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Room- and illumination-related effects of an artificial skylight

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An artificial skylight has been developed which aims at creating an impression of a daylight opening in the ceiling by means of an artificial sunspot and a blue sky with perceived infinite depth. It is the goal of this work to compare and quantify the perceived room atmosphere created by this artificial system with that created by a conventional lighting system. A total of 100 subjects participated in a randomized controlled study within which the short-term effects on room lighting- and room atmosphere-appearance were determined. Both the artificial skylight and the resulting room atmosphere were perceived as very natural and attractive. Thus, the first strong evidence for the expected positive effects of this artificial skylight was determined.

1. Introduction

1.1 Effects of windows and daylight on humans

It is a well-established fact, scientifically derived, that people prefer windowed rather than windowless indoor environments and especially that windows with views to nature are important for psychological and physiological well-being and health.^{1–3} Three thorough reviews^{4–6} deliver a fundamental insight into the multitude of positive effects of windows in schools, industrial workplaces, offices and hospitals. Specifically, the following properties of windows such as providing a view to the outside, supporting knowledge of the weather and time of day, regulating air quality, reducing feelings of claustrophobia,⁷ monotony or boredom⁸ are responsible for the reported positive

effects, for instance supporting restorative processes after mental exhaustion,^{9,10} reducing self-rated stress,¹¹ improving mood,¹² enhancing executive cognitive functioning¹³ and self-regulation¹⁴ and increasing job satisfaction and the subjective ratings of self-productivity¹⁵ and of physical working conditions.^{16,17}

Employees in windowless offices often compensate for the lack of windows. Heerwagen and Orians¹⁸ were one of the first to investigate how people compensate for the lack of windows. They found that people without access to a real window view tended to use more visual materials (e.g. posters) than those with access to a window, and that the content of such materials was more likely to contain natural scenes and landscapes. In general, scientific analyses revealed four categories of potential window substitutes, namely other apertures (e.g. skylights), paintings/art, living things (e.g. plants) and light panels.

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1.2 Theories about being in contact with nature

Research on the effects of windows and views is mainly guided by three theories from the field of environmental psychology, namely the attention restoration theory, the psycho-evolutionary theory and the biophilia hypothesis. Attention restoration theory^{19,20} focuses on attentional processes that cause people to seek and benefit from restorative experiences by viewing nature. Directing attention to demanding tasks and dealing with disturbing environmental factors may lead to mental fatigue. In contrast, environments that provide a possibility for more undirected attention offer an opportunity to restore mental capacity and thus surroundings dominated by elements of nature are thought to be restorative.

Psycho-evolutionary theory^{21–23} argues that evolution has favoured those individuals who had an adaptive response to unthreatening natural environments that contained elements beneficial for well-being, stress reduction and restoring energy. Viewing unthreatening nature should therefore help people become restored from stress by reducing negative affect; decreasing physiological arousal and regaining psychological, social and physiological capacity.

A third often cited theory (biophilia hypothesis²⁴) about the effects of contact with nature on human health and well-being argues that people possess an inherent inclination to affiliate with natural processes and diversity. A tendency to add elements of nature seems to be a universal human feature and can presumably induce positively valued changes in cognition and emotion, which may further have an impact on the stress level, health and well-being.

1.3 Artificial daylight systems

As the majority of the world's population lives and works in increasingly urbanized environments where looking out of their

windows often means watching concrete buildings, parking lots and roads, this situation motivates the investigation as to whether artificial views could provide beneficial effects similar to those of real views to open landscapes. New light technologies have been developed in recent years that attempt to remedy this lack of windows with a view to nature. Primarily, technologies from the luminaire^{25–27} and display industries^{28,29} have been used for this purpose.

Mostly, the luminaires consist of large panels emitting diffuse light from light sources with correlated colour temperatures (CCT) greater than 6500 K. Sometimes these panels are used to backlight images of natural environments. In most cases, these luminaires vary light intensity and light colour subject to the time of day. Unfortunately, the light distribution of daylight is not imitated by these panels and hence while these systems are indeed suitable for room lighting purposes they do not generate a realistic impression of a natural daylight opening.

Conversely, the display industry tries to compensate for the lack of windows with bright large display arrays which reproduce real external situations captured with the aid of outdoor cameras. However, such monitors do not achieve naturalistic brightness levels and light distributions, and consequently create the impression of an artificial window with high technical complexity but are not suitable for room lighting purposes due to their low light output levels.

1.4 The artificial skylight CoeLux[®]

Over the last decade the Italian physicist Di Trapani and his team have developed an artificial skylight which reproduces the light distribution and visual appearance of the sun and sky indoors in a naturalistic way (see Figure 1). This innovative system is based on the physical reproduction of the phenomena that occur in the atmosphere and are designed to mimic daylight conditions,



Figure 1 Visual appearance of the artificial skylight



Figure 2 Close-up view of the skylight

both in transmitted sunlight and in diffused skylight components.

From a technological point of view, this system is composed of an artificial light source, spectrally very similar to the visible part of sunlight (CCT 5770 K), and of a nano-structured material which recreates the Rayleigh scattering process^{30,31} that occurs in the atmosphere. This scattering phenomenon (that produces the diffuse light) is regulated by an inverse fourth power law with respect to the wavelength. This means that the blue light is almost completely diffused, while the red component is nearly completely transmitted. In such a way, the two sources of natural light (sun and sky) are recreated. The optical design aims to achieve two effects at the same time: a strong and almost parallel light emitted by a circular source producing a uniform beam that enters the room while lighting the diffuser. As a result, the light distribution imitates the outdoor condition typical of a cloudless day: An intense yellowish light component (CCT 5000 K), which mimics the sun, lights the scene casting shadows of the illuminated object and, at the same time, the diffuse skylight component creates blue-toned shadows. Additionally, when gazing towards this lighting system, an observer can experience a

sky with indefinite depth (see Figure 2) and an artificial sun with the dimensions of the real one. Notably, a number of other details can be perceived that imitate nature: Penumbra colour and dimension, the change in shadow colour with the distance of the shadowing object, the apparent movement of the sun across the sky when the observer walks under the window and the brightness ratio of shaded and sunlit areas are only some examples.

Unlike the previously described systems, the CoeLux[®] system gives an impression of real skylight, both because of a realistic opening of the ceiling and of the levels of illumination and brightness. Also, the correctly dimensioned phenomena that occur immediately trick the brain and the light is perceived as coming from outdoors.

