Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Exploring the relationship between light and subjective alertness using personal lighting conditions

To cite this article: J. van Duijnhoven *et al* 2021 *J. Phys.: Conf. Ser.* **2042** 012119

View the article online for updates and enhancements.

Exploring the relationship between light and subjective alertness using personal lighting conditions

J. van Duijnhoven[a], M.P.J. Aarts[a], E.R. van den Heuvel[b], H.S.M. Kort[c,d]

a Building Lighting Group, Department of the Built Environment, Eindhoven University of Technology, Eindhoven, The Netherlands
b Stochastics, Department of Mathematics and Computer Science, Eindhoven University of Technology, Eindhoven, The Netherlands
c Research Centre Healthy and Sustainable Living, University of Applied Sciences Utrecht, Utrecht, The Netherlands
d Building Healthy Environments for Future Users Group, Department of the Built Environment, Eindhoven University of Technology, Eindhoven, The Netherlands

j.v.duijnhoven1@tue.nl

Abstract. The discovery of the ipRGCs was thought to fully explain the mechanism behind the relationship between light and effects beyond vision such as alertness. However, this relationship turned out to be more complicated. The current paper describes, by using personal lighting conditions in a field study, further exploration of the relationship between light and subjective alertness during daytime. Findings show that this relationship is highly dependent on the individual. Although nearly all dose-response curves between personal lighting conditions and subjective alertness determined in this study turned out to be not significant, the results may be of high importance in the exploration of the exact relationship.

1. Introduction

The discovery of the ipRGCs in 2002 was thought to fully explain the mechanism behind the relationship between light and effects beyond vision such as alertness [1]. However, this relationship turned out to be more complicated. Dose-response curves were developed for night-time alertness and other circadian markers whereas this relationship was inconclusive for daytime situations [2]–[4]. The execution of light effect studies including different lighting conditions is time-consuming and complicated. To overcome this issue, a new approach has been proposed to include personal lighting conditions when light-induced effects beyond vision are to be investigated. Personal lighting conditions are continuously measured lighting conditions at the individual level. The study described in this paper is part of a larger field study [5], [6]. The current paper describes further exploration of the relationship between light and subjective alertness. The following research questions were addressed in this study:

- What is the relationship between light levels (illuminances and luminous exposures; vertically measured close to the eye) and subjective alertness?
- What is the relationship between correlated colour temperature (vertically measured close to the eye) and subjective alertness?
- What is the relationship between the duration of light exposure and subjective alertness?

First, it is expected that a higher light level correlates with higher subjective alertness [4], [7]. Second, correlated colour temperature is not expected to correlate significantly with subjective alertness [4], [8]. However, bearing in mind the different spectral sensitivity curve for ipRGCs compared to the photopic curve for vision, some trends may be expected. And third, it is expected that the duration of light exposure influences light effects beyond vision [9]. Although, there have been several studies proving the opposite [10], [11].

2. Methodology

The field study took place in the Netherlands. Sixty-two office workers (49.7 ± 11.4 years old) participated each ten working days in spring 2017. The participants were asked to wear a light measurement device (Lightlog, [12]) vertically oriented at chest level throughout the entire day (from wake time till bed time), keep a diary of their locations and activities, and fill in a survey four times a day. The Karolinska Sleepiness Scale was deployed to investigate subjective alertness. The full study design including the office environment, the (recruitment of the) participants, the protocol, and the data processing is described in a previous paper [5].

2.1. Data analysis

In the exploration of the relationship between light and subjective alertness, the lighting conditions at certain moments relative to the moment the participants filled in the alertness questionnaire were linked to these subjective alertness values. Nine light measures were calculated and included in the analysis:

