as it only requires comparing the current stimulus to the immediate past one. At the 2-back level (medium tasks), participants must remember the order of stimuli over a slightly longer span. They tap when the current stimulus matches the one presented two trials ago. This level increases the cognitive load, as participants need to maintain information from two trials back. The 3-back level (complex tasks) further challenges working memory. Participants tap when the current stimulus matches the one presented three trials ago. Keeping track of stimuli over a longer sequence requires even more mental effort. At each workload level, we calculated the average correct answers, which reflects accuracy, along with the corresponding reaction time for each stimulus (measured in milliseconds) [27].

2.6. Recording of physiological parameters

Measurement of physiological parameters included electroencephalogram (ECG) signals, electrocardiogram (ECG) signals, and the respiration rate (RR). The data were measured using the NeXus-4 system developed by Mind Media Co. The NeXus-4 system is an entry-level biofeedback and neurofeedback device that offers up to two channels of EEG and ECG signals, along with other peripheral measurements like heart rate, skin conductance, and respiration rate. It provides reliable and high-quality signals for physiological research and analysis. The system is also equipped with the BioTrace software, which allows for real-time physiological data measurement and training. The device uses active shielding technology and carbon-coated cables to minimize noise and artifacts, ensuring high-quality ECG and EEG signals. The Nexus-4 can communicate wirelessly in real-time using Bluetooth, allowing for easy data transfer and monitoring during biofeedback or neurofeedback sessions [28].

2.6.1. HRV and RR recording

The Nexus-4 ECG sensor has three electrodes; a negative electrode (black), a positive electrode (red), and a ground electrode (white). The negative, ground, and positive electrodes were attached to the right chest, the left chest below the collarbone, and the right of the sternum in the fourth intercostal space, respectively. HRV was analyzed in ECG signals. HRV is the variation in the time interval between heartbeats. The main variable for HRV is the LF/HF ratio (low frequency (LF) to high frequency (HF). The LF/HF ratio is calculated by dividing the LF power by the HF power. It is indicative of sympathetic-to-parasympathetic autonomic balance. HF band is frequencies between 0.15 and 0.4 Hz, representing parasympathetic activity and LF band is frequencies between 0.04 and 0.15 Hz, reflecting a mix of sympathetic and parasympathetic activity. Higher HF values are generally associated with relaxation and recovery. Moreover, the RR was measured throughout the experiment. The Nexus-4 RR sensor was a respiration transducer belt. This belt is designed to be worn around the chest and is equipped with sensors to detect the expansion and contraction of the chest during breathing. By monitoring these movements, the system can accurately calculate the RR of the individual wearing the belt. Therefore, the LF/HF ratio and RR were collected in both genders during the trial period. Finally, the percentage changes in the data were calculated relative to baseline values.

2.6.2. Electrocardiography (ECG) recording

ECG (electrocardiogram) signals were recorded using electrodes attached to the head and three variables of EEG; ALPHA, BETA, and THETA were recorded at the beginning and end of the experiment. The Nexus-4 EEG sensor (channel A) was used to record the EEG based on the international 10–20 in the placement of electrodes [28]. To record EEG signals, reference electrodes were placed on the mastoid bone of the left ear (black), the ground electrode on the mastoid bone of the right ear (white), and the red electrode on the Cz sit. In this study, we used NuPrep gel (for skin preparation) and EEG 10–20 (Ten20) paste to fix the electrodes and the mean of theta range (4–8 Hz), the alpha range (8–12 Hz), and the mean of the range of beta(12–15 Hz) were recorded. Alpha waves are typically associated with a relaxed and wakeful state, often observed when a person is awake but with their eyes closed. They are prominent during light relaxation. Beta waves are linked to active thinking, concentration, and alertness. These waves dominate in problem-solving, decision-making, or focused mental tasks. Theta waves are associated with deep relaxation, creativity, and dreaming. During deep sleep (REM), theta waves become more prominent.

2.7. Data analysis

The data analysis was conducted using the statistical software IBM SPSS 24. To evaluate the normal distribution of the data at various levels, Mauchly's Test of Sphericity was employed. An analysis of variance (ANOVA) with repeated measures is commonly employed to compare the means of three or more groups where the same participants are involved in each group. Furthermore, Tukey's Test for post-hoc analysis was performed to explore the differences between these means. The study also included reporting the effect size (ES). Additionally, p-values less than 0.05 were deemed statistically significant.

3. Results

3.1. Subjective responses

The mean noise sensitivity for men was 57.16 ± 11.8, while for women, it was 77.56 ± 16.19. Results of the annoyance and fatigue levels experienced by men and women during the eight simulated combined conditions of noise and temperature have been illustrated in Fig. 2. This data suggests that both annoyance and fatigue levels tend to increase with temperature and noise. Females appear to experience slightly higher levels of annoyance and fatigue than males under the same conditions. In summary, women generally reported higher annoyance levels across all conditions compared to men. At 75 dB noise level, both genders experienced greater annoyance than at 55 dB, especially as temperature increased. The lowest annoyance rates for both genders were observed at 22 °C and 55 dBA. Additionally, both men and women exhibited higher fatigue levels with increasing temperature and noise levels. Women tended to experience higher fatigue levels, particularly in higher thermal conditions, while men reported lower fatigue in higher temperatures. The lowest fatigue levels for both genders were at 22 °C and 55 dB, indicating that moderate temperatures and lower noise levels contribute to reduced fatigue.

3.2. Cognitive tasks

The average accuracy and reaction time for both males and females across different tasks (simple, medium, and complex) under two noise levels (55dBA and 75dBA) and four air temperatures (18°°C, 22°°C, 26°°C, and 30°°C) has been shown Table 1. The results show that accuracy and reaction time are affected by noise, air temperature, and task complexity. As the noise level increases, accuracy and reaction time decrease, and the effect is more pronounced at higher air temperatures. Additionally, accuracy and reaction time are higher at lower task complexities. The combined effects of noise and air temperature on accuracy and reaction time are higher than the effects of each factor individually.