1.5 Aims of the study

This study aims at quantifying the appearance of this new artificial skylight and its induced subjective impression of the indoor environment, which is indirectly related to the expected effects on mood, cognition and physiology and to compare it with the effects of a conventional lighting system. Specifically, room atmosphere can significantly change the last mentioned parameters but in general these parameters are also influenced by many non-environmental



Figure 3 The standard room



Figure 4 The test room

factors (e.g. motivation, sleep status, etc.). Therefore, the perceived room atmosphere is expected to be a more stable concept than mood, cognition or physiological reactions and a good starting point to hypothesize about possible psycho-physiological effects of this new artificial skylight.

2. Method

2.1 Experimental setup

The test setup consisted of two adjacent windowless rooms of equal dimensions ($3\text{ m} \times 4\text{ m} \times 2.4\text{ m}$) and achromatic internal design and furniture in a laboratory building in Austria. One room was equipped with three conventional louvre luminaires (in the following called standard room (Figure 3)) and the second room was equipped with the artificial skylight (in the following called test room (Figure 4)), which simulated a daylight opening on the ceiling with a dimension of $80\text{ cm} \times 195\text{ cm}$.

The artificial sun simulated a sun altitude at noon in June in Austria and was kept in a constant position. By this measure we were able to control the spectrum, intensity and distribution of the light penetrating the mock-up room and thus provide time-invariant indoor illumination in each mock-up.

Within each mock-up, two work stations were installed. In the test room, additionally the seating position was varied so that one group of test persons sat in the shade and one group in the artificially sunlit part of the test room (Figure 4).

2.2 Lighting parameters

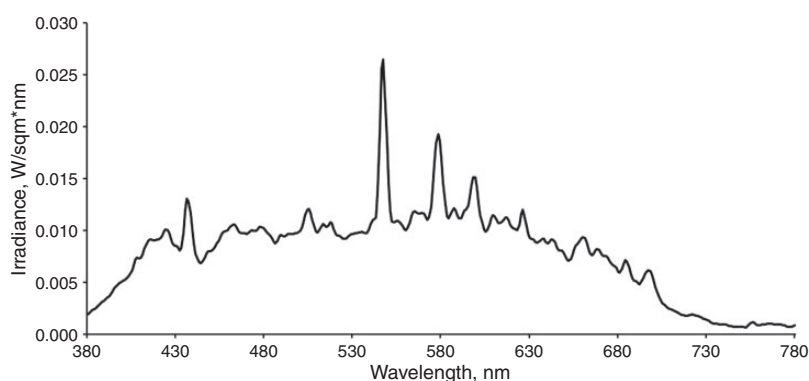
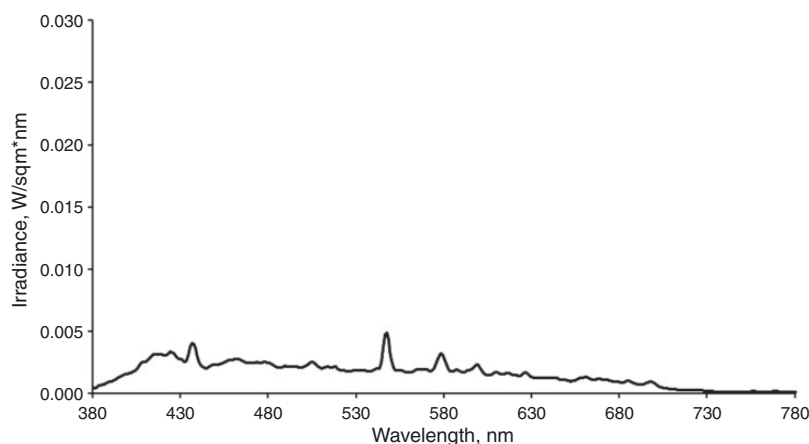
Illumination in the two mock-up rooms varied considerably from a photometric point of view due to the different lighting technologies used in the two rooms. Particularly, under the artificial skylight system illuminance uniformity was lower (the horizontal illuminances varied by a factor of more than 10 on the worktable) and the CCT differed remarkably within the mock-up room (4661 K where exposed to artificial sunlight and 7863 K under artificial skylight). To generate comparable illumination scenarios as far as possible, luminous flux levels and colour rendition properties were aligned in each test room. A detailed photometric characterization of the lighting scenarios can be found in Table 1.

2.3. Test procedure

Data collection within each mock-up room lasted for 1 hour within which three questionnaires (room lighting- and room atmosphere-related questionnaires and connected-to-

Table 1 Photometric documentation

	Light Spectrum	Other Photometric Measures
Test room – seating position ‘sun’	Figure 5	CCT ~ 4970 K, CRI ~ 88 Mean corneal illuminance = 850 lx Horizontal illuminance within working area: 1215 lux (min: 176 lux, max: 2239 lux) Light source technology: metal halide lamp (Philips MSR 575 HR) Luminous flux within mock-up (at 80 cm height): 5525 lumen
Test room – seating position ‘shade’	Figure 6	CCT ~ 7863 K, CRI ~ 91 Mean corneal illuminance = 150 lx Horizontal illuminance within working area: 1215 lux (min: 176 lux, max: 2239 lux) Light source technology: metal halide lamp (Philips MSR 575 HR) Luminous flux within mock-up (at 80 cm height): 5525 lumen
Standard room	Figure 7	CCT ~ 4661 K, CRI ~ 89 Mean corneal illuminance = 330 lx Horizontal illuminance within working area: 739 lux (min: 379 lux, max: 961 lux) Light source technology: fluorescent lamp Luminous flux within mock-up (at 80 cm height): 5050 lumen

**Figure 5** The spectral power distribution of the ‘sun’**Figure 6** The spectral power distribution of the ‘shade’

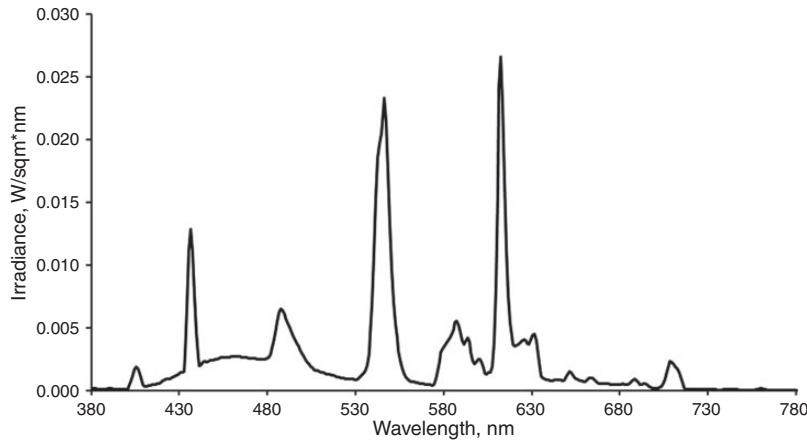


Figure 7 The spectral power distribution of the ‘standard’

nature questionnaire) were filled out at the beginning and the end of the light exposure. In between subjects executed a neurocognitive test sequence. The results of the surveys are described in detail in this publication. Lighting impacts on neurocognitive parameters will be published elsewhere in the near future.

