CHRONOBIOLOGY IN DIVERGENT THINKING: HOW DESIGNERS ARE AFFECTED BY TIME OF DAY

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ABSTRACT

Chronobiology is the science that studies the role of time in biology. The study of time in human bodies revealed the presence of internal rhythms related to the time of day. Considering divergent thinking as one of the essential cognitive activities of conceptual design, this paper presents the results of investigating the effect of time of day on designers' brain activity while performing divergent thinking tasks. An experiment was run with a revised Alternative Uses Task, measuring brain activity with an electroencephalogram (EEG) device. Students with different educational backgrounds were recruited for this experiment, including engineering and industrial design students, to determine if the time of day affected them differently. The brain waves and related power results show significant differences with respect to the time of day and educational background. The differences are particularly evident considering the interaction of these factors. Further studies are required to understand the relationship between the differences detected and the designers' behavioural performance and to identify which time of day is most effective for idea-generation activities for designers.

Keywords: Conceptual design, Creativity, Design cognition, Chronobiology, Electroencephalogram

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1 INTRODUCTION

Research into design and creativity has evolved in the last two decades (Cascini et al., 2022). Neurophysiological measurement of designers' cognitive processes represents one of the innovative approaches (Balters et al., 2023; Gero & Milovanovic, 2020). Whilst multiple neurocognitive studies have produced significant results, they are still far from results that can be directly used in real design situations (Borgianni & Maccioni, 2020). The neurocognitive approach allows more objectivity than protocol studies, and allows considering tacit, unconscious, and emotional processes while investigating retrospective and introspective cognitive elements in design activities (Balters & Steiner, 2017). Since emotions and regulatory control are crucial for these activities, the present research's contribution is to understand if and how biological rhythms affect designers' performance and brain activities.

The long-term goal is to determine if it is possible to define a better time of day for scheduling design activities. The study of this time element is referred to as "chronobiology", a branch of biomedical sciences investigating how biological rhythms affect humans (Rietveld, 1990). This stream of research has recently increased its relevance in medical and psychological studies. There are still only a few applications in non-clinical contexts, but the active role of these rhythms on cognitive performance has been largely established (Correa et al., 2020; Valdez et al., 2008).

The current work focuses on designers' brain activities during divergent thinking, which represents one of the crucial cognitive processes involved in ideation in the conceptual design process (Lee & Ostwald, 2022; Shah et al., 2012). The research questions raised by chronobiology, in this paper, are:

- How does the time of day affect designers' brain activities during divergent thinking?
- Does the time of day affect the brain activities of engineering design and industrial engineering design students differently?

An experiment was run with a revised version of the Alternative Uses Task (AUT) (Guilford, 1967; Mazza et al., 2023) as a proxy for divergent thinking. Brain activity was measured using an EEG (electroencephalogram) cap during this experiment. The analyses mainly focus on circadian rhythms by investigating the time of day and its implications for designers' divergent thinking activities. Chronotypes are discussed. The study included the role of the educational background in these activities since recent results from neurophysiological studies have shown this is a factor (e.g., Vieira, et al., 2020). During the experiment, multiple behavioural data were collected (response time, strategy adopted to find solutions, and number of words of responses) and eye tracking data. The analysis and the discussion of this data are out of the scope of the present document.

The remainder of the paper starts with the background that summarizes the main contributions to the topic in the literature. The Methods and Data section presents the experiment protocol and data processing, and the Results and Discussion section provides and contextualizes the main findings. The Conclusion section presents some methodological limitations and future research.

2 BACKGROUND

Conceptual design is one of the main foci of design research, and its initial phase is characterized by designers' idea generation activities (Christiaans, 1992). The centrality of creative processes and divergent thinking in idea generation and conceptual design is widely confirmed in the literature (Bilda et al., 2006; Lee and Ostwald, 2022; Shah et al., 2012). Divergent thinking is one of the fundamental cognitive activities in creative idea generation and it represents the exploration of a novel solution to a weakly structured or unstructured problem (Hay et al., 2017). Its role is crucial in design as a foundation of the creative outcome of design activities and is considered a long-term driver of success in product development (Howard et al., 2008). The design literature has studied the impact of time by looking at the task's duration (e.g., Perttula & Liikanen, 2006; Zeng, 2012), but - differently from other domains - the time of day and chronobiology have not been investigated.

