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Monitoring manual control of electric lighting and blinds

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This paper reviews, validates and extends present knowledge of the degree and kind of manual control strategies of blinds and electric lighting systems that are used in private and two-person offices. A new monitoring setup was applied from March to December 2000 in 10 daylit offices in Germany that featured manually operated electric lighting and automatically controlled external venetian blinds with manual override. The data shows that individuals consistently followed the same control strategy for their electric lighting and blinds. Groups of individuals tended to activate their electric lighting according to Hunt's probability function, although there was a large spread between individual control levels. All subjects used their blinds to avoid direct sunlight above 50 W/m^2, and incoming solar gains above 50 klux (~450 W/m^2). They also were more willing to accept automatic blind opening than closing.

1. Introduction

In recent years there has been a growing interest into the research and development of *integrated lighting control systems.*[1] These systems coordinate the control of automated electric lighting and blind systems — which usually operate in isolation — with conventional building energy management systems, such as heating and cooling units.[2,3] The assumed benefits of this system integration are that it should yield an overall gain in occupant comfort and energy performance over conventional systems,[2] while still being 'cost-effective and practical'.[4] Previous research addressed the technical feasibility of integrated lighting controls[2,3] and their acceptance by the occupants.[4] Less effort has been made to identify the basic behavioural patterns that govern when and how office occupants use their manual or automated electric lighting and blind controls. A deeper understanding of these underlying patterns could lead to:

1) advanced control algorithms that mimic individual switching decisions; and
2) more reliable energy performance predictions of manually and automatically controlled lighting and shading systems.

The objective of this paper is to review, validate and extend results from previous field studies on manual lighting and blind control in private or two-person offices. Based on a literature review (Section 2), a new field study has been carried out in 10 offices with a SSW orientation. The objectives of the field study, experimental setup, results and discussion are presented in Sections 3 through 6.

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2. Previous research findings

Previous field studies on manual lighting and blind control in private or two-person offices unanimously yielded that switching behaviour is *individual but not arbitrary* i.e., while switching thresholds vary within a group of subjects, individuals use their controls *consciously* and *consistently*.[5–13] This observed consistency forms the theoretical basis for the formulation of user behavioural models. Field data further suggests that individual control is partly governed by a number of basic behavioural switching patterns i.e., quantitative correlations that relate user manipulations to external stimuli, like temperature and lighting levels or arrival/departure at the work plane. Key findings from previous work, that are further discussed in the following, are summarized in Table 1.

2.1 Manual control of electric lighting

Electric lighting provides suitable indoor conditions for visibility and other occupant needs. The required illuminance levels vary with the user's activities, age, degree of fatigue and cultural background.[14] Apart from this principal task of electric lighting, the act of switching on the lighting can also be interpreted as a signal that the occupant is 'at work and has not left for the day'. This range of perceived roles of electric lighting can cause individuals to follow drastically different lighting control strategies:

1) Love[11] observed that subjects in six offices with a southern orientation could be assigned to: (1) people who switch on the lights for the duration of the working day and keep it on even in times of temporarily absence (L1a in Table 1); and (2) people who use electric lighting only when indoor illuminance levels due to daylight are low (L1b). Love concluded that the switching behaviour is as much dependent on the individual as on the daylight availability.
2) Jennings *et al.* measured the energy saving potential of various lighting control strategies in private offices over a 7-month period.[7] Although the paper concentrated on energy savings due to occupancy and dimming controls, the published data also revealed that in only eight out of 35 offices occupants had their lighting activated less often than they were at their work place i.e., they 'sometimes occupied their offices without switching on overhead lights'[7] (L1b).
3) Maniccia *et al.* collected 8 weeks of data on the manual switching patterns in 58 private offices and found that 74% of the observed subjects dimmed their lighting, and that 'some occupants sometimes worked with their lighting off' (L1b).[6]

2.1.1 Switch-on

The first studies on manual switching patterns of electric lighting systems in offices were carried out by Hunt in the late 1970s.[5,15] Hunt used time-lapse photography to measure lighting status and user occupancy. Hourly mean diffuse and global irradiances were synchronously recorded so that Hunt could establish a correlation between the times of switching of electric lighting systems and the extremes of a period of occupation. His major findings were:

1) all lights in a room are switched on or off simultaneously (L2);
2) switching mainly takes place when entering or vacating a space (L3); and
3) the *switch-on probability* on arrival for electric lighting exhibits a strong correlation with minimum daylight illuminances in the working area. This correlation is depicted by the solid line in Figure 1 (L4).

2.1.2 Switch-off

Pigg *et al.* investigated in 63 private offices under what conditions people turn off their lighting when leaving the office.[13] In agreement with (L3) in Table 1, Pigg's results established that electric lighting tends to be manually switched off when a work place is vacated, and that the length of absence from an office determines the probability that a manually controlled electric lighting system is switched off (L5 and black