Subjects adapted to the room lighting conditions for 5 minutes at the beginning. Adaptation took place in a seated position either at the fixed seating position in the standard room or at one of the two seating positions in the test room (‘shade’ or ‘sun’). After adaptation, the above-mentioned questionnaires were filled out on a computer screen. To limit visual impairments the screen was located on the desk with solely artificial skylight illumination. Afterwards subjects executed neuropsychological tests for approximately 45 minutes. After a short break of 3 minutes, subjects filled out the three questionnaires again.

Since the questionnaires were presented at the beginning and the end of the light exposure, short- and long-term impressions of the room lighting systems could be quantified. The subjects participated in a randomized controlled trial with a repeated measures cross-over design. Thus, all 100

subjects experienced the situation under the conventional lighting system and in the test room either in the seating position ‘sun’ ($n=40$) or seating position ‘shade’ ($n=60$). Data collection in each mock-up room lasted for 60 minutes. Before changing to the other mock-up room a short break of 15 minutes took place, where the test persons stayed outside the mock-up rooms but within the laboratory building. Data collection took place between 9:00 and 17:00 hours from Monday to Friday in February and March 2014.

2.4 Questionnaires

A slightly modified questionnaire, originally developed by Vogels,³² was applied to quantify the perceived room atmosphere. The questionnaire consisted of 38 atmosphere terms that had to be rated with respect to the room appearance on a four-point Likert scale (rating categories and numerical coding were 1 = ‘not at all’, 2 = ‘little’, 3 = ‘rather’ and 4 = ‘very’) instead of a seven-point Likert scale as in Vogel’s questionnaire. All items of this questionnaire are tabulated in Appendix B. In the original language (Dutch) and with its English and German translations.

A second questionnaire, developed by the authors, measured how participants perceived

and appreciated the room light appearance. Subjects had to rate six room lighting-related bipolar adjective pairs on a six-point Likert scale (ratings were coded numerically from 0 to 5). The item list, in English and German language, can also be found in Appendix C.

The third questionnaire included only one item,³³ namely ‘connectedness to nature’. Subjects had to rate this item on a four-point Likert scale (rating categories and numerical coding were 1 = ‘not at all’, 2 = ‘little’, 3 = ‘rather’ and 4 = ‘very’). Data collection took place in Austria and thus all questionnaires were in German language.

2.5 Subjects

One-hundred healthy subjects (without current medical treatment and medication) and with very good colour perception capabilities (tested with the Ishihara plates before study inclusion) were enrolled. If necessary subjects wore their vision aids (glasses or contact lenses) during the investigation. The mean age of the test persons was 28 years (minimum: 18 years; maximum: 67 years). Fifty-seven out of 100 test persons were female. All subjects gave their written informed consent before data collection started and were compensated for study participation with 50 Euro. All subjects were recruited by means of an advertisement notice at the local university, took part in lighting impact research for the first time and had never before seen CoeLux®.

2.6 Statistical data analysis

Three factorial analyses of variance with repeated measures were applied to all 45 items of the three questionnaires. Factor time, with the two levels ‘short-term effects’ and ‘long-term effects’ was integrated as a within factor, and the two factors light with the two levels ‘test room’ and ‘standard room’ and seating position with the two levels ‘test lighting with seating position sun’ and ‘test lighting with

seating position shade’ were integrated as between factors in this statistical analysis procedure. Subsequently, LSD *post-hoc* tests were calculated if necessary. All data were included in the statistical analysis after a check for outliers. The partial eta-squared (η_p^2) measure was used to report on the effect size (effect sizes are classified as small with $0.01 \leq \eta_p^2 < 0.06$, medium with $0.06 \leq \eta_p^2 < 0.14$ and large with $0.14 \leq \eta_p^2$). All graphs within this publication show mean values and standard error of the means. Standard deviations can be found in the corresponding tables. All significant differences due to the LSD *post-hoc* tests are drawn within the graphs. The level of significance (p-value) was fixed at 0.05. Statistical analyses were done using the software package STATISTICA 10.0.

3 Results

3.1. Room lighting-related effects

Room lighting was rated significantly more pleasant ($p < 0.001$) in the test room than in the standard room. Neither the factor time nor the interaction between light and seating position, nor the interaction between time, light and seating position reached the significance level. However, the interaction between time and light was significant ($p = 0.017$). Subjects perceived room lighting more unpleasant in the standard room after 1 hour stay ($p = 0.015$). This effect was not detected in the test room (see Figure 8).

Room lighting in the test room was rated more attractive ($p < 0.001$) and more natural ($p < 0.001$) than in the standard room. Statistical analysis did not reveal any significant time or interaction effects.

