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Chronobiology of pupil dilation in design students during idea generation

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Abstract

Chronobiology studies physiological variations due to the time of day, an unexplored factor in design research. This paper explores the effect of time of day on designers' physiological responses in idea generation. Convergent (CT) and divergent (DT) thinking, as building blocks of designing, are explored using pupil dilation as a proxy for cognitive load. Time of day and educational background are explored for engineering and industrial designers. Results show a larger pupil diameter in the afternoon than in the morning, especially for DT, with higher values for industrial designers.

Keywords: design cognition, idea generation, chronobiology, pupil dilation, educational background

1. Introduction

Humans are strongly affected by time of day, both in their biological and cognitive activities (Horne & Östberg, 1976; Schmidt et al., 2007), and its study is called chronobiology. Recent studies suggest that pupil dilation is strongly affected by diurnal variations (Spitschan, 2021). This could be a reason for some contradictory results from design cognition research (Balters et al., 2023). The time of day could represent a confounding variable. Chronobiology is an inadequately explored variable in design research, and there is preliminary evidence that the time of day is a factor in design cognition (Colombo et al., 2023).

Eye activity is one method for investigating human cognition (Spitschan, 2021) and is complementary to protocol analysis, other physiological measurements, and neuroimaging design studies (Borgianni and Maccioni, 2020). Research results support the hypothesis that some eye activity correlates with ideation cognitive processes (Balters et al., 2023). Some eye-related measures have been correlated with components of cognition (attention, learning, memory, etc.) and emotion (arousal, affective involvement, avoidance behaviors) (Eckstein et al., 2017). Among them, pupil dilation is a physiological measurement found to be a proxy for cognitive load (Spitschan, 2021).

The present study investigates the role of time of day on designers' pupil dilation during an ideation activity. Here, ideation is measured by the proxies of divergent thinking (DT) and convergent thinking (CT). Designers from different educational backgrounds have been shown to have different neurophysiological responses (Vieira et al., 2020). For this reason, participants in this study were design students from two educational backgrounds: industrial design students (IDSs) and engineering design students (EDSs).

The hypotheses to be tested are:

1. Chronobiology influences designers' pupil dilation differently in CT and DT.
2. Educational background influences pupil dilation differently in CT and DT.
3. Chronobiology and educational background interact with pupil dilation in CT and DT.

The hypotheses are related to the assumption that pupil dilation is expected to be larger for higher cognitive load and effort (Rodemer et al., 2023). Humans typically perform cognitive tasks better during the late morning than in the afternoon (Facer-Childs et al., 2018), when a higher effort is expected as well as wider pupil diameter (Daguet et al., 2019). IDSs are commonly exposed to DT tasks and are expected to have a lower cognitive load, with a smaller pupil dimension. The two factors are expected to interact with a higher pupil dimension for the EDSs in the afternoon.

The present contribution is part of the research that aims to increase the knowledge from physiological studies in design research. If the results provide support for the hypotheses, they can then represent an initial direction for studies that can lead to a more conscious scheduling of tasks, which can be applied to daily tasks. They can then be differentiated by their cognitive activities across the work daytime. If the educational background affects the pupil dimensions and hence cognitive load, this could potentially lead to changes in design education to reduce the effects of time of day on cognitive load.

The paper is divided into four sections. The Background section briefly analyses the state of the art in chronobiology and cognition, particularly concerning pupil dilation, contextualizing the research within design research. The Methodology and Data section presents the experiment, the equipment adopted, and the data processing methods. The Results and Discussion section presents the main experiment results with their related interpretation, comparing these results with the literature. The Conclusion focuses on remarks and the main takeaways of the study, with suggestions for further explorations.

2. Background

This section starts by explaining chronobiology and the related main findings in human cognition. A brief understanding of the eye tracker is also presented to explain the measurement and role of pupil dilation. Then, relevant design studies are reported to distinguish the main findings from design neurocognition and to frame the context of the study in design research.

