DAYLIGHT IN OFFICE BUILDINGS—THE USERS' RESPONSE

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1. INTRODUCTION

Fully glazed buildings have increased in popularity throughout the world's building sector. Office buildings are often especially designed with a high glazing ratio to fulfil representative architectural tasks. However, a high glazing ratio is also likely to result in a high solar load and glare problems, which cause an unsatisfactory working environment that can reduce employee productivity severely. Furthermore, it creates high cooling loads resulting in immense maintenance costs. Solutions provide light direction to illuminate the space naturally and shading to avoid glare as well as to reduce cooling loads.

Many studies have been carried out on thermal comfort, others on lighting issues, but mostly under artificial lighting conditions or under the exclusion of sunny conditions. The performance of light directing elements under sunny conditions and the resulting lighting quality so far has not been investigated. Especially under sunny conditions, however, conflict between the use of daylight, the need for solar protection, and the view to the outside occur and have not been assessed.

To fill this gap an intensive monitoring program has been conducted at the University of Dortmund investigating different innovative shading and light directing devices (2001–2006). Simultaneously user acceptance studies have been carried out to evaluate lighting quality issues. This paper discusses some of the results on the subjective rating of the indoor lighting environment. Space and light perception often does neither correspond with the lighting levels set in regulations mostly for artificial lighting conditions nor the control strategies for shading devices. The objective of the work was to clarify the interdependencies between the conflicting needs and to point out user preferences which are important for a productive environment.

2. BACKGROUND

Office buildings often suffer from insufficient use of daylight and a restricted outside view due to conventional shading systems. However, the comfort conditions depend on multiple criteria such as thermal conditions as surface temperature and indoor air temperature, lighting conditions and the contact to the outside, noise, air quality and ventilation rates as well as control strategies and privacy. An intensive literature review has been carried out at the beginning of the study to reflect the results of research, to compare the known results with existing results, and to answer open questions.

Regarding possible disturbances through one of these factors, an unsatisfactory lighting environment in office buildings will be announced by between 57% [1] and 66% [2], most of them concerning the artificial lighting devices. The possibility to interact with the indoor environment enhances the user comfort and satisfaction with the working environment [2][3] as well as an adequate contact to the outside and sufficient use of daylight. Conventional shading devices more than likely create a conflicting situation between the need for solar control to avoid overheating and excessive glare and the need for daylight to avoid artificial lighting and additional internal loads [4].

In the last decade a number of light directing and complex shading systems have been developed to avoid these conflicts [5]. These usually use the upper part of the windows to provide daylighting and to reflect it in combination with a reflective ceiling deep into the room; the lower part of the window takes care of shading and glare protection but mostly provides only a restricted view. Figure 1 shows the principles of a well designed façade for office buildings.

A number of studies have been carried out on the perception of artificial lighting devices (e.g., [6][7][8]) reflecting the distribution and the brightness which is

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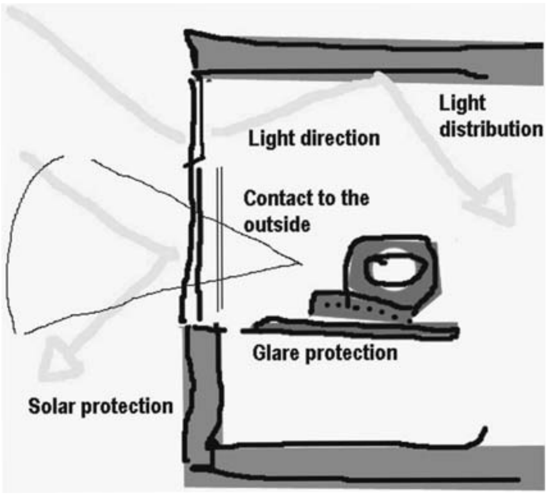
FIGURE 1. Tasks for a daylit office space.



most comfortable for the user. Less studies have been done on the influence of daylit spaces on the user (e.g., [9][10][11][12]). These have been carried out mostly with respect to view and/or to overcast conditions. But no studies have been carried out to assess any comfort issues with light directing and/or complex facade systems under sunny conditions when issues such as the level of daylight, glare, and the view out are most critical.