2.1 Chronobiology

Chronobiology is the science that studies the role of time in biology, both in animals and plants and has been extended to human sciences. The main elements introduced by chronobiology are the biological rhythms and chronotypes.

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Biological rhythms constitute the internal clock of humans, and researchers focus on their implications in several biological measurements (such as body temperature; Baker et al., 2001). These rhythms are clustered in three main categories (Horne & Östberg, 1976), as follows:

- Infradian Rhythms: rhythms that last more than 24 hours, repeated only every few days/weeks/months;
- Ultradian Rhythms: rhythms shorter than 24 hours, repeated in multiple cycles in one day. They regulate physical, emotional, and spiritual functions. They often last several hours and include the ingestion of food, circulation of blood, excretion of hormones, different stages of sleep and the performance curve;
- Circadian Rhythms: These rhythms take approximately 24 hours, i.e., the human sleep/wake cycle or the leaf movements of plants. Many effects of circadian rhythms directly and immediately affect humans; therefore, they are the most extensively researched.

On the other hand, the chronotype is the biological propensity of the human body to sleep at a specific time. In addition to regulating sleep and wake times, chronotype influences appetite, exercise, and core body temperature. There are mainly two chronotypes (Giampietro & Cavallera, 2007; Venkat et al., 2020):

- Morning Type: people who prefer waking up early in the morning tend to perform better in school and at work because their bodies are more active during those hours;
- Evening Type: people who stay awake late at night are more inclined to creative thinking and related activities.

To identify the human chronotype of an individual, the Morning-Eveningness Questionnaire (MEQ; Horne & Östberg, 1976) and the Munich Chronotype Questionnaire (MCTQ; Roenneberg et al., 2003) are the most adopted questionnaires, both based on self-assessment (Di Milia et al., 2013).

2.1.1 Psychology and neurophysiology

The main biological measurements related to the internal biological clock in humans are summarized in Figure 1 (DeYoung et al., 2007), demonstrating that humans are strongly affected by them. Circadian rhythm has the strongest influence on several characteristics of brain functions (Lehnertz et al., 2021). Some initial findings suggest that chronobiology is also strongly related to age (Cornelissen & Otsuka, 2017), representing a potential hidden factor in several studies. Circadian rhythms have been identified in brain activities, through studies using fMRI (functional magnetic resonance imaging), fNIRS (functional near-infrared spectroscopy), and EEG (electroencephalography) signals, though, there is a lack of physiological measurements in this field (Correa et al., 2020). In studies of brain waves, the literature shows a higher level of activity during the afternoon hours for all frequencies (Petersen & Harmon-Jones, 2009).

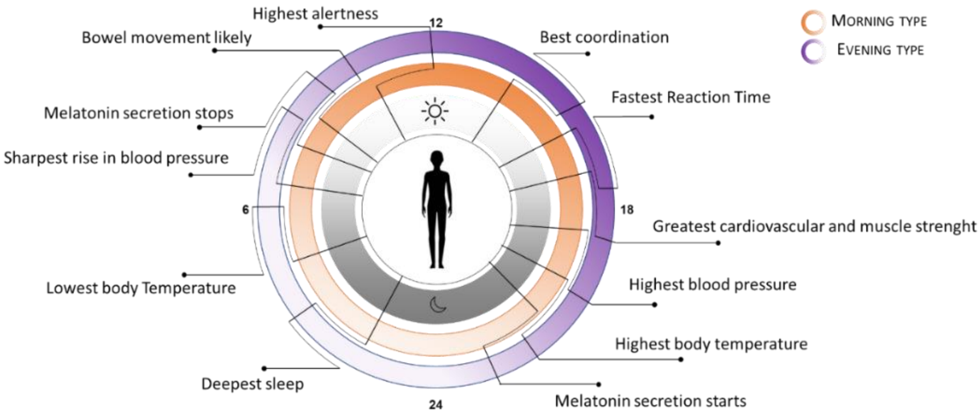

Figure 1 – The role of circadian rhythms in daily activities

2.1.2 Cognitive performance, decision making, and problem solving

The internal biological clock in humans is related to the ability of individuals to perform better or worse on a given task during the morning or afternoon, depending on their type. Experimental studies have been conducted on human cognitive performances, with several limited insights (Carrier & Monk, 2000; Xu et al., 2021). For instance, tasks of a more schematic and repetitive type are generally better performed in the morning, unlike tasks of a more creative type (Mackenberg et al., 1974). The effects of

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circadian rhythms are mainly investigated in attention, working memory and higher-order functions (such as cognitive association, inhibition, and flexibility). The behavioural and neurocognitive results in the literature are still inconsistent (May et al., 2005; Xu et al., 2021). Furthermore, the chronobiology effects interact with age in cognitive performance (Bonnefond et al., 2003).