Table 1 Selected findings from previous studies

	Manual control of artificial lighting	Reference
(L1)	people usually pertain to either of the following two behavioural classes: (a) people who switch the lights for the duration of the working day and keep it on even in times of temporarily absence and (b) people who use electric lighting only when indoor illuminance levels due to daylight are low.	Love 1998
(L2)	all lights in a room are switched on or off simultaneously	Hunt 1979
(L3)	switching mainly takes place when entering or vacating a space	Hunt 1979, Love 1998, Pigg 1998
(L4)	the *switch-on probability* on arrival for artificial lighting exhibits a strong correlation with minimum daylight illuminances in the working area.	Hunt 1979, Love 1998
(L5)	the length of absence from an office strongly relates with the manual switch-off probability of the artificial lighting system	Pigg 1998
(L6)	the presence of an occupancy sensor influences the behavioural patterns of some people. On the average, people in private offices with occupancy control are only half as likely to turn off their lights upon temporarily departure than people without sensors	Pigg 1998
	Manual control of blinds	**Reference**
(B1)	people consciously set their blinds in a certain position. The blind position of choice seems to be a result of weighing positive and negative effects over a period as long as weeks or months whereas diurnal blind operations are rare.	Rubin 1978, Rea 1984
(B2)	people are more likely to accept that their blinds are extraneously opened than closed.	Rubin 1978
(B3)	blind occlusion is higher in southern than in northern offices as people tend to use their blinds to block direct sunlight.	Rubin 1978, Pigg 1998
(B4)	beyond a threshold direct solar radiation onto a facade of about 50 W/m^2 blind occlusion is proportional to the depth of sunlight penetration into a room.	Inoue 1988
(B5)	individual manual blind manipulation varies from never to daily in the same facade and tends to take place at the extremes of a working day	Lindsay 1993

bars in Figure 2). Another important result of Pigg's study was that the presence of an occupancy sensor influenced the behavioural patterns of some people. On the average, people in private offices with occupancy control were only half as likely to turn off their lights upon temporarily departure than people without sensors (dark gray bars in Figure 2).

2.2 Manual control of blinds

Blinds serve diverse purposes. They often act as a combined heat and glare protection device to maintain adequate visual and thermal comfort conditions under sunny ambient sky conditions, and/or to reduce the cooling loads.[8,10] Blinds are also employed to provide visual shelter i.e., privacy, for the users. Only a very limited number of studies concerning the manual operation of blinds have been carried out so far.

Rubin investigated manual switching patterns of internal venetian blinds in some 700 private and two-occupant offices with northern or southern facade orientations using photography analysis.[8] Climatic conditions were approximated by

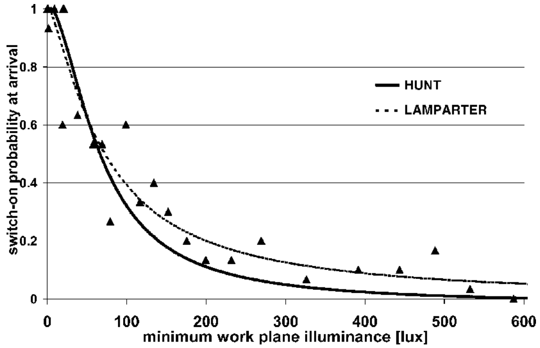


Figure 1 Comparison of the switch on probabilities upon arrival found by Hunt in the Lamparter building. The triangles correspond to measured switch-on probabilities in the Lamparter building

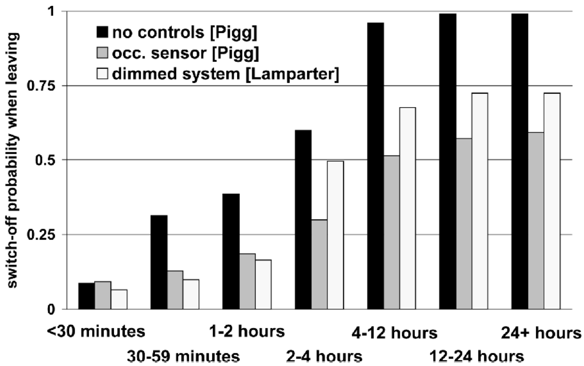


Figure 2 Comparison of measured switch-off probabilities for different times of user absence for a lighting systems without controls and with an occupancy sensor (according to Pigg), as well as for the dimmed, indirect system from the Lamparter building

attributes like *clear and sunny* or *hazy and humid*, and five blind occlusions were differentiated. Rubin's main results were:

1) People *consciously* set their blinds in a certain position. The blind position of choice seems to be a result of weighing positive and negative effects over a period as long as weeks or months, whereas diurnal blind operations are rare (B1).
2) People are more likely to accept that their blinds are *extraneously* opened than closed (B2).
3) Blind occlusion is higher in southern than in northern offices as people tend to use their blinds to block direct sunlight (B3).

Rubin could not establish inter-seasonal or daily changes in how blinds are set i.e., the recorded blind positions seemed to be independent of sky condition, season and time of day.

Rea continued Rubin's work and analysed blind positions on three facade orientations in a high-rise office building in Ottawa, Canada, on a cloudy and a sunny day.[9] External photos were taken in the morning, at midday, and in the afternoon. The results revealed a strong positive correlation between mean blind occlusion and incident irradiance, even though Rea found no adjustment of blinds throughout the day. Rea's findings support that occupants manipulate their blinds consciously to reduce penetration of solar radiation (B1 in Table 1). Whether solar heat or glare reduction were the driving forces for the blind manipulations could not be resolved from Rea's results. Given that people refrained from changing the blind position throughout the day, Rea concluded – in agreement with (B1) – that they have a long-term perception of solar irradiances. This inertia of people to react towards changing sky conditions might resemble the tendency of people to only operate their electric lighting upon arrival or departure (L3).