Table 1 demonstrates that under temperature conditions of 18 °C and 22 °C with a quiet noise level (55 dBA) and simple and medium tasks, women exhibit higher accuracy than men, and their reaction time is lower than men. However, women perform accurately in complex tasks but have a higher reaction time. On the contrary, as the tasks are

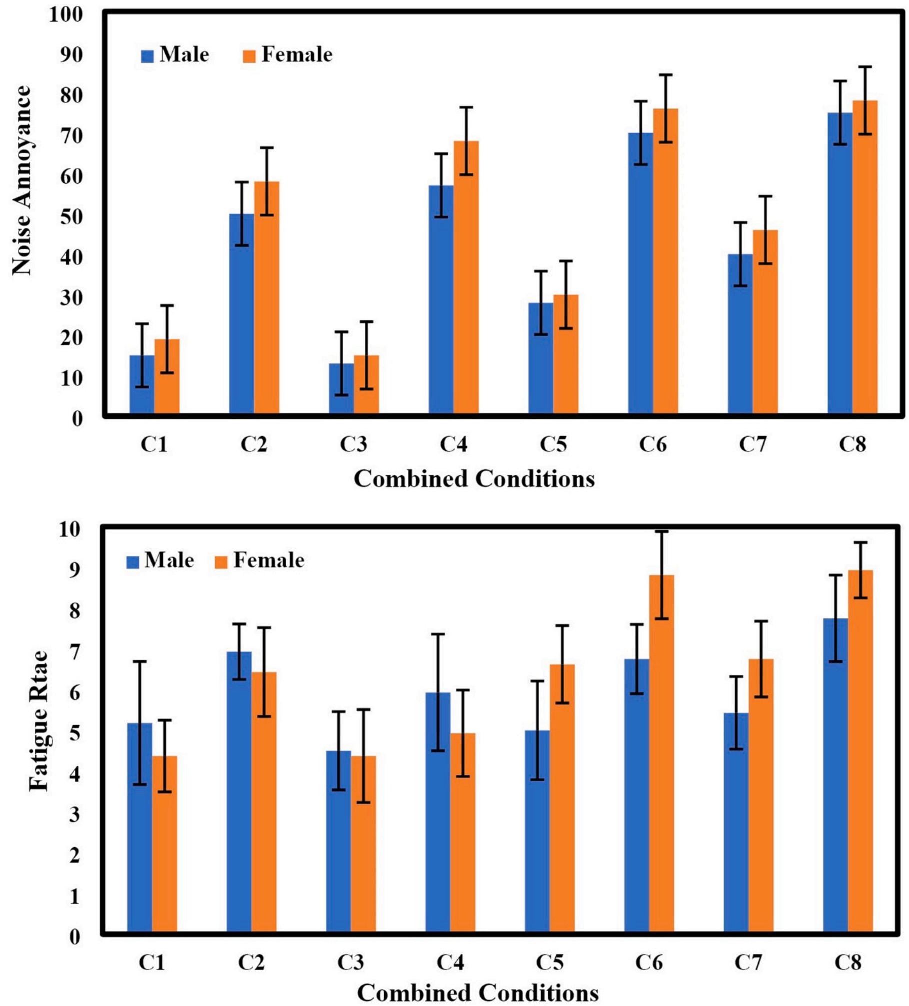

Fig. 2. Means ± SE of noise annoyance and fatigue rates of males and females in eight simulated conditions of noise and temperature
C1: Air temperature:18°°C and Noise level: 55dBA
C2: Air temperature:18°°C and Noise level: 75dBA
C3: Air temperature:22 °C and Noise level: 55dBA
C4: Air temperature:22 °C and Noise level: 75dBA
C5: Air temperature:26 °C and Noise level: 55dBA
C6: Air temperature:26 °C and Noise level: 75dBA
C7: Air temperature:30 °C and Noise level: 55dBA
C8: Air temperature:30 °C and Noise level: 75dBA

complicated and air temperature (26 °C and 30 °C) increases, men have higher accuracy and further reaction time than women.

The table also reveals that under the same temperature conditions and with varying task complexities, when the noise level is increased (75 dBA), accuracy and reaction time decrease in both genders. Women slightly outperform men (higher accuracy and lower reaction time) in temperature conditions 18 °C and 22 °C at each level of tasks. Conversely, men indicate better performance (higher accuracy and lower reaction time) in temperatures 26 °C and 30 °C at each level of tasks.

Regardless of gender, there is a significant difference in average accuracy at the same temperatures with quiet noise conditions (55dBA) with each level of task conditions ($P < 0.005$). Similarly, a significant difference exists between the average accuracy and average reaction time in different temperatures and noise conditions 75dBA with each level of task ($P < 0.005$).

Table 2 indicates the influence of gender on the average accuracy and response time to stimuli. The impact of gender on the mean accuracy and mean reaction time under varying temperature conditions with a quiet noise level (55 dBA) and medium and complex tasks was statistically significant ($p < 0.05$). Moreover, the effect of gender on the mean accuracy and mean reaction time under different temperature conditions with a high noise level (75 dBA) and medium and challenging tasks was also significant ($p < 0.05$). The gender effect on mean accuracy in three levels of tasks and two noise conditions was estimated to be 2.5 %, 29 %, 16 %, 2.7 %, 27.7 %, and 31.5 %, respectively. Furthermore, the gender effect on mean reaction time in three levels of tasks and two noise conditions was estimated to be 1 %, 41.1 %, 15.1 %, 2 %, 13.4 %, and 15.8 %, respectively.

3.3. Physiological parameters

3.3.1. The LF/HF ratio and respiration rate

Figs. 3 and 4 illustrate the LF/HF ratio values and respiration rate of the men and women during 1 h under eight simulated combined conditions. The value LF/HF ratio rises with increasing air temperature. The LF/HF ratio is elevated at 75 dB noise level. However, among females, the LF/HF ratios and RR were higher at temperatures of 26 °C and 30 °C,

Table 1
Means ± SD of accuracy and reaction time of males and females in simple, medium, and complex tasks across eight combined conditions of noise and air temperatures.

