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Investigating the effect of wearing masks on office work in indoor environments during a pandemic using physiological sensing

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ABSTRACT

The spread of pandemics has adverse effects on the lives of people in various ways. For people who need to work in the office and other indoor environments, wearing a mask has become an essential precaution to reduce the spread of the virus and thereby the risk of disease transmission. Therefore, it is important to understand how wearing a mask will affect people while they are performing daily office work. This paper aims to investigate the effect of wearing a mask on the physiological responses and task performance of those who work in office environments during the pandemic period. The two most commonly used masks (i.e., cloth and surgical masks) are chosen for evaluation. The work engagement, mental workload, skin conductance level (SCL), heart rate (HR), as well as the overall performance of 20 subjects while they are completing simulated office tasks are collected and analyzed. Although the results vary across different individuals, they reveal that wearing a mask during a pandemic period will potentially reduce the mental workload and SCL of people for specific types of tasks. In addition, the task performance (correct number and correct rate) of the subjects is worse when wearing a mask, which is highly correlated to the results of the mental workload and SCL. However, there is no one-size-fits-all pattern to conclude the effect of wearing masks on work engagement and HR. This study provides a valuable reference for those who need to wear a mask while working.

1. Introduction

Due to the spread of the new coronavirus (COVID-19), people's lives have been affected in different ways. Indoor environments are particularly important to slow the spread of the virus, resulting in additional requirements of maintaining good indoor air quality [1–3] and wearing face coverings in common places like office environments and public gatherings [4,5]. For example, as recommended by the United States Centers for Disease Control and Prevention (CDC), people should wear masks in public events, gatherings, or anywhere with other people, as masks can provide a barrier to respiratory droplets and thus prevent the spreading of COVID-19 [6]. The Occupational Safety and Health Administration (OSHA) recommends employees wear cloth face covering at work to reduce the spread of the virus and thereby the risk of disease transmission [7]. Similarly, the World Health Organization (WHO) also considers wearing masks as a key measure to suppressing transmission of the pandemic and saving lives [8].

To overcome the economic recession during the pandemic period [9], people's working styles have become more and more flexible. For example, employees can choose to work from home and only return to the office seldomly [10]. Nevertheless, not every home has a suitable workplace [9] and home office work requires more online effort and greater concentration during communication, thereby generating visual, auditory, and mental overload [11]. Moreover, it is unavoidable for some employees to go back to the office from time to time to perform professional tasks [12,13]. Therefore, it is crucial to understand the potential effect of wearing a mask on people's productivity and wellness while they are performing work in office-type settings.

Although the efficacy of face masks in preventing the spread of the respiratory virus is confirmed by previous research [14], it may also cause some adverse effects on people [15]. For example, wearing an efficacious mask will affect the respiration cycles, and lead to increased expired air retained within the breath zone [16]. The concentration of carbon dioxide (CO_2) in the breath zone will rise significantly after wearing a face mask. This may cause an increase in physiological stress due to the low level of oxygen [17]. In addition, previous studies have shown that wearing a mask for a long time may influence people's health and comfort due to the poor ventilation underneath the mask [15,

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17,18]. Despite some general effects of wearing masks have been studied, there is a lack of systematic investigation to understand the effect of wearing masks on the performance and mental health of individuals who work in office-like indoor environments (the setting, social features, and physical conditions in which people could perform office work [19]). This raises an important question: since wearing masks may adversely impact the breath zone air condition in different aspects, how will it affect the physiological responses (e.g., work engagement, mental workload, and skin conductance level) and task performance of people while they are performing office work?

To answer this question, an experiment is needed. Based on the literature, specific types of physiological data are correlated with human psychological states. For example, the brain signal is correlated with psychological stress [20], and galvanic skin response (GSR) is proven as a good indicator of detecting emotions [21]. Therefore, instead of collecting data in subjective approaches such as questionnaires, the experiment is designed based on physiological sensing. The experiments are conducted in a controlled lab environment, and computer-based cognitive tasks are designed for the subjects to simulate typical office tasks. Meanwhile, the subjects' physiological responses and performance are recorded. Based on previous research, work engagement ("a positive, fulfilling, work-related state characterized by vigor, dedication, and absorption [22]") and mental workload ("the 'costs' a human operator incurs as tasks are performed [23]") can directly affect the productivity of the employee [24–27]. In addition, skin conductance level (SCL) and heart rate (HR) are found relevant to the general changes in autonomic arousal [28–30]. Therefore, these physiological indicators are measured under the scenarios with and without masks. Based on the guideline of CDC and OSHA, the two most common types of masks used during the pandemic, cloth and surgical masks [6,7] are used in the experiments. The collected experimental data is further analyzed and compared to provide insights into the effect of wearing masks on the subjects. The objectives of this study can thus be summarized as: (1) to investigate the effect of wearing different mask types on work engagement; (2) to understand the effect of wearing different mask types on the mental workload; (3) to investigate the effect of wearing different mask types on other important physiological responses (i.e., SCL and HR); and (4) to compare the task performance of the subjects before and after wearing a mask.

This paper is organized as follows. Section 2 reviews the related work. Detailed methodology is described in Section 3, which includes two major parts: (1) experimental design, and (2) data collection and process. Section 4 shows the experimental results and analysis, and Section 5 provides a discussion of the results and limitations, followed by conclusions in Section 6.

2. Related works

This section provides three main literature review categories to support the motivation and methodology of this study. First, existing literature on the effect of wearing masks on people's life and wellness are reviewed. The research gaps in previous studies are identified based on this literature review. Second, the utilization of physiological data to evaluate people's states is reviewed to support the usage of biosensors in the experiment. Third, to support the design of the cognitive tasks, the conventional methods of evaluating the task performance of office workers are reviewed.

2.1. Effect of wearing a mask on people

In order to understand how wearing masks could affect people, different experiments were conducted in previous studies. For example, to investigate the effect of wearing a mask on the social life of people, an experiment was carried out to measure the effect of masks on emotion recognition. The subjects were asked to assess the emotional state (i.e., angry, disgusted, fearful, happy, neutral, and sad) of faces covered by masks. The results showed that wearing face masks would cause huge confusion for people and their ability to perceive others' emotions, which added a negative effect on social interaction [31]. Moreover, potential side effects of wearing masks on people's wellness were studied by Geiss [32], who investigated how wearing face masks affected the CO_2 concentration in the breathing zone. Three types of masks (i.e., surgical mask, cloth mask, and KN95 mask) were tested. It was revealed that after wearing a face mask, the concentration of CO2 (between nose and mouth) increased to a range between 2150 and 2875 ppm, which was significantly higher than the maximum acceptable indoor level of 1000 ppm based on ASHRAE and OSHA standards [7,33].

In addition, the impact of wearing a mask on physiological stress was explored by analyzing the heart rate variability (HRV). The results indicated that higher stress might be caused by wearing a mask [17]. Another study investigated the influence of wearing masks on people's health and comfort through physiological sensing and questionnaires, suggesting that in a warm environment, wearing a mask for a long time could make people feel hot and humid [15]. Moreover, the effect of wearing N95 and surgical masks were compared. Subjects wearing different types of masks were asked to perform intermittent exercise on a treadmill, showed that skin temperature (ST) and humidity inside the surgical masks were significantly lower than N95 due to better air permeability [18]. Furthermore, the effect of wearing a mask on body temperature and HR during exposure to electromagnetic fields (EMF) was explored. The results showed that a mask could help stabilize the vital body signs within a normal range [34]. Despite the previous studies, it is still not clear how wearing a mask during a pandemic period will affect the mental health, work engagement, and task performance of individuals who work in office-like indoor environments. A better understanding of this can be important for improving the wellness and productivity of office workers.

2.2. Measurement of office worker physiological responses

Different methods have been investigated to evaluate office workers' states using their physiological responses. According to previous studies [25–27], a higher work engagement could lead to higher productivity. Therefore, studies have tried to correlate work engagement with brain waves as they could be directly measured through an Electroencephalography (EEG) headset. For example, using the average overall power of the brain waves as the indicator of the occupants' engagement, Choi et al. [35] found that the best attention of the subjects was associated with the environment that achieved a slightly positive Predicted Mean Vote (PMV). Similarly, researchers have extensively investigated mental workload as it was also found to be correlated with people's task performance [24,28,36,37]. To obtain the effect of the thermal environment on people's mental workload, EEG was used in previous studies [24,28] to directly measure the mental workload. The results from these studies showed that warmer environments would slightly increase the mental workload.