2.1. Chronobiology

Chronobiology is an area of biology concerned with studying the role of time in living organisms. Its focus is extensive, and humans are just a small part of it (Horne & Östberg, 1976). In humans, chronobiology was initially focused only on the sleep-wake cycles, but its effects have been noticed in neurobehavioral and cognitive performance (Roenneberg et al., 2003).

Brains are strongly affected by time of day, as well as the daily fluctuations of body temperature, hormone secretion, heart rate, blood pressure, sleep and wake periods, and cognitive functions. Such fluctuations are not linear in a day, and their pattern is still under investigation (Schmidt et al., 2007). The main findings are twofold: biological rhythms and chronotypes.

First, biological rhythms are cycles that characterize different aspects, categorized according to their duration. They depend on the year, the season, the day of the month, the time of day, and the instant in which the human being is. Their role is explained in Figure 1.

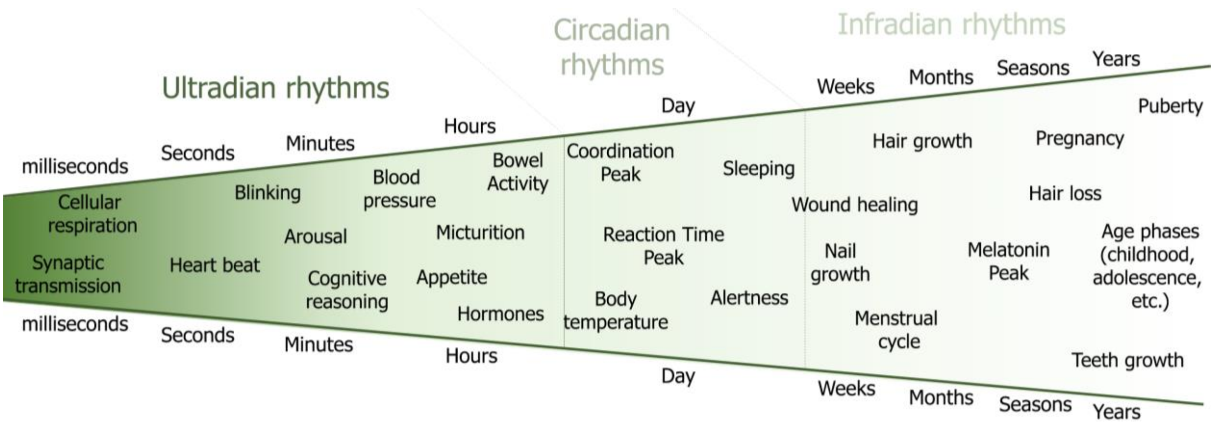

Figure 1. Chronobiological rhythms

During the day, human activations show fluctuations that are also strongly dependent on individuals. An important factor that explains a large portion of such individuals' variability, is their chronotype. This variable explains individual differences, such as people who perform better in the morning (morning chronotype) or afternoon or evening (evening chronotype), as shown in Figure 2. These differences are investigated through self-evaluation (questionnaires), and the main ones adopted are the Morning-Eveningness Questionnaire (Horne & Östberg, 1976). Chronotypes historically fall into one of two categories, but some studies demonstrate that they are not dichotomic but rather a continuum (Schmidt & Bao, 2017).

