Review article

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Influence of the perceived size of a light source on non-visual effects in humans

https://doi.org/10.1515/aot-2020-0041
Received July 5, 2020; accepted September 14, 2020; published online October 5, 2020

Abstract: Light not only enables humans to perceive their surroundings, but also influences their sleep–wake cycle, mood, concentration and performance. Targeted use of these so called nonvisual effects could also have a positive contribution in automobiles by keeping passengers alert, minimizing error rates or bootsting attention in general. Since construction space in vehicle interios is scarce, this study compared the influence of differently-sized light panels and thus solid angles on nonvisual effects. In a counterbalanced order, 32 volunteers were exposed to three lighting conditions in the morning: *baseline* (12 lx, 2200 K), *small* (200 lx, 6500 K, 0.05 sr) and *large* (200 lx, 6500 K, 0.44 sr). During each session of 60 min, alertness, concentration and working memory were assessed before and during light exposure. After data analysis no significant main effects of light, measurement point or interaction between light and measurement point could be seen.

Keywords: alertness; bright light exposure; non-visual effects; solid angle.

1 Introduction

Looking at the role of light in the interior of a car, it can be seen that its role has changed significantly in recent years. Whereas in the past, interior light was used exclusively to make the environment inside the vehicle visible, nowadays it covers a much wider role. For example, specifically positioned light sources in the form of ambient lighting are able to increase the attractiveness and the quality of the interior as well as the feeling of safety as perceived by the passengers [1]. Developments such as autonomous driving will push this change forward and offer interior lighting the opportunity to support the transformation of the interior into a mobile working and living environment through functional interior lighting and innovative lighting concepts. One of these concepts could be the targeted use of nonvisual effects of light.

It has been known for some time that light not only enables vision, but also has other physiological and psychological effects on humans. These nonvisual effects include suppression of the hormone melatonin, changes to the circadian rhythm, body temperature, alertness and task performance [2–5]. Since the discovery of intrinsically photosensitive retinal ganglion cells (ipRGCs), a third type of retinal photoreceptor, research has shown that these cells play a decisive role in influencing these nonvisual effects of light [6–8]. They are most sensitive to wavelengths ranging from 460–480 nm and are directly or indirectly connected to parts of the brain responsible for circadian rhythm, alertness, mood or cognition [9–15].

Studies were able to show that exposure to monochromatic blue light can lead to increased alertness, accuracy and working memory performance [16–19]. Similar effects can be seen using blue-enriched white light [20–23]. Brighter illuminance levels as compared to lower illuminance levels seem to be more reliable to elicit alerting light effects [22, 24], although illuminance levels as low as 90–180 lx at eye level have been proven sufficient to exert a significant effect on alertness and brain activity [25]. Illumination of the lower part of the retina, and thus upper visual field is more effective in suppressing melatonin than illumination of the upper retina [26, 27]. With regards to duration, exposure to blue light for 18 min was able to trigger increased brain activity [14]. Nonvisual effects of light can be seen during the night as well as during the day [14, 18–20, 22–24, 28–32]. Keis et al. [31] were able to show beneficial effects of blue enriched white light on students' performance in the morning. Practical

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studies showing positive effects of blue enriched white light on concentration, performance and alertness in everyday life focused on environments like classrooms and offices [29, 31, 32].

With regards to vehicles, some nonvisual effects offer the potential to positively support the passengers of cars, for example by reducing error rates while driving [33] or generally increasing the ability to grasp information [29]. But one crucial photometric parameter that is required for a more practical, user-oriented approach toward nonvisual effects—especially in vehicle interiors, where construction space is scarce—has been neglected in past studies: the solid angle or perceived size of the light source. While most previous studies report illuminance at eye level and other photometric parameters, without knowledge of the perceived size of the light source, it is not possible to estimate the light sources' image size and illuminance on the retina. Since ipRGCs are spread across the whole retina in primates with a higher density around the fovea [34], the number of ipRGCs hit by light differs greatly depending on the image size on the retina. Thus, the intensity of nonvisual light effects could vary with image size on the retina or solid angle of a light source.

