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Investigating the Relationship between Noise Exposure and Human Cognitive Performance: Attention, Stress, and Mental Workload Based on EEG Signals Using Power Spectrum Density

Rahmaniyah Dwi Astuti [1,*], Bambang Suhardi [1], Pringgo Widyo Laksono [1] and Novie Susanto [2]

[1] Department of Industrial Engineering, Faculty of Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia; bambangsuhardi@staff.uns.ac.id (B.S.); pringgowidyo@staff.uns.ac.id (P.W.L.)

[2] Department of Industrial Engineering, Faculty of Engineering, Universitas Diponegoro, Semarang 50275, Indonesia; nophie.susanto@gmail.com

* Correspondence: rahmaniyahdwis3@student.uns.ac.id

Abstract: A pervasive environmental stressor is one that damages mental and physical health as well as cognitive abilities by producing noise at a specific frequency and level. Current noise pollution levels pose a significant threat to public health, potentially leading to impaired cognitive function, increased stress, and other negative health consequences. This study aims to investigate the relationship between noise exposure and human cognitive abilities using a comprehensive analysis of power spectrum density (PSD) derived from EEG signals. Twenty-four participants completed the experiment to identify the effect of exposure to different noise levels (55 dB, 65 dB, 70 dB, 75 dB, 80 dB, and 85 dB) and two types of continuous and intermittent noise. The Stroop Color–Word Test and the Emotive Epoch EEG are cognitive task instruments used during experiments. Behavioral performance (accuracy and response time) and power spectrum electroencephalographic density were collected and analyzed. The methodology involved collecting EEG data from participants exposed to controlled noise stimuli and a subsequent PSD analysis to uncover frequency-specific patterns associated with cognitive processes. Attention levels were measured by examining beta wave activity, while stress responses were evaluated through an alpha wave analysis. Additionally, mental workload was assessed by considering the overall distribution of PSD through the theta-to-alpha ratio. The results revealed a significant relationship between the exposure to noise types and levels and human cognitive ability. The analysis of the power spectrum density on the cognitive aspects of attention and stress yielded results indicating that participants were in the best attention condition and in a relaxed or unstressed state when exposed to noise levels of 65 dB in both continuous and intermittent noise types. For the mental workload aspect, participants exposed to both continuous and intermittent noise types at a noise level of 70 dB began to indicate the presence of mental workload. These findings supported the importance of considering the impact of environmental noise on human cognitive well-being and demonstrated the potential of EEG monitoring as an objective tool for assessing the impact of noise on cognitive performance.

Keywords: noise; cognitive performance; EEG; power spectrum density

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Citation: Astuti, R.D.; Suhardi, B.; Laksono, P.W.; Susanto, N. Investigating the Relationship between Noise Exposure and Human Cognitive Performance: Attention, Stress, and Mental Workload Based on EEG Signals Using Power Spectrum Density. *Appl. Sci.* **2024**, *14*, 2699. https://doi.org/10.3390/app14072699

Academic Editor: Heecheon You

Received: 28 January 2024
Revised: 15 March 2024
Accepted: 20 March 2024
Published: 23 March 2024

1. Introduction

At the enterprise and industry level, the development of technology and information communication has changed the nature of work. Work has changed from being dominated by physical activity to work or activities that are dominated by mental/cognitive demands and abilities. Humans act as operators who carry out control functions, so cognitive abilities, especially those related to perception and decision-making, are very important. Physical factors of the work environment in the workplace can affect the good and bad performance of labor and can even affect work productivity. The physical factors in question are the physical state of an environment or workplace, which includes the noise, temperature, lighting, air humidity, vibration, ultraviolet radiation, electromagnetic waves, and color. One of the work environment hazards that can affect performance is environmental noise [1].

Environmental noise can affect the daily functions of humans including their cognitive, motivational, and emotional functions [2]. A noise is an unpleasant or potentially harmful sound [3]. There is some noise in most workplaces; this includes noise from nearby roads, the inane talk of co-workers, and emissions from machinery and other devices [4]. Noise exposure can cause two kinds of health effects: auditory effects and nonauditory effects. Auditory effects are effects on hearing loss, while nonauditory effects are effects not on hearing [5]. Nonauditory effects include stress, related physiological and behavioral effects, and safety concerns [6]. Nonauditory effects include behavioral performance, workplace safety, information processing, speech impairment, cognitive impairment, concentration, stress, and emotions [7]. Noise in the workplace is of increasing concern due to its health implications, particularly hearing loss. Nonetheless, for now, there is a tendency to emphasize the nonauditory effects caused by noise [8]. This is because the influence of noise on human brain activity and cognitive function is often underestimated [5].

In 1930, it was believed that the health effects of noise were limited to hearing loss. A study published in the Journal of the US Acoustical Association concluded that the impact of noise on humans goes beyond damaging hearing [9,10]. After advances in the scientific field in the 1960s, many studies were conducted in the 1970s to assess the annoyance caused by environmental noise [11,12]. Exposure to noise causes disturbances to calmness and physiologically increases physical provocation and anxiety [13]. Noise exposure can have early and late effects. One of the primary impacts is that of decreased cognitive function, which can commonly lead to occupational accidents [14].

Noise can directly adversely affect cognitive performance (through nonauditory effects such as workload or stress) in the workplace [4,15]. Noise has different negative effects, ranging from the impairment of cognitive processes to damage to mental and physical health [16]. Impaired cognitive function occurs, leading to decreased performance, human error, and eventually increased accidents in jobs involving cognitive performance [17]. Whether noise degrades cognitive function depends on a number of factors, including the kind of noise, task difficulty, duration of noise exposure, sound pressure level, and frequency spectrum [15,18,19]. Studies suggest that the most important factor is the sound pressure level [19]. Studies related to noise exposure conducted by researchers before mainly discussed the physical impact on workers (auditory effects) [20–22]. Studies on cognitive performance during noise exposure in the exposure–effect relationship that have been done subjectively using questionnaires have limitations [23–25] because subjective measurements or assessments are more likely to use subjective perceptions of the sources or participants so that they can reduce the objectivity of the study results.

Several studies have shown that worker's performance and well-being are negatively affected by exposure to workplace noise above 85 dB [26–28]. However, the effects of medium occupational noise on cognitive performance have not been well studied [29]. Working individuals are often exposed to medium noise levels (e.g., <85 dB) while performing cognitive-based tasks. Exposure to such noise may affect an individual's cognitive performance and influence the desired level of performance [25]. Medium-level noise is described as unwanted sounds or loud noises <85 dB that affect an individual's attention [25], working memory [30], long-term memory, and reading comprehension [31]. Other studies have confirmed that direct links exist between increased noise levels and decreased cognitive performance [19,32,33]. Cognitive function consists of mental processes such as attention, perception, memory, decision-making, problem-solving, and response time [34]. Noise can interfere with cognitive process, impair attention, increase stress levels, and increase mental workload [15,24,27,35,36]. Some workplaces require workers to use cognitive abilities in carrying out tasks that are required in the workplace environment. Many work environments such as banking, offices, control rooms, and industrial workplaces such as assembly workplaces, and so on, involve cognitive functions. Workers in these environments typically have to deal with a variety of difficulties, including the need to pay attention, recall information quickly, and varying levels of task complexity. They are also usually exposed to medium noise levels [37–39]. Noise exposure is one of the factors that can interfere with a worker's performance in the environment [40]. Noise exposure in different workplaces and outside the workplace is considered a problem. Noise that is incompatible with professional duties is very harmful to a person's personal safety, efficiency, and health [12]. Therefore, an assessment of the effects of noise on cognitive performance can be beneficial in reducing human error and increasing productivity in such work. In addition, further studies have been recommended by the European network regarding noise exposure in mid-level workplaces and the examination of the relationship between cognitive performance and noise exposure [17].

