Subjective Ratings of Biological Effective Light in Seminar Rooms and How to Handle Small Sample Sizes of Ordinal Data

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Abstract. Our field study was conducted to examine the influence of biologically effective lighting in students' natural environment. A group of 21 regular master students were exposed to two different lighting scenarios. A developed questionnaire was used to collect subjective ratings according to overall indoor environmental quality. Data produced with questionaires are ordinal data. To analyse this type of data, especially with small sample sizes, an adequate statistical method is needed. This paper uses selected data from the field study to introduce one method based on rank data. Three questions were analysed to compare the subjective ratings of our probands according to the new biologically effective lighting. German seminar rooms or classrooms are built with a high daylight factor. Daylight is a strong confounder for field studies in rooms like that, which can't be controlled in a very good way. We know from other studies that the concentration of carbon dioxid is a second very strong confounder which must be considered. Typical classrooms with 60 - 80 m^2 furthermore limit the sample sizes. As well as know from other lab and controlled field studies that there can be measurable effects in the protection of health. Further testing with classrooms with a less daylight factor or in regions of less daylight might promise a better advantage to students.

Keywords: Seminar room · Artificial lighting · Blue-enriched white light · Illuminance · Indoor environmental quality · Small sample size · Ordinal data · Statistical method

1 Introduction

Light is more powerful than most of us would have recognized until the early nineties of the last century. Light with a high illuminance level and daylight-white coloured leads to an increased alertness [1]. Light is able to increase the performance of night shift workers [2–4]. And Fleischer showed that light could be used to increase the vigilance [5]. Especially since Brainard et al. [6] and

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Thapan et al. [7] in 2001 independently published that the exposure of light, especially the blue spectra, could cause melatonin suppression in humans; a new field of research for different groups of interest was born. Besides medical scientists, psychologists and biologists, engineers and architects are also involved in answering questions about how light influences humans [1].

Very interesting is the fact that in the world of science only two studies has been known up until January 2008 dealing with modern artificial lighting systems; they are neon tubes and their effects at schools [1]. The first study took place in Sweden. Two objectives were declared: how light effects the production of stress hormones and classroom performance. The authors used observational techiques to operationalize the ability to concentrate. They found out, that there must be a systematic seasonal variation of stress hormones (with higher levels in summer than in winter). Moderate or low levels of stress hormones appeared to increase individual concentration, they concluded [8].

Secondly an elemantary school in Manchester was equipped with dynamic lighting. No effects could be found, [9] cited in [1]. In the meantime since 2008, more results were published in this context. The effects of variable lighting (variable in illuminance and colour temperature) on students' performance and attitude were investigated at the University Medical Center Hamburg-Eppendorf. Barkmann et al. found out, that students "made fewer errors, particularly fewer errors of omission", by using a standardized test of attention [10] and a special light program called "Concentrate" (very bright, cold light: 1.060 lx, 5.800 K) [11]. The "reading speed" (...) "rose significantly" and "students and teachers rated" the new light "positively and found it useful" [ibidem]. This study was done with neon tubes as well.

A current paper investigated effects of light in two German high schools. To prove their hypotheses, they equipped two classrooms in each of the two schools with an LED lighting system. The system consisted of a direct part (OSRAM Siteco Quadrature II LED, CCT: 4.000 K) and an indirect part (customized LED modules, CCT: 14.000 K). Vertical illuminance levels, measured at the eye-level in sitting position, were about 300 lx and the correleted colour temperature (CCT) was about 5.500 K. Compaired with two standard classroom illuminations (First: 3.000 K and second: 3.500 K (at the eye-level)) the results show "beneficial effects of blue-enriched white light on students' performance". Keis et al. wrote that "in comparison to standard lighting conditions, students showed faster cognitive progressing speed and better concentration" [12]. Keis et al. [ibidem] used the same standardized test of attention [10] as Barkmann et al. [11]

