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Does Task Complexity Matter? Event-Related Potential (ERP) Data Analysis of the Stroop Effect in Relation to Thermal Conditions

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Abstract

The correlation between indoor thermal environments and cognitive performance is a topic of interest across diverse academic spheres. This study explores how the comfort of the indoor environment, the complexity of tasks, and the ability to control inhibition are connected. We use a method called event-related potential (ERP) analysis to study this connection. ERPs are brain responses that are linked to specific events or stimuli and are related to different cognitive functions.

Previous studies have identified three ERP components associated with inhibition control as assessed by the Stroop task (N200, N400, N600). Our prior research has emphasized the significant impact of indoor temperatures on inhibition control within the Stroop task. This study builds on that research by looking at how the complexity of a task can change the relationship between indoor temperatures and inhibition control. We use ERP analysis to see how different indoor temperatures affect brain responses (specifically N200, N400, and N600 components) in tasks of varying complexity.

Our research is unique in that it uses ERP analysis to study how task complexity and indoor temperatures affect cognitive function. We conducted our study in a controlled environment with ten mechanical engineering students. The students completed tasks at different temperatures while we recorded their brain activity using Electroencephalogram (EEG).

Our findings suggest that thermal comfort can significantly impact inhibition control, especially in more complex tasks. This research has implications for engineering education and environmental design. Understanding how indoor temperatures affect cognitive function can help us create better learning and working environments for engineers.

. **Keywords**: Cognitive performance, event-related potentials (ERPs), indoor environmental quality, inhibition control, Stroop task, task complexity, temperature effects

Introduction

The intersection between thermal comfort and cognitive performance has become a focal point across diverse fields including environmental engineering, occupational health and safety, sustainability, and green building, etc. From an energy perspective, buildings, including educational institutions, contribute significantly to global primary energy consumption, accounting for approximately 45% of the total energy usage. This percentage continues to grow annually, solidifying buildings as the most energy-consuming sector [1,2]. Notably, a substantial portion of this energy consumption is attributed to heating, ventilation, and air conditioning (HVAC) systems [3]. The primary objective behind this substantial energy consumption is to establish comfortable indoor environments. ASHRAE, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, emphasizes the intricate balance between comfort and energy consumption, setting standards to enhance indoor environmental quality (IEQ). This delicate relationship between comfort provision and energy usage underscores the importance of exploring how thermal comfort influences cognitive performance within indoor environments [4].

Literature Review

Previous studies have extensively demonstrated the impact of temperature fluctuations on cognitive performance. For instance, Perez, Josean, et al., (2005) in a study examining the impact of temperature exposure on student performance, found that brief exposures of just 10 minutes to either cold (61°F) or warm (81°F) temperatures significantly affected academic achievement. Comparatively, students in rooms maintained at 72°F (22°C) demonstrated a 14% improvement in scores over those in colder environments and an 18% enhancement over those in warmer settings [5].

Other studies have similarly emphasized the detrimental effects of thermal stress on cognitive functions, revealing impairments in attention, reaction time, and executive processing under conditions of heat stress [6][7]. Lan et al. (2011) conducted neurobehavioral and typing assessments in controlled indoor environments set at two distinct temperatures (22°C and 30°C), highlighting that thermal discomfort induced by elevated air temperatures significantly compromised overall performance [8]. Moreover, research by Pepler and Warner (year) showcased an inverse U-shaped relationship between indoor thermal conditions and learning performance. Their findings suggested that participants exhibited optimal task-solving abilities at an indoor temperature of 26.7°C, completing assigned tasks in the shortest time possible [9]. These studies collectively underscore the intricate relationship between indoor thermal environments and cognitive performance, revealing noteworthy impacts on academic achievement and cognitive functions across varying temperature conditions.

Other researchers have delved into factors influencing the association between indoor environmental quality and cognitive performance. Prior investigations have indicated that this correlation is influenced by both task complexity and the severity of environmental conditions. Gaoua, Nadia, et al., [10] highlighted that while simple tasks remain unaffected, complex tasks are notably susceptible to extreme heat stress. Conversely, Watkins, Samuel, et al., [11] revealed that moderate and extreme cold stress negatively impact the performance of both simple and complex tasks.