In addition, parameters such as SCL, HR, ST, and blood pressure were also measured as major indicators of people's physiological responses. For example, different biosensors were used to collect and compare the SCL, HR, and tympanum temperature under different thermal environments. Higher levels of SCL were foundwhen people were performing tasks in warmer environments, while no obvious pattern was found in HR and tympanum temperature [28]. Similarly, the effect of long-term indoor thermal history was investigated by comparing the physiological responses indicated by HR, ST, systolic blood pressure, and diastolic blood pressure. The study indicated that indoor thermal history had no significant effect on those physiological responses [38]. Moreover, Deng et al. [39,40] proposed a method to estimate work engagement and investigate the effect of lighting conditions using easily measurable physiological data including SCL, HR, and ST, which suggested that the effect of lighting conditions varied across individuals. These previous studies confirmed the feasibility of using physiological indicators (e.g., brain waves, SCL, and HR) to evaluate the well-being of office workers. However, none of the studies have tried to investigate the effect of wearing a mask on physiological responses, which is important for those who need to wear masks while working, especially during pandemic periods.

2.3. Cognitive tasks to evaluate the performance of the office workers

Cognitive tests that could represent the typical office tasks were commonly used to measure the performance of the office worker. Several studies have conducted performance tests to assess the cognitive functions of office workers. For example, to evaluate the cognitive functions of perception, thinking, learning, and memory of office workers under different thermal environments, an experiment was used by Lan et al. [41]. Similarly, cognitive tasks such as number calculation, reading, and reaction were used in several studies to assess the performance of the office worker [42–44]. Some of the studies [42,45] found significant effects of the indoor environment (e.g., air temperature) on test performance. In addition, the memory test was used to evaluate people's brain activities, which indicated that the amount of cortical spectral activity from frontal areas and parietal were higher during the moments when things were remembered [46]. Moreover, a strategic management simulation software tool was applied to evaluate the decision-making performance of the office worker, suggesting that higher cognitive function scores could be achieved in green building conditions compared with conventional ones [47]. Regarding the experimental design, these studies provide the support of using cognitive tasks to simulate the daily tasks of the office worker.

Overall, although the physiological measurement and cognitive task have potential, they have not been used to study the effect of wearing masks on individuals who are working in office-like indoor environments. Therefore, in this study, physiological measurement is integrated with cognitive tasks to bridge the identified gap.

3. Research methodology

In this study, a comprehensive framework was developed to investigate the effect of wearing masks on work engagement, mental workload, SCL, HR, and task performance, as shown in Fig. 1. To simulate daily office work, subjects were asked to perform three cognitive tasks including number addition, visual search, and digit recall. Three sections of experiments were conducted: (1) the subject performed cognitive tasks without any mask (baseline); (2) the subject wore a surgical mask to perform cognitive tasks; and (3) the subject wore a cloth mask to perform cognitive tasks. The surgical mask and cloth mask were selected because they were the two most commonly used masks recommended by different authorities [6,7] at the time of the experiment. The surgical masks used in this study are 3-ply masks that filter against 99% of particles larger than 0.1 μm. The cloth masks used in this study are 3-ply 100% cotton masks. As one of the most commonly used colors, blue was chosen for the surgical mask. Black was chosen for cloth masks as it is also one of the most common colors and people trust cloth masks with black color more than others [48]. An EEG headset was used to capture the subjects' brain signals to obtain their mental workload and engagement level. Related physiological data including GSR signals and HR were also collected by corresponding sensors. The final results of the tasks were automatically graded to indicate the subjects' performance. Detailed steps of the experiment are discussed in the following sections.

3.1. Subjects and experimental design

To ensure the generality and reliability of the results, the subjects confirmed that they had no reported mental disorder or physical disability. The selection process made sure there was no restriction on the professional field or personal characteristics such as gender, height, and weight. In total, 20 subjects (9 females and 11 males) aged between 20 and 30 were recruited. All the subjects were graduate students at the University of Michigan who usually spend most of their time doing office-like tasks such as preparing for presentations and working on manuscripts among other tasks. Each subject was asked to come to the lab at the same time for three days, where they spend a total of 80 min. On each day, the subjects either did not wear a mask or wear one of the two types of masks. All subjects received a monetary award upon completio/'n of all phases of the experiment. In order to respect the COVID protocols at the time of the experiment (i.e., October 2021), only one subject was allowed in the room per session.

The dimensions of the room and the experimental setup are shown in Fig. 2. The room used for the experiment was an office space used by graduate students located in the basement of the Civil and Environmental Engineering building at the University of Michigan. It did not have any windows and was accessible through a single door that was kept closed during the experiment. It was fully controlled by a central Heating, Ventilation, and Air Conditioning (HVAC) system with mixing ventilation. The maximum total airflow rate supplied by two cassette fan coils at the ceiling was 600 m^3/h, with around 10% of outdoor air using recirculation. The same amount of air in the room was exhausted into a return grille. The locations of the fan coils and exhaust grille can be found in Fig. 2. The air velocity surrounding the subjects was measured as less than 0.01 m/s (using the ANNMETER AN-856A with the resolution of 0.001 m/s and the accuracy of ±3% + 0.1 rdg). The settings of the room environment were consistent during all experimental sessions to ensure identical air velocities and CO2 levels. The environmental parameters were continuously measured using the GC-0010 COZIR sensor with the accuracies of ±0.2 °C for temperature, ± 3% for relative humidity, and ±50 ppm for CO2 at a distance of less than 1 m from the subjects. In addition, a light meter with an accuracy of 1 lux was used to ensure a lighting level of 500 lux. The placement of the COZIR sensor and the positions of the equipment for measuring lighting level and air velocity can be seen in Fig. 2. Table 1 shows a summary of the measured indoor environments compared with the recommended ones by ASHRAE [33] and U.S. General Services Administration [49].

A guideline was proposed for the subjects to follow to ensure similar

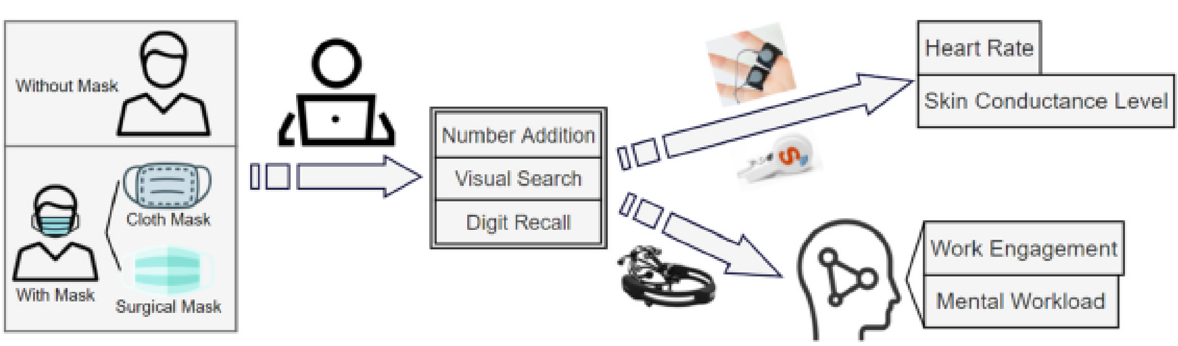

Fig. 1. Framework for investigating the effect of wearing masks on physiological data.

Fig. 2. Experiment room dimensions and experimental setup.

Table 1
Environmental conditions during the experimental sessions (mean ± standard deviation).

	Air Temperature (°C)	Relative Humidity (%)	Lighting Level (Lux)	CO_2 level (ppm)
Measured	24 ± 0.2	35 ± 5	500 ± 10	450 ± 50
ASHRAE [33,49]	19.4–27.8	<65	500	<1000

initial mental states and good data quality. The guideline includes: (1) try to get enough sleep on the night before the experiment and maintain the same sleeping schedule during the three days of the experiment; (2) avoid eating or drinking foods that might cause excitement (e.g., caffeine, alcohol) during the experiment period; (3) wear the same level of clothing (trousers, short-sleeved shirt) throughout the experiment; and (4) keep the hair dry and clean before conducting the experiment to ensure proper contact of the EEG electrodes to the scalp. Before starting the experiment, each subject was randomly assigned a unique ID number as the reference for the collected data. This also ensured no personally identifiable information (e.g., name) of the subjects was used during the data collection and analysis. In addition, all experiments followed COVID-19 public health recommendations to ensure the safety of the subjects and the research staff.