In a preliminary study, Novotny et al. examined the influence of different solid angles on melatonin suppression [35]. Although the study has its limitations in regards to its statistical informative value due to a low number of only six participants, the data of Novotny et al. shows a trend that the larger light source they used is more effective in suppressing melatonin than their small light source (same illuminance at eye level). This information has to be used with caution, because the larger light source used a slightly different spectrum, which was more efficient in suppressing melatonin.

In a first study, Niemeyer & Neumann investigated the influence of differently sized light panels on nonvisual effects. Here, different solid angles revealed no significant effect on subjective alertness, reaction times or short-term memory, while keeping illuminance at eye level constant [36]. In hindsight, the objective tests used in [36] are seen as not ideal. Data of the memory test revealed a ceiling effect, thus the test might have been too easy. For research on nonvisual effects, reaction time tests seem to provide mixed effects [37] and are hard to compare due to nonstandard measurement equipment.

In order to further investigate the influence of different solid angles on nonvisual effects, the study by Niemeyer & Neumann [36] was repeated in a slightly adjusted way, using different tasks and a shortened study protocol. The aim of the study was to show that light in general can influence human alertness and analyse whether the perceived size of a light source plays a role in this. Additionally, we present a light simulation of the eye based on the setup of this study.

2 Simulation of retinal illumination

To visualize the role of a light sources perceived size on retinal image size and illuminance, we ran a simulation in SPEOS (optical simulation software) using the geometric and photometric setup that can be seen in this study. In two scenarios, two differently sized light sources were placed in the upper visual field of the eye. The first light source is perceived at a solid angle of 0.05 sr, while the second light source is perceived at a solid angle of 0.44 sr. In Figure 1, the setup for the simulation of the large light source can be seen, as well as the outline of the small light source. For each separate simulation, luminous flux of both light sources was adjusted in a way that both light sources produce an illuminance of 200 lx at eye level in the direction of gaze. The measurement of illuminance at eye level is used in most studies on nonvisual effects. An explanation for these specific lighting parameters is given in the next part of this article. The optical model of the human eye used in our simulation is based on parameters described in [38]. Based on the formula derived by Watson & Yellott, it is assumed that changes in pupil size are more dependent on illuminance than on solid angle [39]. While the model of Watson & Yellot is weighted by the photopic luminosity curve $V(\lambda)$, which corresponds to a mixture of the L and M cones in the retina, recent research has shown that all photoreceptors (including ipRGCs) have some influence on the diameter of the pupil [40]. Thus, the model of Watson & Yellot might not be enough to predict pupil size. Nevertheless, we assume the formula to be a good starting point for our simulation. Therefore, the pupil diameter for both scenarios is set to 2.67 mm.

With a luminous flux of 365 and 450 lm respectively, large and small light source produce an illuminance of 200 lx at eye level, as shown in Figure 2. Looking at the retina, the place where ipRGCs—the cells responsible for non-visual effects—are located, a different situation arises. As expected, the image size of the larger light source is bigger than the image of the small light source. The illuminance of the large image is 13 lx, while the illuminance of the small image is 81 lx (see Figure 2). This shows that although the illuminance at eye level is the same for both light sources, image size and illuminance on the retina differ greatly.