The classification of task complexity remains a subject of debate, as it can be influenced by various factors, such as an individual's familiarity with the task. Nevertheless, tasks demanding greater cognitive effort, attention, or those involving dual tasks or higher cognitive skills, are typically considered complex. Lee Taylor [12], in a comprehensive review paper, presented a table (Table-1) categorizing tasks into simple and complex based on earlier studies up until the publication year - 2016.

Table 1. Categorization of simple and complex cognitive tasks [12]

Simple cognitive tasks	Complex cognitive tasks
Mental transformation	Arithmetic efficiency
Monitoring	Attention
Memory recall	Complex motor coordination
Numerical vigilance	Dual tasks
Choice reaction time	Executive function
Short term memory	Mental addition
Simple arithmetic	Recall capacity
Simple visual orientation	Sustained attention
	Tracking
	Vigilance
	Visual motor tracking
	Working memory tasks

Various studies have extensively examined different aspects of cognitive abilities using various techniques to understand how brain activity is affected by thermal conditions. For example, Hocking et al. [13] studied the impact of thermal stress on cognitive performance in tropical environments among military personnel. They used psychometric test batteries that included tests like the Rey auditory verbal learning test, inspection time, digit span test, spatial working memory tasks, and the AX-continuous performance task. These tests assessed attention, memory, verbal learning, information processing, and concentration. The study found that under challenging thermal conditions, there was an increase in amplitude and a decrease in latency in steady-state visual evoked potential recordings, indicating increased effort to maintain performance. Using the Steady State Probe Topography (SSPT) analysis technique, they also observed deficits in working memory, information retention, and information processing.

Furthermore, Choi et al., [14] evaluated participants' attention abilities as indicators of productivity across various room temperatures using electroencephalogram (EEG). Their results revealed optimal performance within the 0 to +1 Predicted Mean Vote (PMV) range. Additionally, techniques such as functional magnetic resonance imaging (fMRI) [15-17], Functional Near-Infrared Spectroscopy (fNIRS) [18], Positron Emission Tomography (PET) scans [19-20], and Magnetic Electroencephalogram (MEG) [21-22] have also been instrumental in cognitive neuroscience research exploring the interface between thermal conditions and brain activity.

The electroencephalogram (EEG) is a noninvasive and cost-effective neuroimaging technique that detects brain cell activity through electrodes placed on the scalp. EEG signal is divided into distinct frequency bands, including delta (0–4Hz), theta (4–8Hz), alpha (8–13Hz), beta (13–30Hz), and gamma (30–50Hz), each associated with specific physiological functions. For instance, the delta band is prevalent during deep sleep, whereas the beta band is linked to arousal states. Event-related potentials (ERPs) represent time-locked EEG activities triggered by specific sensory, cognitive, or motor events or stimuli. Each ERP component corresponds to particular cognitive functions and exhibits characteristic timing, amplitude, polarity (positive or negative), and scalp distribution

[23]. For instance, the N200 component manifests as a negative potential (N) and typically peaks between 100 and 300 milliseconds after stimulus onset.

In a prior investigation [24], we conducted an ERP-based study to assess the impact of indoor temperature on the inhibition control ability among engineering students [24]. Cognitive inhibition control denotes the capacity to consciously suppress or override automatic thoughts, impulses, or behaviors that might be irrelevant or unsuitable within a specific context [25-26]. This ability forms an integral part of the executive functions, encompassing higher-order cognitive processes vital for self-regulating, planning, problem-solving, and overall academic achievement. Our methodology involved employing the Stroop/Reverse Stroop paradigm to evaluate inhibition control and examine the potential influence of indoor thermal conditions on this cognitive ability. The Stroop effect serves as a measure of cognitive inhibition, characterized by prolonged reaction times (RT) when identifying the ink color of an incongruent color–word pair (for instance, the word "blue" printed in green ink) in comparison to a matched color-word combination. Conversely, the Reverse Stroop test involves participants naming the word color printed in either congruent or incongruent ink colors [25].