2.1.3 Conceptual design, idea generation, and divergent thinking

Conceptual design is characterized by multiple activities and cognitive processes (Hay et al., 2017). Among them, idea generation and divergent thinking are crucial and often investigated in design research. Idea generation, or ideation, generates multiple and varied ideas by engaging in divergent thinking (Lee & Ostwald, 2022). Divergent thinking involves problems with non-univocal solutions, such as design problems (Guilford, 1967). Psychologists have investigated these processes extensively and from a neurocognitive perspective. The AUT is the most commonly adopted test by psychologists and cognitive scientists to measure divergent thinking, and the Torrance Test for Creative Thinking (TTCT) (Torrance, 1968) to measure creativity. Design differs from creativity tasks due to the multiple cognitive functions that include divergent and convergent thinking (Li et al., 2021). In conceptual design, ideation and divergent thinking have been established as activities (Shah et al., 2012), and design research on these tasks is focused on a micro level (Lee & Ostwald, 2022).

In chronobiology, multiple investigations have been conducted into the study of creative and divergent thinking. Morning chronotypes generally showed lower performance in divergent thinking (Silva et al., 2009). An experiment involving TTCT showed a higher alpha and beta power level in the parietal lobe during the evening for evening chronotypes, indicating the existence of a neurophysiological foundation for the personal tendency and a more intense propensity towards creative work for evening chronotypes (Giampietro & Cavallera, 2007). However, the time of day represents an unexplored factor in design neurocognition. The effect of time of day on designers' creativity performance during divergent thinking tasks is investigated only in one study of design education using TTCT and considering the students' background (Wang et al., 2010). This study focused on design education and shows differences only for design students during the time of day regarding the originality of the outcomes. Several studies showed the relevance of background in designers' EEG responses (e.g., Colombo et al., 2020; Vieira et al., 2020).

2.2 Brain anatomy and brain waves

Over the last two decades, brain studies have become an increasingly active research area, primarily due to the reduced cost of the equipment and the ready availability of processing software (Gero & Milovanovic, 2020). Neurocognition "is a branch of neuroscience and biological psychology that focuses on the neural mechanisms of cognition" (APA, 2016). Design neurocognition is the neurocognitive study of designers. Most design neurocognition studies adopt one of three non-invasive brain activity measurement tools EEG, fNIRS, or fMRI (Balters et al., 2023; Borgianni & Maccioni, 2020; Gero & Milovanovic, 2020). The discussion of fNIRS and fMRI is out of the scope of this work, since it uses EEG.

EEG is used to study the electrical signal from the cerebral cortex. The output of EEG is a set of voltage values as a function of time for each electrode, providing evidence of the brain waves or neural oscillations. An EEG brain wave is defined mainly by five characteristics: topography, frequency, amplitude, phase, and latency (Freeman & Quiroga, 2013). Topography and frequency are the main features adopted in cognitive neuroscience and used here. Topography represents the anatomical loci where the waves are recorded, usually related to an electrode's positioning. The main brain regions, described in Table 1, are defined as lobes (APA, 2016), and depicted in Figure 2(a), along with the positioning of the electrodes in Figure 2(b).