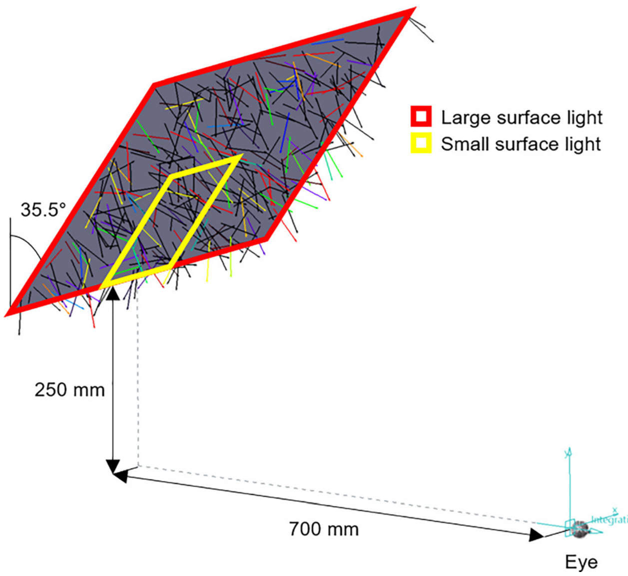

Figure 1: SPEOS (optical simulation software) setup used for the lighting simulation of the large surface light (red outline) with a solid angle of 0.44 sr. The eye with the detector surface can be seen in the bottom right corner. Additionally, the outline of the small surface light with a solid angle of 0.05 sr is indicated in yellow.

3 Method

3.1 Design & participants

In order to be able to observe the effect of different light scenarios on the individual, the study design of the first study by Niemeyer & Neumann [36] was largely adopted. Three lighting scenarios were presented, which were completed by each test person:

One scenario was a *baseline* scenario with dim background light inspired by the idea of a commuter driving or being driven to work in the morning while the sun is rising. Hence, a colour temperature of 2200 K and an illuminance of 12 lx in the direction of gaze were chosen for the *baseline* scenario.

Two additional scenarios were displayed using differently sized overhead lighting panels. These light panels could represent potentially nonvisual effects triggering light sources mounted on the ceiling on the inside of a car. Inspired by the perceived size of a makeup light with a folded out mirror in the rear of an Audi A8, a solid angle of 0.05 sr was chosen for the *small* light panel. Due to limited space in vehicle ceilings, the solid angle of the *large* light panel was set to 0.44 sr. Both scenarios with overhead light panels were set to a colour temperature of 6500 K and an illuminance of 200 lx at eye level in the direction of gaze. Illuminance and colour temperature were derived from studies cited in the introduction that were able to trigger nonvisual effects of light during the day. Additionally, illuminance was limited to 200 lx in order to avoid glare.

The duration of each scenario was 60 min. Test persons were able to choose between three starting times (08:00, 09:15 or 10:30 am). In order to avoid being influenced by different starting times and successive scenarios, test persons were asked to stick to one time slot and