ERP analyses across various studies have consistently identified components associated with the Stroop effect. Primarily, the N200, a negative deflection occurring approximately 200 milliseconds post-stimulus within the frontal and anterior cingulate cortex regions of the brain, has been linked to inhibition control [26-27]. A section of the literature highlights the N400, a prominent negative component peaking around 400 milliseconds, as pertinent to interference control in Stroop tasks [28-29]. The N400 reflects the higher cognitive demand involved in managing the interference between conflicting sources of information, such as ink color and word name in incongruent conditions. Additionally, alongside the N200 and N400, studies have reported a late negativity in frontal regions or a late positivity in centro-parietal regions, typically occurring around 600 milliseconds [29-30]. These late components are indicative of processes like executive engagement, conflict resolution, response selection, or semantic reactivation post-conflict resolution.

In our previous study [24], we found that the N200 component was consistently prominent, and we also observed occurrences of the N400 and late positivity related to the Stroop effect. We detected prefrontal neural network activity linked to the N200, suggesting a potential relationship between temperature and the N200 component's amplitude. While we did not find significant differences in prefrontal electrodes' amplitude due to temperature variation, we did note a significant influence of indoor temperature on reaction time, particularly in the incongruent condition of the Stroop test. However, thermal conditions did not significantly affect the congruent condition or the data from the reverse Stroop test [24] (see Figure-1). Our conclusion emphasizes the greater significance of thermal comfort in complex tasks compared to simpler ones, highlighting the varying impact of indoor thermal conditions based on task complexity. Our previous research underscores the differential effect of thermal comfort on complex tasks compared to simpler ones, illustrating the task-dependent impact of indoor thermal conditions on cognitive inhibition. In this current study, we aim to investigate the influence of task complexity on the relationship between thermal conditions and inhibition control, assessed through ERP analysis.

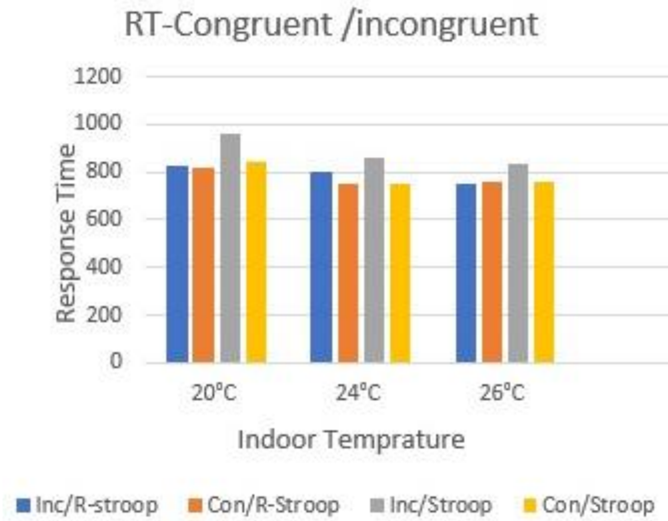

Figure-1 Response time in congruent and incongruent conditions [24]

Understanding how environmental factors such as room temperature can impact cognitive process is essential for educators seeking to create optimal learning environments. By elucidating the differential impact of thermal comfort on inhibition control across varying task complexities, this research informs educational practices, emphasizing the pivotal role of optimal thermal conditions in fostering cognitive well-being. Educators can use this information to design learning environments that promote cognitive function and enhance student learning outcomes.

Research Methodology

This study developed a comprehensive framework aimed at exploring the influence of task complexity on students' learning ability in response to varied thermal environments. Three temperature levels were chosen following ANSI/ASHRAE standards employing the Predicted Mean Vote (PMV) model representing thermal sensations experienced by occupants: 20°C/68°F (PMV=-2, cool), 24.4°C/75.92°F (PMV=0, neutral thermal sensation), and 26°C/78.8°F (PMV=+1, slightly warm).

The experimental procedures were conducted within a psychrometric chamber situated at University of Oklahoma in the United States. This chamber, equipped with air conditioning, ventilation systems, CO_2 sensor, humidity and temperature sensors, provided controlled environmental conditions. Throughout the experiments, the selected temperatures and other factors remained consistent, maintaining stable conditions.