Cognitive performance can be seen in a person's ability to complete cognitive activities, which include reading, writing, listening, speaking, thinking, learning, planning, solving problems, making decisions, and interacting with computers. Various studies measure cognitive performance through test results. Activity types, or task types, in learning activities are related to reading, searching, remembering, and attention [41]. One type of task used in measuring cognitive performance is the Stroop Color–Word Task (SCWT), commonly referred to as the Stroop Test, where subjects are asked to read a series of colored words and expressions as quickly as possible [42–44]. The representation of the Stroop Color Test type of cognitive task for working in industry lies in the ability of workers to cope with distractions, process information quickly and accurately, and handle complex and diverse tasks [45].

Some different techniques can be used to measure the cognitive and physiological reflex parameters of individuals exposed to noise [12]. The effects of noise can be measured through brain activity and the waves it produces [16]. Electroencephalography (EEG) is a tool that can record the electrical signals produced by the brain as actions and responses to stimuli are collected from a person [46]. Cognitive theory suggests that the brain is deeply involved in emotions. Basic emotions utilize certain cortical and subcortical systems within the brain and are distinct from the electrical and metabolic activity of the brain [47]. The function of the EEG is to record the electrical activity of the brain, where the resulting signals are sent to the nerve cells of the brain. EEG can be measured non-invasively after placing electrodes on the surface of the scalp. The advantage of using EEG is that the results can be used to determine a person's level of confrontation with noise. We can also know the constant psycho-physiological indicators in an individual, so an explicit response from the individual is not required [48]. According to cognitive theory, emotions affect the brain significantly. Basic emotions depend on specific cortical and subcortical systems and are different from the electrical and metabolic processes of the brain. Because of this, EEG is one of the most widely used and trustworthy methods of brain imaging that may be used to examine brain activity in people who are under stress, including that caused by noise [49]. EEG signals measure every change in the electric field caused by brain activity with millisecond accuracy. To determine the relationship between voltage and EEG signals, a wide range of frequency bands are often measured. Among these bands are alpha (8–12.5 Hz), theta (4–8 Hz), and beta (12.5–30 Hz) [16]. A decrease in the beta frequency range and an increase in the alpha frequency band improve cognitive function [50]. A decrease in alpha band strength and an increase in theta and beta band strength are indicative of neurological disorders [51]. The rhythm of beta forces in EEG is positively correlated with stressful scenario experiences in the temporal lobe [49].

Exposure to environmental noise has long been identified as a factor that can affect human health, including cognitive capacity. However, its impacts on specific cognitive functions such as attention, the stress level, and mental workload still require a deeper understanding. In an attempt to analyze these impacts, we adopted an EEG signal analysis approach utilizing the SCWT test, which is a powerful indicator for evaluating cognition. This study aimed to investigate the relationship between the noise type and level and cognitive performance on the SCWT cognitive task based on a power spectrum density analysis of EEG signals. We investigated how information derived from the EEG spectrum for the investigation of noise exposure affects cognitive performance by using frontal brain load indicators to analyze aspects of attention, stress, and mental workload by combining EEG recordings with cognitive task performance.

2. Materials and Methods

The method used to analyze the results of the EEG signal output is power spectrum density (PSD). The dimension used by PSD is power per Hz. PSD is usually shown for spectrum continuity [52,53]. The frequency domain is based on the approximate spectrum density of the signal power and is calculated using a periodogram or parametric methods [54]. A short-time Fourier transform (STFT) is used to convert EEG signals into spectrum domains. After converting a signal to the frequency domain using a STFT, the power spectrum density (PSD) can be calculated. PSD is an important signal quality in the frequency domain that represents the contribution of each frequency component to the overall signal segment's intensity [55]. Since the noise type and level affect how noise impacts brain signals and cognitive function, this study focused on two types of noise, namely continuous noise and intermittent noise, with noise levels below 85 dB, namely 55 dB, 65 dB, 70 dB, 75 dB, 80 dB, and 85 dB levels. In this study, the determination of noise level as an independent variable is based on a previous study that categorized noise levels into three categories: low (55 dB, 65 dB), medium (70 dB, 75 dB), and high (80 dB, 85 dB) [16,25,35,49].

A schematic overview of this experiment is presented in Figure 1. The experiment was followed by a paper-based survey to assess the overall experiment and identify any difficulties faced during the experiment. The whole experiment lasted for an average of 210 min per participant. Participants were allowed to stop and leave the experiment in the case of any difficulties encountered while experiencing distress.

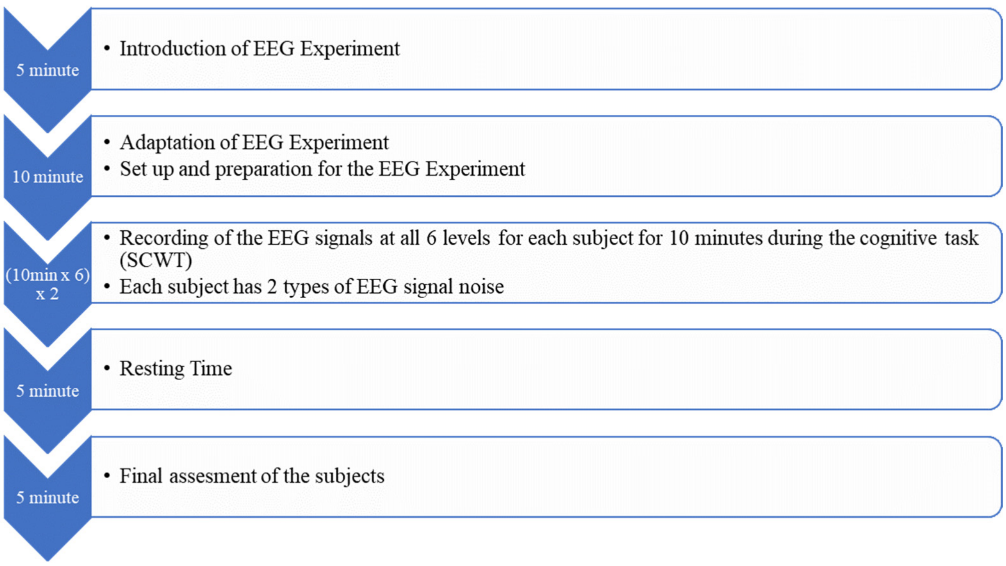

Figure 1. Experimental Protocol.