Glare ratings did not reach significance level between the test room and the standard room. Additionally, only one interaction (light $\times$ seating position) was significant ($p = 0.011$ – see Figure 9) and thus glare ratings were the same in the standard room and the test room in the seating position sun

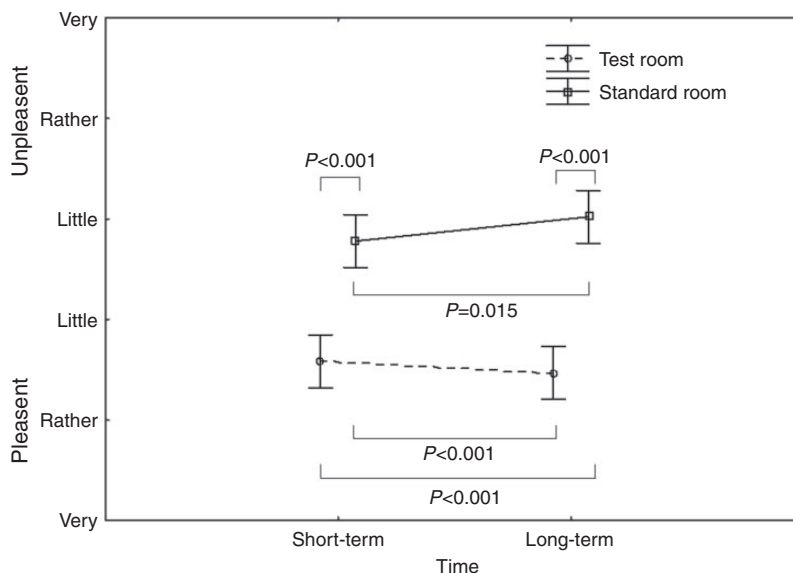


Figure 8 Interaction time $\times$ light (pleasant-unpleasant) – LSD *post-hoc* tests

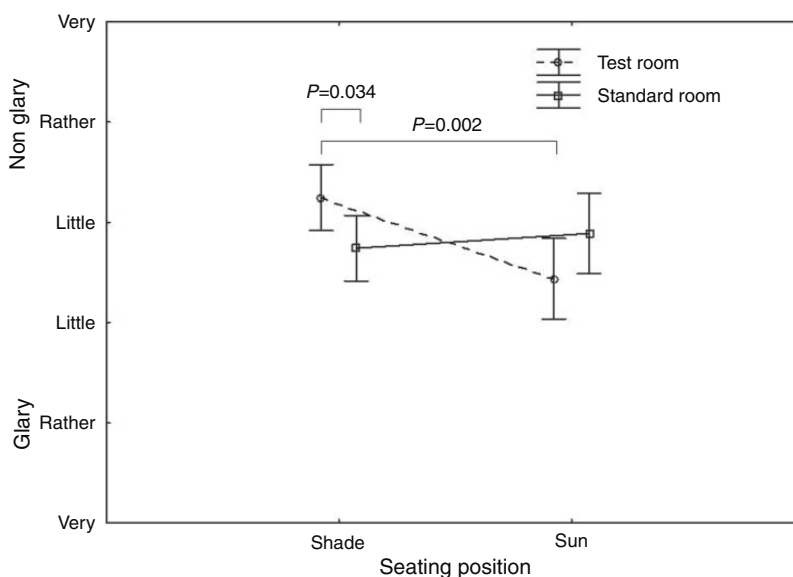


Figure 9 Interaction light $\times$ seating position (glary-non-glary) – LSD *post-hoc* tests; seating position varied in the test room but not in the standard room

but significantly reduced in the seating position shade.

The test room was rated significantly less bright than the standard room ($p=0.018$). Additionally, the interaction between light and seating position reached significance level ($p<0.001$ – see Figure 10) and thus in the seating position shade of the test room, room illumination was perceived less bright than in the other two test conditions.

Room lighting was perceived as less even in the test room ($p<0.001$). In general, perceived inhomogeneity in the test room significantly decreased over time ($p<0.001$) but still was higher than in the standard room (see Figure 11).

A detailed tabular description of all statistical analysis of room-lighting-related effects can be found in Appendix A1.

3.2. Room atmosphere-related effects

All 38 items of the room atmosphere questionnaire were rated highly significantly different ($p<0.001$ for all items) in the test room in comparison to the standard room. Specifically, ratings of the items frightening,

threatening, oppressive, depressed, hostile, lethargic, chilly, cool, boring, exciting, restless, business-like, formal, musty, tense and uncomfortable were lower in the test room. Additionally, room atmosphere was perceived as less cosy, tranquil, active, relaxed, uninhibited, cheerful, hospitable, safe, mysterious, pleasant, spatial, social, inspiring, intimate, lively, luxurious, personal, romantic, calm, stimulating, warm and accessible in the standard room. We could not reveal any significant interactions between the two factors light and seating position and between the three factors time, light and seating position within a single item of the questionnaire. However, six out of 38 items were rated significantly different over time (i.e. the rating of the items ‘threatening’, ‘uninhibited’ and ‘restless’ increased and the items ‘active’, ‘safe’ and ‘stimulating’ decreased over time within each mock-up room – see Appendix A.3) and a significant interaction between the two factors time and light in the item ‘cosy’ could be revealed (i.e. the rating decreases in the standard room over time – see Figure 12). Details of all

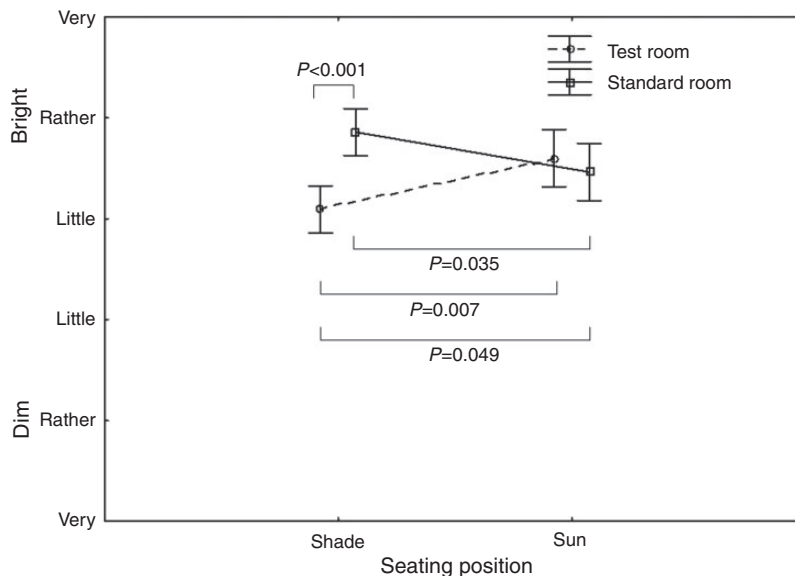


Figure 10 Interaction light $\times$ seating position (dim-bright) – LSD *post-hoc* tests; seating position varied in the test room but not in the standard room