Ten mechanical engineering students, aged between 22-32 years, participated in the study. All participants had normal or corrected-to-normal vision and no history of brain disease. The Stroop task, administered through the Neurobs Presentation software, facilitated EEG data acquisition synchronized with stimulus presentation. The EEG system employed was a 24-channel system from mBrainTrain, utilizing M1/2 as the reference electrode. Electrode placement followed the

10/20 international system (refer Figure-2). Participants performed the Stroop task across three separate days, each at different temperature setting, while wearing the EEG cap within the psychometric chamber. So, we have 288 data from each participant. EEGlab, a Matlab plugin, facilitated the preprocessing of EEG data, applying a finite impulse response (FIR) filter ranging from 0.5 Hz to 100 Hz and a notch filter from 58 Hz to 62 Hz to eliminate electrical noise. An independent component analysis was performed to remove non-brain-related artifacts.

During the event-related potential (ERP) analysis, the data were segregated based on test type (Stroop/Reverse Stroop) and congruency conditions. Specifically, condition 1 encompassed data from the Stroop test and incongruent pairs, while condition 2 involved reverse Stroop and congruent condition data. A 30 Hz low-pass filter was applied to each ERP segment, eliminating amplitudes beyond approximately +/−100 μV to increase data quality.

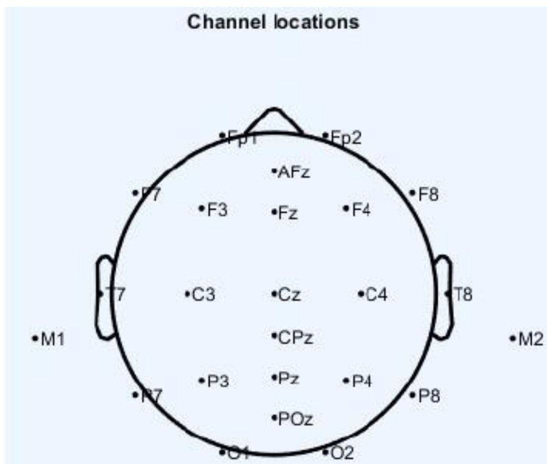

Figure-2 10/20 International placement system

Results

ERP waveform plots were generated for each condition at varying temperatures. In our prior investigation, we observed notable N200, in certain instances and N400, and late positivity in some cases [24]. In this current study, the ERP waveform analysis displayed similar outcomes in both condition 1 (stroop/incongruent) and 2 (reverse stroop/congruent) across all three thermal conditions. However, while evaluating the ERP waveforms, we concentrated on frontal electrodes and identified the negativity peaking at 600ms as representative of interference resolution.

The electrodes exhibiting the highest amplitudes for N200 were F4 and C4. For N400, maximum amplitudes were recorded on electrodes C4 and F8. Additionally, considerable N400 amplitude was observed on some T8 and O2 electrodes across different temperatures and conditions. The highest N600 amplitude was observed on electrodes Fp2 and C4, with sporadic instances recorded on O1 and T8 electrodes. To illustrate the waveform differences between condition 1 and condition 2, a difference waveform (Bin3= Bin2 (condition 2) - Bin1 (condition 1)) was generated. While Bin3 indicated amplitude changes around the specified time limits, visual inspection did not reveal a distinct pattern change attributable to variations in temperature (Figure-3).