Table 1. Brain lobes topography and roles (Freeman & Quiroga, 2013)

Region	Topography	Role
Pre-Frontal, **Fp**	Most Anterior	Attention, planning, working memory, expression of emotions and appropriate social behaviours
Frontal, **F**	Anterior	Decision-making, planning, insight, judgment, the ability to concentrate and impulse control
Central, **C**	Central, continental	Also called insula; emotions, taste, self-awareness, motor control of functions such as swallowing and speech articulation; addictive cravings; procedural memory

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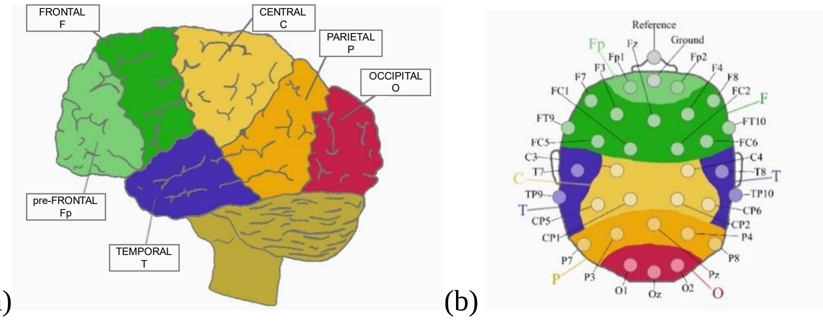
Temporal, **T**	Lower central	Auditory projection, association, high visual processing; memory
Parietal,**P**	Upper central	Somatosensory activities (such as visual, auditory activities, size and texture perception)
Occipital, **O**	Most posterior	Process visual stimuli, and it characterizes all the visual functions



(a) (b)

Figure 2. (a) Main brain regions, (b) electrode positioning and region clusters

The EEG measurements are also classifiable by the constituent frequencies (cycles per second, measured in Hertz (Hz)) of the measured signal. The EEG frequency bands have each been associated with various behaviours. Their constituent frequencies and commonly related behaviours, normal subjects, are reported in Table 2 (Freeman & Quiroga, 2013; NeuroHealth, undated).

Table 2. Brain waves & related cognitive activities (Freeman & Quiroga, 2013)

Band	**Frequency**	**Cognitive Activities**
Gamma	> 30 Hz	Gamma frequencies have been related to self-control, "Eureka!", intelligence, and peak awareness.
Beta	12.5-35 Hz	Beta frequencies have been related mainly to normal cognitive functions when awake. Concentration, arousal, alertness, motivation, problem-solving and general thinking are the most related activities.
Alpha	7.5-12.5 Hz	Alpha frequencies have been correlated with creativity, focus, engagement, and learning.
Theta	4-7.5 Hz	Theta frequencies have been related to deep sleep, inner peace, healing, fantasy, imagery, and deep meditation.
Delta	0.5-4 Hz	Delta frequencies have been related to deep sleep stages, pain relief and abnormal processes; high delta levels are correlated with a decreasing awareness of the physical world and accessing information from the unconscious mind.

Alpha, beta, and theta bands are most interesting here, with a particular focus on the alpha band since it has the most evidence in creative cognitive activities (Benedek, 2018; Mazza et al., 2023).

3 METHODS AND DATA

The experiment used a revised version of the AUT to study divergent thinking (Mazza et al., 2023). Participants were presented with 40 everyday objects to complete the task and asked to find common and uncommon uses. The revised protocol was divided into two blocks, each composed of 20 items, one asking for the most uncommon use for the objects (divergent thinking) and the other asking to find the most common use (convergent thinking).

The cognitive activities were measured using a reference period before each trial to ensure consistency and reduce the subjectivity of the measurements. Each trial was composed of a fixation cross in the centre of the screen for 5 seconds (both for reference recording and inter-trial pause), and the presentation of a written stimulus for 0.5 s. Then a fixation cross – identical to the previous – appeared again in the centre of the screen for a maximum of 30 seconds, representing the idea generation period. During this period, participants were instructed to press the space bar as soon as they wanted to vocalize their ideas. The instructions for the task were standardized, and the presentation order of the

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two blocks was counterbalanced. The presentation of the instructions and the task were administered in the native language of the participants to avoid translation processes.
The experiment involved 40 volunteer participants, all students (age M=23.7, SD =2,55; 12 females and 28 males). They have been clustered into industrial design engineering students (IDE) and engineering design students (engineers), based on their educational backgrounds. Participants were divided into two clusters for the time of day variable: AM for data collection that occurred before noon, PM for data collection that occurred after noon. Lunch occurred before noon. These clusters represent a macro distinction among the time of day due to the exploratory nature of the present study. The different clusters for educational background and time of day are reported in Figure 3.