Inoue *et al.* took photos of offices facades of four air-conditioned high-rises in Tokyo, Japan, to extract the manual control of venetian blinds.[10] Synchronously with the photographs, direct and diffuse irradiances were collected. The total measurement period was one to three weeks for each high-rise and the measurement interval was one hour. Occupancy was assumed in an office for the whole working day, if the blinds were operated at least once. The major findings of Inoue's study are that beyond a threshold direct solar radiation of about 50 W/m^2, blind occlusion is proportional to the *solar penetration depth* into a room (B4 and Figure 3).[16] The solar penetration is defined as the distance from the facade that direct sunlight can penetrate into an office.[10]

Lindsay *et al.* investigated venetian blind use

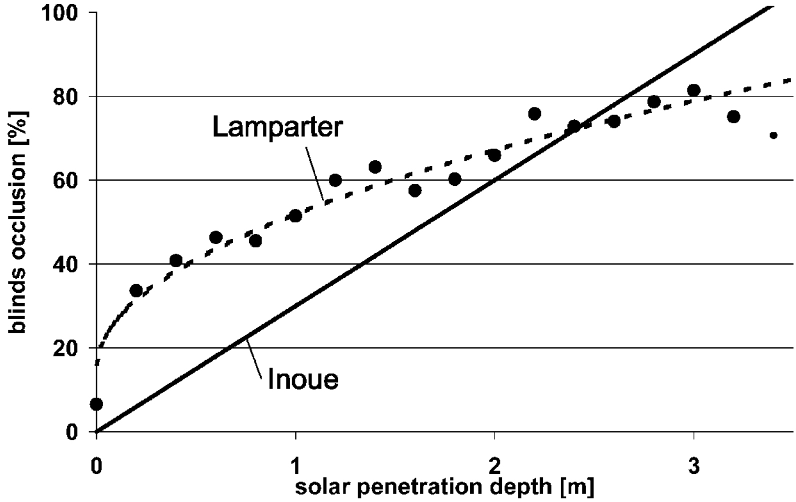


Figure 3 Mean blind occlusion for different solar penetration depths for all investigated offices, for the occupied times when the direct solar irradiance was above 50 W/m². The straight line corresponds to Inoue's fit, whereas the parabolic graph (-) is fitted to the Lamparter data. The parabolic fit corresponds to $y = 15 + \sqrt{-0.116 + 1359x}$ with y = blind occlusion (%) and x = solar penetration depth (m)

in five different office buildings in England[12] using time lapse photography to measure blind occlusions and slat angles. In contrast to B1, they found that regular blind manipulation occurred in a number of offices, and that the individual blind manipulation rates for different windows in the same facade ranged from never (0%) to daily (100%), with an average around 40% (B5). Blinds were operated in response to the amount of sunshine and the position of the sun with respect to the facade, which is in qualitative agreement with B4. People tended to manually lower the blinds during the days, as direct sunlight penetrated onto their facade, whereas they mainly retracted them at the end of the working day or early in the morning. Even though the one building which tended to overheat in the summer had the highest mean blind occlusion, Lindsay speculated that the general motivation for people to use blinds is to avoid glare rather than to prevent overheating. This assumption is supported by Inoue's conclusion (B4) which states that direct sunlight as low as 50 W/m², which corresponds to relatively low solar gains, does already trigger increased blind occlusions.

Pigg also monitored blind usage, and his data confirms (B3) that blind occlusion is significantly lower in northern than in southern offices.[13] In Pigg's survey 37% of the subjects stated that they used blinds to reduce glare on their computer screen.

Bülow-Hübe investigated preferred settings of an awning and an external venetian blind system for 50 subjects in two test offices in Lund, Sweden.[17] During the experiment she let the subjects adjust their shading devices and found that they were frequently used throughout the day to control glare, and that the existence of sunlight patches in the room tends to trigger the use of shading devices (B4).

3. Objectives of the field study

All the above mentioned studies indicate that electric lighting use mainly appears when occupants arrive and leave their workspace, whereas blinds are mainly used to block direct sunlight.

As all of these switching patterns have so far only been identified *in isolation* for different users, buildings and countries, this study aims to:

1) test whether previously identified switching patterns can be qualitatively, quantitatively and synchronously reproduced; and
2) understand whether a manually controlled electric lighting system and automatically controlled blinds with manual override are operated in symbiosis or independently from each other.

4. Experimental set-up

4.1 Building description

Figure 4(a) shows a photograph of the *Lamparter* building which is situated in Weilheim near Stuttgart, Germany, and consists of two rows of offices on each side facing SSW and NNE. Only the SSW offices were considered in this study (see a typical floor plan in Figure 4b). As no active air-conditioning system had been installed, the offices relied on a careful management of incoming solar gains in the cooling period, and a passive cooling approach with nocturnal ventilation and earth-to-air heat exchanger as part of the ventilation system.

Both the electric lighting and external venetian blinds were connected to a European Installation Bus (EIB). The electric lighting consisted of two purely indirect luminaires, each with 2×58 W, which were manually switched on and off. Lighting levels were automatically dimmed via a ceiling mounted illuminance sensor which was connected to a closed-loop control system. At full capacity, the system yielded some 400 lux on the work plane.

Figure 4(c) provides a sketch of the daylighting concept. External two-component blinds acted as a combined heat and glare protection device and were supported by an external lightshelf. The blinds were operated both automatically and manually. Manual blind control was possible at all times, and any manual blind manipulation disabled the automated blind control for 2 hours. When active, the automated control system fully lowered/retracted the blinds if the illuminance onto the SSW facade exceeded/fell below 28 klux. When the blinds were automatically lowered, the lower set of slats was closed, whereas the upper slats were kept horizontal to redirect daylight deeper into the room.

4.2 Occupant description

The 10 offices were occupied by a total of six females and eight males, resulting in six private and four two-occupant offices. In the latter offices, the same electric lighting and blind systems were operated by both occupants. All 14 subjects continuously occupied the same work places throughout the whole monitoring period.