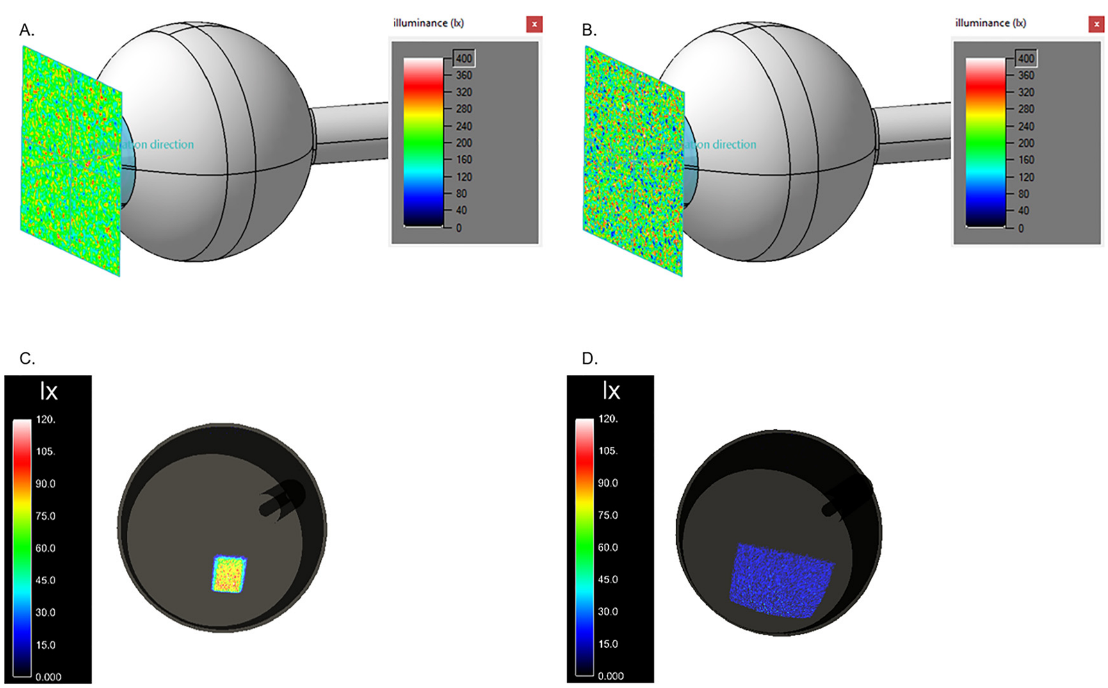

Figure 2: Measurement of illuminance for simulated lighting scenarios – Using the large light source, 200 lx can be measured at eye level (A), while 81 lx can be measured on the retina (C). Using the small light source, 200 lx can be measured at eye level (B), while 13 lx can be measured on the retina (D).

leave at least one day's break between the individual sessions. In addition, the order of the scenarios among the test persons was varied by means of counterbalancing.

Prior to the start of the study, interested participants were asked to complete the German version of the "Morningness-Eveningness-Questionnaire" [41]. Chronotypes of the "extreme morning type" and "extreme evening type" were excluded from the study. Finally, 32 volunteers (8 women and 24 men) with an average age of 30.8 ± 10.7 (SD) participated in the study. Participants were asked to stick to their regular sleep–wake cycle during the study and not to drink caffeinated beverages before a trial. The study was conducted in September 2019.

3.2 Setting

The same test environment as in [36] was used to conduct the study (see Figure 3). Office workplaces were integrated into three separate cabins, which could be shielded from external light. The lighting scenario could be adjusted with light sources positioned inside the cubicle.

The *baseline* scenario with background light was generated by a small lamp placed on a desk (hereinafter: desk lamp). The illuminance at eye level of the test subject was 12 lx at a colour temperature of 2200 K.

For the second and third scenario (*small* and *large*) an overhead mounted lamp was switched on. Its perceived size could be varied between 0.05 and 0.44 sr by means of an aperture (*small*: 145 × 190 mm, *large*: 400 × 560 mm). In both cases the illuminance at eye level of the test person was 200 lx at a colour temperature of 6500 K. The spectrum of the overhead lamp can be seen in Figure 4. Based on [42], illuminance levels of the *baseline*, *small* and *large* scenario for each photoreceptor can be seen in Table 1. A calibrated Gigahertz-Optik BTS25-EF spectrometer was used to measure illuminance and colour temperature.

In order to ensure a comparable head position between sessions and participants, test persons had to adjust their chair height and distance to the overhead lamp before each session. This was done by aiming their gaze at a marker on the rear wall of the cabin that was only visible from one position. The seating position and perceived size of the small overhead light were determined to correspond to the seating position of a passenger in the rear of an Audi A8 looking at a folded-out make-up light.

Figure 3: Test environment resembling an office workplace. A small lamp placed on a desk is used for dim background lighting, while an overhead light panel is switched off or on and varied in size for different lighting scenarios [36].

3.3 Measurements

To measure non-visual effects of light, both subjective and objective data was collected.

As in [36], subjective alertness/fatigue was assessed using the "Karolinska Sleepiness Scale" (KSS) [43]. Here, test persons rated their tiredness/wakefulness on a nine-level scale ranging from "1 – extremely alert" to "9 – extremely sleepy, fighting sleep".

Working memory was assessed using an implementation of a "Complex Span Task" (CST) by Stone and Towse [44]. During the CST, subjects were asked to memorize the position of a sequence of two to five blinking squares in a 4x4 matrix, which was shown on a screen. In order to increase the level of difficulty, simple abstract forms were shown between the letters and participants were asked to state whether the form was symmetrical in its vertical axis or not. At the end of each sequence, the position of the individually shown blinking squares had to be reproduced in the correct order. Participants were awarded one point per correct reproduction. With three repetitions per level of difficulty a maximum of 12 points could be achieved.