Parameters	Gender	Air temperatures				P-value	ES
		18 °C	22 °C	26 °C	30 °C		
55 dB(A)							
Accuracy							
Simple task	Male	84.750 ± 11.63	89.169 ± 7.25	83.375 ± 13.87	75.937 ± 17.36	**<0.003**	0145
	Female	86.187 ± 10.99	89.792 ± 7.84	84.250 ± 11.75	80.000 ± 10.53		
Medium task	Male	70.000 ± 09.68	83.857 ± 6.35	88.310 ± 09.12	86.250 ± 07.16	**<0.001**	0.178
	Female	82.875 ± 09.57	87.293 ± 5.65	69.125 ± 11.63	67.562 ± 12.27		
Complex task	Male	68.250 ± 11.55	79.533 ± 6.57	79.000 ± 06.57	76.375 ± 11.65	**<0.000**	0.267
	Female	71.312 ± 11.68	85.888 ± 6.67	66.125 ± 07.35	65.500 ± 07.82		
Reaction time							
Simple task	Male	478.88 ± 167.34	467.81 ± 105.23	443.00 ± 135.08	452.00 ± 124.88	<0.979	0.002
	Female	463.19 ± 196.21	460.69 ± 127.82	490.56 ± 096.99	453.94 ± 149.86		
Medium task	Male	478.88 ± 167.34	523.00 ± 124.57	553.50 ± 088.21	597.44 ± 060.34	<0.362	0.034
	Female	426.31 ± 116.69	461.69 ± 163.23	418.31 ± 119.34	404.38 ± 091.76		
Complex task	Male	501.37 ± 152.56	548.06 ± 143.57	544.12 ± 093.15	519.75 ± 127.06	**<0.005**	0.138
	Female	517.88 ± 189.62	567.69 ± 162.27	401.50 ± 066.78	372.06 ± 083.37		
75 dB(A)							
Accuracy							
Simple task	Male	72.43 ± 07.79	74.81 ± 6.50	78.93 ± 12.78	66.68 ± 15.54	**<0.001**	0.186
	Female	79.81 ± 10.23	78.93 ± 6.99	74.81 ± 14.01	64.62 ± 11.43		
Medium task	Male	67.43 ± 11.27	69.87 ± 5.69	71.93 ± 10.38	68.06 ± 13.82	**<0.008**	0.126
	Female	68.62 ± 12.81	72.06 ± 7.63	57.18 ± 05.78	55.87 ± 12.98		
Complex task	Male	57.75 ± 10.53	68.75 ± 9.95	68.06 ± 08.40	67.56 ± 09.14	**<0.000**	0.228
	Female	58.87 ± 12.61	70.93 ± 4.41	54.81 ± 07.99	53.56 ± 09.14		
Reaction time							
Simple task	Male	457.31 ± 113.15	428.94 ± 82.70	461.50 ± 80.48	515.56 ± 130.73	**<0.001**	0.174
	Female	422.63 ± 192.78	423.94 ± 57.70	493.25 ± 89.72	580.25 ± 138.71		
Medium task	Male	507.19 ± 097.93	454.94 ± 82.10	574.81 ± 86.21	569.31 ± 091.38	**<0.000**	0.297
	Female	504.36 ± 125.41	459.94 ± 96.19	614.50 ± 58.43	625.06 ± 116.60		
Complex task	Male	527.25 ± 165.86	491.87 ± 58.19	570.56 ± 93.23	593.69 ± 098.66	**<0.000**	0.424
	Female	0490.06 ± 91.46	473.38 ± 67.43	683.00 ± 53.47	699.13 ± 112.57		

Note. Accuracy: Percentage of correct answers, Response time: Average response rate to the stimuli , ES: Effect size.

Table 2
Effect of gender on the mean accuracy and response time of males and females under exposure to two noise levels four conditions of air temperatures and three levels of workload.

Parameters	Workload	Source	Type111 sum of squares	Mean square	f	P-value	ES
Accuracy							
18°C, 22°C, 26°C, &30°C VS 55dBA	Simple task	Gender	97.95	97.95	0.781	>0.384	0.025
18°C, 22°C, 26°C, &30°C VS 55dBA	Medium task	Gender	930.04	930.04	12.260	**<0.001**	0.290
18°C, 22°C, 26°C, &30°C VS 55dBA	Complex task	Gender	410.84	410.84	5.730	**<0.023**	0.160
18°C, 22°C, 26°C, &30°C VS 75dBA	Simple task	Gender	56.44	56.44	0.786	>0.382	0.026
18°C, 22°C, 26°C, &30°C VS 75dBA	Medium task	Gender	1110.11	1110.11	11.482	**<0.002**	0.277
18°C, 22°C, 26°C, &30°C VS 75dBA	Complex task	Gender	1146.00	1146.00	13.807	**<0.001**	0.315
Response time							
18°C, 22°C, 26°C, &30°C VS 55dBA	Simple task	Gender	4668.19	4668.19	0.293	>0.592	0.010
18°C, 22°C, 26°C, &30°C VS 55dBA	Medium task	Gender	390949.03	390949.03	20.930	**<0.001**	0.411
18°C, 22°C, 26°C, &30°C VS 55dBA	Complex task	Gender	129222.57	129222.57	5.340	**<0.028**	0.151
18°C, 22°C, 26°C, &30°C VS 75dBA	Simple task	Gender	6439.70	6439.70	0.614	>0.439	0.020
18°C, 22°C, 26°C, &30°C VS 75dBA	Medium task	Gender	31156.32	31156.32	4.625	**<0.039**	0.134
18°C, 22°C, 26°C, &30°C VS 75dBA	Complex task	Gender	52609.57	52609.57	5.621	**<0.024**	0.158

as well as at 75 dB noise level, compared to males. Conversely, males exhibited higher LF/HF ratios and RR at temperatures of 18 °C and 22 °C, as well as at 55 dB noise level, compared to females.