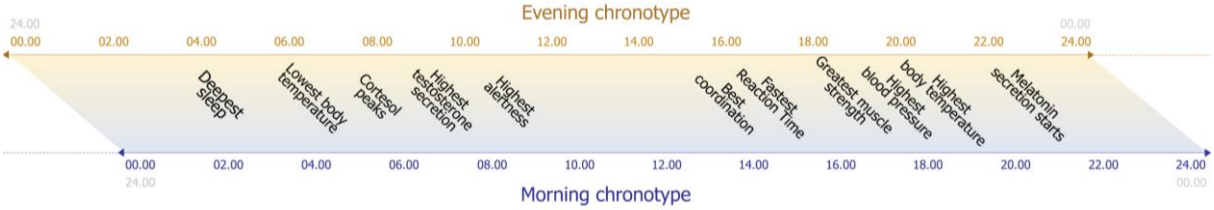

Figure 2. Human daily fluctuations and chronotypes

Chronobiology effects on cognition and pupil dilation

Cognitive performances are affected by time of day (Schmidt et al., 2007). Studies found that cognitive performances have a negative peak in the late afternoon, more evident according to the chronotype (Sabaoui et al., 2023). Among the cognitive performances affected by chronobiological factors are memory, attention, logical reasoning, and complex executive functions (Schmidt et al., 2007). Decision-making is one of the main activities explored in relation to chronobiology (Sabaoui et al., 2023).

Some studies have shown that there could be an optimal timing for several activities, defining the "circadian performance rhythm" with a duration of 24.8 hours (Aschoff & Wever, 1976). Several other studies explored the effects of time of day on human cognition but adopted a wide range of tasks that reduce the possibility of generalizing results. Complex cognitive activities seem to be noticeably affected by the time of day, related to reduced focused attention and distraction (May, 1999).

Pupil diameter appears to vary with circadian rhythms (Gaddy et al., 1993). The studies on chronobiology and eye tracking mainly focus on light exposure, aiming to understand the pupil's physiological behavior: the pupil response to light stimuli varies during the day (Münch et al., 2012). Chronobiology has been inadequately investigated in psychological and neuropsychological domains (Schmidt & Bao, 2017) with inconsistent results in the literature (Xu et al., 2021).

2.2. Eye-tracker device, measurements, and pupil dilation

An eye tracker is a device to measure the successive targets of an individual's visual fixation as they observe displays and to measure the behavior of their pupils (APA, 2016). Eye tracker devices can be see-through glasses or remote, based on infrared signals, or virtual reality. The main measurements of the eye tracker are presented here. Fixation represents a period of static gaze in a specific location, and saccades represent the rapid movement of eye gaze, usually between two consecutive locations (Mahanama et al., 2022). Another measure, gaze direction, is often used as a proxy for (visual) attention. Eye gaze is usually studied through regions of the visual field in front of the participant, called areas of interest (AOI).

One measure is pupil dilation, which is the focus of the present paper. Pupil dilation is a measure of human arousal and is related to cognitive load. It has been adopted as a proxy measure of task difficulty (Gavas et al., 2018; Mitre-Hernandez et al., 2021). Pupil diameter seems to be affected by the typology of the task, becoming wider during creative conditions (Agnoli et al., 2019; Mazza et al., 2023). Pupil size is affected by several factors, such as light, cognitive processes, spontaneous fluctuations, sleepiness, and age, and is affected by diurnal variation (Spitschan, 2021). Pupil size has large changes when people face significant variations of the stimuli and environment, but very small differences when people change their cognitive state (Mahanama et al., 2022). On average, the human pupil is considered constricted size when it measures a diameter less than 2.5 mm, normal size when it is 2.5 to 4.5 mm, and dilated size when it is 4.5 to 8 mm (Spitschan, 2021), Figure 3.