Additionally, a d2-R test was used to assess concentration [45]. Here, test items consist of the letters *d* and *p* arranged in several lines. One to four dashes were arranged either individually or in pairs above and/or below the letters. Participants were asked to scan the lines and mark every *d* with two dashes. Here, a maximum of 130 points could be achieved.

Karolinska sleepiness scale (KSS) and complex span task (CST) were assessed digitally on the computer provided in the test cabin, while d2-R was completed on paper.

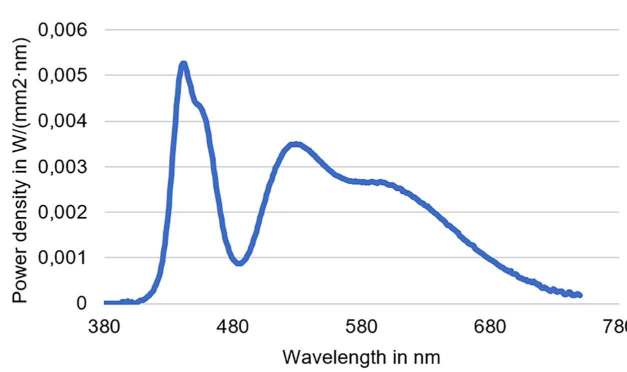

Figure 4: Spectral power distribution of the overhead light panel at 200 lx and 6500 K.

Table 1: Spectrally weighted α-opic daylight illuminance levels for lighting scenarios baseline, small & large based on [42].

Scenario	α-Opic equivalent daylight illuminance (lx)				
	S-cone	M-cone	L-cone	Rhodopic	Melanopic
Baseline	1	8	12	4	3
Small & large	208	191	196	176	168

3.4 Procedure

At the start of each session, participants were asked to take a seat in the cabin assigned to them and adjust their distance from the monitor and height of their chair as described before.

Each session can be divided into two main parts: A phase with background light by the desk lamp (12 lx, 2200 K) and a phase with the corresponding light scenario (*baseline*, *small* or *large*). The study protocol can be seen in Figure 5.

The first phase with background light had a duration of 25 min. For the first 10 min, the study procedure was explained to the participants. In order to familiarize themselves with the forthcoming tasks, they completed shorted versions of said tasks. Afterwards the first measurement block with a duration of 15 min followed. It is to note that KSS was completed twice per block. Once at the beginning and once at the end of the block.

The second phase with a duration of 35 min followed afterwards. Depending on the assigned lighting scenario, the overhead light panel was either switched on or left switched off. During the first 20 min of the second phase, participants were asked to watch a nature documentary without sound on their monitor. Afterwards the second measurement block of 15 min followed and the session was completed.

Before their first session, participants gave their written informed consent for their participation. The study was approved by the works council of Audi AG.

3.5 Statistical analysis

Statistical analysis of the collected data was done using a two-way repeated measures analysis of variance (ANOVA) in "RStudio". Lighting scenario and time/measurement block were used as independent variables, while the task results (KSS, CST or d2-R) were used as dependent variables. If required, results were adjusted with Greenhouse–Geisser correction. After finding significant results, Bonferroni corrected *t*-tests were calculated. The significance level was 5%.

Due to incomplete data sets, five participants had to be removed for the KSS analysis and two participants were left out of the CST analysis.

4 Results

4.1 Subjective sleepiness/alertness (KSS)

Mean values of subjective sleepiness/alertness as assessed by KSS with 95% confidence intervals (CI) can be seen in Figure 6. While participants sleepiness/alertness remained roughly the same with the overhead lamp switched on (*small* and *large*), an increase in subjective alertness can be seen between the end of the first and start of the second measurement block with the overhead lamp switched off.