- The mean illuminance over the 20 minutes before filling in the alertness questionnaire ($\bar{E}_{20\ min}$);
- The mean illuminance over the hour before filling in the alertness questionnaire ($\bar{E}_{1\ hour}$);
- The mean illuminance over two hours before filling in the alertness questionnaire ($\bar{E}_{2\ hours}$);
- The mean illuminance from start wearing the Lightlog that day till the moment of filling in the alertness questionnaire ($\bar{E}_{day}$).
- The total luminous exposure received in the 20 minutes before filling in the alertness questionnaire ($H_{20\ min}$);
- The total luminous exposure received in the hour before filling in the alertness questionnaire ($H_{1\ hour}$);
- The total luminous exposure received in the two hours before filling in the alertness questionnaire ($H_{2\ hours}$);
- The total luminous exposure received from start wearing the Lightlog that day till the moment of filling in the alertness questionnaire (H_{day}).
- The mean correlated colour temperature over the 20 minutes before filling in the alertness questionnaire ($\overline{CCT}_{20\ min}$).

These nine measures are called *light measures* in the remainder of this paper.

The durations for which the light measures were calculated were chosen because Vandewalle, Maquet, and Dijk (2009) suggested that exposure to light can modulate brain activities (e.g., alertness) after 20 minutes [13]. The longer durations were added to examine the effect of duration of light exposure on the relationship between light and alertness.

2.2. Statistical analysis

The statistical analysis consisted of three main steps:

1. Basic descriptive statistics were calculated for subjective alertness and the nine light measures. In addition, Kendall's tau correlation coefficients were calculated for the relationships between the light measures and subjective alertness.

2. The repeated data of subjective alertness and the light measures of individuals was analyzed with a non-linear mixed model in the form of a sigmoidal curve of the light measure. The model existed of a subject-specific dose-response curve. The model can be written as Equation 1.

$$Y_i = \mu_i + e_i \tag{1}$$

Where:
Y_i = The measured subjective alertness of participant i;
μ_i = The expected value for subjective alertness of participant i;
e_i = The residual with ei ~ N(0,σ2)

The expected value μ_i is assumed to be of the form as shown in Equation 2. The subjective alertness (Y_i) was subtracted with 1 (the scale was transformed to 0-8 instead of 1-9) to increase the fit of the model. This transformation explains value 1 in Equation 2.

$$\mu_i \equiv \mathbb{E}(Y_i \mid X_i = x) = 1 + M \times exp\{Z_{0i} + Z_{1i}x\}/[1 + exp\{Z_{0i} + Z_{1i}x\}] \qquad (2)$$

Where:
μ_i = The expected value for subjective alertness of participant i;
x_i = The (transformed or scaled) light measure of participant i;
1+M = The unknown maximal possible value of Y_i (lowest subjective alertness);
M = The range of possible subjective alertness values;
Z_{0i} = The Y-intercept for the individual dose-response curve (varies per participant);
Z_{1i} = The slope for the individual dose-response curve;
(Z_{0i},Z_{1i}) bivariate normally distributed with $\begin{pmatrix} Z_{0i} \\ Z_{1i} \end{pmatrix} \sim N\left(\begin{pmatrix} \beta_0 \\ \beta_1 \end{pmatrix}, \begin{pmatrix} \tau_0^2 & \rho\tau_0\tau_1 \\ \rho\tau_0\tau_1 & \tau_1^2 \end{pmatrix}\right)$

At first, it was investigated whether a (logarithm) transformation of the light measures was necessary for the light measures to be inserted in the model (Equation 1). This evaluation was conducted with the corrected Akaike's information criterion (AICC). Low values of the AICC indicate a good fit [14]. Deciding about this choice resulted in a common choice for all observed light intensities. The estimates (and their 95 % confidence intervals) of the model parameters were determined. The coefficients of determination (R^2) of the fitted models were also established, using linear regression analysis on the observed subjective alertness and the predicted subjective alertness from the fitted models.

3. The percentage of participants that have an individual negative slope (i.e. Z_{1i}<0) was calculated. This negative slope would imply that higher light measures would increase subjective alertness (lower values on Y_i, as the KSS scale runs from 1 (extremely alert) to 9 (extremely sleepy)). This direction is according to expectations based on literature. The significance of the random slope was tested using likelihood ratio tests, to understand if the steepness of the dose-response curve changes with participants. The likelihood ratio test determines whether the differences between the slopes of the individual curves (τ_1^2) differ significantly from 0.