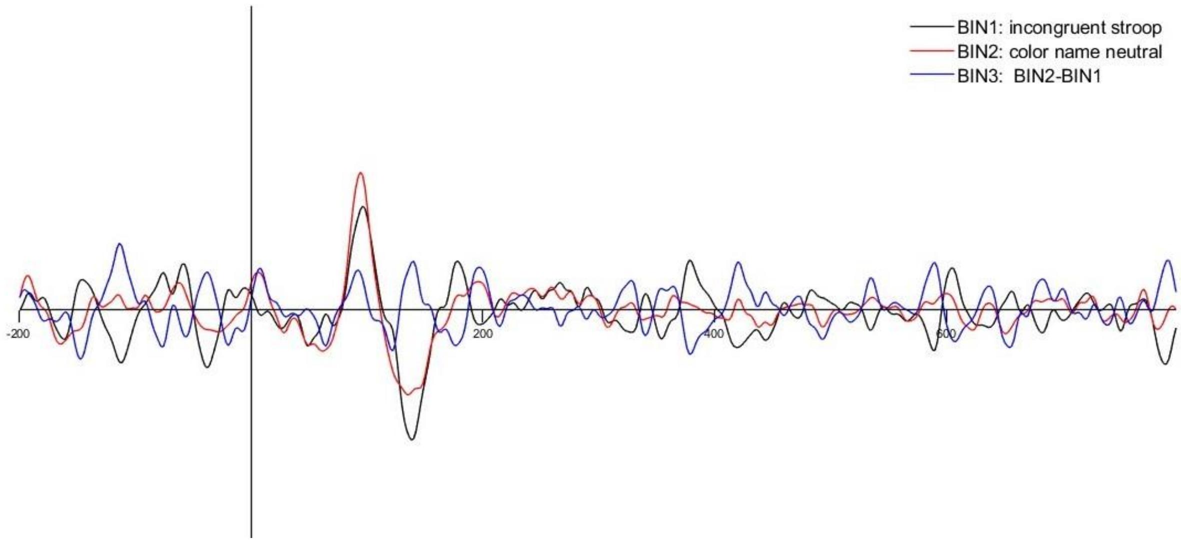

Figure-3 Evident N200-ERP waveform plot (Bin 1, Bin2, Bin3) participant 1-at 20°C F4 electrode (-100 700ms)

For comparison, the average mean amplitudes of N200, N400, and N600 were computed independently for the right and left frontal and central zone channels (Fp1, Fp2, AFz, F3, F4, F7, F8, Fz, C3, C4, CPz) within both condition 1 and condition 2, across all three distinct temperature settings as depicted in Figure-4.

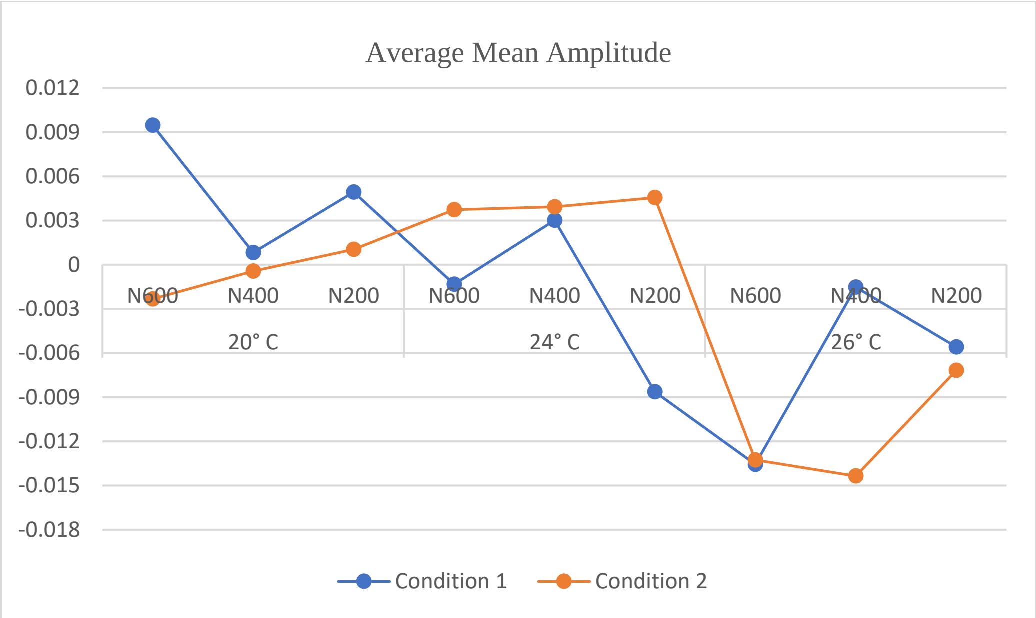

Figure- 4 Comparing condition 1 and 2, average mean amplitude in three indoor temperatures

The comparison revealed an inverse relationship at 24°C in contrast to 20°C and 26°C. Specifically, at 24°C, there is higher negativity observed in N200, N400, and N600 in condition 1. This pattern aligns with the expected relations among N200, N400, and N600 concerning cognitive inhibition, interference control, and interference resolution. Elevated negativity is linked to heightened brain activity in the incongruent condition involving more complex tasks. Conversely, at 20°C and 26°C, the observed pattern is entirely the opposite. This suggests an indicator of how thermal discomfort influences cognitive brain function, as demonstrated by ERP components. Notably, all N200, N400, and N600 components exhibit lower amplitudes in incongruent and complex conditions, signifying that thermal discomfort might heighten cognitive load by distracting individuals or inducing discomfort, thereby altering cognitive processing.