4.3 Data acquisition

The experimental set-up was designed to collect a long-term data set, including environmental conditions such as direct and diffuse irradiances, indoor temperatures, illuminances on the facade and work plane illuminances as well as occupancy in the offices and the status of the blinds and the electric lighting. This extensive data collection has been realised through four data acquisition systems:

1) User occupancy and indoor temperatures in the offices were measured by ultrasonic presence sensors and an onset HOBO™ standalone data logger, which were joined together as a single measuring device. The HOBO™ is a low-cost, stand-alone data logger that continuously measured and recorded the temperature at the workstations in 15-min intervals. The ultrasonic sensors were attached directly to the underside of the monitors located at all workstations. The HOBO data acquisition system proved to run reliably.
2) Indoor illuminances were also measured by illuminance sensors integrated in the HOBO™ data loggers. Unfortunately, the signal from the sensors was of insufficient quality because of poor sensor quality, and because occupants tended to place working

(a)

(b)

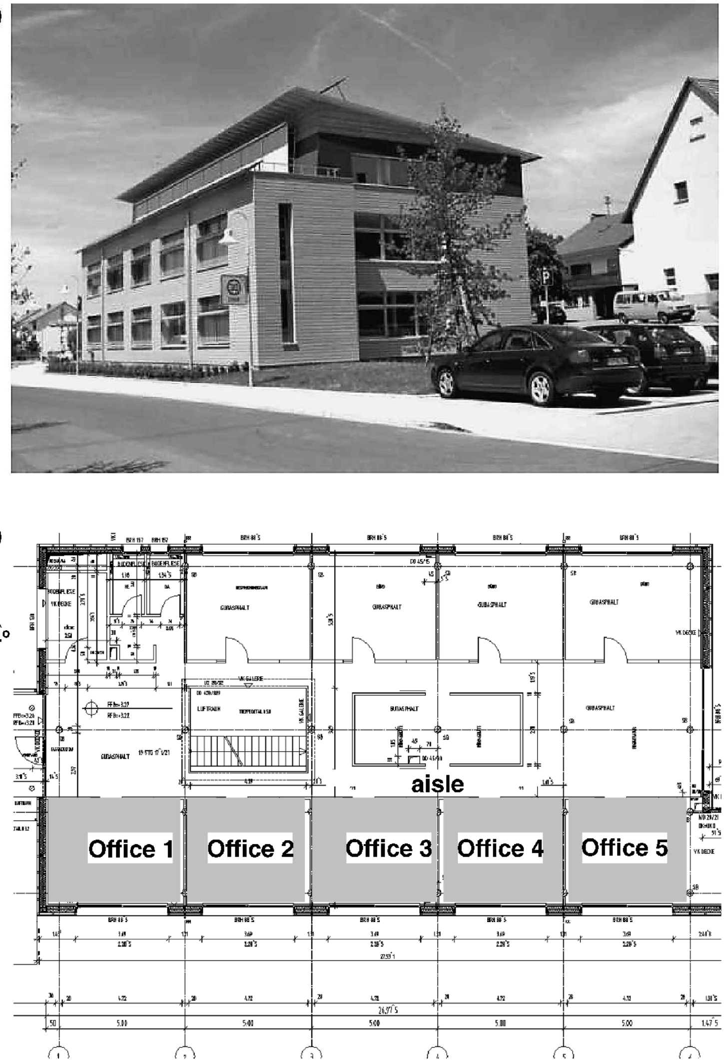


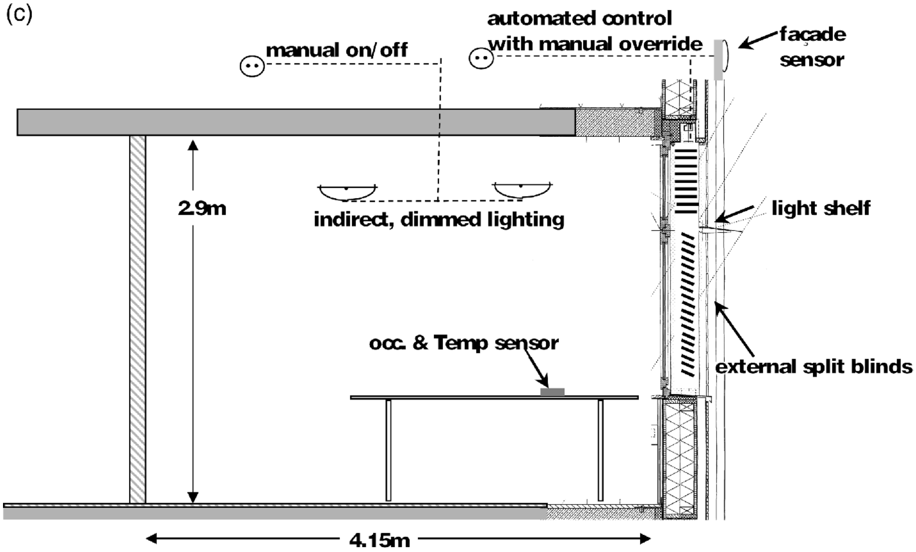
Figure 4 **(a)** Photograph of the monitored Lamparter building (architects: Meier-Weinbrenner-Single, Nürtingen, Germany). **(b)** Typical floor plan of the building. The field study was carried out in the offices with the SSW facade orientation (marked grey). **(c)** Daylighting concept in the offices. **(d)** Example video capture from the data acquisition system for the blind settings

material on top of the desktop sensors. Therefore, the dynamic RADIANCE-based daylight simulation method DAYSIM[18,19] was used to simulate the indoor illuminance distribution in the offices, based on measured direct and diffuse irradiances.