The acceptance of the lighting environment is based on the perception of light but also of the space under penetration of light and independent criteria such as the indoor temperature, the overall well-being, or the task that has to be fulfilled. One task of the literature review was to identify the most relevant questions and possible gaps. The most influencing criteria, which so far have been investigated based on the literature review and other research projects of the institute, are:

- The positioning of lighting in relation to other climatic issues in the interior
- The control mechanism and the individual control
- The assessment of different shading devices
- The brightness
- Glare through daylight and the acceptance of its grade
- The quality of the view out
- The effects of light on productivity
- Lighting effects and perception of space
- Effects of space lighting on health
- The acceptance of lighting colours
- The subjective perception of space

The identified shortcomings are listed in the following section:

- Often user acceptance studies have been carried out without simultaneous monitoring; therefore they do not represent any comparable values.
- There are no acceptance studies on complex daylighting systems under sunny conditions with direct sun on the facades (which is the most conflicting issue).
- Mostly acceptance studies have been only carried out with one system; a comparison of different assessments, therefore, is not possible.
- The complexity of perception under daylit conditions have been investigated only rarely.
- There are no evaluation methods on a comparative basis for solar protection devices of different functions.

The following section describes the methodology used for the study under the above-mentioned criteria. The aim was to cover most of the shortcomings and to address most of the important interdependencies.

3. METHODOLOGY

3.1 Location and systems overview

By the year 2000 the necessary requirements for testing facilities had already been installed at the University in Dortmund in Germany [13][14][15]. These facilities could also be used for the purpose of this study. An unshaded south-west facing façade on top of a University building was equipped with six different systems and furnished equally (Figures 2 and 3).

The north facing façade has been equipped with blinds; a thermal separation of the six office spaces has not been carried out—only visual disconnection.

The study has been conducted comparing different shading and light directing devices under sunny conditions and with closed or active systems [13]. Therefore, six different systems have been installed, some of which only represent the reduction of incident radiation, others representing the use of daylight through light direction. An overview of the installed systems is given in Figure 4.

FIGURE 2. South-west facing façade.

FIGURE 3. Floor plan of the testing facilities.

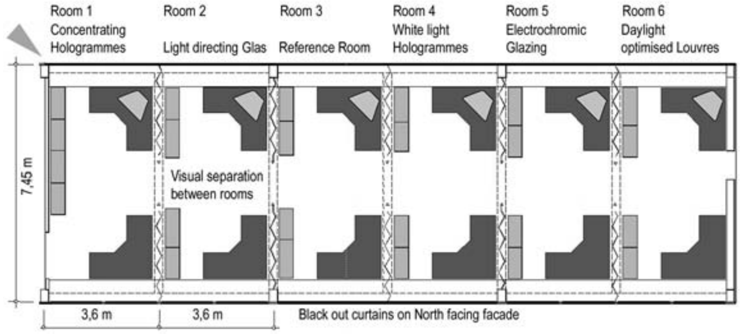
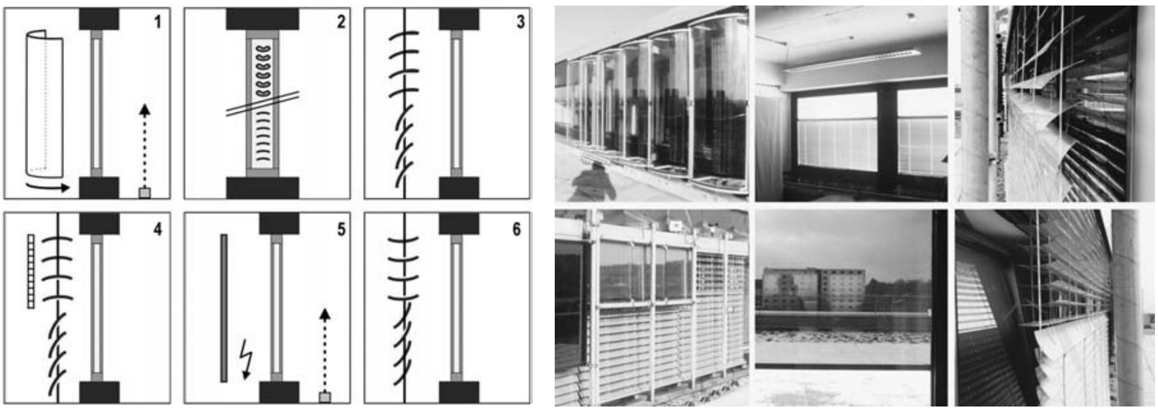