3. Results

3.1. Descriptive statistics

Table 1 provides the descriptive statistics of subjective alertness and the nine light measures. Although the correlations between H_{day} and subjective alertness and between $\overline{CCT}_{20min}$ were found to be significant, the correlation coefficients show that this correlation was in both cases negligible (i.e., $\tau \leq |0.1|$).

Table 1: Descriptive statistics. The correlation coefficients (Kendall's tau and corresponding significance levels) describe the correlation between the light measure and the subjective alertness. The abbreviations for the light measures were described in the methods section. * indicates statistical significance (p<.05)

(Light) measure	**Mean**	**Standard deviation**	**Kendall's tau correlation coefficient**	**Significance level (of correlations with subjective alertness)**
Subjective alertness (on original KSS scale 1—9)	3.037	1.278	1.000	N/A
$\bar{E}_{20\ min}$ [lx]	749.3	2618	-.025	.153
$\bar{E}_{1\ hour}$ [lx]	924.9	2529	-.019	.291
$\bar{E}_{2\ hours}$ [lx]	2056	4512	.007	.697
$\bar{E}_{day}$ [lx]	996.0	1274	.013	.476
$H_{20\ min}$ [lxh]	248.6	872.6	-.026	.141
$H_{1\ hour}$ [lxh]	936.0	2532	-.019	.288
$H_{2\ hours}$ [lxh]	1088	2370	.002	.907
H_{day} [lxh]	5301	7446	.07*	<.001
$\overline{CCT}_{20\ min}$ [K]	4342	875.9	-.038*	.032

3.2. Dose-response curves light and subjective alertness

Non-linear mixed models, in the form of sigmoidal curves, were determined demonstrating subject-specific dose-response curves between subjective alertness and each of the light measures. No transformation on the light measures was needed for the dose-response model. A logarithmic transformation of the light measure was only better for the light measures $H_{2\ hours}$, H_{day}, and $\bar{E}_{day}$, but not for the other six light measures. Nevertheless, all light measures were numerically scaled by 25000 to enable easier interpretation of the dose-response curves. The parameter estimates of the determined models are reported in relative rates in Table 2.

Table 2: Parameter estimates for determined models for the relationship between the nine light measures (scaled by 25000) and subjective alertness. All model parameters can be found in the model specifications (see Equation 1 and Equation 2). The abbreviations for the light measures were described in the method section. * indicates statistical significance (p<.05)

Light measure (scaled)	Fixed parameters			Covariance parameters			
	M	**β_0**	**β_1**	**τ_0**	**τ_1**	**ρ**	**σ**
$\bar{E}_{20\ min}$ [lx]	6.30 [2.43;10.2]	-0.81 [-1.76;0.14]	0.43 [-0.43;1.30]	0.61 [0.36;0.85]	1.32 [0.29;2.35]	-0.14 [-0.73;0.46]	0.99 [0.96;1.03]
$\bar{E}_{1\ hour}$ [lx]	6.98 [1.54;12.4]	-0.96 [-2.09;0.18]	0.11 [-0.49;0.70]	0.57 [0.33;0.81]	0.91 [0.16;1.67]	0.11 [-0.53;0.75]	1.00 [0.96;1.03]
$\bar{E}_{2\ hours}$ [lx]	6.46 [2.21;10.7]	-0.82 [-1.83;0.19]	-0.20 [-0.51;0.11]	0.61 [0.36;0.87]	0.46 [0.05;0.88]	-0.43 [-0.98;0.11]	1.00 [0.96;1.03]
$\bar{E}_{day}$ [lx]	6.54 [2.05;11.0]	-0.84 [-1.89;0.20]	-0.35 [-1.33;0.62]	0.60 [0.35;0.86]	0.95 [0;2.47]	-0.31 [-1.25;0.64]	1.00 [0.96;1.03]
$H_{20\ min}$ [lxh]	6.38 [2.22;10.6]	-0.83 [-1.83;0.16]	-1.24 [-1.39;3.87]	0.61 [0.36;0.86]	4.01 [0.90;7.13]	-0.11 [-0.71;0.50]	0.99 [0.96;1.02]
$H_{1\ hour}$ [lxh]	6.93 [1.64;12.2]	-0.94 [-2.06;0.17]	0.10 [-0.49;0.68]	0.57 [0.33;0.81]	0.89 [0.14;1.63]	0.11 [-0.53;0.75]	1.00 [0.96;1.03]
$H_{2\ hours}$ [lxh]	6.58 [2.06;11.1]	-0.85 [-1.89;0.20]	-0.39 [-0.98;0.19]	0.61 [0.35;0.86]	0.88 [0.10;1.65]	-0.41 [-0.96;0.15]	1.00 [0.97;1.03]
H_{day} [lxh]	5.38 [3.49;7.28]	-0.62* [-1.22;-0.01]	0.32* [0.08;0.55]	0.68 [0.45;0.91]	0.36 [0.05;0.67]	-0.01 [-0.61;0.60]	0.99 [0.95;1.02]
$\overline{CCT}_{20\ min}$ [K]	6.58 [1.90;11.3]	-0.81 [-1.91;0.29]	-0.31 [-1.52;0.90]	0.55 [0.17;0.93]	0.34 [0;5.64]	0.57 [-1;1]	1.00 [0.97;1.04]