3.1.1. *Timeline*

Fig. 3 shows the details of the experimental timeline for each of the daily sessions. When the subjects reached the lab, they were first given 30 min to relax and prepare for the experiment. During this time, the research staff explained the details of the experiment and provided the

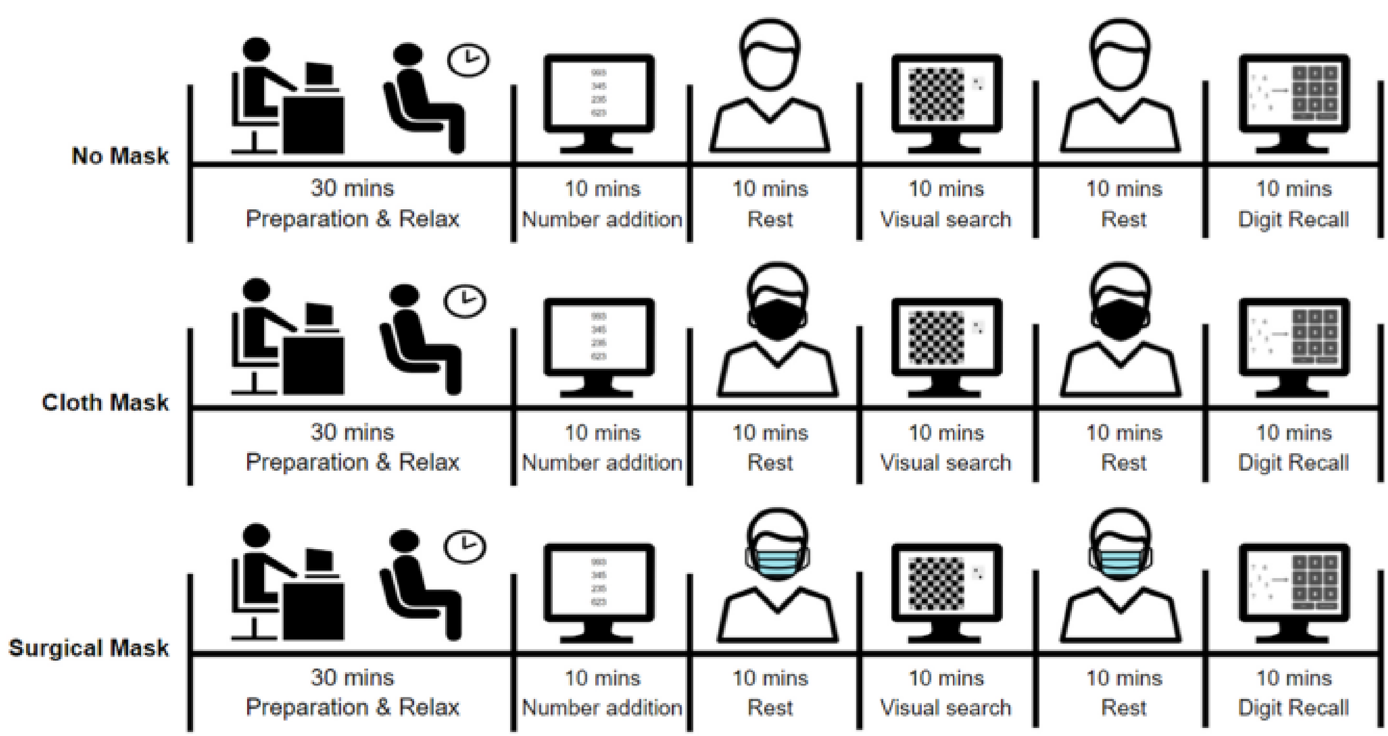

Fig. 3. Experimental timeline.

subjects with instructions. As shown in Fig. 2, during the experiment, the subjects needed to wear sensors to allow the collection of their physiological data (i.e., EEG signal, GSR signal, and HR). The time for each cognitive task was designed to be around 10 min. To avoid fatigue, a 10-min break was given between two cognitive tasks. The procedures for the three sessions of the experiment were identical. For one of the sessions, the subjects performed the tasks without any masks. For the sessions with masks, the subjects wore the masks during the whole experiment including the relaxation and preparation periods. The design of the total experiment timeline and the time allocated per cognitive task is consistent with similar studies in the literature. For example, an experiment was designed by Su et al. [50] to investigate the impact of HVAC terminal devices on occupants' thermal comfort and cognitive performance. Three different types of terminal devices were selected as the variables of three scenarios. The time for performing the cognitive tasks for each scenario was set to be 10 min, with a total experimental time of 75 min for each subject. Similarly, Lee et al. [51] designed an experiment to investigate the effect of indoor CO2 concentration on cognitive performance and EEG signal, the duration of performing the cognitive task was set to be 5 min with a total experimental duration of 30 min for each subject. To eliminate the effect caused by the order of the different scenarios, the order of the sessions in this study was fully randomized. The protocol of the experiment was reviewed and approved by the Institutional Review Board at the University of Michigan.

3.1.2. Design of cognitive tasks

To simulate the common daily tasks, three cognitive tasks were designed. According to previous studies, adding numbers and searching for specific patterns could be used to arouse the thinking and perception of the subject [24,52–54], and digit recall performance was used to estimate the level of concentration [46]. Fig. 4 shows the three designed computer-based cognitive tasks, and the details of the tasks are shown below:

- Number addition: For the number addition task, a few randomly generated numbers are shown on the screen. The subjects are required to calculate the sum of the numbers. After solving one problem, the subjects can continue to the next. The subjects should do the calculation without a calculator as fast as they can. The task has two parts, the first part contains six one-digit numbers while the second part contains four three-digit numbers. The duration for the first part is 4 min and the total duration of the task is 10 min.
- Visual search: The visual search task contains the target patterns for the subjects to search as fast as they can. The overall interface contains 9×9 grids, 41 of them are white squares while the other 40 are black. Each white square contains 5×5 pieces of small boxes, with two of them being black. There is a target white square shown on the right side of the screen that can match one of the small white squares in the 9×9 grid. The subjects should find the target square in the grid and enter the result in the text box using the index of row and column. After finishing one, the subjects can go to the next. The total duration of the task is 10 min.
- Digit recall: The task is trying to test the short-term memory of the subjects, which is adapted from a traditional test named the Wechsler Adult Intelligence Scale (WAIS) [55]. During the task, random digits (0–9) appear on the screen. There is a time gap of 200 ms between every two digits. Each digit lasts for 800 ms on the screen. Once all the digits are displayed and disappear, the subjects are asked to repeat them in the correct order by clicking a number pad. After finishing one, they can click "Continue" to go for the next one. There are two parts of the task, the first part (the easy part) contains 5 digits while the second part (the hard part) contains 11 digits. There are 18 trials for the easy part and 18 trials for the hard part. The total duration of the task is about 10 min. During the process, there is a message on the screen to show how many digits will be displayed.

3.2. Physiological data collection and process

3.2.1. Measurement of brain waves using EEG

The EEG headset collects the voltage changes caused by brain activities by placing electrodes at specific locations on the scalp surface of humans. The cognitive states of the human can thus be reflected by the collected voltage changes [56]. A low-cost EEG headset, Emotiv EPOC+, was used in the experiment. It contains 14 channels and allows easy setup with only saline solution. The data sampling frequency was 128 Hz. The collected data could be visualized in real-time through a Bluetooth connection and was stored on an ordinary laptop.

The raw data strings obtained from the electrodes were in form of floating-point values with approximately 4200 μV of DC offset, and they normally contain noise [57–59]. The noise normally consists of both extrinsic and intrinsic artifacts. The extrinsic artifacts can be removed using a band-pass filter with a frequency from 0.5 Hz to 65 Hz [60]. The intrinsic artifacts usually contain eye and muscular movements [61,62] and need more effort to deal with. Therefore, a denoise process was required to pre-process the raw data. Previous studies have proposed several methods for denoising the intrinsic artifacts [63–67]. For example, a toolbox was developed to help with the removal of artifacts of EEG signals [64].

Fig. 5 summarizes the procedures to process the EEG raw data based on the methods in previous studies. Before conducting any data analysis, DC offset should be removed, followed by the denoise process. The muscular movement, eye blinking, and eye movement should be removed through the denoise process [61,62]. EEGLAB was used as the tool to conduct the denoise process in this study. After denoising, Fast Fourier Transform (FFT) was applied to obtain the band power of different frequency ranges. The frequency bands used in this study included Delta (1–4 Hz), Theta (4–8 Hz), Alpha (8–12 Hz), Beta (12–25 Hz), and Gamma (>25Hz) [24,68,69]. The obtained power of different frequency bands could thus be used to calculate the work engagement and mental workload.

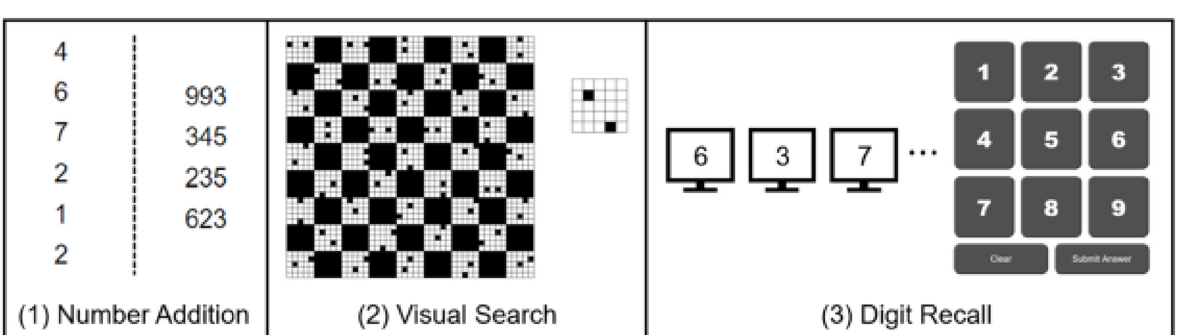

Fig. 4. Design interface for cognitive tasks.