FIGURE 4. Overview of the installed systems as scheme (left) and photograph (right).



The systems include two shading devices such as photovoltaic elements with concentrating hologrammes redirecting direct solar radiation onto photovoltaic panels (1) and electrochromic glazing (5). The other four systems consist of light directing elements such as a light directing glass (reflects direct light onto the ceiling deep into the space) and louvers in between two layers of insulating glass (2), light directing louvers (3), white light hologrammes for light direction in combination with light directing louvers (4), and daylight optimised louvers with concave lamellas which can be controlled separately in the upper and lower part (6).

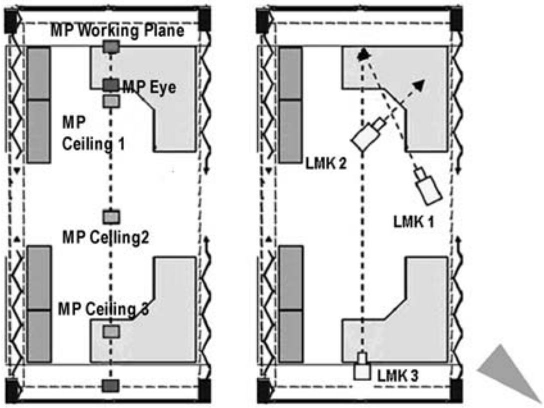
3.2 Monitoring program

An extensive monitoring database has been created to simultaneously measure the objective (monitoring program) and subjective data (questionnaires). It has been developed according to the IEA Task 21 [16] program to allow comparison and has been extended for the use of this study. The monitoring program included readings of luminance with ccd- cameras (two positions of the user and from the back wall), outdoor and indoor illuminances (vertical at eye height and from the back wall and horizontal in the working plane and at the ceiling), indoor and outdoor temperatures, the status of the shading devices, and the artificial lighting components over a whole year. This program was complemented through occasional colour measurements [14]. The positions of illuminance sensors and the luminance cameras are indicated in Figure 5.

3.3 Development of questionnaires

Simultaneously, user acceptance studies have been carried out to asses the performance of the systems in

FIGURE 5. Illuminance (MP) and luminance (LMK) sensor positions for the standard office spaces.



a real working environment. These were based on existing questionnaires and adapted to the requirements for this study [16]. A total of 336 questionnaires and statements of around 30 “naive” people (not involved in the subject of lighting design) have been evaluated on a short term basis (approximately half an hour). The respondents, after a short introduction into the topics and some of the special terms, followed a strict action plan allowing the correct adaptation of the eyes to the lighting environment and a statistical rotation plan to assess all six spaces with different solar protection devices over a period of a whole year. The questionnaires have been carried out under sunny conditions with direct sun on the façade to evaluate the most critical situation. To evaluate the complexity of perception under different conditions, questions included lighting issues, issues connected to the lighting environment, and independent questions. Furthermore different types of questions have been developed to always double the answers of the users and to enable users to give more accurate answers.