2.1. Participant and Noise Source

The study involved a total of 24 students, with 12 males and 12 females. Participants were then divided into two groups according to the type of noise in this experiment. Each group consisted of 12 participants, with 6 males and 6 females. The inclusion criteria encompassed no color blindness, the absence of prior cardiovascular disorders, refraining from alcohol and caffeine consumption for 12 h before testing, maintaining a "normal" Body Mass Index (BMI) within the range of 18.5 to 25.0 kg/m^2, and having no history of sleep disturbances. Before testing, participants were required to achieve a "normal" score on the DASS-21 questionnaire, indicating that they were not currently experiencing symptoms of depression, panic, or stress [56]. Furthermore, participants were briefed on the study's purpose and nature, and they were asked to provide written consent to participate in the study after receiving the necessary information.

This experimental study was conducted in a controlled laboratory experimental room with a temperature of 26 °C and room lighting of 250 lux. The dimensions of the experimental room were H = 4.5 m, L = 4.5 m, and W = 3.5 m. All participants were exposed to different noise levels. Participants received only one exposure to the noise level in each experiment. The noise in this experiment represents the sound of industrial machinery at levels of 55 dB, 65 dB, 70 dB, 75 dB, 80 dB, and 85 dB. The type of noise used was continuous and intermittent. Participants were exposed for twenty seconds to high-level noise and then dramatically switched to low-level noise. After that, for five seconds, participants were not exposed to noise. Then, again, participants were exposed for twenty seconds for the intermittent type. Participants were exposed to constant or persistently fixed noise levels for the continuous type. Furthermore, the noise exposure level was measured using the Krisbow (Jakarta, Indonesia) KW Envirometer 5-in-1 Sound Level Meter 10176832. To modify the sound and obtain a stable sound, Adobe Premiere Pro software (Version 22.0) was used, and the noise of the industrial machine was played back using audio speakers on a smart TV.

2.2. Cognitive Task Measurement

Participants in the study completed cognitive tasks at six different noise levels, and the results were used to determine their cognitive performance index, which comprises accuracy percentage and total response time. Accuracy measures how precise or accurate participants are in completing SCWT tasks. Accuracy is measured by counting the number of correct answers participants make when completing an SCWT task. The greater the number of correct answers, the higher the accuracy rate of participants. Response time measures how long participants take to complete a SCWT task. Response time is measured in seconds, from the moment the stimulus is presented to the participant's response. Shorter response times indicate better cognitive and information-processing abilities.

2.3. Statistic Analysis

Statistical analyses were performed using SPSS software (version 26.0) to calculate the percentage of correct answers and the average response time of each participant. Given that the response time data rejected normality and the sizes of the two samples were inconsistent, the Mann–Whitney test was performed to test the difference in response time according to the answers. After testing the homogeneity of variance using Levene's test and the normal distribution of data using the Shapiro–Wilk test, the behavioral performance data and rating values against normality and population variance were different. Therefore, the Kruskal–Wallis ANOVA test with nonparametric methods was used to validate the differences in content and the degree of noise effects on response accuracy and response time.

2.4. EEG Recording and Analysis

EEG signals are recorded using Emotiv-EPOC to collect continuous brain waves. Electrodes are placed at the frontal (AF3, AF4, F3, F4, F7, F8, FC5, FC6), temporal (T7 and T8), parietal (P7 and P8), and occipital (O1 and O2) regions, along with two reference electrodes (CMS/DRL located at P3 and P4). For this experiment, eight electrodes, including AF43, AF4, F3, F4, F7, F8, FC5, and FC6, were focused on the frontal region to be observed, as illustrated in Figure 2. Their placement corresponds to the international 10–20 electrode placement system. The device complied with safety standards for radio frequency emissions and electrical safety. Permission for this trial was obtained by Dr. Moewardi General Hospital under research ethics code No. 1203/IX/HERC/2022.

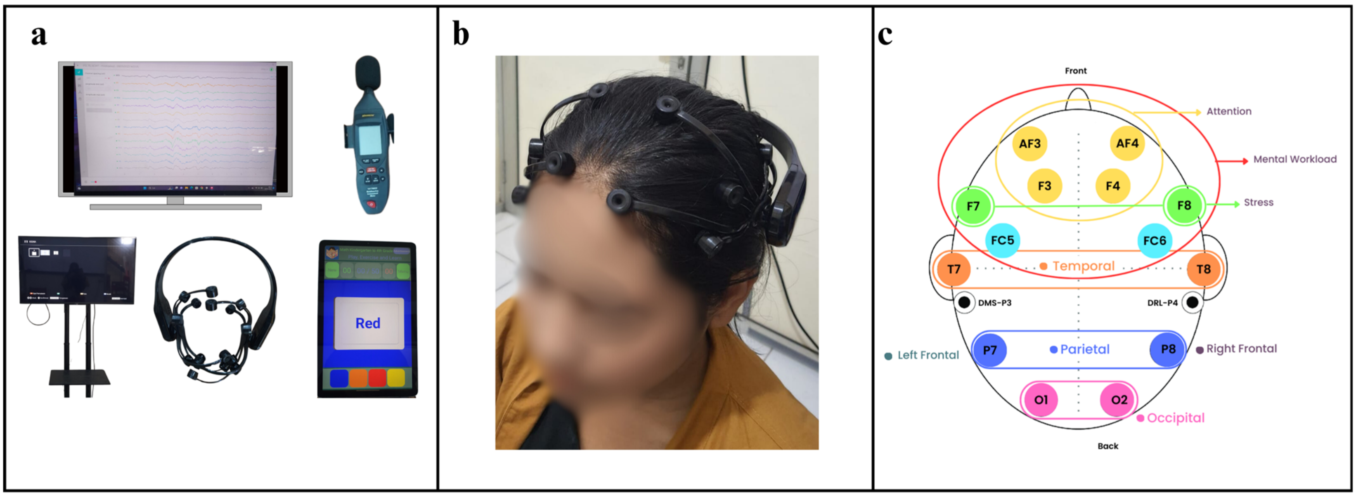

Figure 2. (**a**) Equipment of the EEG Experiment; (**b**) An actual photograph showing the experimental setup in the laboratory; (**c**) Electrode placement on the Emotiv Epoch.

EEG signals are recorded in the form of signals in the time domain, while to obtain alpha, beta, and theta waves, it is necessary to know the frequency of the signal. To convert a time domain into a frequency domain, signal processing is required to convert the signal. A method that can be used to obtain frequencies is based on spectrum estimation calculations using power spectrum density (PSD) [57–59]. PSD is a measure of how strong brain activity is at various frequencies. It is calculated by squaring the magnitude of the Fourier transform and is usually calculated for a specific time interval [55,60,61]. The results of PSD calculations can be visualized in graphic form. The PSD graph shows the intensity of brain activity in various frequency ranges. An Emotiv-EPOC with 14 electrodes which were wet via saline was used to collect the continuous brain waves. The electrodes are mounted at the frontal (AF3, AF4, F3, F4, F7, F8, FC5, and FC6), temporal (T7 and T8), parietal (P7 and P8), and occipital (O1 and O2) regions, along with two reference electrodes (CMS/DRL located at P3 and P4). Different cognitive states correspond to different indicators, some being controversial due to different experimental tasks [35,62]. In this study, after reviewing the relevant literature, three indicators were selected as cognitive performance measurement metrics, namely the cognitive aspects of attention measured based on the prefrontal beta signals of the AF3, AF4, F3, and F4 channels, stress aspects measured based on the alpha lateral frontal cortex signals of the F7 and F8 channels, and the mental workload aspects based on the theta/alpha ratios of the AF3, AF4, F3, F4, F7, F8, FC5, and FC6 channels [35,62,63].