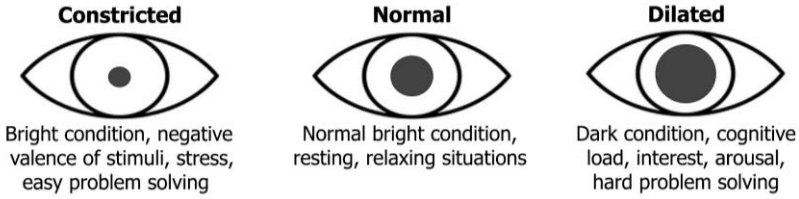

Figure 3. The main interpretations of pupil dilation

2.3. Physiology, eye tracking, and divergent thinking in design

Eye tracking and pupil dilation in design research

Applications of eye tracking in design include research on (i) design reasoning (e.g., Tahira et al., 2012; Yu & Gero, 2020); (ii) users' interacting with products (e.g., Borgianni et al., 2019; Du & MacDonald, 2014), (iii) validating solutions (e.g., Metha et al., 2020); (iv) creativity (e.g., Goucher-Lambert, 2019; Sun et al., 2014); and (v) reaction to stimuli in ideation (e.g., Dybvik et al., 2022). Designers' mental and emotional states have been associated with the pupil dimension with a "U model": for average difficulty of tasks the pupil diameter decreases, while it is larger in easy and very difficult tasks (Petkar et al., 2010). During creative ideation designers' pupils dilate, representing a higher level of concentration (Sun et al., 2014). Finally, pupil dilation has already been investigated for subjects with different backgrounds. Designers and managers were compared through the measure of their pupil diameter, as a measure of cognitive load, in the comprehension of visual representation and sketches as stimuli in conceptual design, with smaller diameters for designers (Self, 2019).

2.4. Divergent thinking in design ideation

Design research has investigated how designers' minds and bodies activate during ideation in different circumstances (e.g., Li et al., 2021; Shealy et al., 2020; Vieira et al., 2022). Several cognitive activities are used to characterize ideation; among them, divergent thinking (DT) and convergent thinking (CT) are cognitive building blocks (Hay et al., 2017). In general, DT represents a cognitive activity related to an ideation activity for a problem without a univocal solution. In contrast, CT is related to an ideation activity for a problem with a univocal solution (Guilford, 1967). In design, DT is related to identifying or exploring new alternatives or solutions, i.e., constructing the design space (Gero and Milovanovic, 2022). CT is related to exploring the design space, as in concept selection (Lee & Ostwald, 2022).

The Alternative Uses Task (AUT) is one of the most commonly used tasks in the literature for measuring DT. The limit of this task is that it does not adequately replicate the concept generation phase of conceptual design, since it focuses on a single cognitive activity among many that make up conceptual design. Design tasks and the AUT are different. The former has a problem-to-solutions approach, starting from a problem and moving to solutions. Conversely, the AUT has a solution-to-problems approach, starting from the solution and moving to problems it can address. In conceptual design there are multiple problem-to-solutions activities and multiple solution-to-problem activities. For instance, during the identification of affordances or product's second usages in a circular economy perspective, designers' cognitive reasoning could be similar to AUT. Other DT tasks have also been adopted by design researchers (Li et al., 2021).

3. Methodology and data

The study adopted a revised version of AUT, with a CT condition, where participants were asked to find the most common uses, and a DT condition, where participants were asked to find the most uncommon uses (Mazza et al., 2023). The starting condition was counterbalanced among participants. The instructions for the task were standardized, and participants were trained with two examples.

Forty everyday objects (e.g., book, fork, hammer, pillow) were adopted as stimuli, and each stimulus was randomly assigned to one of the conditions. Before the presentation of each stimulus, a pre-trial reference period of 5 seconds was recorded (considered as baseline). The stimulus was presented for 0.5 seconds, and then the ideation period started. Once the participant had generated the idea, s/he was asked to press the space bar and then vocalize the idea. Finally, a five-second-inter-trial pause was inserted.

The sequence of each trial is depicted in Figure 4. The total duration of the experiment was around 40 minutes.

Students (N = 40) were recruited as volunteers (age M=23.7; SD=2.55). Participants were divided into four groups based on their educational background (IDS vs EDS) and the experiment time of day (morning = AM or afternoon = PM). The educational background was defined considering their course of study, while the time of day was analyzed with two macro-clusters: before noon (AM) and after noon (PM), due to the study's exploratory nature. Participants were asked not to drink and eat at least 2 hours before the experiment session. A limitation of eye tracking is the distortion related to contact lenses and glasses. Participants wearing them were not included.