Table 3 presents mean changes of the LF/HF ratio and respiration rate for both males and females across different task complexities (simple, medium, and complex) under two noise levels (55dBA and 75dBA) and four air temperatures (18 °C, 22 °C, 26 °C, and 30 °C). The results show that noise, air temperature, and task complexity affect the LF/HF ratio and respiration rate. The LF/HF ratio and respiration rate are higher at the noise level of 75 dB than 55 dB, and the effect is more pronounced at higher air temperatures. The combined effects of noise and air temperature on the LF/HF ratio and respiration rate are higher than the effects of each factor individually. Additionally, the LF/HF ratio and respiration rate were higher at complex tasks.

Table 3 also demonstrates that at temperatures of 18 °C and 22 °C with a quiet noise level (55 dBA), men exhibit slightly higher changes in the LF/HF ratio and respiratory rate (RR) than women. However, as tasks become more complex and air temperatures increase to 26 °C and 30 °C, women experience greater changes in the LF/HF ratio and RR than men.

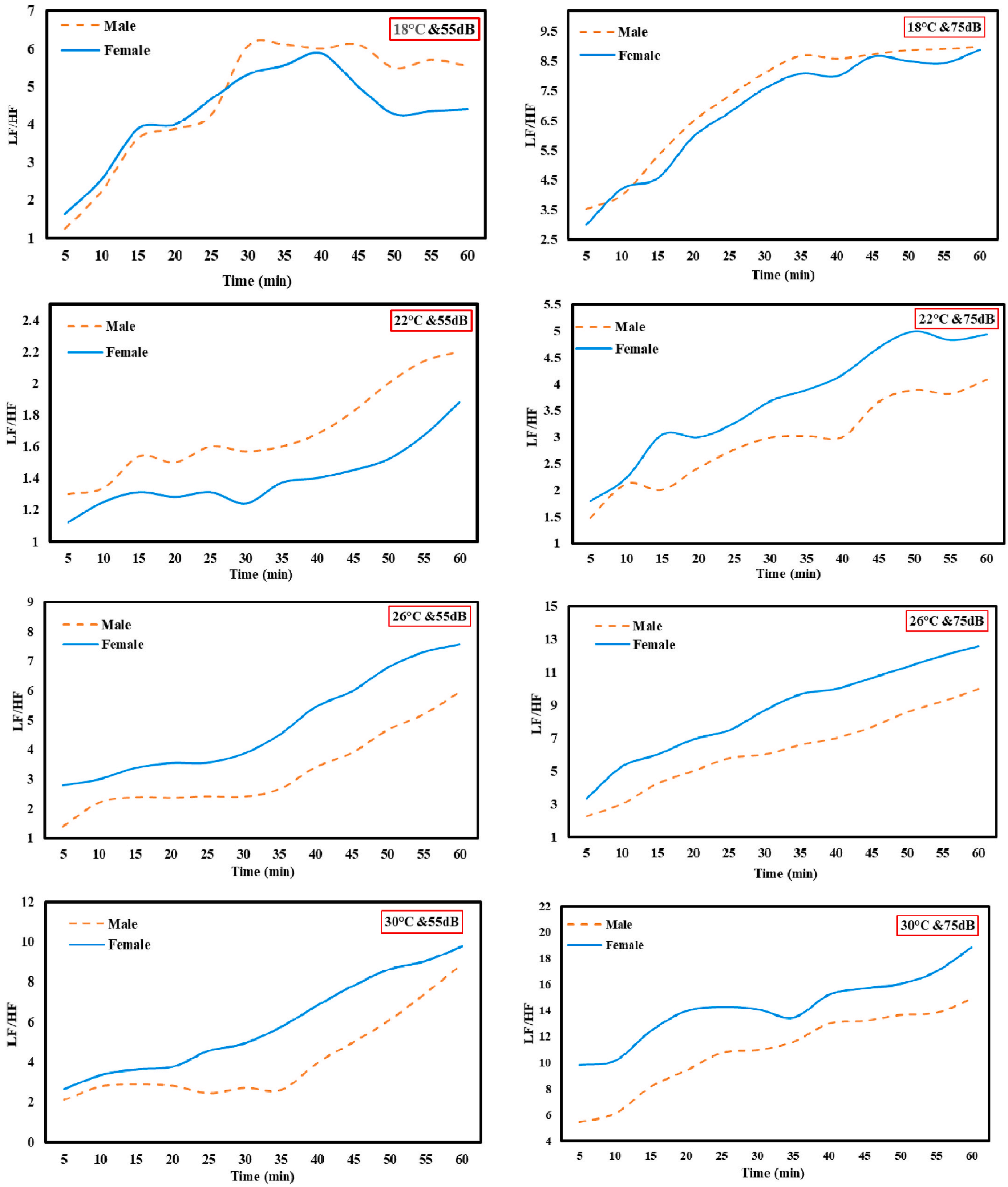

Fig. 3. The LF/HF ratio of men and women during 1 h under eight simulated combined conditions.

When the noise level increases to 75 dBA under the same temperature conditions and varying task complexities, both men and women show increased LF/HF ratio and RR changes. Specifically, men demonstrate more significant changes in the LF/HF ratio and RR at 18 °C and 22 °C with a noise level of 75 dB across different task levels. Conversely, women experience more pronounced LF/HF ratio changes and RR at 26 °C and 30 °C with the same noise level. Regardless of gender, there is a statistically significant difference in the average change in LF/HF ratio