Our objectives are increasing the rare knowledge about effects of dynamic light (variate illuminance and colour temperature by time) of students at universities (ages between 21 and 35) and adding the technical component of concentration of carbon dioxide into account, which seems to have been forgotten as a covariate in previous studies. We also used the standardized test of attention [10] mentioned above to be comparable, which is not part of this paper. Secondly, we used a questionaire to investigate students' subjective ratings of different indoor environmental quality parameters; they are lighting and carbon dixode, for example. By using questionaires (results are most of the time rank data at the ordinal level), one challenge is to find the right statistical method which is able to offer mathematically correct answers. We want to introduce a method based on rank data for small sample sizes of dependent groups to find in [15] and present some first results of our study according to subjective ratings of students corresponding to dynamic blue-enriched LED light in a seminar room in Munich.

2 Method

2.1 The Test Environment

At the Munich University of Applied Sciences, a typical German seminar room was rebuilt in summer of 2012. With the technically new equipped seminar room, it shall be possible to answer research questions according to biologically effective light on the one hand and, at the same time, indoor environmental quality parameters. The room is now equipped with 32 different types of sensors and measuring points. Besides the indoor air temperature, the indoor humidity and the concentration of carbon dioxide (all of them measured at three different spots), the illuminance inside (at each light band) and outside (in front of the facade) is measured. Some relevant dimensions are documentated as follows: ground area: 77,9 m^2, room depth: 9,0 m and percentage of transparent surface: 55,3 %, orientation: south-western. One of the aims was to create a test environment, in which the students do not feel like being in a lab. The study was set as a field study with all its difficulties. The subjects are real master students, using the seminar room the entire time for their readings. Figure 1 shows the rebuilt seminar room with two different types of lights switched on.

2.2 Light Sources

The seminar room is now equipped with a direct light part using 18 Lumilux T5 HE 35 W neon tubes with a correlated colour temperature of 3.000 K and an indirect part using 144 white and 72 blue light emitting diods (LED) with the possibility to scale the correlated colour temperatur from 6.500 K up to 13.000 K (at the ceiling). The whole system was built by OSRAM GmbH; Munich, Germany. Two different scenarios were programmed. The first curve is called "baseline". According to the former light system, the seminar room was equipped with an illuminance of 300 lx horizontal [16] and a correlated colour temperature of 3.000 K was programmed without any variation by time. A second curve called "dynamic light" starts with 100 lx (vertical at eyelevel) and goes up to nearly 300 lx. The correlated colour temperature starts at the level of 3.000 K and goes up to 5.000 K (also measured vertically at eyelevel). This level of correlated colour temperature equates to [17] which was released after the design of experiments was done. Figure 2 shows the two different light curves measured with Jeti Spectro-Radiometer specbos 1211 and closed blinds in February 2013.

Fig. 1. Photographic picture of the Munich seminar room with the biologically effective light system, the picture consists of two different parts: left: 100 % blue LEDs and 0 % white LEDs are switched on, right: 100 % white LEDs and 0 % blue LEDs are switched on. Between these two stages, the software calculates the dynamic curve which will be shown below (see: Fig. 2)

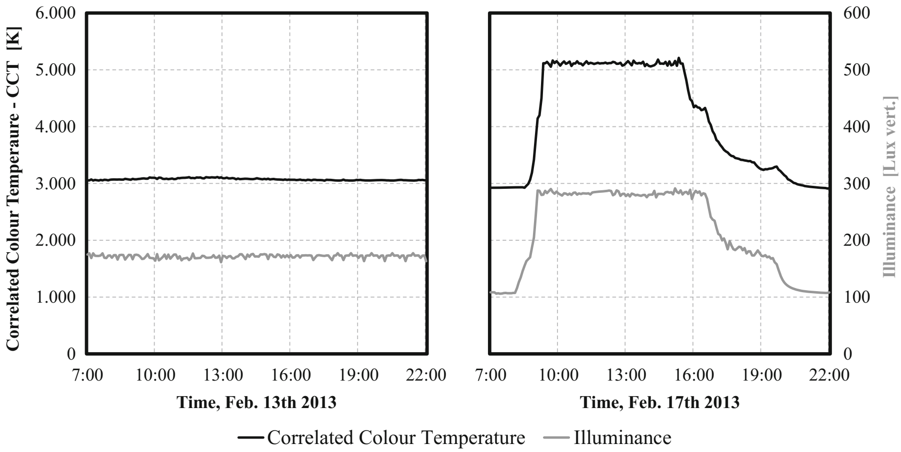

Fig. 2. Comparison of the two different light scenarios presented in the lecture hall, left: baseline, right: dynamic curve, all of them measured between two light bands at 1,20 m and a Jeti Spectro-Radiometer specbos 1211