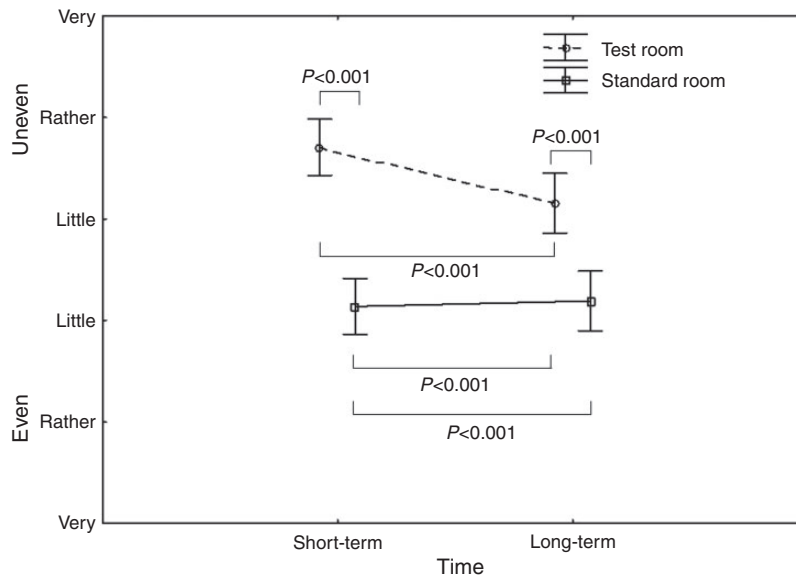


Figure 11 Interaction time $\times$ light (even-uneven) – LSD *post-hoc* tests

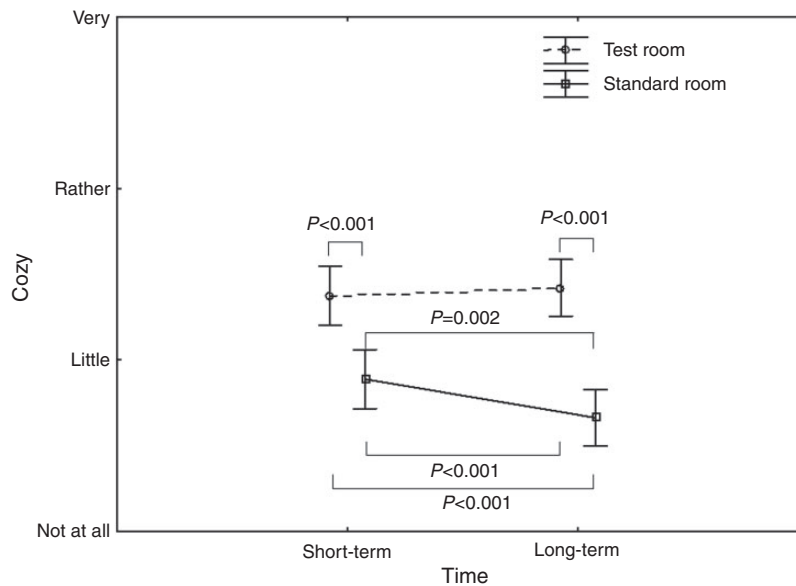


Figure 12 Interaction time $\times$ light (item 'cosy') $\times$ LSD *post-hoc* tests

statistics can be found in Appendix A.2 and A.3.

3.3 Connected to nature-related effect

Perceived connectedness to nature was significantly higher in the test room than in the standard room ($p < 0.001$). We could neither reveal a significant impact of time nor significant interactions between the three factors light, time and seating position. Details on the statistics can be found in Appendix A.4.

4. Discussion

4.1 Room lighting-related effects

Natural preference refers to the human tendency to prefer natural substances over their synthetic counterparts, for instance in the domains of food and medication. In four studies, Haans³⁴ has recently confirmed that the natural preference is also operative in the domain of light. His investigation is consistent with our room lighting-related results. Our study shows that the new artificial skylight system was clearly preferred for indoor illumination purposes compared to standard louvre luminaires. Room lighting was perceived as significantly more natural, pleasant and attractive. Effect sizes of these differences were large and surprisingly prevailed in both seating positions in the test room. In comparison, in the standard room, the rating of pleasantness of the room illumination decreased over time, although the effect size of this decrement was small. This leads to the conclusion that the imitation of an incoming sunlight, the visual impression of skylight at noon and the visual appearance of a daylight room were successfully implemented.

The perceived brightness of the room in the seating position 'shade' was lower than in the seating position 'sun' in the test room and in the standard room as well. This result could be explained by the fact that subjects were exposed to noticeably lower luminance levels

in the seating position 'shade' (a maximum of 500 cd/m^2 in the seating position shade versus $15,000 \text{ cd/m}^2$ and more than $1,000,000 \text{ cd/m}^2$ when gazing directly at the lamps of the louvre luminaires or the artificial sun of the CoeLux[®] system). Surprisingly, brightness ratings did not differ between the standard room and the test room in the seating position 'sun' although the associated maximum luminances in the field of view and mean illuminances at eye level (330 lx in the standard room and 850 lx in the seating position sun) varied considerably. It can be assumed that the perfect imitation of a skylight scenery (bright artificial sun with small solid angle and a view to an artificial sky with indefinite depth) under reduced absolute photometric parameters accounted for the reduced room brightness ratings under the CoeLux[®] system.

Astonishingly, glare ratings did not differ in the test and standard room although variances in vertical illuminances at eye level were remarkable (150 lx in the seating position 'shade', 330 lx in the standard room and 850 lx in the seating position 'sun'). Glare ratings in the seating position 'sun' and the standard room did not differ either. Again it can be assumed that the dimension of the glare source and the perfect imitation of a natural outdoor lighting scenario on a cloudless day generated an indoor lighting scenario which is highly preferred and thus do not have a massive influence on subjective glare evaluation. It has to be mentioned though, that we could reveal a significant different glare rating between the two seating positions in the test room. It should be noted at this point that a glare evaluation of CoeLux[®] according to current artificial lighting standards (i.e. the method of unified glare rating – see CIE 190:2010³⁵) is not allowed because a central assumption for the application of this rating method is violated (the solid angle of the artificial sun is smaller than 0.0003 sr). In addition, a daylight-based glare evaluation

(e.g. daylight glare probability DGP^{36}) affirms that discomfort glare plays a minor role in all three lighting scenarios ($DGP < 0.35$).

Finally, ratings of brightness uniformity were different between the standard room and test room. An evaluation of the brightness uniformity within the working area (i.e. ratio of minimum to mean horizontal illuminance at the desk) supports this finding. In the test room, calculated uniformity was 0.145 whereas it was 0.512 in the standard room. In parallel, statistical analysis revealed a large effect size of this difference by means of our subjects' ratings. It has to be mentioned that the perception of brightness inhomogeneity decreased over time in the test room (subjects got partly accustomed to the inhomogeneity) but did not reach the perceived level of homogeneity in the standard room at the end.