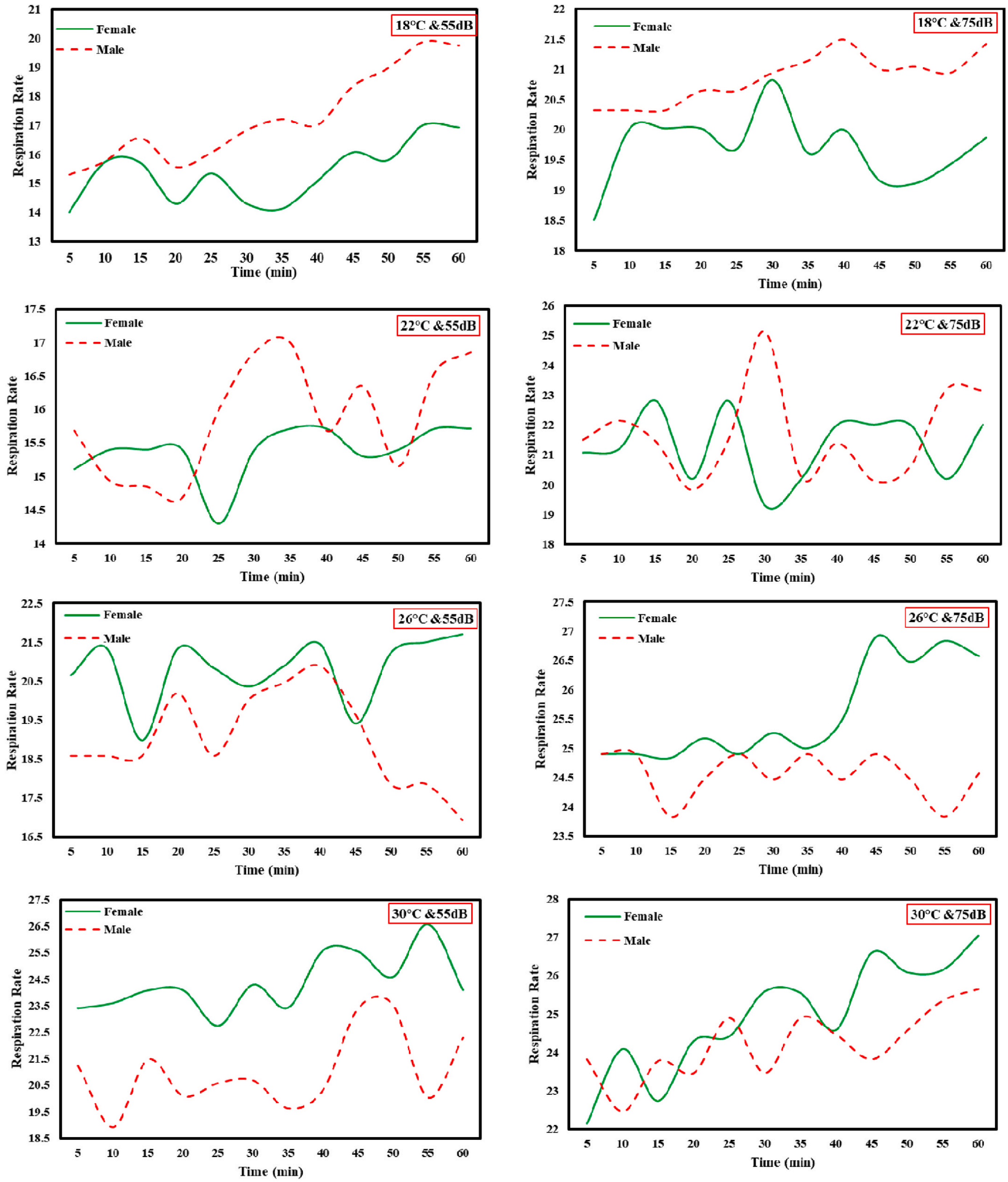

Fig. 4. Respiration rate of men and women during 1 h under eight simulated combined conditions.

and RR when comparing the same temperatures under quiet noise conditions (55 dBA) across various task complexities ($P < 0.005$). Similarly, significant differences exist between the average changes in LF/HF ratio and RR at different temperatures and noise levels of 75 dB, considering each level of task complexity ($P < 0.005$).

Table 4 shows how gender impacts the average LF/HF ratio and RR changes during exposure to varying noise levels, air temperatures, and workload levels. Specifically, gender significantly affects the LF/HF

Table 3
MD ± SE of changes in LF/HF and respiration rate of males and females under exposure to two noise levels four conditions of air temperatures and three levels of workload.

Parameters	Workload	Gender	Air temperatures				ES	p-value
			18 °C	22 °C	26 °C	30 °C		
55 dBA								
LF/HF	Simple task	Male	3.63 ± 4.92	1.54 ± 9.33	2.39 ± 4.14	2.88 ± 4.02	0.042	>0.275
		Female	3.89 ± 4.70	1.45 ± 2.13	3.38 ± 3.17	3.62 ± 2.44		
LF/HF	Medium task	Male	6.08 ± 3.91	1.60 ± 8.55	2.41 ± 5.33	2.60 ± 4.09	0.129	**<0.007**
		Female	5.32 ± 5.44	1.17 ± 1.72	3.86 ± 2.56	4.93 ± 1.94		
LF/HF	Complex task	Male	5.71 ± 4.80	2.14 ± 2.92	5.19 ± 3.29	7.46 ± 1.22	0.288	**<0.000**
		Female	4.36 ± 3.08	1.67 ± 2.06	7.30 ± 2.50	9.03 ± 3.95		
RSP	Simple task	Male	2.21 ± 5.60	1.66 ± 5.68	3.66 ± 5.56	5.02 ± 2.16	0.224	**<0.001**
		Female	1.52 ± 2.84	1.18 ± 2.02	4.47 ± 1.48	5.71 ± 1.68		
RSP	Medium task	Male	3.22 ± 6.19	2.59 ± 5.11	3.60 ± 5.12	6.20 ± 1.95	0.226	**<0.001**
		Female	2.20 ± 4.33	1.96 ± 3.54	4.78 ± 1.94	7.13 ± 1.71		
RSP	Complex task	Male	6.10 ± 3.49	5.02 ± 2.51	5.75 ± 8.39	7.08 ± 6.45	0346	**<0.001**
		Female	5.29 ± 4.89	4.11 ± 2.69	7.52 ± 5.00	8.34 ± 1.34		
75 dBA								
LF/HF	Simple task	Male	5.31 ± 4.96	3.25 ± 4.99	4.24 ± 2.88	6.16 ± 2.48	0.199	**<0.001**
		Female	4.56 ± 3.85	2.01 ± 4.10	6.01 ± 4.03	8.40 ± 2.56		
LF/HF	Medium task	Male	5.69 ± 4.80	4.68 ± 5.15	6.59 ± 3.24	7.59 ± 2.87	0.308	**<0.001**
		Female	4.08 ± 7.30	2.99 ± 3.99	9.67 ± 2.68	13.44 ± 1.29		
LF/HF	Complex task	Male	8.92 ± 4.60	4.03 ± 7.35	9.25 ± 1.97	11.64 ± 2.26	0.457	**<0.001**
		Female	7.43 ± 6.86	3.81 ± 4.47	12.02 ± 1.25	16.95 ± 3.49		
RSP	Simple task	Male	4.79 ± 1.79	3.21 ± 2.61	3.70 ± 3.61	6.40 ± 2.22	0.382	**<0.001**
		Female	3.85 ± 1.96	2.07 ± 2.47	6.97 ± 1.13	7.62 ± 1.38		
RSP	Medium task	Male	5.50 ± 1.72	4.40 ± 4.52	6.45 ± 2.63	7.51 ± 2.15	0.507	**<0.001**
		Female	3.72 ± 2.22	3.28 ± 3.69	9.91 ± 1.35	11.08 ± 1.37		
RSP	Complex task	Male	4.40 ± 3.58	5.59 ± 4.36	6.60 ± 3.79	8.27 ± 2.34	0.517	**<0.001**
		Female	3.97 ± 2.56	3.55 ± 2.70	10.04 ± 1.49	11.42 ± 0.97		