Statistically, to assess the impact of temperature on the amplitude of these ERP components, mean amplitudes for N200, N400, and N600 in fronto-central electrodes were separately analyzed for each temperature and across two conditions 1 and 2. Mixed design ANOVA tests were conducted on this data for each component individually. The results from the mixed design ANOVA tests indicate a highly significant effect of different temperature levels on N200 (p<0.001), N400 (p<0.001), and N600 (p<0.001) ERP wave amplitudes. This is in concordance with the observations depicted in Figure-1, affirming that temperature significantly influences ERP wave amplitude.

The subsequent segment of the mixed design ANOVA report unveils intriguing findings when examining the impact of the two different tasks. The non-significant p-values at a 95% confidence level for N200 (p = 0.2815), N400 (p = 0.273), and N600 (p = 0.6922) suggest no statistically significant disparity between the two tasks concerning their overall effect on ERP wave amplitude. However, it's notable that N600 displays the least variance concerning task difference. This suggests that N200 and N400 serve as better indicators for discerning between tasks.

In the statistical analysis presented here, the examination delves into the interaction between task and temperature. Significant p-values across all three components (N200 (p=0.036), N400 (p=0.003), N600 (p=0)) indicate that the influence of temperature on ERP wave amplitude differs notably between the two tasks. This indicates that while temperature exerts a significant overall impact on ERP amplitude, the extent of this impact varies contingent upon the specific task being performed (Stroop and incongruent tasks vs. Reverse Stroop and congruent tasks). This finding aligns with existing research and our prior study, emphasizing the influence of task complexity on the thermal effect [24].

To assess which task condition exerts a greater impact on thermal influence, a post-hoc analysis was conducted. The Kruskal-Wallis's test, coupled with multiple comparisons using Dunn's method and Bonferroni correction, was employed for this analysis. Within condition 1, the influence of temperature on N200 (p<0.001), N400 (p<0.001), and N600 (p<0.001) indicated a statistically significant effect on ERP. These results strongly suggest rejecting the null hypothesis, signifying a substantive difference in ERP due to temperature variations in condition 1. Conversely, within condition 2, the impact of temperature on ERP component amplitudes (N200 (p=0.8638), N400 (p<0.001), N600 (p=0.8324)) presented a more intricate scenario. In condition 2, temperature exhibited a significant effect solely on N400, while N200 and N600 amplitudes remained unaffected by temperature. In summary, ERP components displayed a greater susceptibility to temperature changes in condition 1 compared to condition 2. This outcome underscores the significance of thermal comfort in tasks associated with cognitive inhibition, suggesting that thermal comfort plays a more pivotal role in complex tasks related to cognitive inhibition.

Additionally, topographical maps were generated for various components (100ms-300ms for N200, 300ms-500ms for N400, 500ms-700ms for N600) plus a total timeline(100ms-700ms) and segregated according to conditions. These maps depicted that the Centro-frontal regions consistently served as the primary active brain cortex during the tests for both conditions across all temperatures and ERP components. Nevertheless, deviations from this pattern were observed, particularly in condition 2, where other regions such as occipital and temporal regions showed activity in certain cases (Figure-5).