The experimental research design is shown in Figure 3. The EEG device used is the EEG Emotiv EPOC X (Emotiv, San Francisco, CA, USA), which has 14 channels with a sampling rate of 128 Hz. A bandpass filter (1–30 Hz) is used to record EEG data, the raw data is recorded using Emotive Pro software (Version 3.0), and raw data preprocessing is done using EEGLAB (Version 2023) on MATLAB (Version R2021a) ToolBox. The data processing of a set of net EEG data involves feature extraction and classification. EEGLAB STUDY is used in the data processing step of EEGLAB. EEGLAB STUDY is a feature to statistically analyze and process the input data from EEG signals. The processing output using EEGLAB STUDY in this study shows the power spectrum at alpha, beta, and theta frequencies as well as topography when subjects were treated to each type of noise and noise level. Power spectrum density (PSD) in the context of an electroencephalography (EEG) signal is a representation of the distribution of energy or signal strength at various frequencies. PSD EEG signals measure the strength or amplitude of the brain's electrical activity over a wide range of frequencies. The PSD analysis of EEG signals involves the process of transforming time-domain signals into frequency domains using the Fourier transform method. In the results of the PSD analysis, information about the strength or amplitude of brain activity at a certain frequency can be identified. Determining the average power of an EEG signal is a way to measure the distribution of energy or brain activity over a specific frequency range and provide important information about the level of brain activity at different frequencies during certain conditions [64]. Average power spectrum density (APSD) refers to the distribution of the average power of a signal in a frequency domain. It provides information about the distribution of a signal's power along various frequency components. In the context of EEG, the APSD can help identify different brain frequency activities, such as delta, theta, alpha, and beta waves [65].

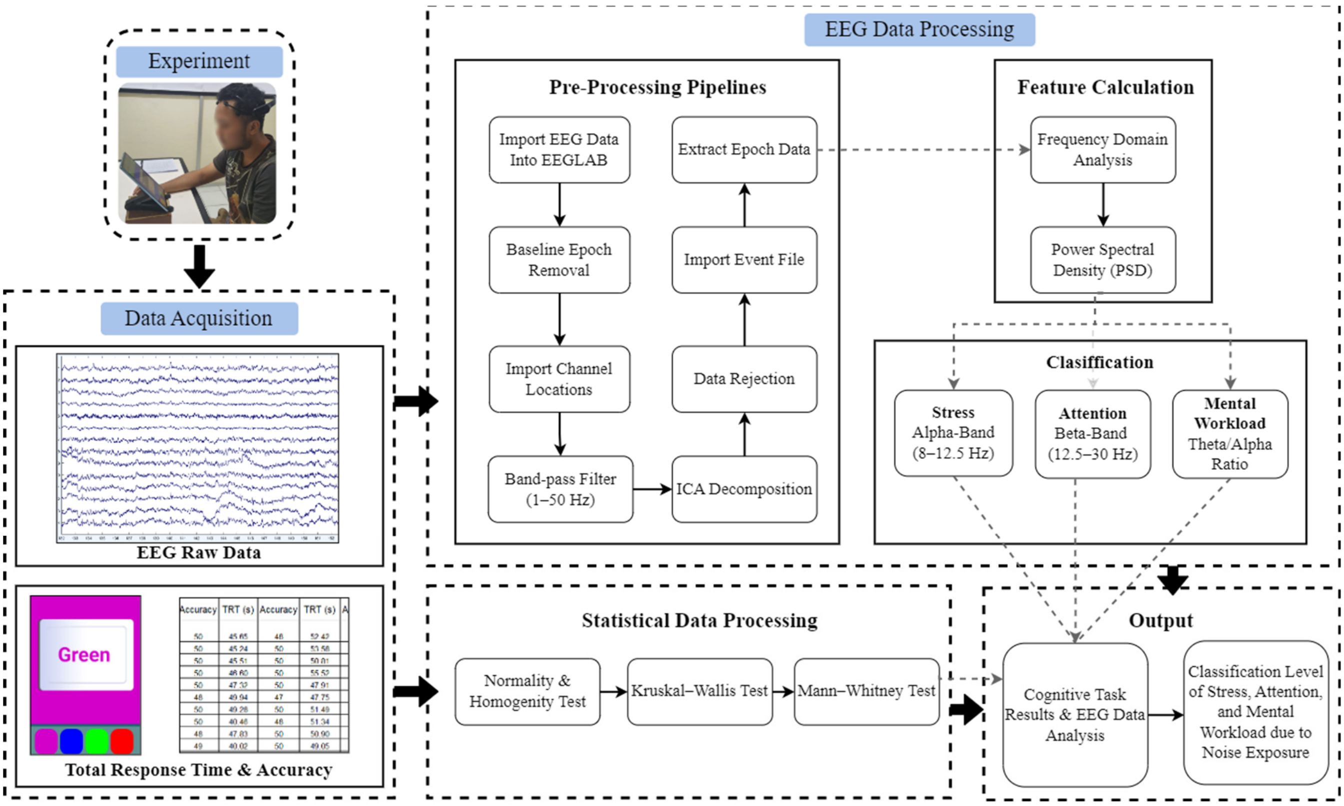

Figure 3. Experimental Research Design.

3. Results

The descriptive statistics of the noise level on the total response time are presented in Figure 4. The average total response time of continuous noise for males exceeded that of females in groups exposed to noise levels of 55 dB, 65 dB, 70 dB, 75 dB, 80 dB, and 85 dB. Likewise, for intermittent noise, the average total response time for males surpassed that of females in groups affected by noise levels higher than 55 dB, 65 dB, 70 dB, 75 dB, 80 dB, and 85 dB. This implies that on response time scores, males tend to experience greater noise impact than females in situations of continuous and intermittent noise exposure.

The descriptive statistics of noise level on total response time are presented in Figure 5. The average accuracy score in the continuous noise category for the female group was lower than the average score for males in the group exposed to higher noise levels at 55 dB, 65 dB, 70 dB, 75 dB, 80 dB, and 85 dB. For intermittent noise, males' average accuracy scores fell below the average for females in the group who experienced higher noise levels at 55 dB, 65 dB, 70 dB, 75 dB, 80 dB, and 85 dB. Accuracy scores with continuous noise exposure show that males are more likely to be affected by exposure than females. For intermittent noise exposure, females are more likely to experience high noise exposure than males.