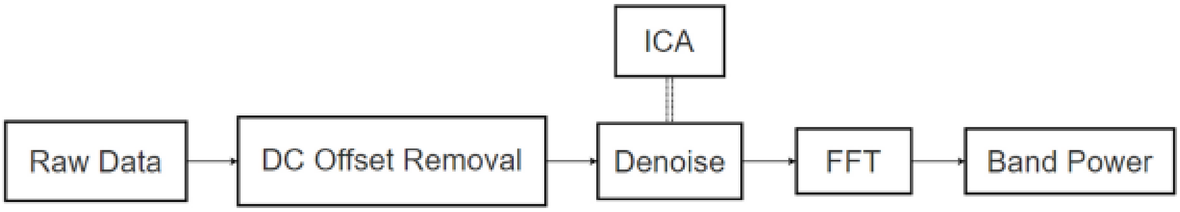

Fig. 5. Process of EEG raw data.

3.2.2. Calculation of work engagement and mental workload using EEG data

Based on previous studies, the frontal asymmetry index (FAI) could be calculated by alpha power in the right relative to the alpha power in the left cortex to indicate work engagement [70–77]. The frontal asymmetry was found related to motivation and emotion in response to different situations [78]. In addition, it was claimed that higher FAI was associated with positive feelings, motivation, and engagement [22,79,80]. Therefore, the work engagement of the subjects was represented by the FAI in this study. FAI could be calculated based on Eq. (1) [70,71]. F3 and F4 electrodes are commonly being used to indicate the frontal region and their positions are shown in Fig. 6.

Previous studies have shown that higher frontal theta power and lower parietal alpha power were associated with higher mental workload [81–83]. The frontal power is usually represented by the brain signals from F3 and F4, and parietal power is commonly indicated by P7 and P8 [81–83]. Therefore, the ratio of frontal theta power to parietal alpha power shown in Eq. (2) was used as the indicator of mental workload in this study. Fig. 6 shows the positions of the related electrodes for the mental workload.

$$Frontal\,Asymmetry\,Index = ln\left(\frac{Alpha\ power\ of\ F4}{Alpha\ power\ of\ F3}\right) \quad (1)$$

$$Mental\,Workload\,Index = \frac{F3\,Theta\ power + F4\,Theta\ power}{P7\,Alpha\ power + P8\,Alpha\ power} \quad (2)$$

where F3, F4, P7, and P8 refer to signals from the specific electrodes of the EEG headset.

3.2.3. Measurement of SCL and HR

GSR signal can reflect the changes in autonomic arousal [29] and may also affect the activity of the central neural [84,85], indicating it is correlated to brain activity. The SCL is considered the tonic component of the GSR signal which could be measured directly from the sensors. The usage of SCL to indicate human physiological responses has been confirmed in previous studies [28,38,86]. For example, the SCL could reflect sympathetic activity [30,87,88]. In addition, previous studies have reported that SCL could be used to reflect the mental workload [89,90]. Therefore, SCL was also measured as an accessory of EEG signals [28] in this study. The Shimmer3 GSR + Unit was used to measure the GSR signals of the subjects, and the tonic component was obtained as the SCL. In addition, several studies have used HR as the physiological indicator for body conditions [91–93], as it has been proven to be relevant to the emotional well-being of humans [94–97]. Therefore, it is used to help with the analysis of the human physiological responses in this study. As shown in Fig. 2, GSR data was collected using Optical Pulse Ear-Clip. During the experiment, the electrodes of the sensors were attached to the subjects as securely as possible to ensure the quality of the collected data.

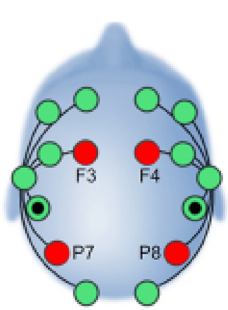

Fig. 6. Positions of related electrodes.

3.3. Data analysis

There was a total of 20 valid datasets from the subjects. The datasets were stored in separate CSV files from different equipment. As the data collection frequency was 128 Hz, there were more than 75,000 data samples for each dataset. To conduct an ANOVA for the dataset of each subject, the original raw data was pre-processed to obtain data points with a specific time window of 8 s based on the related studies [75,98].

3.3.1. Within-subject analysis

As the purpose of this study was to investigate the effect of wearing masks on individuals, the analysis was first performed on the datasets of each subject separately. The mean and standard deviation of work engagement, mental workload, SCL, and HR for each subject were calculated. Repeated measures ANOVA was applied to determine whether there were significant differences in these physiological responses in three mask-wearing scenarios. This was followed by a post hoc test (Tukey's HSD) to find out if there are significant differences between the specific pairs - cloth mask versus no mask, cloth mask versus surgical mask, or no mask versus surgical mask. For each mask-wearing scenario of the within-subject comparison, datasets for the physiological responses were constructed based on the 8-s time windows. Therefore, the post hoc test could be used to determine whether two datasets (for different mask-wearing scenarios) are significantly different.

3.3.2. Analysis across all subjects

The general effect of wearing a mask was also analyzed by combining the results from different subjects. However, the ranges of physiological responses vary a lot across different subjects. For example, the SCL of one subject may range from 0 to 1 μS while for another subject it may be between 3 and 5 μS. One reason for this difference is the effect of the psychology of the subjects in the experimental environment [99,100]. Therefore, to eliminate the distinct ranges of the results caused by personal differences, a standardization of the results, given in Eq. (3), was performed before analyzing the general effect of wearing a mask across subjects [101]. The standardized results reflect how much of the standard deviation of the value in one scenario is offset from the mean from the subject's mean value. For example, the standardized value of 1 indicates that the value in this scenario (with a specific mask or no mask) is larger than the mean value of this subject by one standard deviation. The standardized values eliminate the effect caused by the range differences in physiological data of different subjects and reflect the relative changes of each subject. As for the post hoc test across all the subjects, the mean values of the results for each subject were used, thus for each scenario, 20 data points from 20 subjects were included.

$$Standarized(x_i) = \frac{x_i - \mu}{\sigma} \quad (3)$$

Where x_i is each data point from one specific subject in different scenarios, μ is the mean value of the data points from the specific subject, and σ is the standard deviation of the data points

3.3.3. Assumptions of the ANOVA and post hoc test

There are several assumptions to ensure the reliability of ANOVA and post hoc test: (1) each observation of the dataset is independent of every other observation; (2) the residuals of the data are normally distributed; (3) the variances of the differences between all combinations of related groups are equal. Since the experiments were conducted on different subjects on three different days, assumption (1) was true. In addition, the Shapiro-Wilkinson test [102] was conducted to validate the normality of the residuals of the data for both within-subject and across-subjects analysis. For the data across all the subjects, the results showed that the p-values of the datasets were larger than 0.05; thus, there was no sufficient evidence that these datasets did not come from a normal distribution, which supported assumption (2). Similarly, the variances of the differences between different groups of the data were tested using the Brown-Forsythe test [103], and the corresponding p-values were larger than 0.05 for all the datasets, which supported assumption (3). The validation of these assumptions supported the reliability of ANOVA and post hoc test for the across-subject analysis. Regarding the within-subject data, the Brown-Forsythe test also confirmed the similar variances of the datasets. The Shapiro-Wilkinson test suggested non-normal distribution of the residuals for most of the datasets. However, it has often been reported that the violation of normality should not be a serious concern, especially when there are enough data points (e.g., >20) with similar variances [104]. Therefore, the ANOVA and post hoc test were also confirmed applicable for within-subject analysis.

4. Results

4.1. Comparing the effect of wearing a mask on work engagement (FAI)

Fig. 7 shows the average work engagement represented by the FAI for different subjects (subjects 1 to 9 are females and subjects 10 to 20 are males) while they were performing the cognitive tasks. Based on the data points from the 8-s time windows, a p-value of 0.05 was used in this study to determine if there were significant differences between any two pairs of the results. As a result, significant differences were found in most cases while the results varied across individuals. However, the results also indicated that the effect of wearing a mask on people's work engagement varies across individuals. For example, the work engagement of subject 3 with a surgical mask was the highest across all cognitive tasks while the results were opposite for subject 10. In addition, the effect of wearing a mask was negligible in some scenarios such as the results of subject 14. The post hoc test also indicated that the effects within the subjects might not be always identical for different cognitive tasks. Taking subject 4 as an example, work engagement without masks was the highest for the digit recall task, while it was the lowest for the visual search task.