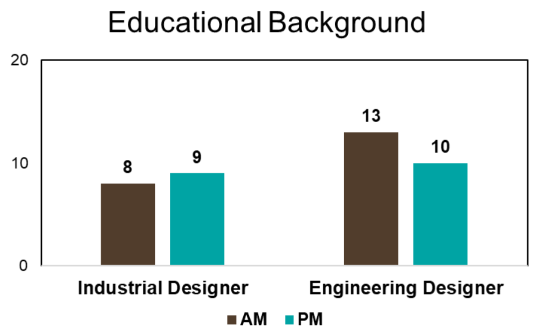

Figure 3 - Educational background and time of day among participants

One of the factors that could influence the results was the natural lighting, since it plays an important role in chronobiology (DeYoung et al., 2007). The experiment was conducted in Lulea (Sweden), during December and January, with controlled lighting in the laboratory.
An EEG cap with 33 channels (32 active + 1 ground) with a sampling rate of 500 Hz and a reference electrode that was placed on the tip of the nose. Electrodes were applied following the 10-20 system, and their impedance was kept below 5kOhm to get high signal quality.
The EEG signals were pre-processed using Independent Component Analysis (ICA) to remove the muscular and external artifacts. The signals were computed as the power generated for each band in the measured signal related to the brain activities: delta, theta, alpha, beta, and gamma. The Task Related Power (TRP) was computed as the difference between the value recorded during the idea generation period and the reference period for each electrode, for each band as follows (Pfurtscheller & Lopes da Silva, 1999):

$$\text{TRP} = \log(\text{PowerIdeaGeneration}) - \log(\text{PowerReference}) \tag{1}$$

The TRPs are adopted to measure the event-related desynchronization/synchronization (ERD/ERS). ERD represents an electrophysiological correlate of an activated cortical area, large values of ERS are related to brain states with reduced information processing (Pfurtscheller & Lopes da Silva, 1999).
The outlier detection was executed by removing the measurements that generated values outside the range of $\mu \pm 2\sigma$ per each band, for each electrode, for each item. The electrodes were grouped by averaging TRPs referred to electrodes from the same brain region according to the 10-20 system, as depicted in Figure 2. For the statistical analyses, each area's TRP was considered a dependent variable for a 2x2 ANOVA with factors time of day (Morning, AM, vs Afternoon, PM) and educational background (engineers vs IDE).

4 RESULTS AND DISCUSSION

Three participants showed problems during the EEG data processing and were removed from the analyses. Thirty-seven participants were used for the following analysis and results, with 17 engineering and 20 IDE students. The analysis presented here focused only on the divergent thinking block, where participants were asked to find uncommon uses. The statistical analyses on the TRPs were run on each band. For each band, each brain region was considered the dependent variable. The analysis was a 2x2 repeated-measurement ANOVA, with between-subject factors of educational background and time of day. The analysis was also extended to the interaction of the factors.
In Figure 4, each graph represents a different frequency band, respectively, beta, alpha, delta, and theta. The gamma band is not presented here because it has no significant results related to the factors

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analyzed. The brain regions (see Figure 2a) are represented on the x-axis, and the TRPs values are on the y-axis. On the top of each graph, different colors highlight the statistical significance (p-value < 0.05) of the factors and their interaction: yellow for the time of day, blue for the educational background, and red for their interaction. Significance is represented with a star symbol; conversely, the dot represents no significant difference. The different combinations of educational background and time of day are differentiated by the color and pattern of the lines and different markers: IDEs-AM with black continuous lines and triangles as markers; IDEs-PM with black dotted lines and circles as markers; Engineers-AM with grey continuous lines and triangles as markers; Engineers-PM with grey continuous lines and circles as markers. For instance, in the graph on the top-left, the first column represents the pre-frontal brain region (Fp), where IDEs-AM and Engineers-PM have similar small positive beta TRPs; IDEs-PM and Engineers-AM have similar higher beta TRPs. Here, time of day and educational background (yellow and blue on the top of the column) are not significant (p > .05), so they are dots; their interaction (red on the top of the column) is significant (p < .05), so it is a star.