In analysis of variance no significant main effect of lighting scenario ($F(2, 52) = 2.80$, $p = 0.07$, $\eta_G^2 = 0.04$) or measurement block ($F(1.2, 46.8) = 2.85$, p [GG] $= 0.07$, $\eta_G^2 = 0.01$) was found. No significant interaction between lighting scenario and measurement block was found ($F(6, 156) = 2.11$, $p = 0.06$, $\eta_G^2 = 0.01$).

4.2 Working memory (CST)

CST analysis can be seen in Figure 7. Participants were able to increase their CST performance from the first to the second measurement block independent of lighting scenario. Nevertheless, the increase in CST performance seems a bit more pronounced in scenarios with the overhead panel switched on.

Statistical analysis revealed a significant main effect of measurement block ($F(1, 29) = 8.95$, $p < 0.01$, $\eta_G^2 = 0.02$) that can be explained with a learning effect. No main effect of lighting scenario ($F(2, 58) = 0.36$, $p = 0.70$, $\eta_G^2 < 0.01$) or interaction between lighting scenario and measurement point ($F(2, 58) = 0.57$, $p = 0.57$, $\eta_G^2 < 0.01$) were found.

4.3 Concentration performance (d2-R)

Concentration performance scores are shown in Figure 8. It can be seen that the concentration performance of participants increased from the first to the second measurement block across all light scenarios. As in the CST, increase in concentration performance seems a bit more pronounced in sessions where the overhead lighting is switched on.

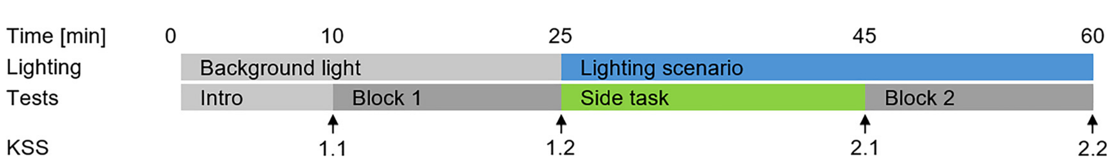

Figure 5: Overview of the study protocol (adjusted from [46]).

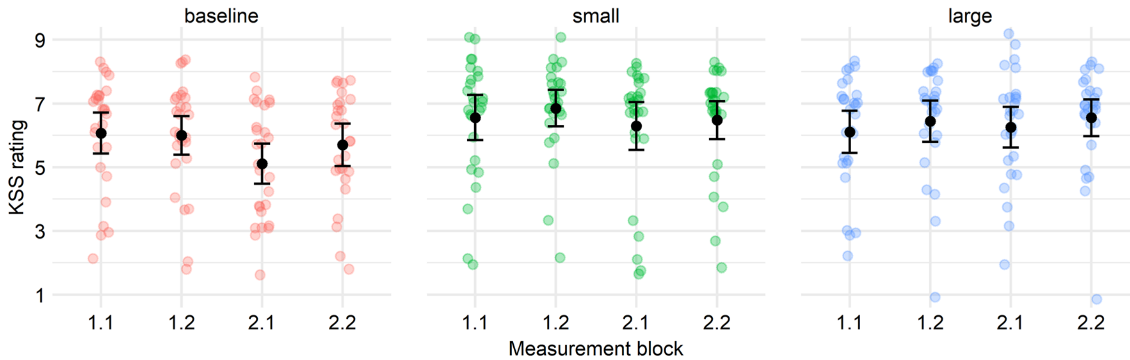

Figure 6: Karolinska sleepiness scale (KSS) ratings for each lighting scenario and measurement block. Means and 95% confidence intervals are shown. Additionally, each individual rating can be seen.