3) Direct and diffuse irradiances and the facade illuminance were collected with two Schenk Sternpyranometers 8101 and an Ahlborn illuminance sensor type 4.3 FLA613 via a central data acquisition system which was installed on the roof of the building and maintained by the Fachhochschule Stuttgart.[20] As the data acquisition system had some initial problems, data was only sporadically collected until the end of July 2000, resulting in 142 days of data.

4) Electric lighting was operated via an EIB sys-

(c)



(d)

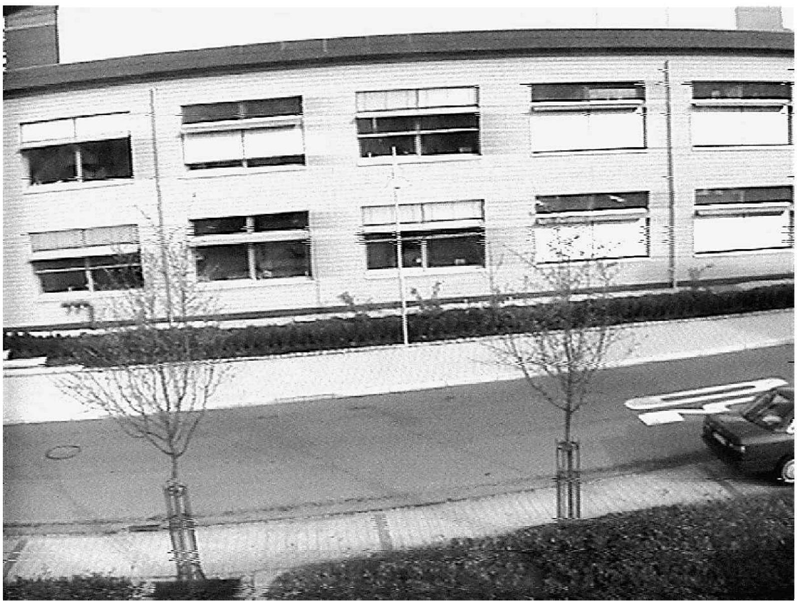


Figure 4 continued

tem so that the status (on/off) of the switches could be directly recorded with a Linux PC, which was connected to the EIB system. The dimmable lighting controls did not allow the requesting of the dim level via the EIB system. Informal observations of the authors indicated that the dimming system was properly commissioned in all offices.

5) Blind settings in the offices were recorded using a video camera with a sender that was mounted outdoors on the neighboring residential building facing the southern facade of

the Lamparter building. The camera continuously sent pictures to the data acquisition system. An example picture is shown in Figure 4(d). Whenever a change in the any one of the southern blinds occurred, the data acquisition system noticed this event via the EIB system, and saved a digital image from the camera after pausing 90 seconds to allow the blinds to fully change positioning. Afterwards, the *blind occlusions* were manually extracted from the collected digital images. The blind occlusion[9] corresponds to the percentage of a window that is covered by blinds. It is independent of the blind slat and provides a simplified linear measure of the state of a venetian blind system.

Any concerns the occupants had regarding the video surveillance camera were addressed during an information session before the data collection started. In order to divert the occupants' attention from the behavioural aspects of the study, technical details of the experimental setup were explained to them with an emphasis on the measurements of the energy flows within the building. Sample photographs of the camera were also shown to the occupants to demonstrate that the resolution was too low to highlight any details within the offices.

The measurement period lasted from 22 March to 3 December 2000. Further details of the experimental setup are provided in Table 3 and reference 21.

5. Results

5.1 Electric lighting

5.1.1 Switch on

All monitored subjects in the Lamparter building spent a considerable amount of time in their offices without the electric lighting being switched on following switching behaviour L1(a) from Table 1. To verify hypotheses L3 and L4, all *switch-on events* were investigated. The analysis yielded that 88% of all events coincided with an arrival, and that these events accounted for 86% of all activated lighting times. Figure 1 compares Hunt's original switch-on probability function (solid line) to the combined data from the 10 Lamparter offices (dashed line). The correlations were calculated according to references 5 and 11. The resulting fitting parameters are listed in Table 3. It is striking to see how similar the two curves in Figure 1 are, considering that they have been collected in single and multiple-person offices in different countries and decades. Figure 5 shows Hunt's switch-on probability function for all 10 investigated offices separately, revealing a considerable individual spread, ranging from a median as low as 38 lux to 410 lux. A similar individual spread had also been reported by Love in two offices with a northern orientation.[11]

Intermediate switch-on events which followed a previous work place occupancy of more than

Table 2 Overview of the collected data

Quantity	Measurement technique	Units	Measurement interval (min)	Data collected (days)
work place occupancy	occupancy sensor	0/1	15	248
indoor temperatures	HOBO data logger	°C	15	248
work plane illuminances	simulated based on direct and diffuse irradiances	lux	5	142
ambient temperature	thermocouple	°C	5	142
global horizontal irradiance	pyranometer	W/m^2	5	142
diffuse horizontal irradiance	pyranometer	W/m^2	5	142
vertical illuminance in facade	illuminance meter	lux	5	142
status of artificial lighting	via EIB system	0/1	5	243
blind occlusion	analysis of digital pictures	%	5	243

Table 3 Fitting parameters for different switch-on probabilities with $y = a + c/\{1 + \exp[-b(x-m)]\}$ for $x > 0$ and $y = 1$ for $x = 0$; y = switching probability and $x = \log_{10}$ (min. work plane ill.)