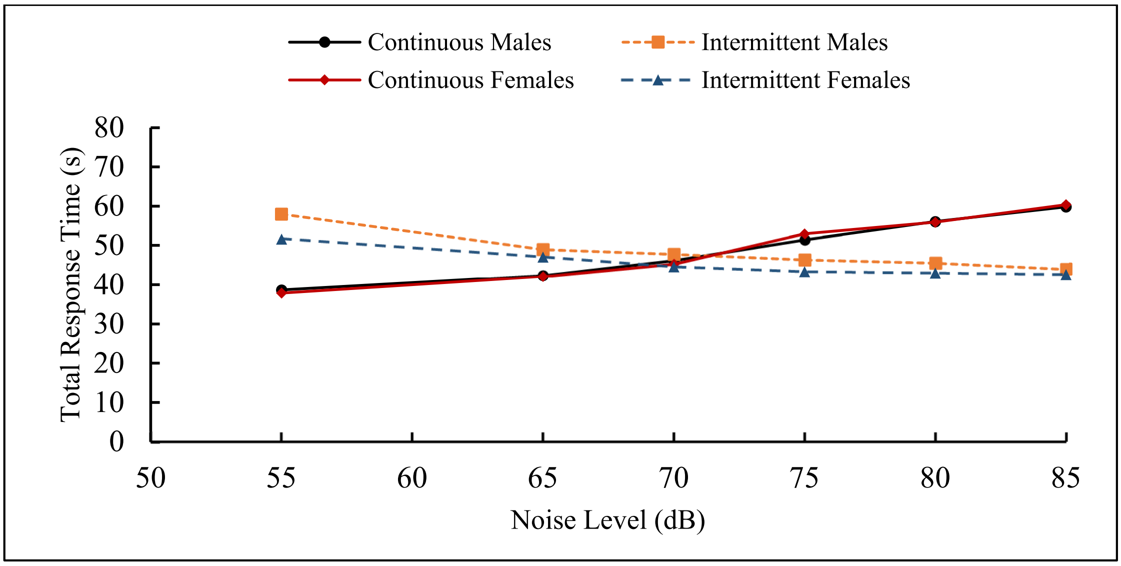

Figure 4. Relationship between total response time on continuous and intermittent noise levels.

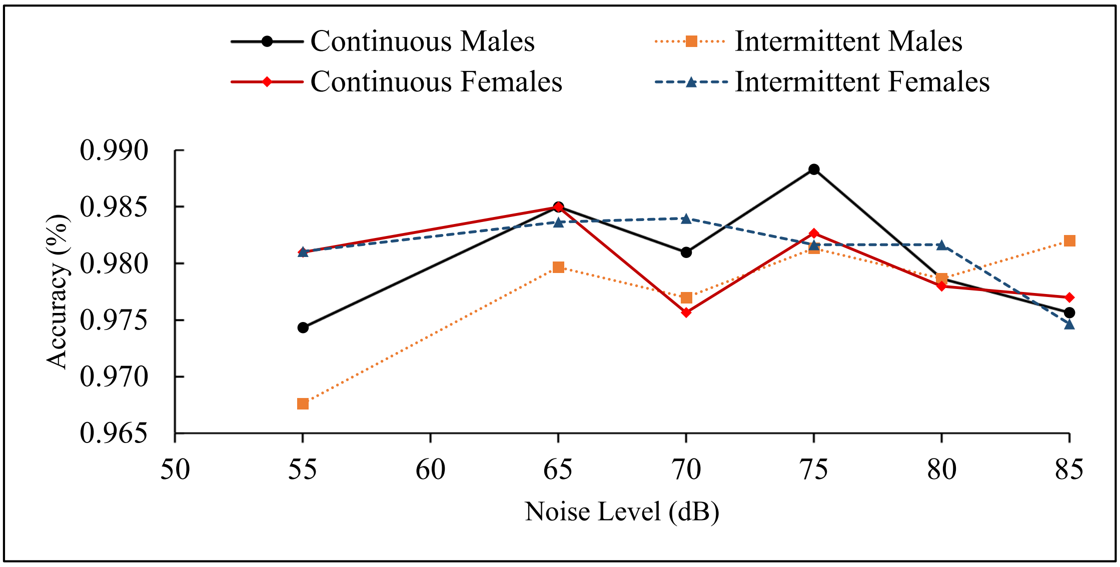

Figure 5. Relationship between accuracy on continuous and intermittent noise levels.

The Kruskal–Wallis ANOVA results on response time and accuracy with continuous and intermittent types of noise showed that the effect of the content and noise levels was statistically significant across the response time and accuracy (Chi-square = 11.07, df = 5, $p < 0.05$), indicating a significant difference between SCWT test results in the noise-affected group with levels of 55 dB, 65 dB, 70 dB, 75 dB, 80 dB, and 85 dB. The Kruskal–Wallis test obtained significant results and can be continued to be utilized in post hoc tests. A post hoc Mann–Whitney test was carried out to determine if there was a significant difference between the two groups of noise levels. From the post hoc test, it was found that in the types of continuous and intermittent noise, the total response time and accuracy were produced, which showed that all noise levels had significant differences with p values.

The cognitive aspect of attention was measured based on the beta signals of channels AF3, AF4, F3, and F4 [35]. Beta signals at frequencies of 12.5–30 Hz recorded from the frontal region are considered valuable biomarkers of attentional control, which have a negative relationship with attentional control [66]. The log power spectrums of attention within noise that is continuous and noise that is intermittent are described in Figure 6a,b.

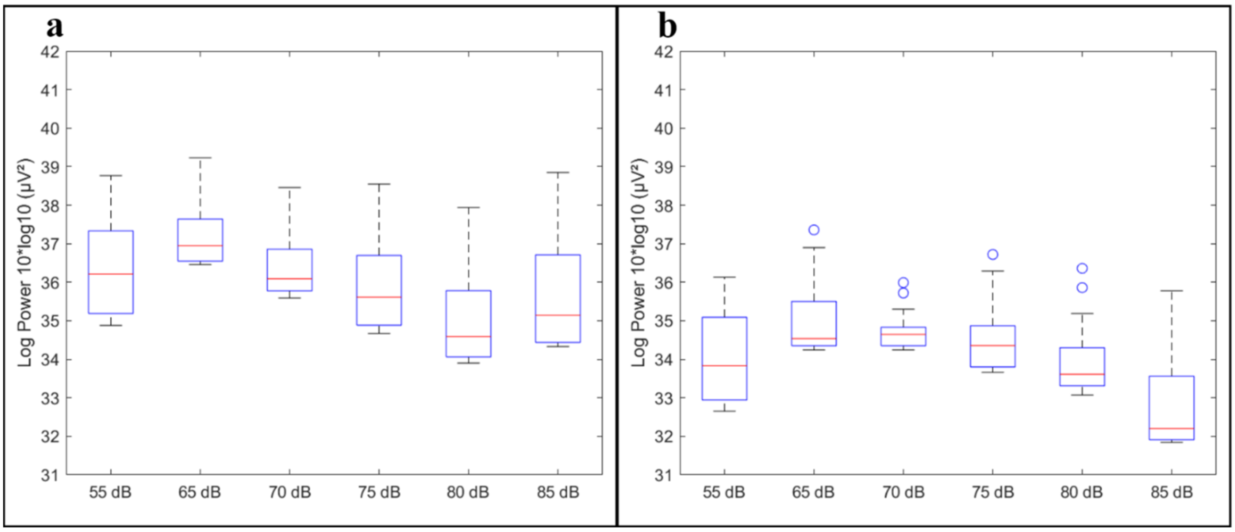

Figure 6. (**a**) Log power spectrum of attention within continuous noise; (**b**) Log power spectrum of attention within intermittent noise.