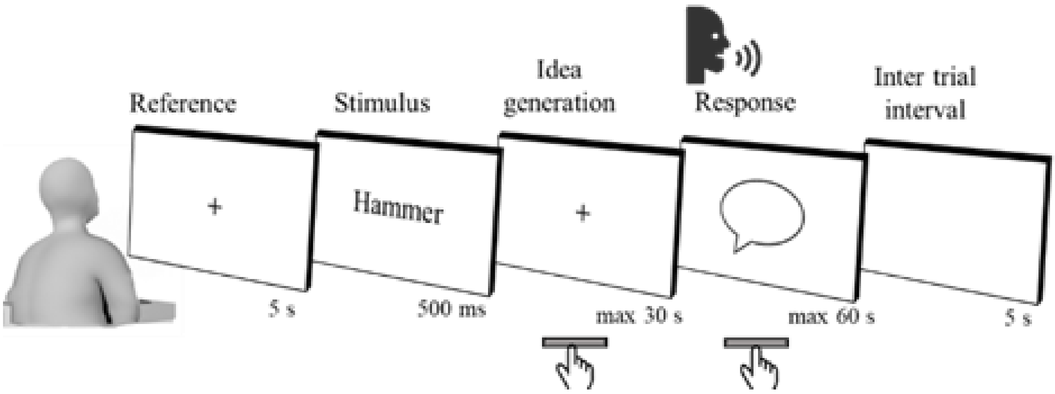

Figure 4. Experiment sequence for each participant for each condition

3.1. Equipment and data processing

A screen-based eye-tracker was used rather than a mobile tracker to ensure a higher resolution and data quality, better calibration procedures, and online correction algorithms for noise and artifact reduction (Andersson et al., 2010). An X2-30 Eye Tracker Compact Edition® from Tobii AB was used to record ocular screen-based data about gaze direction, saccades, fixations, blinking and pupil diameter at a sampling frequency of 30 Hz.

At the beginning of the task, each participant was calibrated for the participant's height and distance from the screen (between 50 cm and 60 cm). Pupil dilation was calculated using the diameter of the pupil. The device measures right and left pupils separately, and then these measurements are averaged. In the literature, there is no evidence of the pupils' different dimensions in the same subject at the same moment. The measurement of pupil size variation could produce very small values, so the software multiplies the pupil measurement by a scaling factor as a pre-processing activity.

Light is an important factor in pupil dimension variation, especially daylight at different times of day. The artificial light in the laboratory was kept at the same intensity in all the experiment sessions. Natural light was managed by using curtains in front of the two windows in the laboratory. Participants were positioned in front of a white wall, with the windows to their backs. The data collection took place in the north of Sweden between December and January, where there was almost no daylight variation.

A reference cross in the middle of the screen was used to establish a reliable baseline for accurately measuring the pupil's size. Different gaze directions can generate distortions in pupil measurement. Only data from gazes at the screen centre were analyzed for pupil size. The participants' movements were monitored through two cameras, and trials affected by such activities were removed.

4. Results and discussion

The statistical analyses are focused on the pupil dimensions for the pre-trial reference period ideation, the ideation period, and the difference between the reference and ideation period. These are the dependent variables of a 3-ways analysis (Condition: Convergent vs. Divergent; Educational Background: IDS vs. EDS; Time-of-Day: AM vs. PM). The results are presented separately in terms of the dependent variables. Only significant results ($p < 0.05$) are reported here.

Pupil dimension in the baseline period

For the baseline period, ANOVA shows significant main effects for Condition (F=35.761; p<0.001), Background (F=12.561; p=0.001), and Time-of-Day (F=9.244; p<0.003). The interaction of Time-of-Day with Condition (F=21.477; p<0.001) is also significant. The other interactions are not significant. Regardless of conditions and backgrounds, the time of day significantly affects pupil diameter, with the larger dimension in the afternoon. Such a difference is confirmed in both the backgrounds and conditions. The DT condition shows greater differences than the CT, except for EDSs in the morning. IDSs generally show smaller diameters than EDSs with the smallest during the morning. IDSs show larger differences between AM and PM in both conditions, compared to EDs, as shown in Figures 5 and 6.