In addition to the within-subject plots, the results across all subjects were combined to study the general pattern of the effects (Fig. 8). For this part, the average values of the results in different scenarios from 20 subjects were used. Due to the significant differences in the range of the results across individuals, the results were standardized based on Eq. (3). Repeated measure ANOVA and post hoc test were applied to determine whether the distribution of the results was significant in different scenarios with respect to each cognitive task. The Cohen's d effect size was applied to show the difference between two groups of data. The results are shown in Table 2, which revealed that there was no general pattern for the effect of wearing a mask on work engagement.

4.2. Comparing the effect of wearing a mask on mental workload

Similar to work engagement, the corresponding results for mental workload were also plotted as per subjects in Fig. 9. To maximize the readability, the y-axes of the plots were adjusted according to the range of the results. Significant differences between wearing a mask (either a cloth mask or a surgical mask) and not wearing a mask were also found in mental workload for most of the subjects (except subjects 8, 13, 14, 15, and 18). The results were also found to be different from person to person. Take subjects 4 and subject 13 as an example, when performing the number addition, the highest mental workload was associated with wearing a cloth mask for subject 4. However, the mental workload when wearing a cloth mask was the lowest among the three mask-wearing scenarios for subject 13.

Similarly, the results across all subjects (Fig. 10) were plotted to investigate the general pattern of the effects of wearing masks, the same standardization was also performed to eliminate the effects of individual differences. The results of ANOVA and post hoc test were shown in Table 3. The results showed that for the number addition, the overall mental workload of the subjects without wearing a mask was higher than when wearing either a cloth mask (Tukey's HSD: $p = 0.003$, $d = 1.006$) or a surgical mask (Tukey's HSD: $p = 0.023$, $d = 0.78$). No significant difference was found between the surgical mask and cloth mask. For the visual search, there was no significant difference in mental workload under different scenarios. As for the digit recall, it was found that the results when the subjects were wearing a cloth mask were lower than without a mask (Tukey's HSD: $p = 0.011$, $d = 0.896$). In general, the results imply that although the effects might vary across individuals, wearing a mask during the pandemic leads to a lower mental workload while people are performing specific types of tasks (i.e., number addition and digit recall).

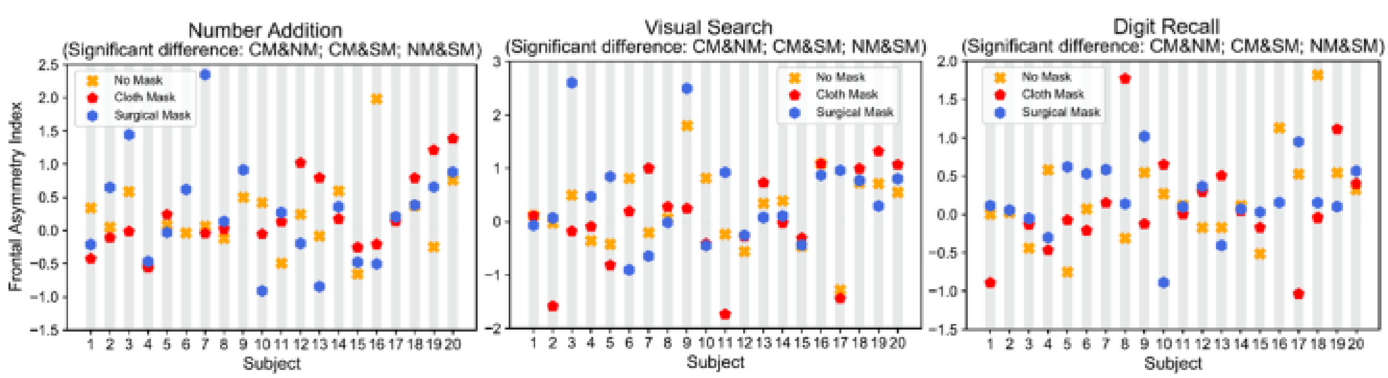

Fig. 7. Average frontal asymmetry index (FAI) of different subjects.

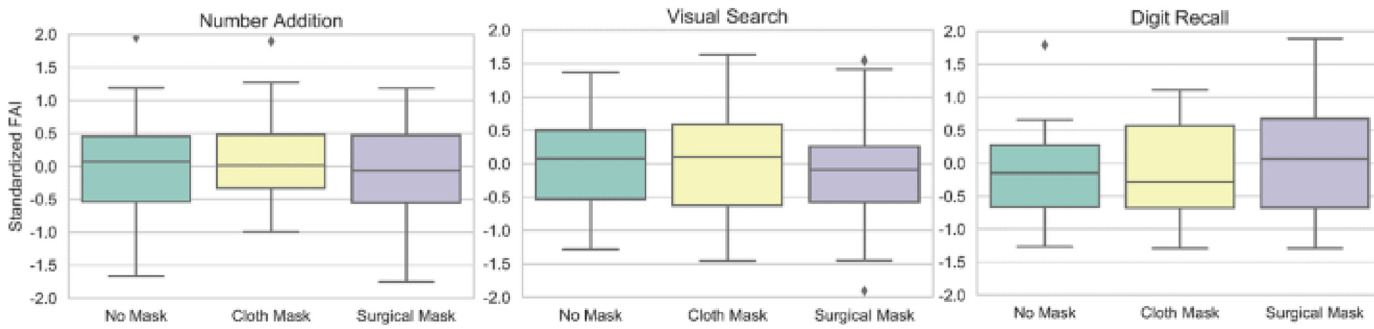

Fig. 8. Standardized frontal asymmetry index (FAI) across all subjects.

Table 2
Statistical analysis for standardized FAI across all subjects (corresponding to Fig. 8).

	Pair	Mean Difference	Effect Size	p-value
Number Addition	CM & NM	0.213	0.162	0.854
	CM & SM	0.390	0.263	0.615
	NM & SM	0.177	0.165	0.9
Visual Search	CM & NM	0.231	0.244	0.766
	CM & SM	0.465	0.381	0.383
	NM & SM	0.234	0.218	0.762
Digit Recall	CM & NM	0.589	0.376	0.378
	CM & SM	0.268	0.193	0.795
	NM & SM	0.321	0.291	0.726

Note: "NM" refers to no mask, "CM" refers to cloth mask, and "SM" refers to surgical mask.

4.3. Comparing the effect of wearing a mask on SCL

As indicated in previous studies, both brain waves and SCL could be used to reflect the mental workload, thus the results of SCL were also investigated as an accessory of EEG signals. Similarly, the results of SCL analysis under three different mask-wearing scenarios were plotted for each subject (refer to Fig. 11). Significant differences were found in most cases while the results varied across individuals. The standardized SCL across subjects was plotted in Fig. 12, and the corresponding results of ANOVA and post hoc test were shown in Table 4. For number addition,

Table 3
Statistical analysis for standardized MW across all subjects (corresponding to Fig. 10).

	Pair	Mean Difference	Effect Size	p-value
Number Addition	CM & NM	1.068	1.006	0.003
	CM & SM	0.238	0.315	0.699
	NM & SM	0.830	0.780	0.023
Visual Search	CM & NM	1.205	0.367	0.417
	CM & SM	0.440	0.540	0.879
	NM & SM	0.765	0.233	0.684
Digit Recall	CM & NM	0.746	0.896	0.011
	CM & SM	0.293	0.452	0.467
	NM & SM	0.453	0.610	0.167

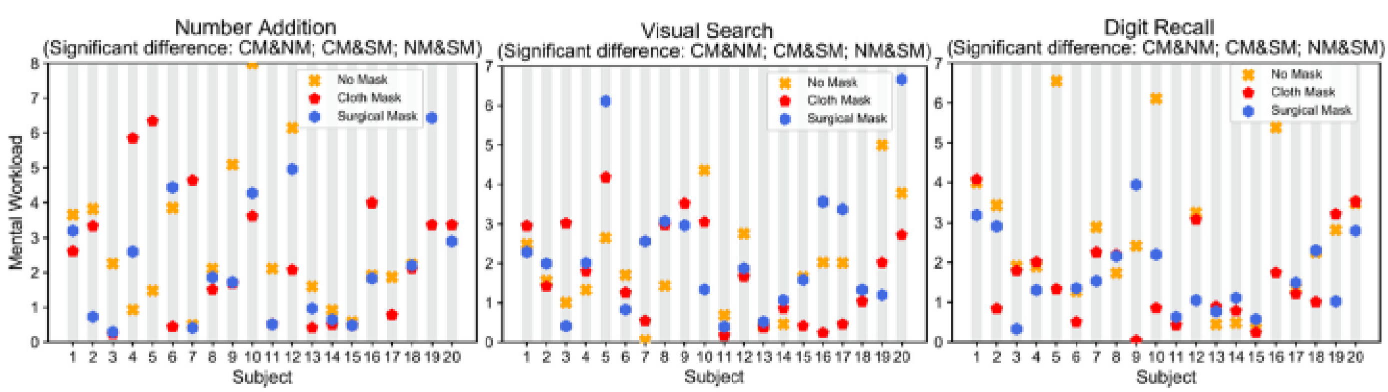

Fig. 9. Average mental workload (MW) of different subjects.