2.3 Chosen Questions

We chose three questions out of the survey instrument to show some first results out of the Munich field study regarding subjective rating of biologically effective light in seminar rooms. To evaluate the data a special method is needed, we want to use this paper to demonstrate a predestined method as well. First of all, we asked the students to rate the importance of indoor air quality for their well-being. Within same question, they were able to rate the importance of artificial light. We asked them to rate how they like the different light settings and, finally, to rate their subjective performance efficiency. (cf. Figure 3)

Q_1 (Importance)

Would you please rate the importance of (***) for your well-being?

A: Indoor Air Quality B: Artificial lighting

Code:	1	2	3	4	5
Possibilities:	extremely important	important	neutral	not important	absolutely unimportant

Q_2 (Favor)

How do you like the artificial lighting system this week?

Code:	1	2	3	4	5
Possibilities:	not a bit	rather bad	neutral	rather good	very good

Q_3 (Efficiency)

At the moment… I feel efficient.

Code:	1	2	3	4	5
Possibilities:	completely	predominant	moderate	less	not at all

Fig. 3. Selected questions the subjects answered according to the artificial lighting system in their lecture hall

2.4 Helpful Method to Calculate Statistics for Small Sample Sizes of Ordinal Data

There are a lot of statistical methods for handling data with ratio or interval scales. To answer research questions with data like this, a scientist may choose a well-known method like a t-test or multifactorial tests like ANOVA depending on the test setting and the research questions. One reason for the large amount of test procedures is that ratio and interval data allow for all mathematical operations with raw data because of the degree of information given by the data. One classic method for testing hypotheses of nonparametric dependent data is the well known Wilcoxon-test. Bortz and Lienert indicate that this method demands at least cardinal scale level (interval or ratio scale) and the test *should* not be used for ordinal scaled data [13]. At page 200 [ibidem] they claim that the Wilcoxon-test used with ordinal data could lead to wrong conclusions. An example for that possibility could be found in [14]. Brunner et al. wrote more concretly that the application of the Wilcoxon-test is *not allowed*, because of calculating differences in using raw data [15]. The authors introducing some different methods for different settings in their book, based on *Nonparametric Marginal Models*. For the exact derivations and further details please look into [ibidem].

Estimation of Relative Treatment Effects (short: RTE). The so called relative treatment effect $p_i = \int H dF_i$ for the group i is estimated after some mathematical conversions Brunner et al. [ibidem] did, by $\hat{p}_i$ as follows

$$\hat{p}_i = \int \hat{H} d\hat{F}_i = \frac{1}{n_i} \sum_{k=1}^{n} \hat{H}(X_{ik}) = \frac{1}{N} \left(\overline{R}_i - \frac{1}{2} \right) \tag{1}$$

Here, $\overline{R}_i = \frac{1}{n_i} \sum_{k=1}^{n} R_{ik}$ is the arithmetic mean of the ranks in the ith experimental group and R_{ik} is the rank of X_{ik} among all $N = \sum_{i=1}^{a} n_i$ observations $X_{11}, ..., X_{an_a}$. [ibidem]