The estimate of the average slope of all individuals (β_1) was nearly never significant at the level of 0.05 (i.e. the 95 % confidence interval often contained the value zero). Only the average slope between H_{day} and subjective alertness was significant. This means that on average there are no dose-response relationships between subjective alertness and the other eight light measures. Table 3 presents for which light measure individuals have their own slope. A significant (p<.05) Likelihood Ratio test indicated that the differences in slopes for the individual dose-response curves (τ_1^2) differ from 0. The significant differences in the slopes for $\bar{E}_{20\ min}$, $\bar{E}_{1\ hour}$, $H_{20\ min}$, and $H_{1\ hour}$ suggest that the relationship between these light measures and subjective alertness is highly dependent on the individual. In addition, the table also provides the percentage of the participants with a negative slope and the predictive power of the fitted model (R^2).

Table 3: Characteristics of the subject-specific dose-response model. * indicates statistical significance (p<.05)

Variable	The R^2 value of subject-specific dose-response model	Percentage of participants with a negative slope	Likelihood Ratio Test	
			Test statistic	**P-value**
$\bar{E}_{20\ min}$ [lx]	39.5 %	14.5 %	13.9*	<.001
$\bar{E}_{1\ hour}$ [lx]	39.3 %	30.7 %	7.3*	.017
$\bar{E}_{2\ hours}$ [lx]	39.2 %	77.4 %	4.7	.064
$\bar{E}_{day}$ [lx]	38.4 %	85.5 %	1.0	.410
$H_{20\ min}$ [lxh]	39.8 %	12.9 %	14.1*	<.001
$H_{1\ hour}$ [lxh]	39.0 %	30.7 %	7.0*	.020
$H_{2\ hours}$ [lxh]	39.1 %	83.9 %	5.2	.050
H_{day} [lxh]	40.1 %	3.2 %	4.0	.089
$\overline{CCT}_{20\ min}$ [K]	37.8 %	95.2 %	0.1	.638

4. Discussion

In this paper, the relationships between personal lighting conditions and subjective alertness were investigated. Subject-specific dose-response curves were developed but showed not to be significant in most of the investigated cases.

First, it was expected that alertness levels would increase for increasing light levels. This relationship was expected for a certain moment of the day with a certain limit for the maximum alertness value. However, all but one average dose-response curves between light measures and subjective alertness showed that there was no significant relationship. The average dose-response curve between H_{day} and subjective alertness was the only one found to be significant. As Table 3 shows, the relationship highly depended on individuals. Although numerous studies reported significant differences between dim and bright light conditions, Souman et al. (2018) reported that 17 of the included 45 studies in their review failed to find a significant effect [4]. They reported that this could have occurred due to too high light levels for the dim conditions and this may have occurred in the current field study as well. Since the lighting conditions in the field study were not controlled, the range of illuminances may have been too small to find significant effects. This suggests that, if the range of personal lighting conditions has to be larger to find a significant relation between illuminances and subjective alertness, it may be very difficult to relate the illuminances of personal lighting conditions of office workers to subjective alertness during daytime. Lok, Woelders, et al. (2018) and Smolders et al. (2018) also tried to develop a dose-response curve between light and alertness during daytime [2], [3]. Lok, Woelders, et al. (2018) reported that the effects of light on alertness during daytime were found to be small if present at all and Smolders et al. (2018) found no clear dose-response curve between 1 hour light exposure and alertness.