4.2 Room atmosphere-related effects

People generally have positive connotations with both daylight and nature. However, these two phenomena have often been studied separately. Recently Beute and de Kort³⁷ presented results of three studies in which effects of naturalness and daylight characteristics on preference are studied simultaneously. They could explore that there exists a clear explicit preference for natural, sunny and bright environments. Consequently, it may be assumed that this new artificial skylight system, which appears very natural and bright and generates a sunlit indoor environment, could also induce a high preference. Within our study a room atmosphere questionnaire was applied to measure preference. This questionnaire consisted of 38 items and had been successfully utilized in studies as a sensible, reliable and objective measure for the quantification of light-induced room atmospheres.^{38,39}

All 38 items of this questionnaire were rated highly significantly different between the two

indoor lighting systems. Effect sizes of these differences were medium to large ($0.06 \leq \eta_p^2$). In particular, this result indicates that subjects clearly preferred the room atmosphere created by the new skylight and supports the hypothesis that this system generates a very naturalistic room impression. Amazingly, this positive review was independent of the seating position in the test room, thus a direct view to the artificial sun is not necessary needed for high preference. A view to an artificial sky and a realistic sunlit area within the room were also sufficient to generate a positive room impression. Interestingly, the four items 'oppressive', 'spatial', 'accessible' and 'uninhibited' that can be assigned to the category spaciousness of the test room were all rated significantly different between the two mock-up rooms although both rooms had no windows. Additionally, it is noteworthy that the perceived room ambience in the test room did not change even after working on neurocognitive tests for nearly 1 hour.

Room atmosphere has the potency to evoke an affective state in a person in accordance with the atmosphere. Thus, quantifying the perceived atmosphere created with this new skylight system and comparing it with the generated atmosphere of standard louvre luminaries is a first important step to establish a deeper understanding of the effects of this lighting system on human beings.

The new skylight system did not imitate the orbit of the sun during the day but provided a static view to a cloudless sky scenario. In the course of our study, subjects stayed in the test room for a relatively short time and thus perhaps did not notice the static lighting situation. So we do not know how the room atmosphere would have been perceived in the course of an hours-long stay in the test room and whether the new skylight system should mimic the real changes in the position of the sun in the sky and provide daylight dynamics for a person with longer exposure duration.

4.3 Connected to nature-related effect

In rooms where windows are absent or the view is dominated by man-made environments, virtual windows and skylights can potentially play a beneficial role. Often a window-like ‘see-through experience to nature’ is generated by using projected photo-realistic scenes or the application of displays and artificial skylight panels. To our knowledge studies so far do not demonstrate a clear positive impact of these artificial skylight systems.^{40–42} In most cases the artificial skylight does not generate a sunlit indoor scenario. Ijsselsteijn *et al.*⁴² demonstrated that motion parallax is essential in creating a convincing virtual window. Additionally, studies which used an artificial skylight panel⁴¹ or HDR sky images⁴³ clearly showed that realism seems to be most important in predicting overall preference for a skylight and people seem to prefer sun patterns that are true to nature. Conveniently, the new artificial skylight system reproduces the physical effects and optical phenomena of natural light in a closed space perfectly. Accordingly, the rating of ‘connected to nature’ was highly significantly different between the standard room and the test room. The positive impression of a naturalistic lighting scenario did not vanish even after mental workload, i.e. after completion of the neuropsychological test battery for 1 hour. The effect size of this difference was the second largest over all items. Only the difference in the ratings of the item ‘natural’ within the room lighting questionnaire gained a slightly larger effect size.

5. Conclusion

The visual appearance of the artificial skylight and the resulting room atmosphere were perceived fundamentally differently and superior to a windowless room ambience generated by standard louvre luminaires. The impression of a daylight room on a

cloudless day was unequivocally generated by this system. The first subjective evaluation of this system and the evaluation generated after short-term mental workload did not change adversely.

These effects are remarkable and let us assume that this new skylight might generate positive long-term psychophysiological effects on human beings, as well as the real counterpart does. Further studies are planned which intend to quantify effects on mood, vision, cognitive performance and physiological markers.

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Appendix A. Results summary**A1 Room lighting-related effects**

Item	light	light × seating position	time	time × light	time × light × seating position
Pleasant–unpleasant T: 1.53 (0.12) S: 2.90 (0.12)	$F(1,195) = 62.9$ $P < 0.001$ $\eta_p^2 = 0.24$ (large effect)	n.s.	n.s.	$F(1,195) = 5.8$ $P = 0.017$ $\eta_p^2 = 0.03$ (small effect)	n.s.
Attractive–unattractive T: 1.77 (0.12) S: 3.17 (0.12)	$F(1,195) = 67.5$ $P < 0.001$ $\eta_p^2 = 0.26$ (large effect)	n.s.	n.s.	n.s.	n.s.
Natural–artificial T: 1.60 (0.12) S: 4.00 (0.12)	$F(1,195) = 200.6$ $P < 0.001$ $\eta_p^2 = 0.51$ (large effect)	n.s.	n.s.	n.s.	n.s.
Glary–without glare T: 2.84 (0.13) S: 2.81 (0.13)	n.s.	$F(1,195) = 6.6$ $P = 0.011$ $\eta_p^2 = 0.03$ (small effect)	n.s.	n.s.	n.s.
Dim–bright T: 3.35 (0.09) S: 3.66 (0.09)	$F(1,195) = 5.7$ $P = 0.018$ $\eta_p^2 = 0.03$ (small effect)	$F(1,195) = 11.7$ $P < 0.001$ $\eta_p^2 = 0.06$ (medium effect)	n.s.	n.s.	n.s.
Even–uneven T: 3.43 (0.13) S: 2.16 (0.13)	$F(1,195) = 46.4$ $P < 0.001$ $\eta_p^2 = 0.19$ (large effect)	n.s.	$F(1,195) = 8.5$ $P = 0.004$ $\eta_p^2 = 0.04$ (small effect)	$F(1,195) = 12.6$ $P < 0.001$ $\eta_p^2 = 0.06$ (medium effect)	n.s.

In parenthesis: the standard error of the mean; n.s.: not significant; S: standard room; T: test room.