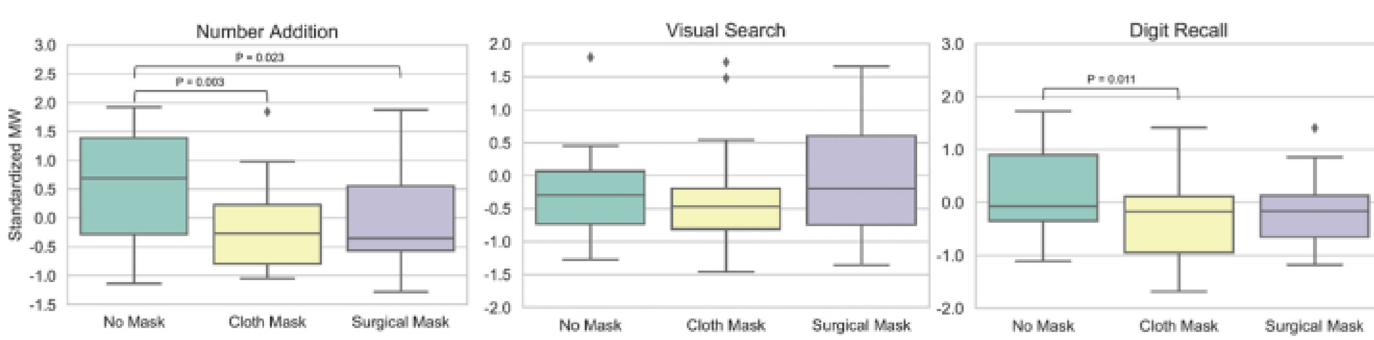

Fig. 10. Standardized mental workload (MW) across all subjects.

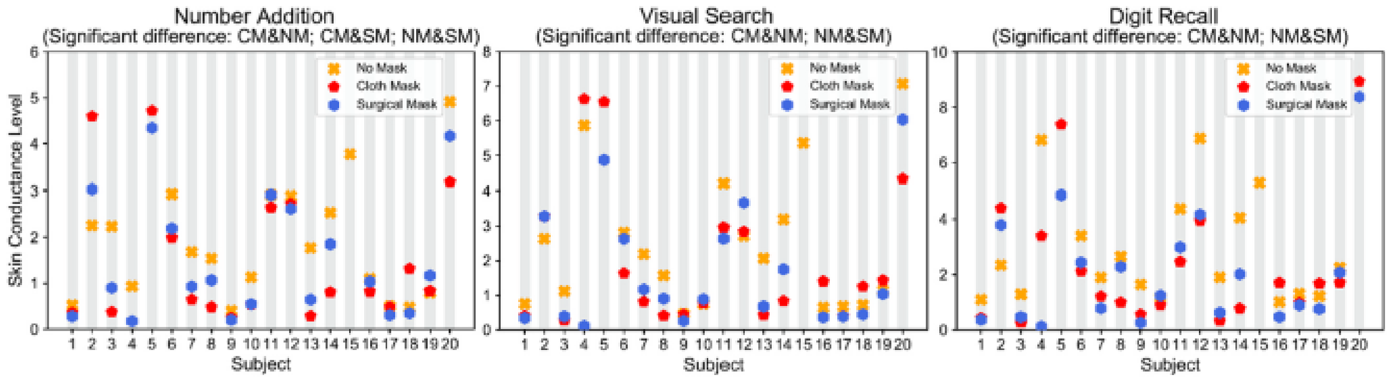

Fig. 11. Average skin conductance level (SCL) of different subjects.

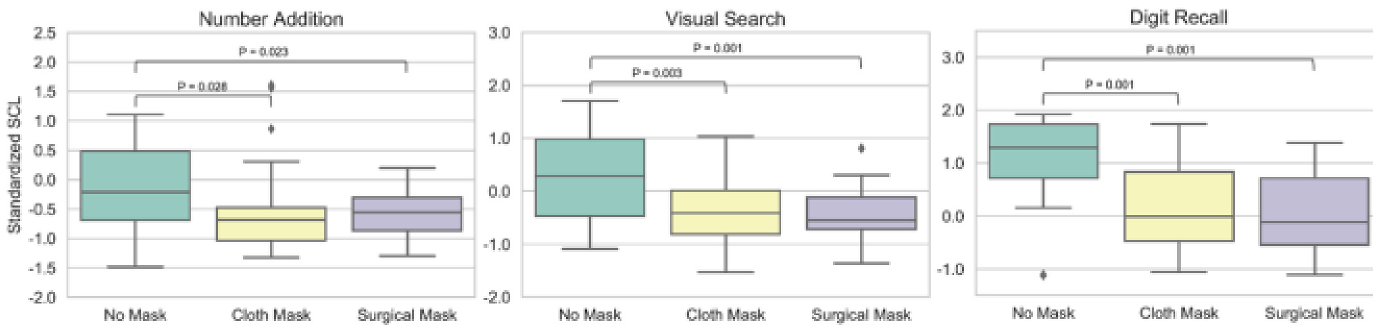

Fig. 12. Standardized skin conductance level (SCL) across all subjects.

Table 4
Statistical analysis for standardized SCL across all subjects (corresponding to Fig. 12).

	Pair	Mean Difference	Effect Size	p-value
Number Addition	CM & NM	0.567	0.737	0.028
	CM & SM	0.019	0.034	0.900
	NM & SM	0.586	0.905	0.023
Visual Search	CM & NM	0.744	0.894	0.003
	CM & SM	0.111	0.199	0.855
	NM & SM	0.855	1.101	<0.001
Digit Recall	CM & NM	1.265	1.193	<0.001
	CM & SM	0.114	0.138	0.900
	NM & SM	1.378	1.292	<0.001

the average standardized SCL without wearing a mask was overall higher than either wearing a cloth mask (Tukey's HSD: $p < 0.028$, $d = 0.737$) or a surgical mask (Tukey's HSD: $p < 0.023$, $d = 0.905$). Similar results were found for both visual search and digit recall tasks. However, there was no significant difference between wearing a cloth mask or a surgical mask. In general, the results indicate that although the effects might vary from person to person, wearing a mask during the pandemic might help reduce the SCL of the subjects for all types of cognitive tasks. If considering the SCL as an indicator of the mental workload, the results are partially consistent with the mental workload measured by brain waves.

4.4. Comparing the effect of wearing a mask on HR

As for HR, Fig. 13 shows similar plots for the results as per subjects. For most of the cases regarding within-subject comparison, the post hoc test indicated that there existed significant differences between the three scenarios. However, according to the comparison of the standardized results across all subjects shown in Fig. 14 and Table 5, there was no one-size-fits-all pattern to conclude the effect of wearing a mask on subjects. For example, for number addition, the results of HR for subjects 6, 14, 17, and 20 were the highest without wearing a mask, while they were

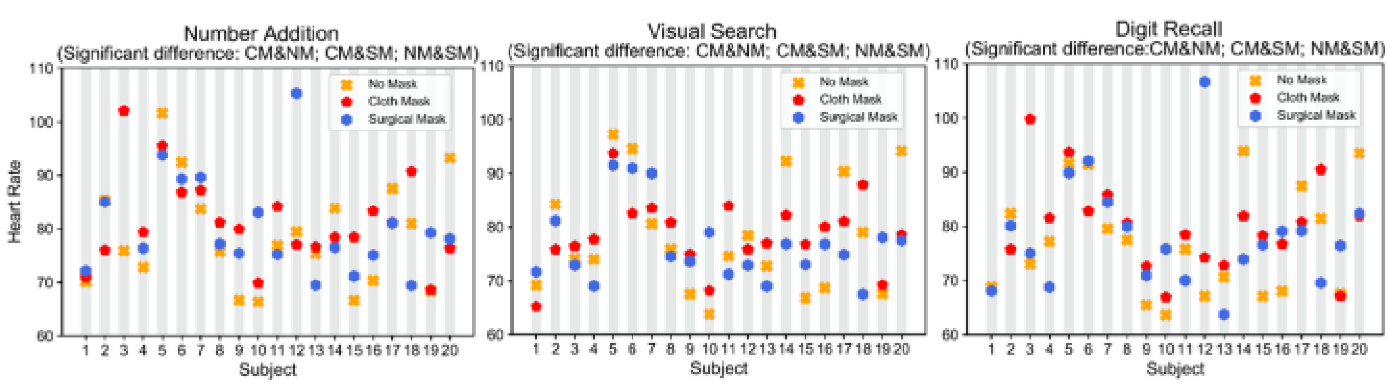

Fig. 13. Average heart rate of different subjects.