Second, the dose-response curves for the relation between the correlated color temperature and subjective alertness showed that this relation was also found to be not significant. Souman et al. (2018) reported that four out of the seven papers included in their review demonstrated a significant effect on subjective alertness with higher correlated colour temperatures [4], suggesting that this relationship is not yet consistently proven. In some studies, even a trend towards the opposite direction of the relationship (a higher correlated colour temperature correlating with lower subjective alertness) was found [9]. Although the dose-response curves between $CCT_{20\ min}$ and subjective alertness in this study were not significant, the direction of the dose-response curve was found to be negative for 95.2 % of the participants indicating that a higher correlated colour temperature corresponded to higher subjective alertness.

And last, the influence of the duration of light exposure on the relation between personal lighting conditions and subjective alertness was investigated. Table 3 shows that, although nearly all dose-response curves were not significant, the percentage of participants with a negative slope (in line with the expectations) increased with an increasing duration. This was the case for all the measures of illuminance and luminous exposure except H_{day}. This may be explained by the variation in the duration of the day in the cumulative light measure H_{day}. The daily luminous exposure was represented in this paper as the luminous exposure from the moment the participants started wearing the device until the moment they filled in the alertness questionnaire. For only 14.5 % of the participants, a negative dose-response curve was found for the relation between $\bar{E}_{20\ min}$ and subjective alertness whereas this was for 85.5 % of the participants for the relation between $\bar{E}_{day}$ and subjective alertness. This suggests that personal lighting conditions averaged over the entire day were relevant to the subjective alertness of the individual.

4.1. Limitations of the study

This study contained some limitations that need to be considered carefully when interpreting the findings of this paper. First, to thoroughly investigate the relationship between personal lighting conditions and subjective alertness, both the personal lighting conditions and the subjective alertness levels need to vary sufficiently. It may be that the personal lighting conditions had a too high or low starting point or a too small range and this may have caused that the relationship was not found to be significant. Since initial lighting conditions may influence light effects on and beyond vision and the lighting preferences of the office worker [15], the starting points of personal lighting conditions may have influenced their feelings of alertness. Furthermore, it may be that the subjective alertness dataset did not suffice. The mean alertness level of participants was relatively high (3.0, which stands for 'alert' on the KSS scale, see Table 1) and moreover the alertness levels may not have varied enough (standard deviation of 1.3, see Table 1). Second, the timing of light exposure was not included in the analyses. All alertness questionnaires were filled in during office hours so it is certain that all dose-response curves concern daytime situations. It would have been relevant to split the entire data set in clusters per time of the day (09:00, 11:00, 14:00, and 16:00).

5. Conclusions and recommendations for further research

Although nearly all dose-response curves between personal lighting conditions and subjective alertness determined in this study turned out to be not significant, the results may be of high importance in the exploration of the exact relationship between personal lighting conditions and subjective alertness. This study demonstrated that the duration of light exposure may be relevant in this relationship. Since this study showed negligible relationships between personal lighting conditions and subjective alertness whereas some other studies did find this significant relationship, it is of high importance to keep performing light effect studies during daytime to get more insight in this relationship. Future studies should consider larger ranges for personal lighting conditions (e.g. by performing the study during multiple seasons or by including office buildings that have a wider variety in lighting conditions inside the buildings) and objective measures for subjective alertness in order to further explore the relationship between personal lighting conditions and subjective alertness during daytime.

Acknowledgments

This research was performed within the framework of the strategic joint research program on Intelligent Lighting between TU/e and Koninklijke Philips N.V. and the Impuls II SPARK program.