Note. LF/HF: change in LF to HF ratio as compared with the baseline, RSP: change in respiratory rate as compared with the baseline.

Table 4
Effect of gender on the mean respiration rate and LF/HF of males and females under exposure to two noise levels four conditions of air temperatures and three levels of workload.

Air temperatures Vs Noise	Workload	Source	Type111 sum of squares	Mean square	f	P-value	ES
LF/HF							
18 °C, 22 °C, 26 °C, &30 °C VS 55dBA	Simple task	Gender	5.04	5.04	0.204	>0.65	0.007
18 °C, 22 °C, 26 °C, &30 °C VS 55dBA	Medium task	Gender	13.54	13.54	0.681	>0.41	0.022
18 °C, 22 °C, 26 °C, &30 °C VS 55dBA	Complex task	Gender	207.49	207.49	4.39	**<0.045**	0.128
18 °C, 22 °C, 26 °C, &30 °C VS 75dBA	Simple task	Gender	8.09	8.09	0.635	>0.43	0.021
18 °C, 22 °C, 26 °C, &30 °C VS 75dBA	Medium task	Gender	87.89	87.89	5.13	**<0.031**	0.116
18 °C, 22 °C, 26 °C, &30 °C VS 75dBA	Complex task	Gender	207.49	207.49	4.39	**<0.045**	0.128
RR (bpm)							
18 °C, 22 °C, 26 °C, &30 °C VS 55dBA	Simple task	Gender	0.22	0.22	0.011	>0.917	0.001
18 °C, 22 °C, 26 °C, &30 °C VS 55dBA	Medium task	Gender	0.428	0.428	0.022	>0.883	0.002
18 °C, 22 °C, 26 °C, &30 °C VS 55dBA	Complex task	Gender	5.87	5.87	0.320	>0.576	0.011
18 °C, 22 °C, 26 °C, &30 °C VS 75dBA	Simple task	Gender	11.58	11.58	3.50	>0.071	0.105
18 °C, 22 °C, 26 °C, &30 °C VS 75dBA	Medium task	Gender	34.11	34.11	5.11	**<0.031**	0.146
18 °C, 22 °C, 26 °C, &30 °C VS 75dBA	Complex task	Gender	33.82	33.82	4.74	**<0.037**	0.147

ratio under different temperature conditions, with statistically significant effects observed for both quiet (55 dBA) and high (75 dBA) noise levels during medium and complex tasks. The estimated effects range from 11.6 to 12.8. Additionally, gender significantly impacts mean respiration rate, particularly under varying temperature conditions, a noise level of 75 dB, and during medium and complex tasks. Overall, gender-related physiological effects are more pronounced in the noise level of 75 dB and medium and complex tasks.

3.3.2. EEG parameters

Table 5 presents the average changes in three EEG parameters—ALPHA, BETA, and THETA—for both genders exposed to two noise levels and four different air temperature conditions. Notably, significant differences exist in the mean changes of these EEG parameters across eight simulated combined noise and temperature conditions. Specifically, as air temperature increases, the mean changes in THETA parameters also increase, while the parameters of ALPHA and BETA decrease. Moreover, when comparing noise levels, the mean changes in EEG parameters were more pronounced at 75 dB compared to 55 dB.

The findings also reveal that at 18 °C and 22 °C, with both noise levels (55 and 75 dBA), alpha and beta waves in women were higher than in men. This suggests that women experience greater comfort, heightened alertness, and improved concentration in cooler temperatures. Conversely, as the air temperature rises to 26 °C and 30 °C, the values of alpha and beta waves decrease in both genders, with a more pronounced effect observed in women.

Additionally, the results indicate that under the same temperature conditions (18 °C and 22 °C) and noise levels (55 and 75 dBA), theta waves in men were higher than in women. However, as the air temperature increases to 26 °C and 30 °C, the values of theta waves in

Table 5
MD ± SE of changes in three EEG parameters—ALPHA, BETA, and THETA of males and females under exposure to two noise levels and four conditions of air temperatures.