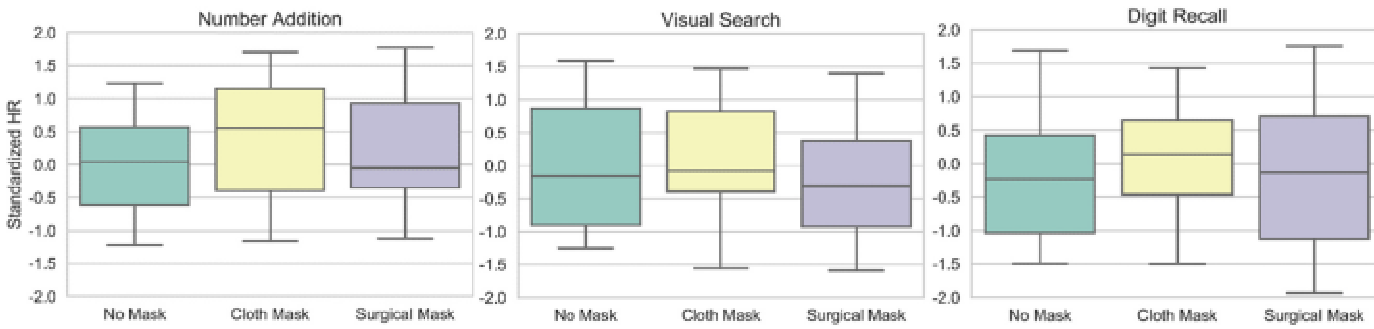

Fig. 14. Standardized heart rate (HR) across all subjects.

Table 5
Statistical analysis for standardized HR across all subjects (corresponding to Fig. 14).

	Pair	Mean Difference	Effect Size	p-value
Number Addition	CM & NM	0.337	0.376	0.513
	CM & SM	0.320	0.327	0.544
	NM & SM	0.017	0.018	0.900
Visual Search	CM & NM	0.108	0.123	0.900
	CM & SM	0.339	0.385	0.475
	NM & SM	0.231	0.246	0.688
Digit Recall	CM & NM	0.128	0.137	0.900
	CM & SM	0.088	0.091	0.900
	NM & SM	0.040	0.043	0.900

the lowest without wearing a mask for subjects 7, 9, 10, 15, and 16. For subject 1, the effect of wearing a mask on HR could be neglected. In addition, the distributions of the heart rate under different scenarios were very similar to each other, and the ANOVA analysis confirmed that there was no significant difference among the distributions.

4.5. Comparing the effect of wearing a mask on task performance

Apart from the physiological responses, the task performance of the subjects under different cognitive tasks is shown in Fig. 15–18. The corresponding results of ANOVA and post hoc test for Figs. 16 and 18 are shown in Table 6 and Table 7, respectively. As seen from the plots for within-subject analysis (Figs. 15 and 17), similar to the physiological responses, the effect of wearing a mask on task performance (correct number and correct rate) varied across different individuals. In addition, some subjects' task performance was more sensitive to the effect of wearing the masks than others.

However, after performing the standardization of the correct number and correct rate of the tasks following Eq. (3), general patterns were found based on the statistical analysis across all subjects. For the correct number of the tasks, Fig. 16 indicated that wearing a surgical mask could reduce the correct number of the number addition task compared with no mask (Tukey's HSD: $p < 0.001$, $d = 0.873$) and wearing a cloth mask (Tukey's HSD: $p < 0.001$, $d = 0.864$), while no significant difference was found between no mask and cloth mask. As for the visual search, the correct number of the tasks was higher when not wearing a mask than wearing either a cloth mask (Tukey's HSD: $p = 0.005$, $d = 1.001$) or wearing a surgical mask (Tukey's HSD: $p < 0.001$, $d = 1.266$), while no significant difference was found between wearing a cloth mask or a surgical mask. The results for digit recall revealed a higher correct number of tasks without a mask compared with a cloth mask (Tukey's HSD: $p = 0.008$, $d = 0.952$). Compared with the correct number, the patterns for the correct rate were slightly different for number addition and visual search. For number addition, the results found the correct rate without wearing a mask is higher than either wearing a cloth mask (Tukey's HSD: $p = 0.039$, $d = 0.764$) or a surgical mask (Tukey's HSD: $p < 0.001$, $d = 1.169$), while no significant differences were found between wearing a cloth mask or a surgical mask (Tukey's HSD: $p = 0.385$, $d = 0.375$). For visual search, no significant difference was found among the distributions of correct rates among three mask-wearing scenarios.

4.6. Investigating the effect of gender on physiological responses and task performance

The results revealed the importance of individual differences. Therefore, this study also explored potential reasons behind the variations. The physiological responses and the task performance were further divided into two groups based on the gender of the subjects. Table 8 shows the detailed results of the comparison. The average values of FAI, MW, SCL, HR, correct number, and correct rate for different genders were calculated and compared. In addition, the independent two-sample *t*-test was performed to further evaluate whether there existed significant differences for each type of physiological response or task performance. The results revealed that no significant difference was found for the MW, SCL, and correct rate. However, the heart rate for females was statistically higher (Tukey's HSD: $p = 0.032$, $d = 0.306$). Moreover, the correct number of tasks for females was also statistically higher (Tukey's HSD: $p < 0.001$, $d = 0.534$). In contrast, the FAI of females was statistically lower (Tukey's HSD: $p = 0.00.066$, $d = 0.315$).

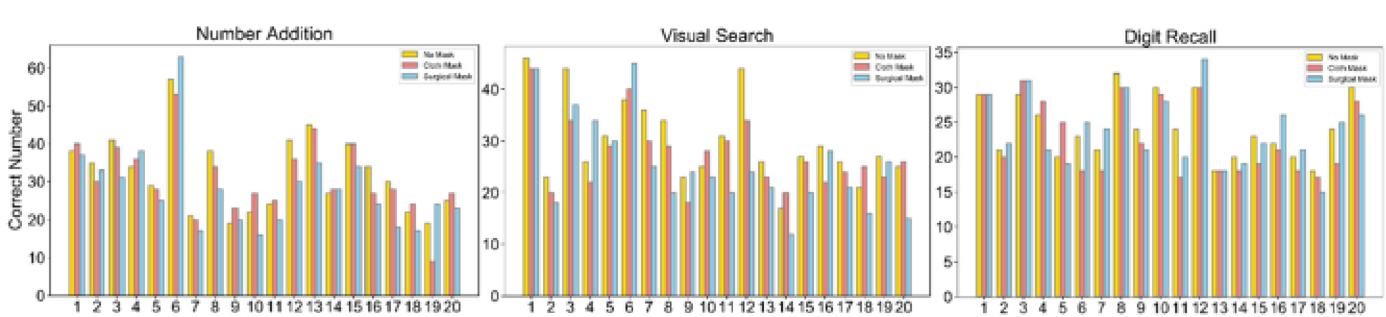

Fig. 15. Correct number of different subjects.

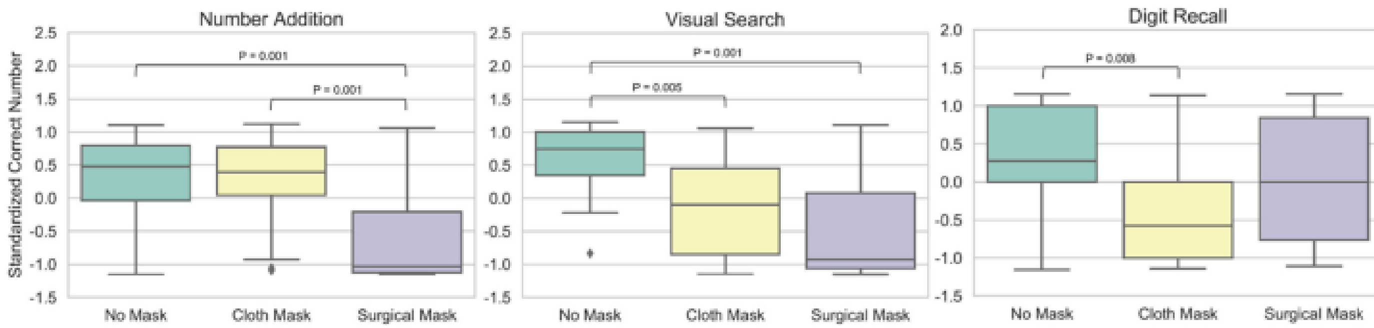

Fig. 16. Standardized correct number across all subjects.