References

[1] D. M. Berson, F. A. Dunn, and M. Takao, "Phototransduction by retinal ganglion cells that set the circadian clock.," Science, vol. 295, no. 5557, pp. 1070–3, 2002, doi: 10.1126/science.1067262.
[2] R. Lok, T. Woelders, M. C. M. Gordijn, R. A. Hut, and D. G. M. Beersma, "White Light During Daytime Does Not Improve Alertness in Well-rested Individuals," J. Biol. Rhythms, vol. 33, no. 6, pp. 637–648, Dec. 2018, doi: 10.1177/0748730418796036.
[3] K. C. H. J. Smolders, S. T. Peeters, I. M. L. C. Vogels, and Y. A. W. de Kort, "Investigation of Dose-Response Relationships for Effects of White Light Exposure on Correlates of Alertness and Executive Control during Regular Daytime Working Hours," J. Biol. Rhythms, vol. 33, no. 6, pp. 649–661, Dec. 2018, doi: 10.1177/0748730418796438.
[4] J. L. Souman, A. M. Tinga, S. F. te Pas, R. van Ee, and B. N. S. Vlaskamp, "Acute alerting effects of light: A systematic literature review," Behav. Brain Res., vol. 337, pp. 228–239, 2018, doi: 10.1016/J.BBR.2017.09.016.
[5] J. van Duijnhoven, M. Aarts, and H. Kort, "Personal lighting conditions of office workers: An exploratory field study," Light. Res. Technol 2021; 53(4), doi: 10.1177/1477153520976940.
[6] J. van Duijnhoven, M. Aarts, E. van den Heuvel, and H. Kort, "The identification of variables influencing personal lighting conditions of office workers," Light. Res. Technol., Dec. 2020, doi: 10.1177/1477153520976950.
[7] C. Cajochen, J. M. Zeitzer, C. A. Czeisler, and D. J. Dijk, "Dose-response relationship for light intensity and ocular and electroencephalographic correlates of human alertness.," Behav. Brain Res., vol. 115, no. 1, pp. 75–83, Oct. 2000, doi: 10.1016/S0166-4328(00)00236-9.
[8] K. C. H. J. Smolders and Y. A. W. de Kort, "Investigating daytime effects of correlated colour temperature on experiences , performance , and arousal," J. Environ. Psychol., vol. 50, pp. 80–93, 2017, doi: 10.1016/j.jenvp.2017.02.001.
[9] K. Dewan, S. Benloucif, K. Reid, L. F. Wolfe, and P. C. Zee, "Light-Induced Changes of the Circadian Clock of Humans: Increasing Duration is More Effective than Increasing Light Intensity," Sleep, vol. 34, no. 5, pp. 593–599, 2011, doi: 10.1093/sleep/34.5.593.
[10] A.-M. Chang et al., "Human responses to bright light of different durations," J. Physiol., vol. 590, no. 13, pp. 3103–3112, 2012, doi: 10.1113/jphysiol.2011.226555.
[11] K. C. H. J. Smolders, Y. A. W. de Kort, and P. J. M. Cluitmans, "A higher illuminance induces alertness even during office hours: findings on subjective measures, task performance and heart rate measures.," Physiol. Behav., vol. 107, no. 1, pp. 7–16, 2012, doi: 10.1016/j.physbeh.2012.04.028.
[12] G. Martin, "LightLog – Brighten your day," 2015. [Online]. Available: http://lightlogproject.org/.
[13] G. Vandewalle, P. Maquet, and D.-J. Dijk, "Light as a modulator of cognitive brain function," Trends Cogn. Sci., vol. 13, no. 10, pp. 429–438, 2009, doi: 10.1016/J.TICS.2009.07.004.
[14] A. Field, Discovering Statistics Using SPSS - 3rd Edition. London: SAGE Publications, 2009.
[15] M. G. Kent, S. Fotios, and S. Altomonte, "Discomfort glare evaluation: The influence of anchor bias in luminance adjustments," Light. Res. Technol., vol. 51, no. 1, pp. 131–146, 2019, doi: 10.1177/1477153517734280.