The Hypothesis $H_0^F : F_1 = F_2$

In what follows, R_{ks} denotes the rank of $X_{ks}, k{=}1, ..., n,\ s{=}1, 2$, among all $N = 2n$ observations and $\overline{R}_.s = n^{-1} \sum_{k=1}^{n} R_{ks}$ the mean of the ranks, $s = 1, 2$. The ranks used for the computation of the statistics are taken from a special layout you will find in [15] at page 25. Let

$$S_{n,0}^2 = \frac{1}{n-1} \sum_{k=1}^{n} (R_{k2} - R_{k1} - \overline{R}_2 + \overline{R}_1)^2 \tag{2}$$

denote the empirical variance of the rank differences $R_{k2} - R_{k1}, k = 1, ..., n$. Then, for large samples, the statistic

$$T_n^F = \sqrt{n} \frac{\overline{R}_2 - \overline{R}_1}{S_{n,0}} \tag{3}$$

has a standard normal distribution $N(0, 1)$ under the hypothesis H_0^F. [ibidem] "For small sample sizes, one approximates the distribution of the statistics T_n^F under H_0^F with a central t_{n-1}-distribution. Simulation studies show that this approximation is fairly accurate for $n \geq 7$ and continuous distributions. For discrete distributions, the quality of the approximation naturally depends on the number of ties. For $n \geq 15$, however, the approximation is satisfactory if not too many ties are present". [ibidem]

3 Results

3.1 Answers of the Subjects, Coded into Rank Data

In the winter semester 2013/14 our questionaire was presented each week for 12 weeks. All required indoor environmental quality parameters were measured per minute and the lighting scenarios alternated each week according Fig. 2. Each Thursday between 9 am and 12 am, the questoinaire was given to the students. For this paper, we chose one week (*base*) in October 2013 (21st until 25th, Baseline light) and one week (*dynamic*) in November 2013 (11th until 15th, Dynamic light). The remaining data show nearly the same results as it will be pointed out below (cf. Table 1). The corresponding rank values (R_1 and R_2) are calculated according to [13] page 41.

Table 1. Ordinal data given from the questionaire (x_1 and x_2), the results of the calculation of the corresponding rank postions (R_1 and R_2) and the rank means. IAQ means Indoor Air Quality

Subject	**Q_1 (Importance)**				**Q_2 (Favor)**				**Q_3 (Efficient)**			
	Baseline IAQ		Baseline Light		Baseline		Dynamic		Baseline		Dynamic	
	x_1	R_1	x_2	R_2	x_1	R_1	x_2	R_2	x_1	R_1	x_2	R_2
1	2	25,5	2	25,5	2	3	4	23,5	3	23,5	2	8
2	2	25,5	1	8	1	1	3	10	4	33	3	23,5
3	2	25,5	2	25,5	5	32	4	23,5	2	8	3	23,5
4	2	25,5	2	25,5	3	10	4	23,5	2	8	3	23,5
5	2	25,5	2	25,5	4	23,5	3	10	3	23,5	3	23,5
6	1	8	2	25,5	4	23,5	4	23,5	2	8	3	23,5
7	1	8	2	25,5	3	10	4	23,5	4	33	3	23,5
8	2	25,5	1	8	4	23,5	4	23,5	4	33	3	23,5
9	1	8	2	25,5	3	10	4	23,5	3	23,5	2	8
10	1	8	3	39	4	23,5	2	3	2	8	2	8
11	1	8	3	39	4	23,5	2	3	3	23,5	2	8
12	1	8	2	25,5	3	10	3	10	2	8	2	8
13	1	8	1	8	3	10	3	10	2	8	3	23,5
14	1	8	3	39	4	23,5	4	23,5	2	8	3	23,5
15	1	8	3	39	3	10	3	10	2	8	2	8
16	2	25,5	3	39	4	23,5	4	23,5	3	23,5	3	23,5
17	1	8	2	25,5	-	-	-	-	3	23,5	2	8
18	2	25,5	3	39	-	-	-	-	-	-	-	-
19	1	8	2	25,5	-	-	-	-	-	-	-	-
20	2	25,5	3	39	-	-	-	-	-	-	-	-
21	1	8	2	25,5	-	-	-	-	-	-	-	-
Rank means:		15,50		27,50		16,28		16,72		17,88		17,12

3.2 Statistical Results

Brunner et al. offer a macro to calculate the statistics via computer in [15]. The macro is called "LD_F1" (corresponding to the introduced model above) and can be downloaded at http://www.ams.med.uni-goettingen.de/sasmakr-ord-de.shtml. The macro has to be used in the statistics software SAS, but with the formulas above, comparable experiments could be calculated by hand. The results are shown in Table 2.