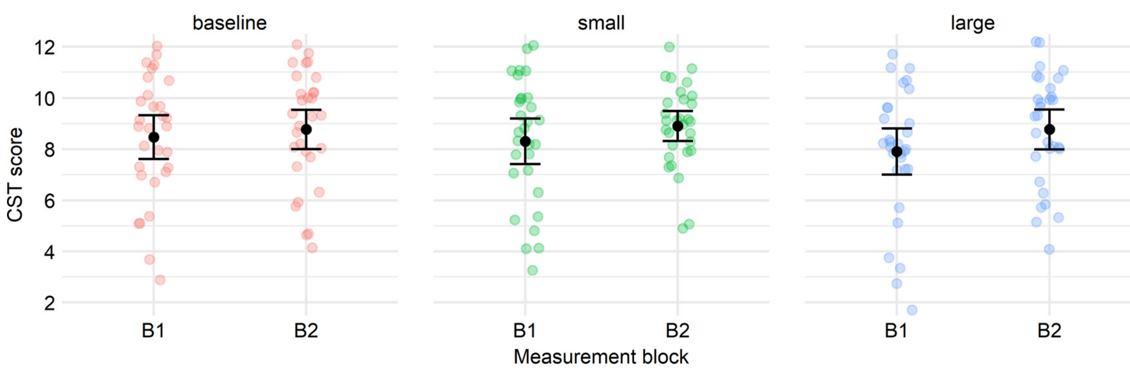

Figure 7: Complex span task (CST) scores for each lighting scenario and measurement block. Means and 95% confidence intervals are shown. Additionally, each individual rating can be seen.

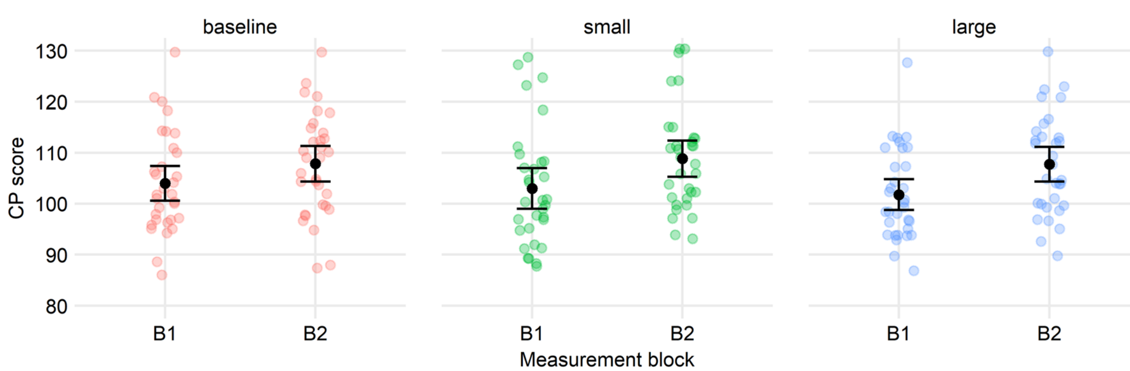

Figure 8: Concentration performance (CP) scores for each lighting scenario and measurement block. Means and 95% confidence intervals are shown. Additionally, each individual rating can be seen.

Again, a significant main effect of measurement block ($F(1, 31) = 157.07$, $p < 0.01$, $\eta_G^2 = 0.07$) due to learning effect could be revealed. Main effect of lighting scenario ($F(2, 62) = 0.39$, $p = 0.67$, $\eta_G^2 < 0.01$) and interaction between lighting scenario and measurement block ($F(2, 62) = 2.77$, $p = 0.07$, $\eta_G^2 < 0.01$) did't reveal any significance.

5 Discussion

The aim of the study presented in this article was to investigate if blue enriched white light is able to influence human alertness and whether or not the perceived size of a light source plays a role in this.

Data analysis revealed that there was a significant main effect of measurement block in regards to working memory (CST) and concentration (d2-R). This effect can most likely be explained by a learning effect. Regarding lighting, no main effect of lighting scenario was found for any of the measurement blocks. The main focus of data analysis was on interaction of lighting scenario and measurement block in order to see whether or not participants alertness and performance changed differently depending on the lighting scenario they were exposed to. Here, no significant interactions were found.