3.4 Analysis process

To carry out the statistical analysis, the resulting database of measurements and questionnaires was separated into ten different topics. These topics have been developed as a result of the above-mentioned literature review. An overview is given in Table 1.

After the completion of one year of questionnaires and monitoring, a full dataset was introduced into statistical analysis software (SPSS). Besides the simple

TABLE 1. Overview of evaluation categories.

Evaluation Categories	
Room temperature	Light direction
View out	Colour and space perception
Glare and reflections	Privacy and aesthetics
Function of systems	Overall comments
Brightness/lighting levels	Working space and well-being

counting and evaluation of measured results, four analysing steps have been carried out with respect to the user acceptance results. These included the simple counting of results as well as the analysis of roomwise counting to evaluate the influence of different façades on the judgement of the interior lighting conditions. The consistency of the dataset was audited, and relations between the topics such as view out and lighting levels have been investigated. The statistical correlation of the subjective results to objective measured data served the findings of the most important measured quantity for each topic. Limiting values for some of the measured data could then be analysed in a fourth step to predict the subjective perception of users with a high probability. This procedure gives more precise information of the user acceptance than mean values can do, as the mean values always depend on each single value and will change severely when single values deviate.

4. SELECTED RESULTS

The results of the study show a great influence of the selected façade system, its design, and function on the office workers response and acceptance. The following results will now be discussed:

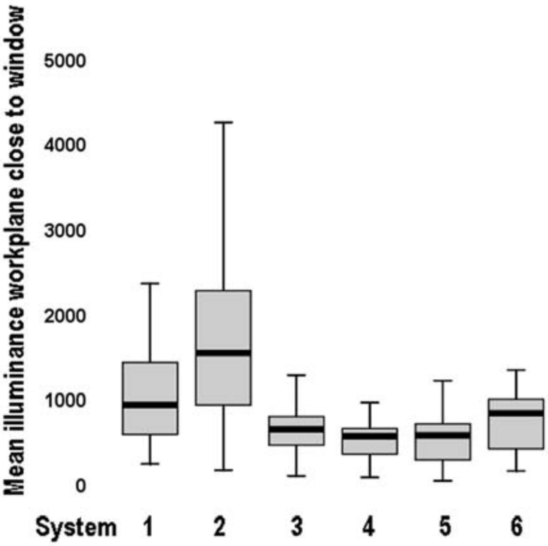
- The perception of brightness in offices
- The function of systems, the room temperatures, and the understanding of cause and effect
- The space perception in correlation to lighting levels and light distribution

Within the study, many more questions, based on an intensive literature review on the topic of lighting in office buildings, have been raised and investigated. The full report of the whole work was published as a PhD thesis in 2006 in the German language [17].

4.1 The perception of brightness in offices

The brightness in office spaces within the regulations is controlled mainly by the illuminance in the work-

FIGURE 6. Work plane illuminances close to the window for all six rooms (black line indicates median value).



ing plane. For offices these are currently 500 lux or 300 lux close to windows, respectively. These values are based on artificial lighting requirements. Comments on daylighting lighting levels are rare.

Measurements taken in each of the six rooms with different daylighting systems result from situations with sunny conditions and closed systems. Figure 6 shows illuminances in the work plane close to the window.

The differences of illuminances in the work plane are very clear. System 2 reaches over 1500 lux as a median, often much more, whereas system 4 and 5 only reach around 500 lux in the work plane but more often even less. This leads automatically to the fact that artificial lighting may be needed with these systems even with sunny conditions.