Variables	Gender	Air temperatures				ES	P-value
		18 °C	22 °C	26 °C	30 °C		
55 dBA							
Alpha (μv)	Male	−0.54 ± 1.26	−0.12 ± 0.96	−1.91 ± 2.34	−2.73 ± 1.82	0.562	**<0.001**
	Female	−0.06 ± 1.74	−0.08 ± 1.17	−2.63 ± 2.34	−4.87 ± 1.19		
Beta (μv)	Male	0.86 ± 0.78	1.44 ± 1.58	−1.83 ± 4.07	−3.23 ± 1.15	0.678	**<0.001**
	Female	1.33 ± 0.77	1.62 ± 0.64	−3.54 ± 1.77	−4.02 ± 1.18		
Theta (μv)	Male	0.92 ± 1.71	1.24 ± 2.30	3.18 ± 2.02	3.76 ± 3.05	0.560	**<0.001**
	Female	0.40 ± 1.94	1.15 ± 1.25	5.05 ± 1.29	6.23 ± 0.98		
75 dBA							
Alpha (μv)	Male	−1.56 ± 1.49	−2.66 ± 1.83	−3.77 ± 0.97	−5.20 ± 2.43	0.696	**<0.001**
	Female	−1.51 ± 0.87	−1.61 ± 1.40	−6.64 ± 2.13	−6.91 ± 1.29		
Beta (μv)	Male	0.01 ± 1.76	−3.61 ± 0.96	−4.11 ± 1.58	−5.39 ± 1.52	0.830	**<0.001**
	Female	0.83 ± 1.67	−3.35 ± 1.23	−6.47 ± 1.27	−6.71 ± 1.35		
Theta (μv)	Male	2.02 ± 1.68	1.30 ± 1.14	3.51 ± 1.13	5.52 ± 2.64	0.738	**<0.001**
	Female	1.61 ± 1.14	1.20 ± 0.55	5.99 ± 1.64	7.44 ± 2.12		

Note. MD: Mean of difference (pre- and post-), SE: Standard error' ES: Effect size.

women surpass those in men. This suggests that women may experience drowsiness or a sense of sleepiness at temperatures of 26 °C and 30 °C, particularly when exposed to noise levels of 75 dB.

Table 6 also indicates that gender significantly impacts the average changes in alpha, beta, and theta waves when exposed to two noise levels and four different air temperature conditions ($P < 0.05$). Specifically, the influence of gender on these waves at different air temperatures and a noise level of 55 dB was 12.7, 15.2, and 22, respectively. Furthermore, the effect of gender on these waves at different air temperatures and a noise level of 75 dB was 17.6, 13.6, and 22.8, respectively.

4. Discussion

Gender is a social construct characterized by women's and men's roles, behaviors, and identities. Gender differences significantly influence our perception of the surrounding environment [9]. Although gender differences tend to diminish with age, it is crucial to consider gender variations in designing and managing indoor environments to enhance performance, especially human acoustic-thermal comfort [29]. While many physical factors have been studied separately to provide a favorite work environment, few studies have focused on designing based on gender in hybrid environments. These physical factors should be considered when designing indoor working environments to create spaces that promote health, comfort, and optimal performance for workers. Therefore, this research investigated comfort and cognitive performance between males and females according to the workload level across various combined conditions of sound and temperature using subjective judgment, cognitive skills, and physiological parameters.

4.1. Subjective responses

Women generally reported a higher level of annoyance across all combined conditions than men. At a noise level of 75 dB, the annoyance rates for both men and women were more significant than those at 55 dB under similar temperature conditions. The lowest annoyance rate was observed for both genders at 22 °C and 55 dBA. However, as the temperature increased in each acoustic condition, women experienced higher annoyance rates. In a research experiment, Beheshti and colleagues found that females exhibited a greater level of annoyance from low-frequency noise than males [13], which is consistent with this study. Moreover, Hill et al. have found that gender plays a significant role in noise sensitivity, with women being more sensitive to noise than men [30]. Table 1 also shows that both men and women experience higher fatigue levels as the temperature and noise levels increase. The highest rates of fatigue have been at 30 °C and 75 dB for both genders. However, women tend to experience higher fatigue levels compared to men under similar combined conditions. Women experience higher fatigue in high temperatures. Conversely, men have reported lower fatigue in higher temperatures. For instance, at 26 °C and 75 dB, men's fatigue levels were relatively lower than women. Previous studies are consistent with these results. Karjalainen's research revealed that females are less content with room temperatures than males and experience cold and hot discomfort more frequently than males [31]. In research on thermal comfort in Japanese residential buildings, Aqilah and colleagues found that during summer, the average comfort temperature for males was notably higher by approximately 1.2 °C–2.2 °C compared to females [1]. Chen et al. discovered that as individuals perceived better acoustic comfort, their thermal sensation ratings improved, conversely, indicating a reciprocal relationship between the two factors [32].

Table 6
Gender effect on the mean changes of theta, alpha, and beta waves of males and females under exposure to two noise levels and four conditions of air temperatures.

Air temperatures VS Noise	Parameters (μv)	Source	Type111 sum of squares	Mean square	f	P-value	ES
18 °C, 22 °C, 26 °C, &30 °C VS 55dBA	Theta	Gender	28.11	28.11	8.44	**<0.007**	0.220
18 °C, 22 °C, 26 °C, &30 °C VS 75dBA		Gender	30.42	30.42	8.87	**<0.006**	0.228
18 °C, 22 °C, 26 °C, &30 °C VS 55dBA	Alpha	Gender	10.88	10.88	5.38	**<0.027**	0.152
18 °C, 22 °C, 26 °C, &30 °C VS 75dBA		Gender	24.19	24.19	6.41	**<0.017**	0.176
18 °C, 22 °C, 26 °C, &30 °C VS 55dBA	Beta	Gender	13.50	13.50	4.35	**<0.046**	0.127
18 °C, 22 °C, 26 °C, &30 °C VS 75dBA		Gender	13.50	13.50	4.73	**<0.038**	0.136

ES: Effect size.

4.2. Cognitive skills

In general, the research shows that women have better accuracy and quicker reaction times than men in 18 °C and 22 °C temperature conditions with a quiet noise level (55 dBA) during simple and medium tasks. Upadhyay and Guragain also discovered that men may not perform as well as women in simple tasks that involve attention, working memory, and color reading under normal circumstances [33], which aligns with this study. However, as task complexity and air temperature (26 °C and 30 °C) increase, men exhibit higher accuracy and faster reaction times than women. Although specific studies are lacking, existing evidence suggests that men perform better at high workloads [34].