Parameter	a	b	c	m	Median (lux)
Hunt's switch-on probability upon arrival	−0.0175	−4.0835	1.0361	1.8223	121
switch-on probability upon arrival from this pilot study	−0.00238	−3.0965	1.0157	1.8536	195
intermediate switch-on probability from this pilot study	0.0027	−64.19	0.017	2.41	241

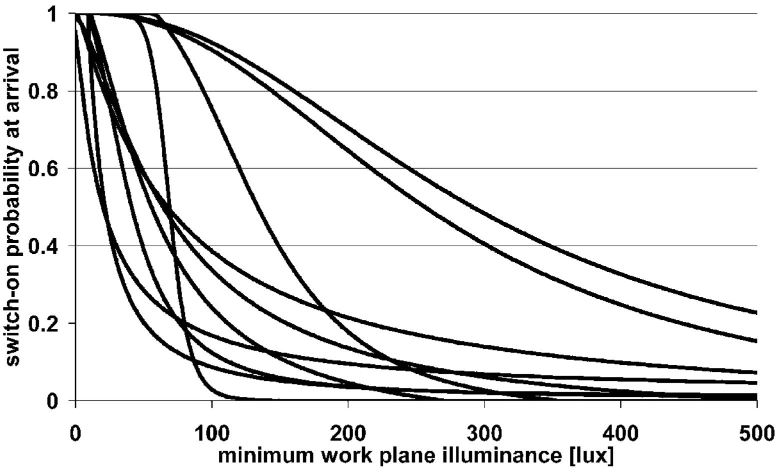


Figure 5 Individual switch-on probabilities as a function of work plane illuminance in all offices

15 min were investigated. Hunt proposed that the switching criterion under such circumstances is equivalent to the one at the beginning of a period of occupation.[15] Figure 6(a) shows the frequency distribution of all monitored intermediate switch-on events in the Lamparter building, revealing that indeed these events were more common at lower than at higher illuminances. Based on this finding, an *intermediate* switch-on probability correlation function comparable to Hunt's arrival probability was calculated, following essentially the same procedure as in the proceeding section to fit the data (While an arrival event is a well defined point in time, an intermediate event takes place within a time period. In Figure 6(b) a time-step-interval of 5 min was used to calculate an intermediate switch-on probability correlation i.e., an event was marked for every time-step at which a work place had been occupied for at least 15 min, and the lighting was switched off.) The resulting probability function exhibits a step-like behaviour (Figure 6b). Below about 240 lux minimum desktop illuminance the probability of a switch-on event lies around 2%. Above this value the probability drops to about 0.5% without further decreasing for higher illuminances. The function does not approach unity for vanishing desktop illuminances due to the scarcity of data. This clearly shows that this curve merely reflects a trend and should be treated with care. It is very likely that parameters which have not been considered in

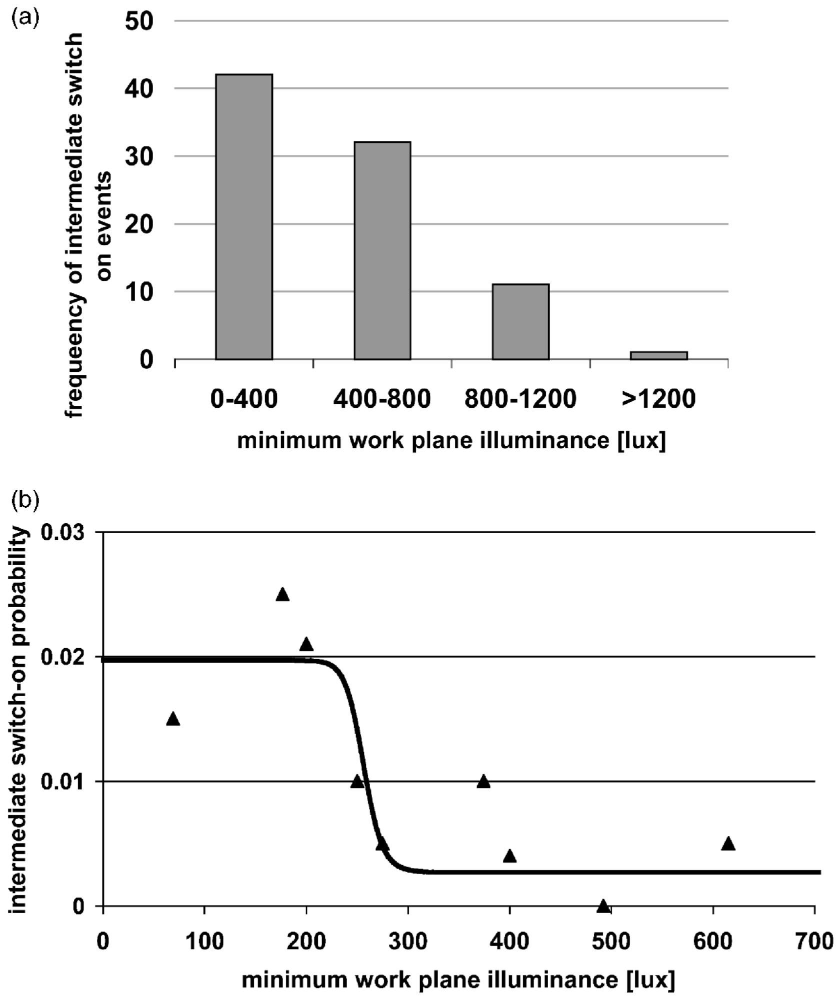


Figure 6 (a) Histogram of intermediate switch-on events ordered by their pertaining minimum indoor illuminances. **(b)** Intermediate switch-on probability for all 10 offices based on 5-min-time-step-intervals

this study – like the type of office work being performed or the alertness of the users – are more suitable to predict the occurrence of intermediate switch-on events. This would also explain the appearance of intermediate switching events above 800 lux (Figure 6(a)) which lie above the range of switching events measured during arrival (Figure 1).