Table 2. Statistical parameters, computed by the statistics software SAS and a special macro called "LD_F1" [15] (IAQ means Indoor Air Quality, RTE means Relative Treatment Effect, see Eq. 1)

Subject	Q_1 (Importance)		Q_2 (Favor)		Q_3 (Efficient)	
	Baseline IAQ	Baseline Light	Baseline	Dynamic	Baseline	Dynamic
n_{sub}	21	21	16	16	17	17
n_{obs}	42		32		34	
Rank means	15,50	27,50	16,28	16,72	17,88	17,12
RTE *(eq. 1)*	0,357	0,643	0,493	0,507	0,511	0,489
Statistics:						
H_0^F *(eq. 3)*	3,830		0,146		-0,256	
t(n-1)	0,00105**		0,885		0,801	

** p < 0,01

4 Discussion

Küller and Lindsten concluded from their study in classrooms that "windowless classrooms should be avoided for permanent use" [8]. The tested seminar room within the present study has a percentage of transparent surface of more than 50 %, which is wonderful for getting enough daylight in. If the main focal point of a study is to determine effects of biologically effective light, however, it must be realized that **daylight** (in winter times as well) is a **strong confounder**. The outside illuminance in the direction of the south reached a maximum of 2.400 lx in week *base* (Thursday forenoon, by the time the questionaire was filled out). The mean illuminance inside was nearly 1.800 lx. In week *dynamic*, the outside illuminace reached 2.300 lx (Thursday forenoon), and the mean illuminance inside could be retained as nearly 1.500 lx. These values may influence the effects of artificial light in a strong way. A **second strong confounder** in school studies is the concentration of **carbon dioxide** indoors. Several studies showed that a high level of carbon dioxid reduce students performance [18]. The performance measured with the d2-test [10] is significant dependent on carbon dioxd, too [19]. Further light studies should consider that, as we did.

Barkmann et al. rudimentally described the building relavant to the parameters of their tested classrooms; they are the sizes of the used classrooms, the directions the windows face (school one: one to north and one to south, school two: both to west), school one has “standard window shapes” and in both schools the relevant windows “were equipped with simple curtains, which could be drawn during normal lessons when the sunlight coming in was especially intense” [11]. Keis et al. didn‘t write about building relavant parameters [12]. Both of the recent studies [11] and [12] didn‘t mention any results from measurements of outside conditions or real inside illuminance confounded by sunlight. Our experience is that in the special case of rooms (classroom, seminar rooms), daylight influences the experience of artifical light. How much the effects are actually confounded must be shown in future studies.

Nevertheless, we found a highly significant difference within the question about the importance of two different aspects of indoor environmental quality. The indoor air quality is “extremely important” said 57 % and 43 % said at least “important”. Compared to only 14 % who answered that light is “extremly important” and nearly one third gave a “neutral” answer to the question. This may mean that the real importance of the influence of light is not really common. No significant differences could be found within the question about students preferences between baseline and dynamic light. This may mean that they dont prefer a scenario and that significant differences within the students’ subjective ratings of their own performance efficiency cannot be found within this data. Although 59 % aswered to feeling “moderately” efficient and 41 % felt “predominantly” efficient during the week of dynamic light, whereas 18 % said they felt “less” efficient, 35 % “moderate” and 47 % ticked “predominant”.

5 Conclusion

Within this paper, we introduced a statistical method for calculating nonparametric dependent ordinal rank data with small sample sizes. The method is well known in the field of medical scientists and biologists, but not really in engineering science, as we had to realise. To offer engineers a possibility to evaluate subjective ratings of their building’s industry projects was one of our aims. Further publications will show our results of the standardized test of attention [10] we did as well, corresponding to the main building-physical covariates we determined: light scenario (daylight) and concentration of carbon dioxide indoors.

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