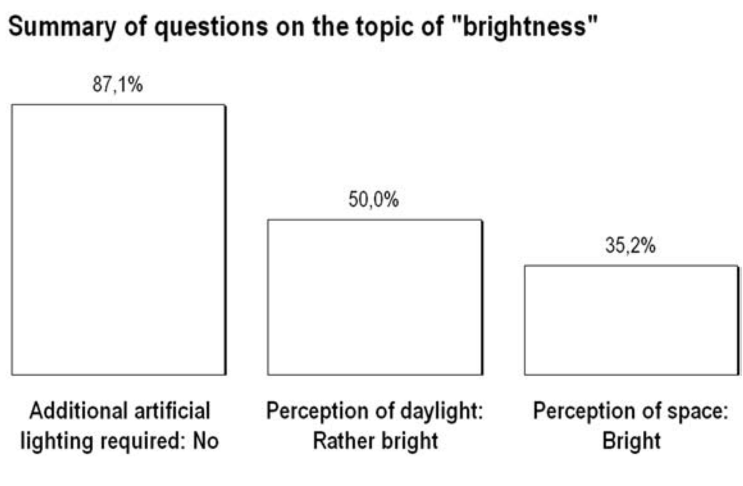
The question for the user acceptance studies asked about the required lighting levels for a feeling of "brightness." Figure 7 shows some of the questions and the resulting answers over the total database.

Overall, almost 90% of the tested people did not require additional artificial lighting under sunny conditions and closed systems but only 35% felt the perception of "brightness"; "rather bright" in contrast is the result of 50% of the questionnaires.

Separated by room, different levels of perception according to the selected question can be seen (Figure 8). The least requirements appear for the question on additional artificial lighting. Here, the best performance has been produced by Room 2 (light directing glass). More critical is the statement on "sufficient daylight in the work plane," but the most critical level of perception is the feeling of "brightness." Here only between 25% (Room 5) and around 80% (Room 2) stated that the room appears "bright," whereas between around 80% and almost 95% of the questionnaire participants did not require additional artificial lighting.

"Brightness," therefore, will be judged on a much more critical level than "sufficient daylight" or "additional artificial lighting required." The most impor-

FIGURE 7. Counting of answers on "brightness."



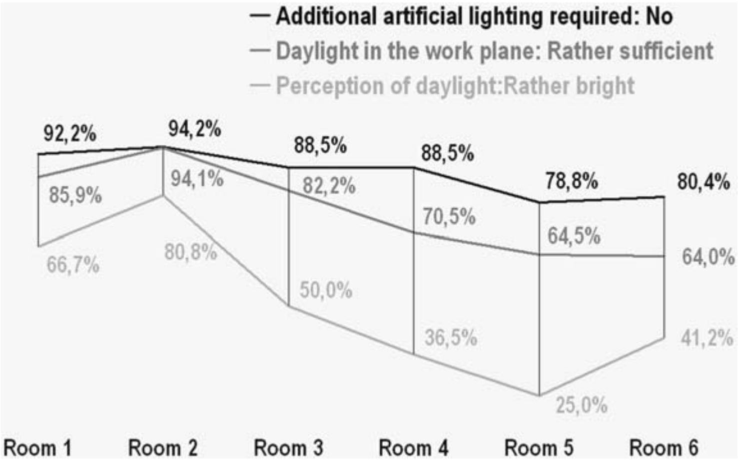


FIGURE 8. Comparison of the different levels of perception of brightness.

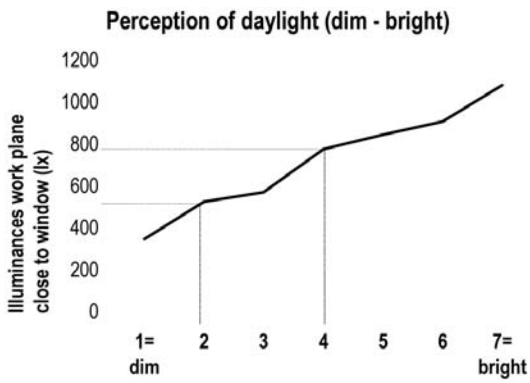
tant information is that the lighting environment will be judged according to the task that has to be fulfilled. This can be done with less brightness. The brightness in a space in contrast will be judged on a different level of perception. Here the users are much more critical.

The correlations to measured quantities are shown in Figure 9 exemplarily for the perception of daylight.