5.1.2 Switch off

The light grey bars in Figure 4 show results for the manually operated, dimmed and purely indirect lighting system that was installed in the Lamparter building. The switch-off probabilities for this lighting system continuously lie below Pigg's results for a manually controlled system. Informal discussions of the authors with the subjects in the Lamparter building indicated that the occupants sometimes did not switch off their lighting when indoor daylight illuminance levels were high, as they failed to notice that it was on. This finding suggests that such a lighting system should be either be coupled with an occupancy sensor or an automatic switch-off once the dimming level has stayed below a threshold value for a certain time span.

5.2 Automated blinds with manual override

This paragraph describes how the occupants in the Lamparter building used their manual override control to influence the setting of their automated blinds (In two-person offices both occupants had control over the same blind system.) A total of 6393 blind changes were recorded during the 174 weekdays measurement period in the 10 offices, resulting in an average of 3.7 blind manipulations per day and office. This high manipulation rate was caused by the automated blind control system as 3005 blind manipulations (47%) were carried out automatically. The remaining manual blind readjustments were grouped into two classes: a manual blind manipulation was interpreted to be a *correction* of the control algorithm if carried out within 15 min after an automated blind readjustment and *independent* otherwise. It was found that 45% of the above mentioned 3005 automated blind adjustments were corrected by the users. This high correction rate confirms findings (B1) that occupants consciously set their blinds – automatically controlled or not – and have a remarkably low tolerance range towards external readjustments. Automated and corrected blind manipulations together accounted for 68% of all blind manipulations.

An analysis of when the investigated subjects corrected an automated blind setting yielded that in 1263 out of 1432 times (88%) the office workers *manually retracted* the blinds after the automated blind system had automatically lowered them. This strong tendency of the occupants to open the blinds was strongest at low solar penetration depths and supports hypothesis (B2) that people are more likely to accept that their blinds are extraneously opened than closed. Qualitatively, occupants only tended to close their blinds after an automated retraction, when a weak winter afternoon sun penetrated deeply into the building.

Concerning the 1973 *independent manual blind readjustments*, only very few tendencies could be extracted from the data. The main difficulty of this part of the data analysis was that for only 811 manual readjustments, ambient sky conditions were simultaneously collected (section 4.2). For these events, the blinds were manually closed on the average at external facade illuminances of 50 klux and opened at 25 klux.

Figure 7 illustrates the correlation between the solar penetration depth and the mean blind occlusion in all 10 offices for all occupied times. The dots (triangles) correspond to occupied times when the ambient direct solar irradiance onto the facade was above (below) 50 W/m^2. The data support B4, that direct sunlight needs to lie *above* 50 W/m^2 to cause glare and trigger people to lower their blinds. Figure 3 compares Inoue's original fit (solid line) of a SSW facing office facade in Tokyo, Japan, with a parabolic fit of the Lamparter data with a minimum direct threshold of 50 W/m^2 (dashed line). The latter qualitatively reproduces Inoue's fit. The main discrepancies are found below 2 m solar penetration, as the Lamparter blind occlusion jumps to over 40% for non-vanishing solar penetrations. Possible reasons for this discrepancy are that Inoue investigated manually controlled blinds, did not measure user occupancy and his occupants were seated a varying distances to the facade.

5.3 Interaction: automated blinds and electric lighting

Figure 8 explores the interaction between electric lighting use and the status of the blinds. The figure reports the position of the blinds for the times when the electric lighting was activated. Three different blind positions are identified: blinds up (fully retracted), blinds not fully retracted and privacy. (It was considered that a user closed the blinds due to privacy concerns, if the blinds were closed while the ambient horizontal illuminance was below 1000 lux.) With the exception of office 5, the blinds were fully retracted on over 80% of the occasions when electric lighting was switched on i.e., the amount of available daylight was usually maximized

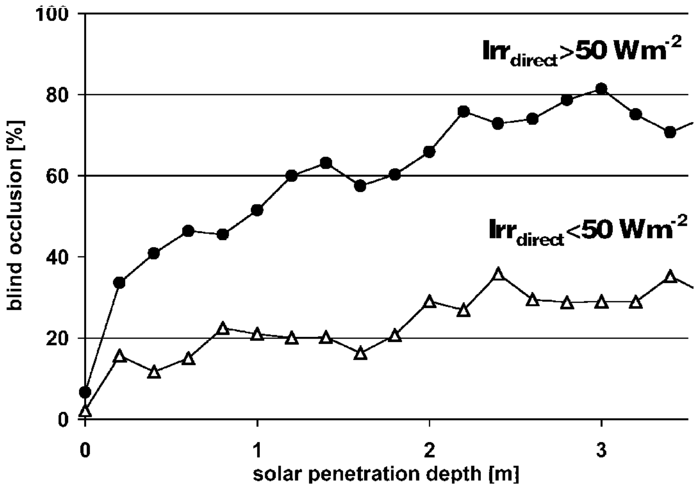


Figure 7 Mean blind occlusion for diffferent solar penetration depths for all the investigated offices for all occupied times. The dots (triangles) correspond to times with ddirect solar irradiances above (below) 50 W/m^2

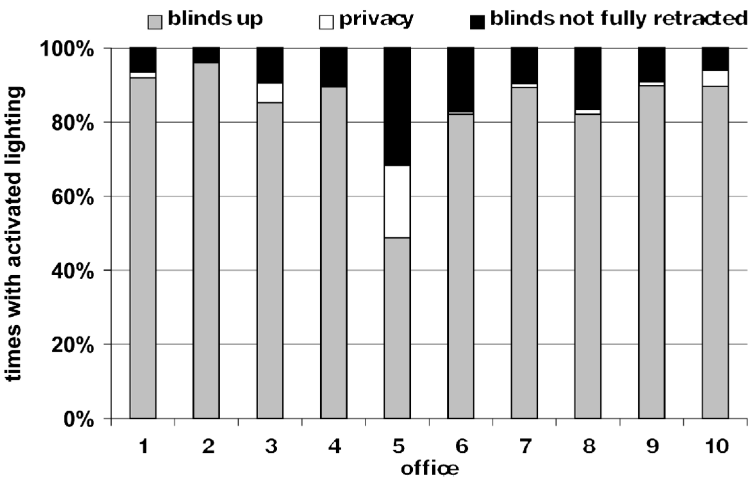


Figure 8 Status of the venetian blinds during hours when the offices were occupied and the lighting was activated

when the occupants activated the electric lighting.