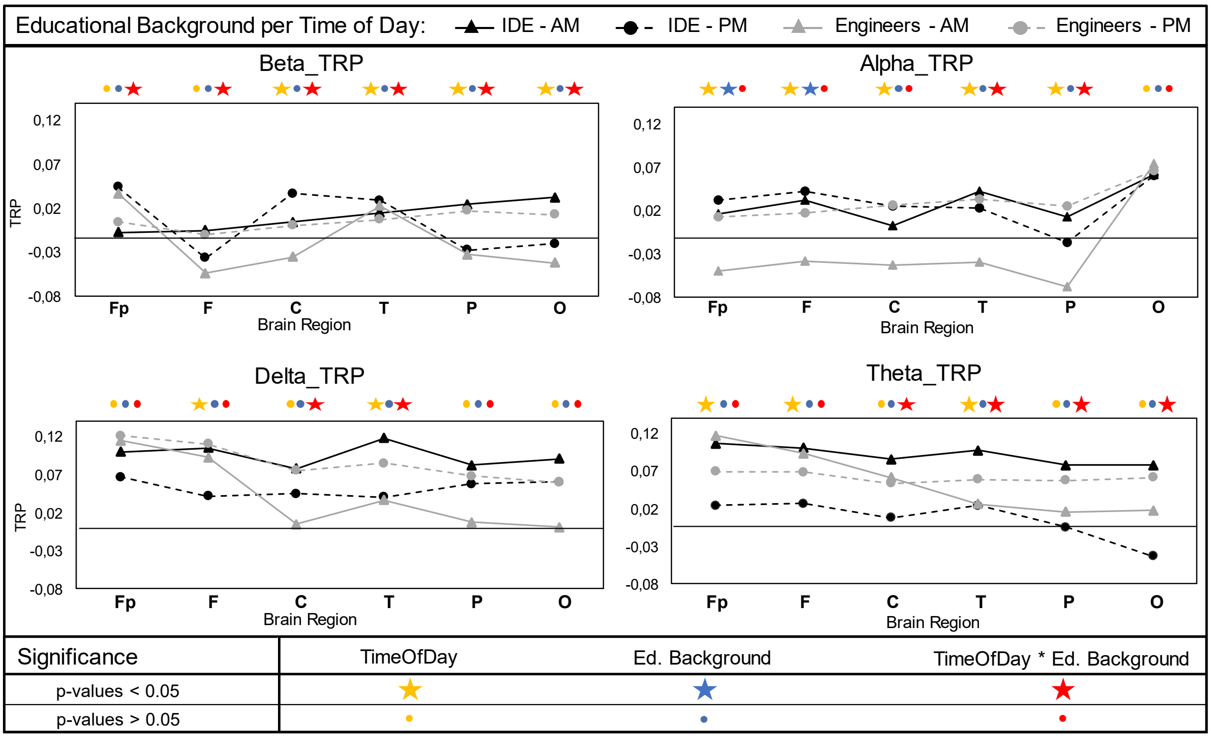

Figure 4. TRPs by bands for different educational backgrounds during the times of day for each brain region Fp, F, C, T, P, and O

Here the results are discussed qualitatively by band, statistical significances of time of day, educational background, and time of day–educational background interaction are indicated in Figure 4:

- **Beta:** IDEs' activations in the morning are like engineers' in the afternoon. This result is consistent with the general distribution of beta, which tends to be very localized and more related to specific regions. IDEs in the afternoon have some similarities of activations to engineers in the morning, except for the central region. These two groups have a beta activation nearly uniformly distributed across the brain with a gradual increase from Fp to O regions, close to zero in the anterior part of the brain, and low positive values for the posterior regions.
- **Alpha:** Alpha activations are higher in the occipital region for both the engineers and the IDEs and the time of day, consistent with previous findings for other unrelated educational backgrounds (Benedek, 2018). Engineers in the morning showed a significantly lower level of alpha power than IDEs in both morning and afternoon and engineers in the afternoon in all the other brain regions, the same results were found for the theta power in most regions. Engineers showed higher activations in the alpha band in the afternoon than in the morning. In the afternoon, these activations make engineers appear like IDEs in general. IDEs showed higher activations in the afternoon than in the morning in Fp, F, and C regions, lower in T and P regions, and similar activations in the O region. Alpha is the only band power that shows significant differences for the educational background as a stand-alone factor.