Figure 6a,b shows the log power spectrum value difference at each noise level. The nonoutlier maximum and median values show the best attention among noise levels. Figure 6a shows log power values in the range of 34 μV^2 to 39.5 μV^2, while Figure 6b shows log power values in the range of 31.5 μV^2 to 38 μV^2.

The cognitive impact of stress is assessed using the alpha signals of channels F7 and F8 [35]. A feature that is commonly employed to quantify stress levels during emotional arousal is the EEG asymmetry index of alpha activity at frequency (8–12.5 Hz); in most stress-related studies, this index appears to decrease under stressful situations [67]. The continuous and intermittent power spectrum of stress caused by noise logs are described in Figure 7a,b.

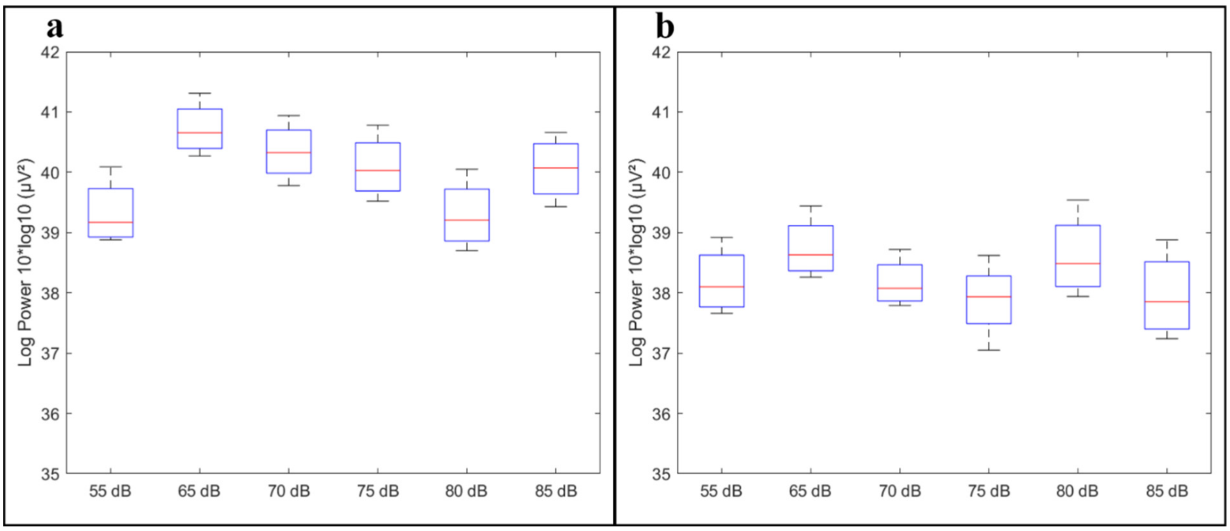

Figure 7. (**a**) Log power spectrum of stress caused by continuous noise; (**b**) Log power spectrum of stress caused by intermittent noise.

Figure 7a,b shows the log power spectrum value difference at each noise level. The nonoutlier minimum and median values show the highest influence on stress among noise levels. Figure 7a shows log power values in the range of 38.5 μV^2 to 41.5 μV^2, while Figure 7b shows log power values in the range of 37 μV^2 to 39.5 μV^2.

The cognitive aspect of mental workload is measured based on the theta-to-alpha ratio, which was calculated by the alpha band strength over the frontal channels AF3, AF4, F3, F4, F7, F8, FC5, and FC6 [35,63,68,69]. The calculation of the theta-to-alpha ratio is performed using the mean value of the PSD alpha band and the average PSD value of the theta band [69]. The mental indices of continuous and intermittent noise on workload are shown in Figure 8.

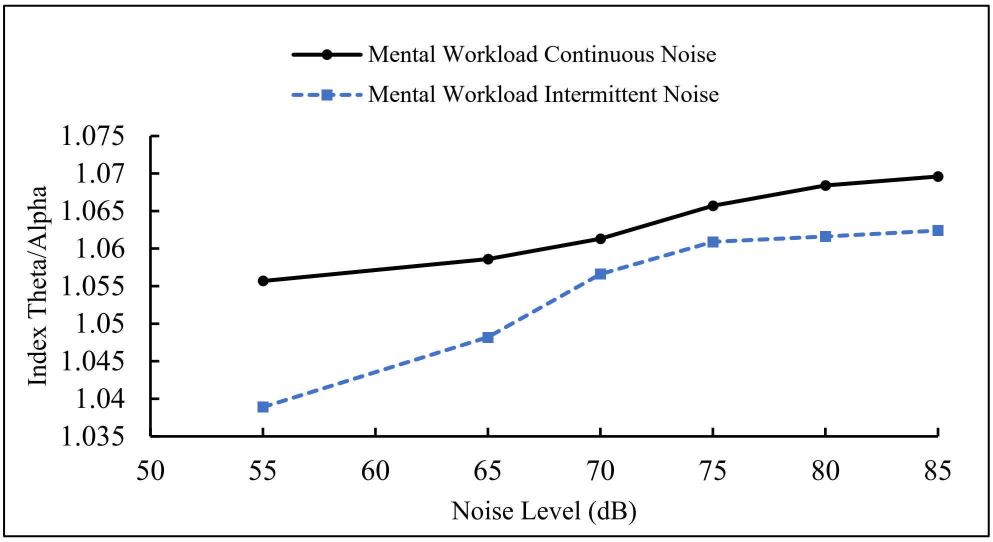

Figure 8. Relationship between the mental workload index and continuous and intermittent noise levels.

Figure 8 shows that the increase in mental workload index value in continuous and intermittent noise is linear to the noise level. The greater the noise, the greater the mental workload index value. Based on Figure 8, the continuous noise mental workload index value is greater than the intermittent noise mental workload index.

In this study, topographic mapping results are shown based on the frontal areas of participants at each noise level in Figure 9a,b. Topography in the study is based on the power spectrum density value scores from $-2\ \mu V^2$ to $2\ \mu V^2$ which are represented in blue as a score with a negative value and red as a score with a positive value. The electrode placement on participants is the AF3 and AF4 electrodes placed on the frontal area located just above the eye area, the F3 and F4 electrodes at the front of the head around the prefrontal area, and the F7 and F8 electrodes in the lateral frontal area.