Pupil dimension in the idea generation period

For the idea generation period, ANOVA shows significant main effects. Condition (F=40.007; p<0.001) shows the relevance of thinking on pupil dilation. Background (F=17.492; p<0.001) also shows significance, indicating that the educational background influences designers' physiological responses. Overall, Time-of-Day (F=5.191; p=0.025) is significant. Such an effect is increased considering the significant interaction between Time-of-Day and Condition (F=4.237; p=0.042).

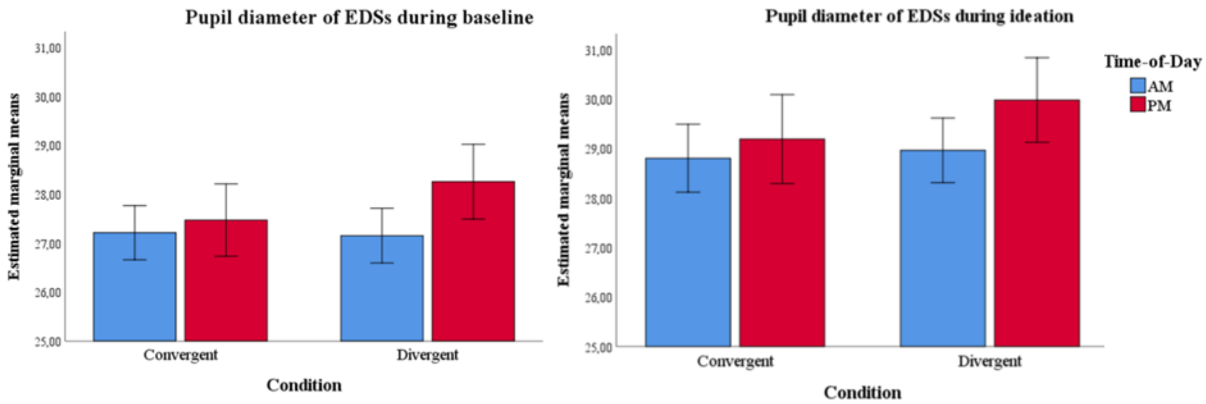

Figure 5. EDSs' pupil diameter during baseline (on the left) and ideation (on the right)

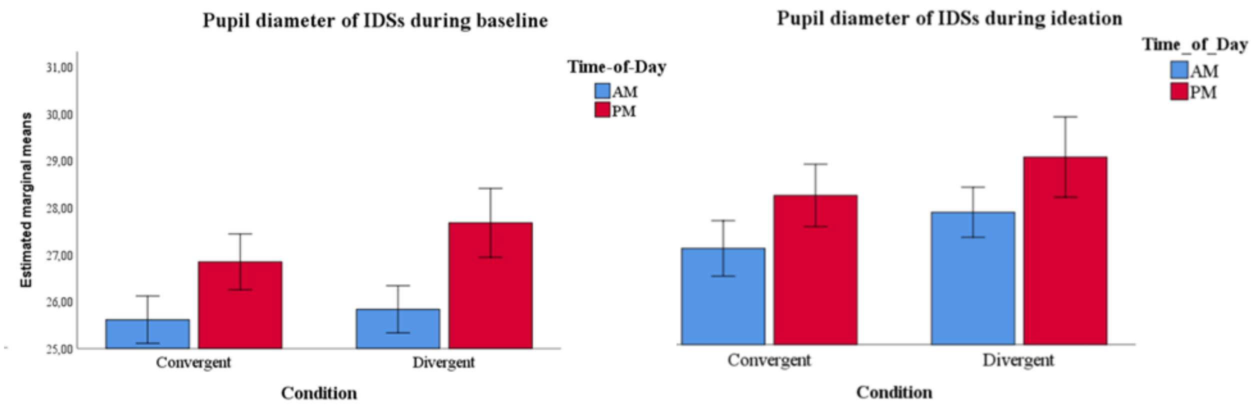

Figure 6. IDS's pupil diameter during ideation baseline (on the left) and ideation (on the right)