Women slightly outperform men in accuracy and reaction time at 18 °C and 22 °C, while men excel at 26 °C and 30 °C across different task levels. In an experimental study, Chang examined the impact of temperature on cognitive tasks. Contrary to this study's results, they found that women tend to perform better than men on math and verbal tasks at higher temperatures than at lower temperatures [14]. Some studies have reported that women generally prefer warmer indoor temperatures compared to men, and this preference seems to align with their cognitive performance. Conversely, men may perform better in cooler environments [35]. Specifically, in office settings, women tend to exhibit better cognitive performance in warmer environments, while men perform better in colder temperatures [36]. However, these findings are inconsistent with our study, possibly due to differences in research methods and conditions.

Furthermore, findings revealed that accuracy and reaction time decreased for both genders when the noise level was 75 dBA under the same temperature conditions and varying task complexities. In this regard, Abbasi et al. fund that females exhibit improved cognitive performance at noise levels of 65 dBA or lower during low mental workloads. In contrast, males outperform at noise levels of 65 dB or higher and high workloads [37]. Sepehri et al. reported that noise had a greater impact on working memory, sustained attention, and reaction time compared to air temperature [38].

4.3. Physiological parameters

Examination of physiological parameters also revealed that noise, air temperature, and task complexity affect the LF/HF ratio and respiration rate. Higher values were observed at 75 dB noise level and higher temperatures. Men show significant changes at 18 °C and 22 °C, while women exhibit pronounced changes at 26 °C and 30 °C. In this regard, Yang et al. have investigated gender differences in metabolic rates and thermal comfort in sedentary young males and females at cool (14, 16, 18, 20 °C) and warm (28, 30, 32, and 34 °C) temperatures. They concluded that females tend to be cooler and less comfortable than males at cool temperatures, which could explain the lower metabolic rates and skin temperatures in females. Males tend to be warmer and less comfortable at warm temperatures, which higher metabolic rates and higher skin wetness in males could explain [39]. These findings confirm the results of our study.

Furthermore, The combined impact of noise and temperature surpassed individual effects. Previous studies have also confirmed that the interaction between noise and air temperature affects neurophysiological responses and thermal comfort [40]. Jafari et al. discovered that combined exposure to noise and heat significantly increased saliva cortisol levels and blood pressure [41]. According to an experimental study by Guan et al., at 30 °C, the rates of thermal discomfort and noise annoyance increased by 1.85 and 1.96 scales, respectively, when the noise levels increased from 55 dB to 85 dB. It was also observed that noise annoyance was higher at 30 °C. Heart rate (HR) also exhibited similar patterns associated with both temperature and noise effects [42]. However, none of these studies have investigated the importance of gender differences in acoustic and thermal comfort.

The study revealed notable variations in EEG parameters based on varying temperature and noise levels. With rising air temperature, theta parameters increased, whereas alpha and beta parameters decreased. Women exhibited higher levels of alpha and beta waves at 18 °C and 22 °C, indicating increased comfort and alertness. However, as the air temperature continued to rise, both genders experienced decreased alpha and beta waves, with women being more affected. In an experimental study on ten male subjects, Wang et al. also confirmed that as the ambient temperature rose, the power of Theta and Alpha activity increased. At the same time, vigilance and frontal EEG asymmetry decreased. Conversely, β activity and the level of alertness and prefrontal asymmetry increased at lower temperatures [43]. Pan et al. also studied the impact of indoor thermal conditions on electroencephalogram (EEG) signals. They discovered that at 22 °C and 25 °C, Theta and Beta waves exhibited high similarity [22]. Beta waves are associated with cognitive tasks and mental engagement. High temperatures can disrupt cognitive tasks and lead to conditions such as anxiety or stress. In men, theta waves were higher at lower temperatures, while in women, they were higher at higher temperatures (suggesting potential drowsiness or sleepiness) and a noise level of 75 dB. However, previous studies also confirmed that beta activity is higher in co-exposure to noise and heat [35].

4.4. Limitations and future study

The current study had several limitations. It focused on a homogeneous sample of individuals aged 25–40 (both males and females), which may not fully represent the larger working population, including older or 'unhealthy' workers. Because the biological response might differ among other groups, the results were limited to the conditions of this experiment, and therefore, subjects' responses may be different in other conditions. Another limitation was that although the sample size was determined based on statistical analysis from previous studies, it may be inadequate in randomized, controlled, single-blinded trial studies. The study specifically investigated two low-frequency noise levels (55 and 75 dB(A)) and four temperature conditions. However, it is essential to acknowledge that in some work environments, a sound pressure level of 75 dB may be too high and unusual. Therefore, future research can investigate acoustic and thermal comfort in connection with motor skills and noise frequency in larger samples. Moreover, it is recommended that further explores the correlation between the subjects' perception of heat and cold, sound perception and EEG signals, and how the subjects' feelings about the physical environment such as the thermal environment and the sound environment are transmitted to the brain, and how the brain responds to EEG signals. However, it is important to recognize that in real-world work settings, other detrimental factors such as lighting, vibration, and air quality also influence gender differences in noise exposure.

5. Conclusion

To sum up, women and men tend to show significant differences in comfort and performance. The key findings from this study are listed below.

1. The annoyance and fatigue rate was higher for both genders at a noise level of 75 dB and temperature >22 °C. However, women experienced a greater noise annoyance rate as the temperature increased.
2. Significant changes in the physiological parameters were observed at 18–22 °C for men and at 26–30 °C for women with the same noise level.
4. Women had higher alpha and beta waves at 18–22 °C, indicating greater comfort and alertness, but these values decreased as air temperature rose.

5. Women outperform men at 18–22 °C, levels of ≤55dBA, and simple and medium tasks, while men perform better at 22–26 °C, levels of ≤55dBA, and complex tasks.
6. Thermal discomfort can negatively impact acoustic comfort and exacerbate cognitive performance in both genders.
7. It seems that designing an indoor work environment with an air temperature of ≤22 °C and noise levels of ≤55 dBA for women and an air temperature of ≤26 °C and noise levels of ≤75 dBA for men is desirable.

CRediT authorship contribution statement

Ali Mohammad Abbasi: Investigation, Funding acquisition, Conceptualization. **Ebrahim Darvishi:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Kourosh Sayehmiri:** Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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