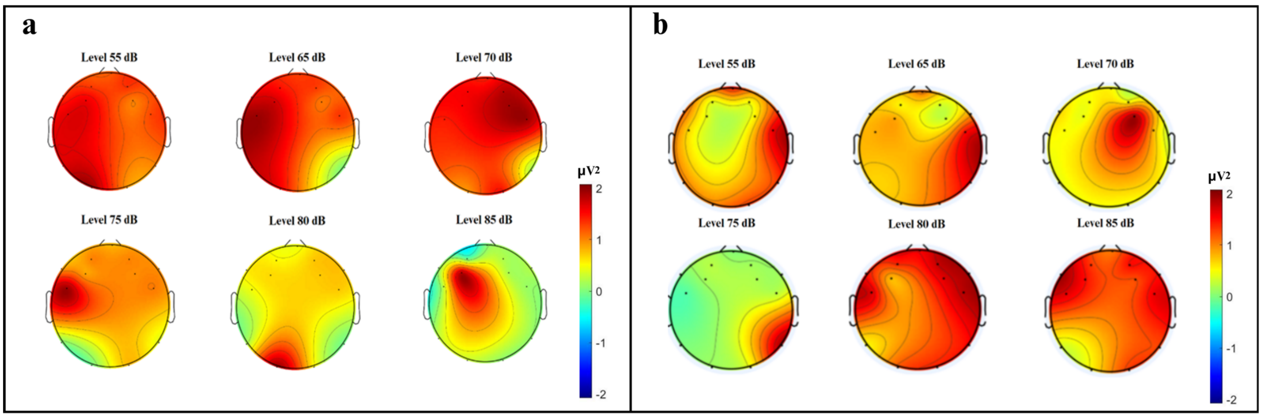

Figure 9. (**a**) Topographic mapping of the relative power of frequency bands during continuous noise exposure; (**b**) Topographic mapping of the relative power of frequency bands during intermittent noise exposure.

The topography at electrodes AF3, AF4, F3, F4, F7, and F8 marked in red at the frontal lobe position shows high power spectrum density values indicating the strong activation of frontal brain areas associated with attentional processing, stress, and mental workload. Topographic results marked in green show less active brainwave activity with low power spectrum density values.

4. Discussion

The results of this study show that the level and type of noise have a significant relationship with cognitive performance based on the response time and accuracy when doing SCWT cognitive tasks. These results are in line with the studies conducted in [35], which found that noise had a significant effect on the overall outcome of response time and accuracy of cognitive tasks. These results also correspond with the studies of [33], who analyzed the effect of noise on attention and short-term memory, finding that response times to stimuli decreased when noise levels were increased. In contrast to those studies, some studies have found that noise does facilitate performance [70]. One explanation might be that noise can promote arousal and provide excitement for relatively uninteresting occupations, which in turn boosts attention span and task participation. Other studies have found that noise decreases accuracy but speeds up reaction times mostly due to the accuracy–speed tradeoff [71]. An empirical study also found an increase in reaction time (RT) and the number of errors caused by noise exposure [72]. Evidence suggests that noise slows response times for information processing [73]. Another study conducted by [8] found that loud noise exposure significantly reduced attention spans and working memory. Preliminary studies that have been carried out also provide results of level noise factors having a significant effect on the total response time of participants when participants complete the trial-making test [74]. A study by [75] displayed that males have faster RTs than females for both auditory and visual stimuli.

EEG is a valuable tool to evaluate cognitive performance based on brain signals and activity patterns [35]. Electroencephalography has certain advantages, which include its being non-invasive, low cost, comfortable, safe, mobile, and having a high time resolution. Therefore, EEG can be a great tool not just for detecting stressors in the environment but also for predicting the negative effects of noise exposure [16]. The analysis of cognitive aspects of attention in this study used the average results of beta power spectrum density signals to measure the cognitive aspects of participants' attention when doing tasks. Beta signals indicate a person's attention is focused on a particular task. The frequency of beta waves is associated with a state of attention and alertness [76]. Based on the type of continuous noise, Figure 6a displays the results of measuring the power spectrum density of the cognitive elements of attention. Participants showed that they had the best attentional conditions at a noise level of 65 dB based on the highest power spectrum log value compared to other noise levels. At the 65 dB level, it is known that the largest power spectrum at the maximum point is at a log power of 39.23 μV^2 at a frequency of 13.2 Hz. The power spectrum at 65 dB decreases to a minimum of 36.5 μV^2 at 26.4 Hz. For the intermittent noise type, Figure 6b shows the results of participants having the best attentional conditions. Based on the average log power spectrum, the noise level of 65 dB gives the largest average log power spectrum with the value of 35.01 μV^2, and the maximum point is at a log power of 37.36 μV^2 at a frequency of 12.7 Hz. The power spectrum at 65 dB decreased to a minimum of 34.24 μV^2 at 24.2 Hz. The results of this experiment on the observed beta signals show that the higher the log power spectrum density value and the condition of the lowest frequency value, the more cognitive aspects of participants have the highest attention or concentration. Based on the results of this experiment, continuous noise at a noise level of 80 dB has the highest influence on attention interference, while intermittent noise at a noise level of 85 dB has the highest influence on participants. Based on the findings of this study, there is a difference in the results of the magnitude of the noise level within the type of noise, namely between the type of continuous noise and intermittent noise, which gives different results, thus proving that the type of noise and noise level can have an influence on the participants' attention. A study by [77] revealed that the Stroop effect and mental calculation performance in 50 dB of noise exposure increased compared to 70 dB of noise. Also, ref. [77] reported that noise exposure higher than 85 dB can cause vulnerability, fatigue, and stress. The results of this study are consistent with the finding that there is an association between low performance and high noise levels [16,17]. Another study provides the results that the effects of noise at moderate levels are more harmful to accuracy, and that attention will be significantly affected by exposure to moderate levels of noise [15]. A study by [78] provides results indicating that sound intensity is significant to the average attentional beta signal.

The analysis of cognitive aspects of stress in this study used the average results of alpha power spectrum density signals. An increase in the alpha band power spectrum along with a decrease in the beta band power spectrum leads to improved cognitive function [23]. An increase in alpha power indicates decreased brain activity (relaxing) [79]. In this study, the results of measuring the cognitive aspects of stress in Figure 7a,b showed that participants were in a relaxed condition (not experiencing stress) at a noise level of 65 dB at exposure to the type of continuous noise based on the largest power spectrum at the level of 65 dB, with the maximum point being at a log power of 41.31 μV^2 at a frequency of 8.13 Hz. The power spectrum at 65 dB decreased to a minimum of 40.27 μV^2 at 11.17 Hz. The higher the noise level, the more participants are in a state of not relaxing (stress). For the type of intermittent noise, participants at the 65 dB noise level are in a relaxed condition with the largest power spectrum at the 65 dB level, with the maximum point being at a log power of 39.44 μV^2 at a frequency of 8.13 Hz. The power spectrum at 65 dB decreased to a minimum of 38.74 μV^2 at 11.55 Hz. A noise level of 80 dB in the continuous noise type and 75 dB in the intermittent noise type has the lowest alpha signal power spectrum value, so participants are in a state of stress at those noise levels. The findings of this study revealed a significant relationship between noise type and noise level with cognitive performance in terms of participants' stress levels when exposed to noise. Studies by [24] showed that noise exposure is significant to job stress and negatively related to job satisfaction. Higher noise levels will cause stress, proving that noise conditions have a positive relationship with increased work stress, in line with the study by [27]. Other study findings also indicated that noise impacts cognitive performance and brain signaling as a stress-inducing factor [11]. In addition, noise level is an important factor that causes interference with cognitive performance, which means that low noise levels are less disruptive to performance than higher noise levels. It can be said that the findings of this study are consistent with the proposition that there is a relationship between poor performance and sound pressure levels [49]. Furthermore, due to increasing stress levels, noise also has a major impact on reaction ability and focus.