This highlights the influence of chronobiology in physiological responses related to designers' cognitive load while performing ideation tasks. During ideation, pupil diameter is significantly larger during the afternoon compared to the morning. This is in line with the results of the baseline. The effect of time of day is also more evident in the DT condition, with larger pupil dimensions than the CT condition, for both educational backgrounds. IDSs show more variation among conditions and times of day, indicating the significance of this interaction. However, the interaction of background with other factors does not appear significant, implying that the observed patterns is consistent independently. In general, EDSs show larger pupil dimensions than IDSs in both the conditions and the time of day, as depicted in Figures 5 and 6.

Pupil dimension (Idea Generation – Reference)
The most relevant results are the measure of pupil diameter variation between the baseline and ideation period. There are significant main effects for Background (F=15.647; p<0.001) and Time-of-Day (F=5.606; p=0.02). Condition (F=3.233; p<0.076) is not significant as a single factor in this case. However, Condition significantly interacts with Time-of-Day (F=4.991; p=0.028). In this analysis, Time-of-Day shows a significant interaction also with Background (F=6.403; p=0.013). These results are not surprising because they are linearly dependent on the previous results.
The variation between morning and afternoon in the convergent condition shows an opposite trend between IDSs and EDSs. The latter shows the highest value again during both the condition and the time of the day. In the afternoon, the former shows lower values, while the latter has slightly higher values compared to the morning. During DT, the effect of time of day decreases the difference between ideation and reference period. This trend is way more evident for IDsS, Figure 7.