Although nonsignificant, looking at the KSS data, a clear difference is noticeable when comparing the KSS data of this study with the first study of Niemeyer & Neumann [36]. While participants in Ref. [36] felt sleepier during the dim light scenario, subjects in this study felt more awake after the side task. This observation runs counter to what was expected and could be explained by individual factors of the subject population, although counterbalancing efforts were implemented. While no influence of solid angle could be observed, just like in [36], the overhead light panel managed to keep participants awake although they had to complete a monotonous side task, i.e. watching a documentary without sound.

In regards to performance evaluation, the tasks used in [36] were replaced due to a noticeable ceiling effect and general concerns regarding comparability. In the case of this study, ceiling effect in both performance tests is much less pronounced.

Why weren't we able to reproduce alerting effects of light with parameters that are known to work from literature?

On the one hand, this may be due to effect size η_G^2, which is quite small for the interaction between lighting scenario and measurement block as presented in the results above, so that the effect was missed with the available number of participants. On the other hand, the combination of selected parameters could have been suboptimal. If effects are found in literature, far more extreme parameters are often used. For example, illuminance can be much higher, light exposure is much longer, the time of day can be in the early morning or late at night or the participants might even have a sleep deficit before the start of the experiment [23, 25, 28, 31].

If a practical application of nonvisual effects of light is considered, these parameters are certainly useful for the use in offices, in workshops or at home. However, when applied to the automobile and its classic use case, such as the way to and from work, this is only partly true. Here, the passenger is available for shorter times and high illuminance levels can pose a safety risk for the driver due to glare. In a study investigating the potential of different car interiors and their potential to support productive work, Pollmann et al. were able to show that bright, blue enriched white light is able to promote performance and lower cognitive load [47]. In comparison to the study presented in this paper, they used a lower illuminance of 50 lx at eye level at a lower colour temperature of 6000 K. Since they also used different levels of outside distractors (visual and acoustic), light wasn't the only influence on the results.

In general, the huge variety of different lighting parameters between studies makes it hard to replicate nonvisual effects. Souman et al. investigated the reliability of nonvisual light effects by taking a look at subjective alertness ratings and reaction times in a systematic literature review [37]. They were able to show that independent of time of day, higher illuminance levels are more reliable in showing significant effects than higher colour temperatures, while a substantial proportion of studies failed to show any significant effects. While it would be possible to increase colour temperature in our case, an increase in illuminance has to be done with caution due to the risk of glare.

Looking at solid angle, although the preliminary study of Novotny et al. [35] as previously described has its flaws, they show a trend towards a larger light source (1.5 m^2) being more efficient in suppressing melatonin than a smaller light source (25 cm^2). Both light sources were positioned at a distance of roughly 90 cm from the observer. Comparing the ratio of differently sized light sources and thus solid angles by Novotny et al. with our study, the difference in solid angle used in our study simply may have been too small to see a difference in nonvisual effects. Furthermore, while the higher retinal illuminance caused by the small light source may be enough to excite only a limited retinal area to saturation, the lower retinal illuminance of the large light source may have been too low to pass a threshold in order to see nonvisual effects. From a physiological point of view, it is not known how ipRGCs are linked and to what extent size and illuminance of the area illuminated on the retina play a role in signal transmission to the brain.

In the future, studies investigating the use of nonvisual effects of light in automobiles should therefore broaden the spectrum of parameters. By simulating a long drive during the night with several breaks, one could use longer exposure times, higher illuminance levels (during a break) and even participants with higher sleep pressure for example. At the same time, however, it should be critically questioned whether the applied parameters can be implemented in a meaningful way in reality.

Acknowledgements: This study was funded by AUDI AG.
Author contribution: AN: Conception and design, data analysis, interpretation of data, drafting the article. LR: Conception and design, data collection. CN: Conception and design. CM: Lighting simulation.
Research funding: This study was funded by AUDI AG.
Conflict of interest statement: Arvid Niemeyer is employed at Audi AG, who also funded the study.

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