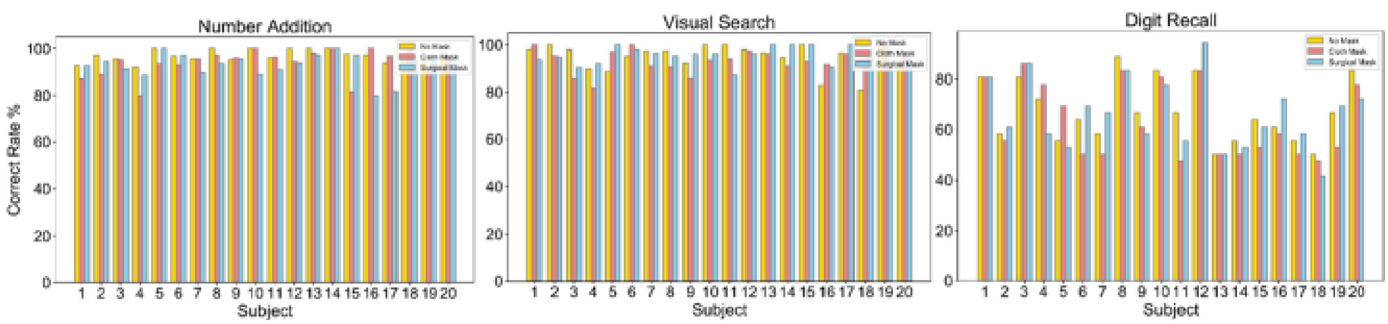

Fig. 17. Correct rate of different subjects.

5. Discussion

In general, there were nonnegligible effects of wearing a mask on work engagement and HR when each individual was considered in isolation. However, the effects varied a lot across individuals, and no one-size-fits-all pattern was found to conclude the effects. The personalized pattern of the effects indicated that people might have different feelings regarding wearing a mask during the pandemic. For example, some might feel safer with a mask and then be more engaged in the tasks, while others might be seriously affected by the worsening air quality in the breathing zone and thereby were not able to concentrate on the tasks they were performing. Moreover, some subjects might be more sensitive to wearing a mask than others. To support the current results, the importance of personal characteristics was also confirmed in previous studies. For example, the individual differences in EEG responses to cognitive workload were confirmed by Matthews et al. [100]. The effects of thermal [24,105] and lighting [39,106] conditions on occupants' physiological and psychological data were also proven to vary across different individuals.

Regarding the mental workload and task performance, while the personal difference cannot be neglected, it was revealed that there existed general patterns to describe the effect of wearing a mask. Supported by brain waves and SCL, general patterns regarding the mental workload were found. Although there were slight differences between the results from brain waves and SCL, a general pattern revealed that wearing a mask could potentially reduce the mental workload of subjects. The possible reason behind this phenomenon might be that people felt more nervous and kept alert in the office during the pandemic period. In contrast, wearing a mask might make them feel safer and thus reduce the intensity of brain activities, thereby reducing their mental workload. The results showed that the number of correct responses to the cognitive tasks was in general higher without wearing a mask in most of the scenarios, and the type of mask also slightly affected the results. The number of correct responses to number addition and digit recall tasks might be related to the mental workload, as the higher mental workloads were associated with more mental effort and thereby resulting in relatively higher outputs of the cognitive tasks. As for the correct rate, the results were consistent with the mental workload indicated by the brain waves, suggesting that a higher correct rate might be associated with a higher mental workload. To explore the potential reasons behind the individual differences, the results were compared as per gender, which suggested a significant difference between females and males regarding the FAI, heart rate, and the correct number of tasks. The results could provide a valuable reference for experimental design

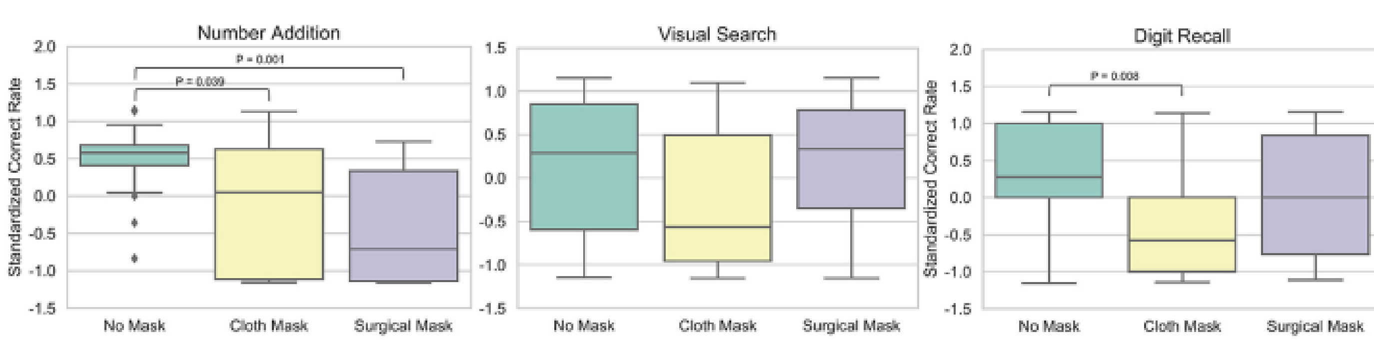

Fig. 18. Standardized correct rate across all subjects.

Table 6
Statistical analysis for the standardized correct number of tasks across all subjects (corresponding to Fig. 16).

	Pair	Mean Difference	Effect Size	p-value
Number Addition	CM & NM	0.009	0.014	0.900
	CM & SM	0.864	1.018	<0.001
	NM & SM	0.873	1.028	<0.001
Visual Search	CM & NM	0.726	1.001	0.005
	CM & SM	0.357	0.464	0.249
	NM & SM	1.083	1.266	<0.001
Digit Recall	CM & NM	0.720	0.952	0.008
	CM & SM	0.446	0.569	0.142
	NM & SM	0.274	0.370	0.471

Table 7
Statistical analysis for standardized correct rate across all subjects (corresponding to Fig. 18).

	Pair	Mean Difference	Effect Size	p-value
Number Addition	CM & NM	0.576	0.764	0.039
	CM & SM	0.305	0.375	0.385
	NM & SM	0.881	1.169	<0.001
Visual Search	CM & NM	0.359	0.434	0.355
	CM & SM	0.388	0.479	0.300
	NM & SM	0.029	0.036	0.900
Digit Recall	CM & NM	0.720	0.952	0.008
	CM & SM	0.446	0.569	0.142
	NM & SM	0.274	0.370	0.471

and data analysis of future studies.

It is worth noting that there are some limitations in this study. For example, to avoid fatigue, each task was set for 10 min. It will be interesting to investigate the effect of longer periods on the performance of the subjects especially fatigue will become another factor to measure. However, the results from this study can be used as departure points for future work where the duration of the experiment or difficulty of tasks is varied. In addition, the subjects in this study were all university graduate students, a more diversified group of people can also be considered in the future. Moreover, the experimental environment might lead to additional tension among the subjects, and the differences in physiological responses in and out of the environmental environment could be future investigated in our future work.

6. Conclusions

This paper investigates the effect of wearing a mask on physiological responses and the performance of individuals who work in office-like indoor environments. The work engagement, mental workload, SCL, HR, and task performance are measured and collected. Based on the results from brain waves and SCL (considered as an indicator of the mental workload), although the results vary across different individuals, wearing a mask can in general lower the mental workload of the subjects while they are performing cognitive tasks. Overall, the results of task performance (correct number and correct rate) are highly correlated to the measured mental workload, indicating that higher task performance is associated with a higher mental workload. However, in most of the scenarios, no significant difference is found between the cloth mask and the surgical mask. Similar to mental workload and task performance, the values of work engagement and HR are significant differences among different mask-wearing scenarios, the patterns vary across individuals. However, there is no one-size-fits-all pattern to conclude the effect of wearing a mask on work engagement and HR. For example, for some subjects, wearing a mask may reduce their work engagement while others may be more engaged with a mask.

One main contribution of this paper is that the proposed method could be used to investigate the effect of wearing masks on occupants directly through physiological sensing. The results provide a deep understanding of how people's physiological responses and task performance may change if they are required to wear a mask as was the case during the pandemic period. The findings from this study could be valuable for those who need to wear a mask while working or policy-makers looking to determine the optimal number of individuals required to work in person in the office on a daily basis.

Table 8
Statistical analysis of the potential effect of gender.

	Gender	Mean	Effect Size	p-value
FAI	Female	0.065	0.315	0.066
	Male	0.255		
MW	Female	2.331	0.162	0.349
	Male	2.093		
SCL	Female	2.510	0.084	0.572
	Male	2.781		
HR	Female	80.218	0.306	0.032
	Male	77.193		
Correct Number	Female	29.864	0.534	<0.001
	Male	24.899		
Correct Rate	Female	85.478	0.084	0.614
	Male	84.274		

CRediT authorship contribution statement

Min Deng: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Xi Wang:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Carol C. Menassa:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Conceptualization.

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

The authors do not have permission to share data.

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