A2 LSD post hoc statistics of room lighting- and room atmosphere-related effects

Questionnaire	Item	Mean (standard error)	Test statistic
Room lighting questionnaire	Even–uneven	Short term: 2.72 (0.10) Long term: 2.46 (0.11)	$P = 0.002$
Room atmosphere questionnaire	Threatening	Short term: 1.18 (0.08) Long term: 1.25 (0.09)	$P = 0.016$
	Active	Short term: 2.20 (0.12) Long term: 2.07 (0.11)	$P = 0.009$
	Uninhibited	Short term: 1.98 (0.12) Long term: 2.09 (0.11)	$P = 0.039$
	Safe	Short term: 1.87 (0.11) Long term: 1.77 (0.11)	$P = 0.044$
	Restless	Short term: 1.52 (0.11) Long term: 1.62 (0.11)	$P = 0.044$
	Stimulating	Short term: 1.82 (0.12) Long term: 1.72 (0.10)	$P = 0.028$

A3 Room atmosphere-related effects

Item	light	light × seating pos.	time	time × light	time × light × seating pos.
Frightening T: 1.19 (0.06) S: 1.53 (0.06)	F(1,195)=17.6; P<0.001 $\eta_p^2=0.08$ (medium effect)	n.s.	n.s.	n.s.	n.s.
Threatening T: 1.13 (0.05) S: 1.45 (0.05)	F(1,195)=20.8; P<0.001 $\eta_p^2=0.10$ (large effect)	n.s.	F(1,195)=5.9; P=0.016 $\eta_p^2=0.02$ (small effect)	n.s.	n.s.
Cosy T: 2.40 (0.08) S: 1.78 (0.08)	F(1,195)=32.4; P<0.001 $\eta_p^2=0.14$ (large effect)	n.s.	n.s.	F(1,195)=6.9; P=0.009 $\eta_p^2=0.03$ (small effect)	n.s.
Oppressive T: 1.28 (0.06) S: 1.80 (0.06)	F(1,195)=35.6; P<0.001 $\eta_p^2=0.15$ (large effect)	n.s.	n.s.	n.s.	n.s.
Tranquil T: 2.43 (0.07) S: 1.75 (0.07)	F(1,195)=45.2; P<0.001 $\eta_p^2=0.19$ (large effect)	n.s.	n.s.	n.s.	n.s.
Depressed T: 1.23 (0.07) S: 1.91 (0.07)	F(1,195)=50.8; P<0.001 $\eta_p^2=0.21$ (large effect)	n.s.	n.s.	n.s.	n.s.
Active T: 2.63 (0.07) S: 1.88 (0.07)	F(1,195)=49.7; P<0.001 $\eta_p^2=0.20$ (large effect)	n.s.	F(1,195)=7.0; P=0.009 $\eta_p^2=0.03$ (small effect)	n.s.	n.s.
Relaxed T: 2.55 (0.07) S: 1.65 (0.07)	F(1,195)=82.3; P<0.001 $\eta_p^2=0.30$ (large effect)	n.s.	n.s.	n.s.	n.s.
Hostile T: 1.21 (0.06) S: 1.73 (0.06)	F(1,195)=38.7; P<0.001 $\eta_p^2=0.17$ (large effect)	n.s.	n.s.	n.s.	n.s.
Uninhibited T: 2.72 (0.08) S: 1.59 (0.08)	F(1,195)=105.0; P<0.001 $\eta_p^2=0.35$ (large effect)	n.s.	F(1,195)=4.3 P=0.039 $\eta_p^2=0.02$ (small effect)	n.s.	n.s.
Cheerful T: 2.55 (0.08) S: 1.53 (0.08)	F(1,195)=90.61; P<0.001 $\eta_p^2=0.32$ (large effect)	n.s.	n.s.	n.s.	n.s.
Hospitable T: 2.39 (0.08) S: 1.59 (0.08)	F(1,195)=49.2; P<0.001 $\eta_p^2=0.20$ (large effect)	n.s.	n.s.	n.s.	n.s.
Safe T: 2.29 (0.07) S: 1.59 (0.07)	F(1,195)=43.6; P<0.001 $\eta_p^2=0.18$ (large effect)	n.s.	F(1,195)=4.1 P=0.044 $\eta_p^2=0.02$ (small effect)	n.s.	n.s.
Lethargic T: 1.57 (0.08) S: 2.72 (0.08)	F(1,195)=99.8; P<0.001 $\eta_p^2=0.34$ (large effect)	n.s.	n.s.	n.s.	n.s.
Mysterious T: 1.88 (0.07) S: 1.43 (0.07)	F(1,195)=18.7; P<0.001 $\eta_p^2=0.09$ (medium effect)	n.s.	n.s.	n.s.	n.s.
Pleasant T: 2.52 (0.08) S: 1.62 (0.08)	F(1,195)=63.1; P<0.001 $\eta_p^2=0.24$ (large effect)	n.s.	n.s.	n.s.	n.s.
Spatial T: 2.56 (0.09) S: 1.86 (0.09)	F(1,195)=31.6; P<0.001 $\eta_p^2=0.14$ (large effect)	n.s.	n.s.	n.s.	n.s.
Social T: 2.23 (0.07) S: 1.57 (0.07)	F(1,195)=44.2; P<0.001 $\eta_p^2=0.18$ (large effect)	n.s.	n.s.	n.s.	n.s.
Inspiring T: 2.55 (0.08) S: 1.53 (0.08)	F(1,195)=90.6; P<0.001 $\eta_p^2=0.32$ (large effect)	n.s.	n.s.	n.s.	n.s.