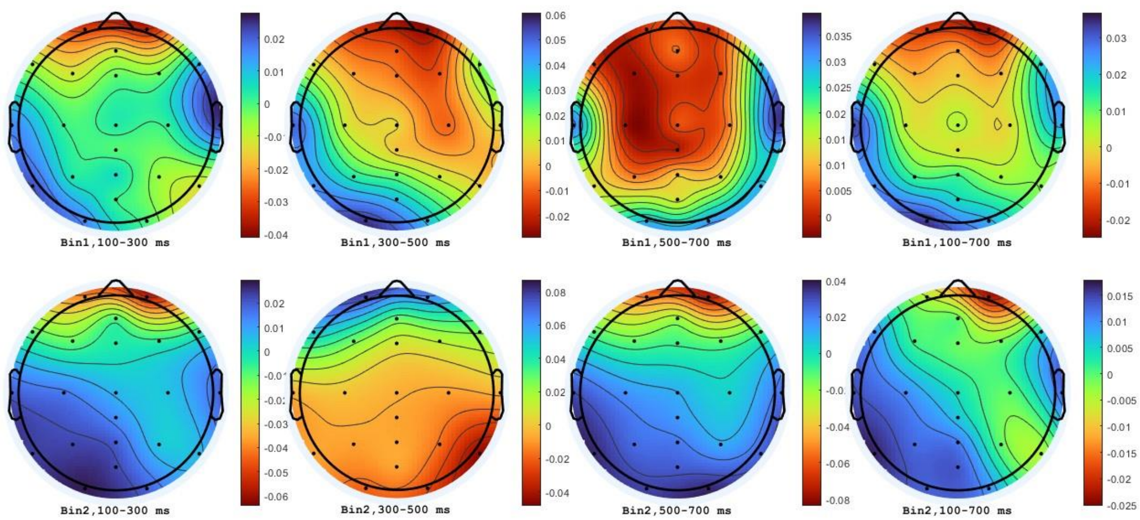

Figure 5- Active Fronto-Central neural network in 100-300 *ms*, 300-500 *ms*, 500-700 *ms*, and 100–700 *ms* time interval - Bin 1 (condition 1) and Bin2 (condition 2)

Discussion and Conclusion

The findings of our study significantly advance our understanding of how thermal conditions impact cognitive function, particularly in educational settings. Previous research, as highlighted by Perez et al. (2005) [5], Lan et al. [8], Pepler and Warner [9], Gaoua et al. [10], and Watkins et al. [11], has consistently demonstrated the influence of temperature on cognitive performance. However, our study goes further by specifically examining how the complexity of tasks interacts with indoor thermal conditions to influence inhibition control, using comprehensive ERP analysis.

Comparing the brain activity measured by the mean amplitude of frontal channels in different temperatures between condition 1 and condition 2 reveals interesting patterns. At 24°C, we observed higher negativity in N200, N400, and N600 in more complex tasks (condition 1), indicating increased brain activity. This pattern changed at 20°C and 26°C, suggesting that thermal discomfort may increase cognitive load, potentially altering cognitive processing. Statistical analysis confirmed that temperature significantly affects the mean amplitude of these ERP components, with variations between tasks highlighting the importance of considering task complexity when studying the thermal impact on cognitive performance. Post-hoc studies further revealed nuanced variations in how ERP components respond to temperature changes, particularly in complex cognitive tasks, indicating a higher sensitivity to thermal fluctuations. These findings are in agreement with existing research indicating the influence of task complexity on thermal effect on cognitive performance [10],[12],[24].

Our results indicate a greater sensitivity of N200 and N400 to task variations and its influence on thermal susceptibility compared to N600. Although research on how thermal comfort influences ERP components is limited compared to other areas, these findings align with some certain prior investigation [24-25]. Some studies also have reported on thermal changes affecting P300 characteristics [35, 36]. However, further research is needed to explore the effects of indoor environmental quality on human cognitive function using ERP methodologies.

Topographic maps showed an active fronto-central network during tasks, with activity in other regions such as occipital and temporal lobes in certain conditions, highlighting the complexity of the relationship between factors of interest.

Our study is pioneering in its use of ERP analysis to explore how thermal conditions, cognitive processes, and task complexity are interconnected. This has significant implications for educational environments and cognitive neuroscience, emphasizing the crucial role of thermal comfort, especially in complex tasks. Understanding this relationship lays the foundation for maintaining optimal thermal environments in diverse educational settings to support cognitive performance.

Importantly, our research extends beyond cognitive neuroscience to offer practical implications for the educational field. The established link between thermal discomfort and hindered cognitive processing, particularly in complex tasks, provides educators and policymakers with a compelling rationale for prioritizing thermal comfort in learning environments. Our findings suggest that maintaining temperatures around 24°C can demonstrably enhance students' ability to effectively encode information during intricate learning activities. Further investigations could delve into the optimal thermal ranges for classrooms with varying learning task complexities. This would establish data-driven guidelines for thermal management within educational institutions, ultimately fostering improved learning outcomes and bolstering student academic achievement.

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