The graph reflecting the median of results (50% exceed the values, 50% are lower) shows that 500 lux in the work plane close to the window will be judged as "rather dim," whereas the tendency to "rather bright" starts at about 800 lux. Please note that the illuminance in the working plane does not directly reflect the perception of brightness, which depends much more on the luminance of the surrounding surfaces. But this comparison nevertheless reflects what most planners are taking as "good" lighting level. In reality, users tend to wish for higher illuminances than in most regulations given.

Expressed in limiting values according to statistical analyses of the quantity of satisfied people, the additional artificial lighting will be requested when outside illuminances are lower than 5581 lux (global illuminance) or 12316 lux (vertical illuminance on facade) and therefore are dependent on the outside conditions. In contrast, the perception of brightness in a space will be stated when illuminances in the work plane exceed 3393 lux or vertical in eye height exceed 3797 lux. "Sufficient daylight" state for most of the users occurred when vertical illuminances in

FIGURE 9. Perception of light (Illuminance close to window), median value of comments.



eye height exceeded 3169 lux. Both questions are related to the indoor illuminances. A summary of the limiting values is given in Table 2.

These values show clearly that the requested values by the building regulations are not enough for the space perception "bright." Furthermore, the vertical illuminance at eye height is a relevant measured quantity that is not included in any regulations.

To assess the brightness further for the illuminances in the working plane, another calculation done based on typical fixed illuminance values. 300 lux represents the values given in regulations for the working plane close to a window, 500 lux on other working planes, and 1000 lux for a better lighting environment. Table 3 shows the summary of that analysis.

TABLE 2. Limiting values for "brightness."

	Illuminance in work plane close to window	Vertical illuminance at eye height	Global illuminance outside	Vertical illuminance on façade outside
Additional artificial lighting required: YES	X	X	> 5581 Lux	> 12316 Lux
Perception of daylight in space: Rather bright	> 3393 Lux	> 3797 Lux	X	X
Daylight at working desk sufficient: YES	> 4442 Lux	> 3169 Lux		> 40039 Lux

TABLE 3. Summary of the probability of answers according to fixed values in the working plane.

	Limiting value 300 Lux	Limiting value 500 Lux	Limiting value 1000 Lux
Additional artificial lighting required: YES	56.4%	54.2%	51.2%
Perception of daylight in space: Rather bright	56.7%	60.4%	65.5%
Daylight sufficient at desk: Rather sufficient	44.7%	46.5%	50.8%

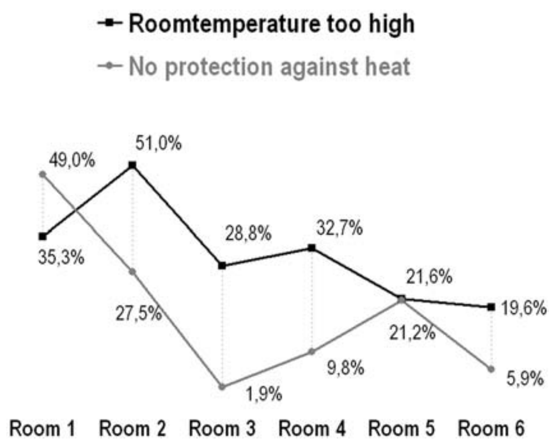
The additional artificial lighting in addition to the natural lighting with closed shading systems and direct sun on the facade shows only a 5% difference, whereas the perception of light shows almost 10% of difference in the judgement of the user.

4.2 The function of systems, the room temperatures, and the understanding of cause and effect

The function of systems plays an important role for the shading coefficient but also for the daylight distribution in an office space. The individual control is stated as "important" for the satisfaction of users [11][18][19][20]. For the judgement of the function, the understanding is an important criterion [22].