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- **Theta:** IDEs showed lower activations in the afternoon than others. In this case, the daytime dominates, engineers and IDEs activate similarly, with minor differences. Based on the interaction with their backgrounds, IDEs tend to be more active in the morning, while engineers are more active in the afternoon. In the pre-frontal and frontal regions, the afternoon activations are lower than the morning ones, where engineers and IDEs show similar values. Engineers in the afternoon have constant theta power activations among regions, as well as IDEs in the morning. In the afternoon, IDEs have lower activation with respect to engineers, but the trend is generally similar, except for a lower value in the P and O regions. IDEs present the same decreased power in P and O regions during the morning.
- **Delta:** Only F, C, and T regions show significant results for time of day, other considerations are based on visual inspections. During the morning, engineers and IDEs show similar activations in Fp and F regions. During the afternoon, engineers and IDEs show similar activities in P and O regions. Delta activations are also often related to static activities or low-level arousal, then the significant differences, especially for central and temporal regions, can be indicative of engineering design students having higher arousal during the morning and IDEs during the afternoon. Engineers showed greater activation in the morning in the Fp regions, and the trend of activations among the whole brain is similar, with lower levels during the morning. IDEs have the highest value during the morning in T, P and O regions.

Alpha and theta power are related to creative tasks. For these band powers, the effect of time of day is significant across most of the brain. In both theta and alpha powers, the IDEs showed higher activations both during the morning and the afternoon. On the other hand, the engineering design students during the morning could be characterized as the ones with the lowest brain activations related to creative activities. IDEs in the morning and engineers in the afternoon show only positive values of TRP in beta, which could be related to ERS. Here, IDEs in the afternoon show ERD in F, T, and P regions. Engineers in the morning show ERD in the same regions and in C. In alpha, only engineers in the morning showed ERD, except for the O, where all the groups showed no significant differences. In the delta band, all the TRPs are positive, indicating that divergent tasks generated ERS in the delta band, regardless of the educational background or the time of day. The same occurs for the theta band, except for the P and O regions of engineers in the afternoon. In alpha, in occipital regions, both IDEs and engineers show ERS both in the morning and in the afternoon. In general, IDEs in the morning showed greater activation than engineers in the morning sessions in all the bands, except that for the pre-frontal region in beta, delta, and theta bands. Fp region is often related to cognitive control functions, influencing attention, impulse inhibition, prospective memory, and cognitive flexibility (Funahashi, 2017).

The results show that chronobiology plays a significant role in design students' neurocognition of divergent thinking. Important considerations could be derived from understanding such differences along with performances and behavioural measurements when applied to designing itself.

5 CONCLUSIONS

The work presented here investigated the role of the time of day on student designers' neurocognitive activations, specifically focusing on the differences between two time periods: morning and afternoon. The investigation also examined if any differences were also related to the educational background of the participants. Creativity represents a major topic of interest for design research, and its foundation is in ideation activities and divergent thinking as a cognitive process. Few studies have already investigated the role of the time of day in the divergent thinking of design students. Thus, the results presented are explorative and show some potentially interesting findings: the time of day influences the design students' neurocognitive activations, affecting their TRPs in alpha, beta, theta, and delta bands.

These results, if paralleled by the activities of designing, could have scientific, design practice, and educational implications. For the scientific implications, the time of day could represent a confounding variable in any statistical analysis creating distortions and/or noise. For design practice, such findings could have indirect implications in helping to define the best time of day for scheduling design activities, especially during the initial ideation phases. The study results could impact education, where the time of school day concerns design students' creativity performance.

One of the main limitations of the present study is the lack of investigation of the chronotypes of the participants, which could lead to the identification of their role in the chronobiology of idea generation. The second limitation is that this contribution is a starting point for the investigation of chronobiology in

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design as it focuses only on one of the sub-activities involved in conceptual design processes. Also, the time of day was divided into only two clusters for morning and afternoon, but a more granular time subdivision would produce a more detailed understanding of the influence of chronobiology. A third limitation is the number of participants, representing a small cohort size relative to the number of variables considered. Finally, the present results should be compared with the behavioural data analysis to investigate if these differences in brain activations are also related to the designers' performances.
For these reasons, the main suggestions for further research are to investigate chronotypes' role, study design tasks, not just divergent thinking, analyse the data using a more granular time division, and correlate activations with design outcomes.

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