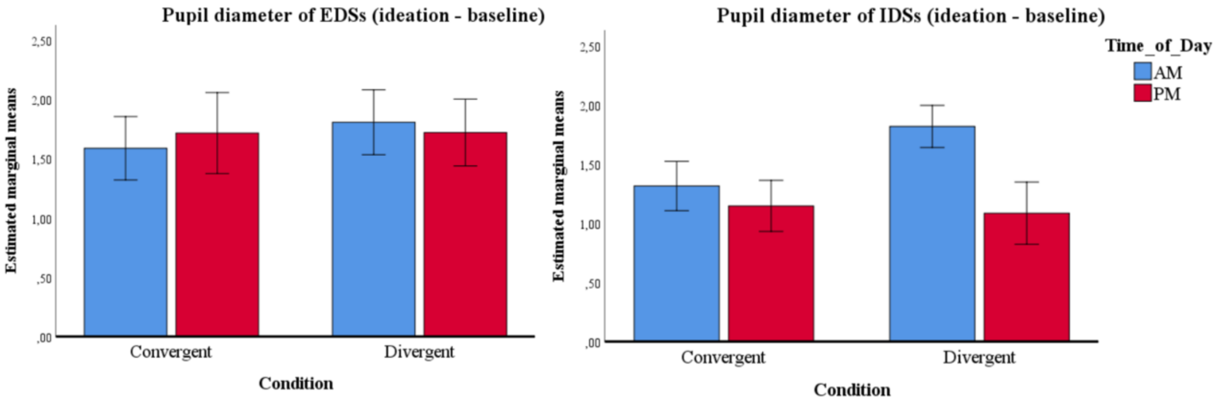

Figure 7. Pupil diameter (Ideation – Baseline) period

4.1. Discussion

The pupil diameter differences during the baseline periods confirm results from the literature in unrelated domains (Schmidt & Bao, 2017). The difference in the baseline between the conditions is also consistent with a larger pupil diameter during creative tasks (Sun et al., 2014). Pupils have larger diameters in the afternoon both for the baseline and ideation periods, regardless of the condition and educational background. These results show an inversion when considering the differences between ideation and baseline. Here, the morning shows greater differences for all conditions and educational backgrounds. Hypothesis 1 (Chronobiology influences designers' pupil dilation differently in CT and DT) is supported by these results, with time of day affecting designers' pupil dilation. These results can be explained by default higher arousal during the afternoon, associated with the larger pupil diameters, which aligns with the literature (Roenneberg et al., 2003).
In general, DT seems to lead to larger pupil diameters than CT. The suggestion is that the cognitive load related to divergence is higher than for convergence, as already found in the literature for other tasks (Nguyen et al., 2019). Such results confirm the validity of the measurements of the present work. However, comparing the different groups with different times of day and educational backgrounds, EDSs show larger pupil diameters during convergent ideation in the morning. This is just one of the results confirming that pupil dimension variability has significant differences in the morning and afternoon during these experiment sessions. In both baseline and ideation periods, IDSs show larger pupil diameters than EDSs in all conditions. IDSs also show higher differences in DT compared to CT. Hypothesis 2 (Educational background influences pupil dilation differently in CT and DT) is supported by the results of this study.
These differences in physiological response can be associated with cognitive functioning. Such fluctuations could be derived from merely reflecting individual sleepiness or alertness linked to the subjective duration of circadian rhythm (Schmidt et al., 2007). The first difference between the two conditions is the different condition task complexity: CT condition requires less effort by participants than DT. The literature shows that some cognitive tasks are affected differently by the time of day

because they involve different abilities (Schmidt & Bao, 2017). Then, the differences between the two task conditions can directly be pointed to different cognitive activities being affected differently by the time of day. The time of day also shows interesting results in its interaction with the educational background, supporting hypothesis 3 (chronobiology and educational background interact with pupil dilation in CT and DT). EDSs show significantly higher cognitive load in all the experiment sessions. This could also be related to the experience with open ideation sessions that are usually more common in industrial design context.

5. Conclusions

This work presents preliminary results from investigating the effect of chronobiology and educational background on pupil dilation during ideation. These results show that designers' pupil dilations are affected by the time of day while performing the cognitive tasks of divergent thinking and convergent thinking. Pupil dilation is associated with cognitive load. Therefore, these results suggest that cognitive load for the same task is affected by time of day. In particular, the cognitive load associated with a task can have a reduced effect in the afternoon, because humans are in a higher arousal condition as a default status.

Educational background also affects pupil dilation for the same cognitive tasks. Chronobiology and educational background interact to affect pupil dilation. Whilst the experiment only considered divergent and convergent tasks, designing is also expected to be affected by the time of day.

The different pupil sizes related to different cognitive states could have scientific and industrial applications. Understanding pupil diameter variation during different times of day has the potential to lead to more effective monitoring of designers' cognitive load, which could be translated into supporting designers. For instance, when DT or CT activations are detected, designers can be aided with stimuli to increase their divergence or convergence.

A limitation of the present study is that chronotypes were not investigated, and with the small size of the cohorts, the dominance of a chronotype in a group can create distortions. Further studies can investigate how these results can be extended by studying participants' chronotypes and how it is linked to educational backgrounds. The time of day is treated as a dual-level factor (AM vs. PM), but it could be useful to have more levels to increase the understanding of humans' responses to diurnal fluctuations. Finally, the sample size of each group is relatively small.

An increased understanding of the effect of chronobiology could be obtained by investigating a larger range of eye behaviors (e.g., fixation and saccades) across time. Establishing more robust results on the effect of chronobiology can lead to industrial implications by redesigning work time schedules and identifying more effective start times for employees resulting in improved performance.

These results provide some preliminary insights into the effect of the time of day and educational background on the designer's pupil dilation while ideating. Since there are significant differences related to accomplishing the tasks in the morning or the afternoon, the time of day needs to be accounted for in any results based on the measurement of pupil dilation.

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