Over the whole database almost 90% stated that the shading device performed "rather well." Nevertheless, an additional protection (such as additional heat or glare protection) was required by 21% of the users' answers. This was mostly the case in Room 1 (PV with concentrating hologrammes) where the "visible" shading function was less clear. Figure 10 shows the results of the judgement of room temperatures against the judgement of the protection function. A missing protection was mostly felt in Room 1, whereas the room temperatures have been judged critical in Room 2. The reason for this is that Room 2 had a higher surface temperature, due to the louvers located in the space between the two layers of glass, which is one of the indicators for the thermal well-

FIGURE 10. Perception of room temperature against the perception of the protection function.



being. For Room 1, and less critical for Room 5, the reasons are the "visible protection" mentioned.

There was no significant statistical correlation of the function with the indoor temperatures nor of the indoor temperatures and the well-being. The conclusion of a correlation between room temperature and the "protection against heat" was therefore not taken by the users. The perception of indoor temperature in contrast correlated with the lighting environment. Disturbing room temperatures were mostly felt when outdoor illuminances where high but the lighting coefficient was low at the same time. The most relevant value for additional protection was the illuminance at eye height. An additional protection was required when values exceeded 3797 lux vertical in eye height, but the system was stated as well functioning when vertical illuminances did not exceed 3169 lux at eye height and 4274 lux in the working plane. The initial function of the shading systems as a protection against heat, therefore, does not play an important role in the assessment of the user; in contrast, glare is seen as a requirement for additional protection.

46% of the users felt disturbed when the shading device could not be controlled individually but was fixed, and 90% stated that the possibility of individual control is important. This supports the results of other studies [11][18][19][20]. The question raised included the cause for using the individual control.

Within the study measurements were taken with fixed status to be able to compare the performance of systems. But at the end of each session of questionnaires, the people had the possibility to readjust their shading device according to their individual needs. Overall, only 46% did not vary their systems whereas between 29% and 74% opened or half opened their lamellas depending on the system they used. Room 2 with the light directing glass was the space with the most unvaried status (55%). The more light the users had in their spaces the less they wanted to change their systems' status. If they changed, it was because they tried to receive more contact to the outside, not because of thermal or lighting quality.

Summarizing the investigations regarding the function of systems, the "visual" protection function [22] plays an important role as well as the individual control [11][18][19][20]. The most relevant value was the vertical illuminance at eye height. There was no correlation to room temperatures; therefore, the individual control was based on the quality and quantity of daylight and the contact to the outside. Thermally controlled shading devices, therefore, are likely to lead to misunderstanding and disturbance.

4.3 The space perception in correlation to lighting levels and light distribution

The architectural layout is known to enhance well-being when properly designed. But in an enclosed space, under which circumstances does the feeling of openness occur, especially in cases with closed shading systems? And how do we relieve the conflicts between the necessary heat protection and the need for the contact to the outside?

Figure 11 shows the results of the questionnaires in relation to the perception of "open," "closed," or "locked in" over the whole database. Most of the users (67%) felt rather "enclosed" in their spaces; only 17% found themselves in an "open" environment.

Roomwise this means that the light directing devices (Systems 2, 3, 4, and 6) not providing any contact to the outside when completely closed perform worse (86% answers "closed") than the shading systems (1 and 5), which have been tested with an additional glare protection (20% answers "closed"). Among the louver systems, the redirecting glass in combination with louvers in between the two layers of insulating glass (System 2) performed best with 14% of statements "open" (others only between 0% to 6%). This statement correlates significantly with the view out but is influenced strongly by the brightness in a room (Figure 12).

The more "bright" the space was the less "enclosed" the users felt.

Another correlation can be found between a noticeable light direction and the view out, where there is a tendency for a more positive statement even with a missing view when effective light direction enlightens the space. Figure 13 shows a summary on the statements of the view out (not disturbing) for the

FIGURE 11. Perception of space.