(continued)

Continued

Item	light	light × seating pos.	time	time × light	time × light × seating pos.
Intimate T: 1.75 (0.07) S: 1.35 (0.07)	F(1,195)=16.4; P<0.001 $\eta_p^2=0.08$ (medium effect)	n.s.	n.s.	n.s.	n.s.
Chilly T: 1.49 (0.08) S: 2.20 (0.08)	F(1,195)=38.3; P<0.001 $\eta_p^2=0.16$ (large effect)	n.s.	n.s.	n.s.	n.s.
Cool T: 1.71 (0.08) S: 2.45 (0.08)	F(1,195)=40.0; P<0.001 $\eta_p^2=0.17$ (large effect)	n.s.	n.s.	n.s.	n.s.
Boring T: 1.58 (0.08) S: 2.63 (0.08)	F(1,195)=86.1; P<0.001 $\eta_p^2=0.31$ (large effect)	n.s.	n.s.	n.s.	n.s.
Lively T: 2.60 (0.07) S: 1.69 (0.07)	F(1,195)=74.2; P<0.001 $\eta_p^2=0.28$ (large effect)	n.s.	n.s.	n.s.	n.s.
Luxurious T: 2.21 (0.08) S: 1.43 (0.08)	F(1,195)=48.7; P<0.001 $\eta_p^2=0.20$ (large effect)	n.s.	n.s.	n.s.	n.s.
Exciting T: 1.30 (0.07) S: 1.78 (0.07)	F(1,195)=24.7; P<0.001 $\eta_p^2=0.11$ (medium effect)	n.s.	n.s.	n.s.	n.s.
Restless T: 1.35 (0.07) S: 2.02 (0.07)	F(1,195)=43.2; P<0.001 $\eta_p^2=0.18$ (large effect)	n.s.	F(1,195)= 4.1 P=0.044 $\eta_p^2=0.02$ (small effect)	n.s.	n.s.
Personal T: 2.11 (0.08) S: 1.62 (0.08)	F(1,195)=20.7; P<0.001 $\eta_p^2=0.10$ (medium effect)	n.s.	n.s.	n.s.	n.s.
Romantic T: 1.59 (0.06) S: 1.19 (0.06)	F(1,195)=22.8; P<0.001 $\eta_p^2=0.10$ (medium effect)	n.s.	n.s.	n.s.	n.s.
Calm T: 2.71 (0.08) S: 2.25 (0.08)	F(1,195)=16.1; P<0.001 $\eta_p^2=0.08$ (medium effect)	n.s.	n.s.	n.s.	n.s.
Business-like T: 2.13 (0.09) S: 2.89 (0.09)	F(1,195)=36.9; P<0.001 $\eta_p^2=0.16$ (large effect)	n.s.	n.s.	n.s.	n.s.
Formal T: 1.67 (0.08) S: 2.80 (0.08)	F(1,195)=105.4; P<0.001 $\eta_p^2=0.35$ (large effect)	n.s.	n.s.	n.s.	n.s.
Musty T: 1.54 (0.08) S: 2.25 (0.08)	F(1,195)=37.1; P<0.001 $\eta_p^2=0.16$ (large effect)	n.s.	n.s.	n.s.	n.s.
Stimulating T: 2.26 (0.07) S: 1.50 (0.07)	F(1,195)=52.5; P<0.001 $\eta_p^2=0.21$ (large effect)	n.s.	F(1,195)=4.9 P=0.028 $\eta_p^2=0.02$ (small effect)	n.s.	n.s.
Tense T: 1.62 (0.08) S: 2.43 (0.08)	F(1,195)=53.1; P<0.001 $\eta_p^2=0.21$ (large effect)	n.s.	n.s.	n.s.	n.s.
Uncomfortable T: 1.37 (0.07) S: 2.13 (0.07)	F(1,195)=58.8; P<0.001 $\eta_p^2=0.23$ (large effect)	n.s.	n.s.	n.s.	n.s.
Warm T: 2.42 (0.08) S: 1.61 (0.08)	F(1,195)=55.7; P<0.001 $\eta_p^2=0.22$ (large effect)	n.s.	n.s.	n.s.	n.s.
Accessible T: 2.61 (0.08) S: 1.81 (0.08)	F(1,195)=55.0; P<0.001 $\eta_p^2=0.22$ (large effect)	n.s.	n.s.	n.s.	n.s.

In parenthesis: the standard error of the mean; n.s.: not significant; S: standard room; T: test room.

A4 Connected to nature-related effect

Item	Light	Light × seating position	Time	Time × light	Time × light × seating position
Linked to nature		n.s.	n.s.	n.s.	n.s.
T: 2.62 (0.08)	F(1,195) = 163.9; P < 0.001				
S: 1.19 (0.08)	$\eta_p^2 = 0.46$ (large effect)				

In parenthesis: the standard error of the mean; n.s.: not significant; S: standard room; T: test room.

Appendix B. Room atmosphere questionnaire

No.	Items (German)	Items (Dutch)	Items (English)
1	beängstigend	beangstigend	frightening
2	bedrohlich	bedreigend	threatening
3	behaglich	behaaglijk	cosy
4	beklemmend	beklemmend	oppressive
5	beruhigend	rustgevend	tranquil
6	deprimierend	deprimerend	depressed
7	dynamisch / aktiv	actief	active
8	entspannend / locker	ontspannen	relaxed
9	feindselig	vijandig	hostile
10	frei / offen / weit	ongedwongen	uninhibited
11	fröhlich / heiter / optimistisch / munter	vrolijk	cheerful
12	gastfreundlich	gastvrij	hospitable
13	geborgen	geborgen	safe
14	gefühllos / apathisch	sloom	lethargic
15	geheimnisvoll	mysterieus	mysterious
16	gemütlich	gemoedelijk	pleasant
17	geräumig	ruimtelijk	spatial
18	gesellig	gezellig	social
19	inspirierend	inspirerend	inspiring
20	intim / innig	intiem	intimate
21	kalt / unfreundlich	kil	chilly
22	kühl / distanziert	koud	cool
23	langweilig / öde	saai	boring
24	lebendig	levendig	lively
25	luxuriös / teuer	luxueus	luxurious
26	nervenaufreibend	enerverend	exiting
27	nervös / unruhig	onrustig	restless
28	persönlich / privat	persoonlijk	personal
29	romantisch	romantisch	romantic
30	ruhig	kalm	calm
31	sachlich / nüchtern	zakelijk	businesslike
32	steif / formell	formeel	formal
33	stickig / muffig	bedompt	musty
34	stimulierend / anregend	stimulerend	stimulating
35	straff / angespannt	gespannen	tense
36	unbehaglich / unangenehm	ongemakkelijk	uncomfortable
37	warm / entgegenkommend	warm	warm
38	zugänglich / erreichbar / offen	toegankelijk	accessible

Appendix C. Room lighting questionnaire

No.	Bipolar adjectives (German)	Bipolar adjectives (English)
1	angenehm–unangenehm	pleasant–unpleasant
2	attraktiv–unattraktiv	attractive–unattractive
3	natürlich–künstlich	natural–artificial
4	mit starker Blendung–ohne Blendung	glary–without glare
5	dunkel–hell	dim–bright
6	gleichmäßig–ungleichmäßig	even–uneven