The analysis of the cognitive aspects of mental workload in this study showed that at a noise level of 70 dB with a theta-to-alpha ratio value that increased from the noise level below, participants started mentioning how noise affected their mental workload. The results indicate a correlation between band ratios and mental workload stages, particularly between theta and alpha bands, aligning with the findings of [63,80]. Additionally, a study by [81] also justifies its potential theta-to-alpha ratio as an indicator of workload. This is based on the assumption that an increase in theta strength bands and a decrease in alpha strength in the frontal brain region are associated with an increase in mental workload [82]. Exposure to significant noise can increase the mental workload of individuals. Mental workload increases with increasing noise levels, and the results are linear in a study by [35]. An EEG analysis of the brain signals revealed the presence of noise in the beta and alpha frequency bands. The relative intensities of the alpha and beta bands increase and decrease, respectively, as noise levels grow [16]. In this case, it may be said that when noise levels increase, attention rates fall even while the relative intensities of the alpha and beta bands increase and decrease.

Based on the results of EEG topography mapping as a spatial representation of brain electrical activity measured from various electrodes placed on the scalp in Figure 9a,b, there is a change in signal strength at each noise level in the continuous noise type (Figure 9a) and the intermittent noise type (Figure 9b). The topography results at all noise levels and noise types display that all active electrodes take turns giving signals. The topographic color map shows the intensity of brain activation [83]. The topography color map of the EEG for the alpha band shows where red represents the maximum value and blue represents the minimum value [84]. Previous studies also stated that beta wave activity is closely related to the level of attention, where the redder the map color on the topography, the higher the level of attentional energy produced [85,86]. A reduction in the relative strength of the beta band as a result of increased noise levels occurred in the frontal, temporal, occipital, and central lobes in the topographic map results of [16].

There were conflicting results regarding the effect of noise on cognitive function in previous studies. Some studies determined that noise had improved cognitive function [87]. While a study concluded that noise had reduced cognitive function [88], previous findings revealed that decreased cognitive function and brain signals were only significant when exposed to noise at 95 dB and not at 75 or 85 dB [16]. Previous study findings stated that intermittent noise had a greater detrimental effect on performance compared to continuous noise [89]. The findings of this study explained that continuous noise had a different impact than intermittent noise on cognitive ability. The difference lies in the individual characteristics, as when individuals face noise, personal characteristics may be important because some individuals may experience decreased cognitive performance while others may not, and some may even show symptoms of increased cognitive performance [90]. The study conducted by [16,91] indicated that the complexity of brain activities increased at moderate frequencies and showed the influence of frequency changes on brain activity. The brain signal analysis indicated that frequency bands such as alpha and beta were affected by noise. With increasing sound pressure levels, the relative power of alpha increased and beta decreased. While various parts of the brain applied complex activities during analysis and confrontation with noise, measuring changes in the temporal lobe was effective in evaluating stress [12]. Alpha and beta bands were correlated with attention, stress levels, and fast brain activities such as decision-making, analysis, and data processing in the frontal lobes. An increase in alpha indicated that subjects felt more relaxed after exposure to noise, after which a decrease in alpha indicated that the tension or relaxation they felt decreased [92,93].

The results of this study are expected to provide recommendations for the development of environmental policies regulating noise levels in various contexts, including workplaces, schools, and urban areas. Stricter standards related to noise levels can help protect the health and cognitive performance of the community. Scheduling cognitive tasks to avoid high levels of environmental noise can help improve focus and cognitive performance. Jobs that require high concentration should preferably be performed when environmental noise is minimal.

This study is an early attempt to study the effect of noise on cognitive performance through physiological measurements. This paper provides a basis for further study because monitoring the cognitive performance of individuals is promising and can be realized. The limitations of the study include that data collection was conducted in the laboratory and that variable noise sources were observed from only one sound source of industrial machinery. For future studies, it is hoped that studies can be carried out in realistic workplaces, such as on production floors or in offices, where the observed variable noise sources not only come from industrial machines but can also involve the sound of music and conversation. Another limitation is that because there is a shorter exposure period in this study to noise than would likely occur at work, the impact is smaller than in real life. EEG is a useful and promising method for assessing a cognitive state and creating links with behavior, even though the linkage between behavioral and cognitive performance has not lived up to expectations. In this study, the sole metric utilized to assess cognitive aptitude is the power spectrum density of the EEG. Future studies should include a range of cognitive scale evaluations along with physiological markers to evaluate cognitive ability.

5. Conclusions

The results demonstrated that exposure to noise types and levels has a significant relationship with human cognitive abilities. According to the results of this experiment on the observed beta and alpha signals, with a higher log power spectrum density value and the condition of the lowest frequency value, the cognitive aspects of participants had the best attentional conditions and relaxed state (did not experience stress) at a noise level of 65 dB for both continuous and intermittent noise types. Based on the results of this experiment on the observed beta signal, continuous noise at a noise level of 80 dB has the highest influence on attention interference, and intermittent noise at a noise level of 85 dB has the highest influence on participants. Based on the results of this experiment on the observed alpha signal, continuous noise at a noise level of 80 dB had the highest influence on stress interference, and intermittent noise at a noise level of 75 dB had the highest influence on participants. The results of the study related to mental workload aspects provide information on the type of continuous and intermittent noise at 70 dB during which participants began to indicate mental workload. The practical implication of this study can be the development of environmental policies that are more friendly to human health and mitigation strategies to reduce the negative impact of noise on cognitive abilities.

Author Contributions: Conceptualization, R.D.A., B.S., P.W.L. and N.S.; methodology, R.D.A. and B.S.; formal analysis, R.D.A. and P.W.L.; investigation, B.S. and N.S.; resources, R.D.A. and P.W.L.; data curation, R.D.A. and P.W.L.; writing—original draft preparation, R.D.A.; writing—review and editing, R.D.A., B.S. and P.W.L.; visualization, R.D.A. and N.S.; supervision, R.D.A., B.S., P.W.L. and N.S.; project administration, P.W.L., B.S. and N.S.; funding acquisition, R.D.A. and P.W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by a doctoral dissertation research grant from Universitas Sebelas Maret (No. 228/UN27.22/PT.01.03/2023).

Institutional Review Board Statement: This study was approved for ethical clearance from Dr. Moewardi General Hospital on 22 September 2022 (No. 1203/IX/HERC/2022).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: This authors would like to express great gratitude to the Rector of Universitas Sebelas Maret for the generous research grant provide in support this study.

Conflicts of Interest: The authors declare no conflicts of interest.

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