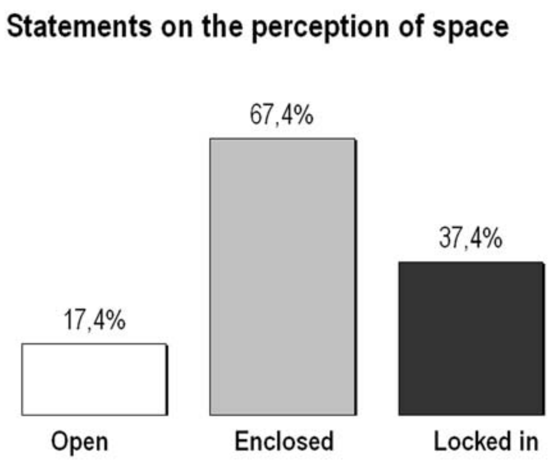


FIGURE 12. Brightness versus openness.

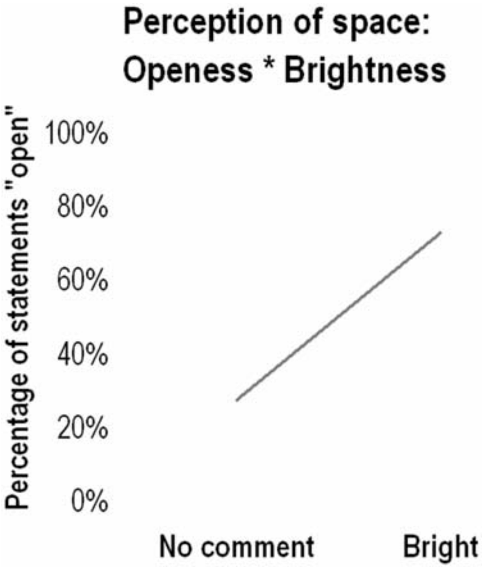
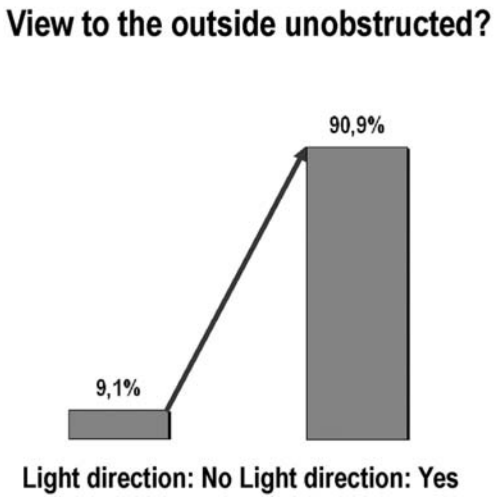


FIGURE 13. The view out with and without light direction (only for louver systems).



louver systems in Rooms 2, 3, 4, and 6. The correlation between light direction and no light direction can be clearly seen.

Thus, the feeling of "openness" can be enhanced with an effective light directing system, or in other words, negative statements on a missing view out or the feeling of "enclosure" can be influenced in a positive way when light direction is used.

5. CONCLUSION

The results of this study show the differences in the resulting lighting quality according to the shading device used. They also show the different levels of acceptance in terms of space perception, brightness, and function.

For the perception of brightness, they show that on the one hand 500 Lux in the working plane are not enough, but requested values are much higher. On the other hand, they show that the measured quantity of illuminance in the work plane often does not reflect the perception of the daylit space.

The judgement of the function of systems is not based on thermal issues mostly used for the automatic control of shading devices but on the view out or the lighting quality. The "visual" protection therefore is the main criterion for the user.

The perception of openness is mainly influenced by the contact to the outside. However, the openness and the statements on the view out can be enhanced through higher lighting levels and efficient light direction deep into the space.

As productivity is directly linked to comfort and well-being, the matter of subjective perception should not be neglected when designing and planning new working spaces. Especially important, the circadian effects of light which have been reported in recent years [24] are likely to be linked with the perception of brightness and the measured quantities of vertical illuminance or spatial luminance. In terms of health and in terms of productivity, both of these aspects have great impact on the costs and efficiency of employees.

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