6. Discussion and conclusions

This section summarizes results from the previous section and discusses their general validity and the possibility of implementing them in building simulation models. More advanced blind control strategies are proposed, and remaining gaps in our knowledge of manual lighting and blind control are identified.

Electric lighting use

All subjects activated their electric lighting according to Hunt's probability correlation pattern, although absolute illluminance threshold levels varied considerably between individuals. *Groups* of individuals followed very similar behavioural patterns independent of the considered office type (Figure 1), whereas *individual* behaviour exhibited a much wider spread (Figure 5). Switch-on events upon arrival accounted for 86% for all switch-on events. The remaining *intermediate* switch-on events exhibited a different and much weaker correlation to desk plane illuminances (Figure 6b), and it is probable that they were mainly triggered by quantities which have not been monitored.

Pigg's correlation between the time of absence from a work place and the probability that the electric lighting was switched off was qualitatively reproduced. Anecdotal evidence suggested that the lower switch-off probabilities found in the Lamparter building compared to Pigg's study (Figure 2) can be partially attributed to the dimmed, purely indirect lighting system.

Blind use

The automated blind control ensured that the blinds were usually retracted when ambient daylighting levels were low. As the dimmed electric lighting system merely provided a maximum desk plane illuminance of 400 lux, the users had to retract their blinds to increase their work plane illuminance beyond this level. The combination of automated blinds and dimmed lighting lead to a daylighting concept in which the electric lighting system and played the role of a 'backup' for the available daylight.

While the users rarely opposed an automated opening of the blinds, they opened their blinds on 45% of the occasions when they had automatically been lowered. Lowering of the blinds was only accepted if incident solar gains were as high as 50 klux (~450 W/m^2), or if direct sunlight above 50 W/m^2 hit the work plane. The high number of user corrections re-enforces that users consciously set their blinds (B1), and that they are more likely to accept that their blinds are extraneously opened than closed (B2).

General validity of results

Even though our knowledge of manual lighting control in offices is still fragmentary, many correlations from former studies could be synchronously and qualitatively re-established in 10 private and two-person offices. This encouraging result implies that the correlations in Figures 1, 2, 3 and 6(b) can be used to model switching behaviour in this type of offices. Their applicability in more open plan settings – in which individuals loosen the perception of ownership over their immediate environment – is questionable as social constraints have been reported to influence individual behaviour.[22]

Advanced blind controls

To reduce the number of manual overrides (and possibly get a higher user satisfaction[23]) for a facade-sensor-controlled blind system, it seems advisable to add a second threshold as to when the blinds are automatically closed. The two thresholds could either be fixed e.g., 28 klux for retracting the blinds and 50 klux for lowering the blinds, or dynamically set by an adaptive control algorithm.[3] A more sophisticated blind control could adapt Inoue's correlation of solar penetration depth with blind occlusion (Figure 3), which was recuperated in the Lamparter building. An advantage of the concept of the solar penetration depth is that it considers the position of the sun with respect to the facade as well as the facade geometry and shading due to surrounding buildings. Therefore, the correlation found in Figure 3 – although it has only been measured in SSW facades – should be principally applicable to any facade with non-vanishing solar penetration depths throughout the year i.e., eastern, southern and western facades. Unfortunately, no sky luminance threshold has been identified so far, that could be employed to predict when blinds are closed in northern facades.

Application in building simulations

The switching patterns found in this study can principally be combined with simulated annual daylight and occupancy profiles, in order to predict the annual energy demand of an electric lighting system for various control options for occupants of private or two-person offices that do or do not use their electric lighting in accordance to ambient daylight levels (L1(a)&(b) in Table 1).[21] From a practitioner's point of view, a missing piece of information to predict a building's annual lighting demand is the actual distribution of users who *do* consider daylight compared to all users. Whereas in Jennings *et al.*,[7] Pigg *et al.*,[13] and Love's[11] studies, the majority of occupants switched their lighting independent of ambient daylight levels, all occupants in the Lamparter building considered daylight. These numbers could be an indication of cultural differences between the light switching patterns of North-American and European office workers. Another interpretation is that different building designs and lighting concepts favour a different behavioural response i.e., that user behaviour is polarized in different buildings.

Manually controlled blinds

The automated blind control lead to a blind manipulation rate of 3.7 per day and office, which is higher than the ones reported for manually operated blinds.[8,9,12] While the automated blind system triggered occupants to adjust their blinds on a daily basis, it remains unclear whether the same occupants would have operated a purely manually controlled blind system with the same regularity. This issue deserves further attention in the future.

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Discussion

Comment 1 on 'Monitoring manual control of electric lighting and blinds' by CF Reinhart and K Voss

M Fontoynont (ENTPE, URA CNRS, France)

In this paper, the authors attempt to establish the major elements for a coherent control of electric lighting and blinds which would satisfy the occupants of office buildings. They have identified users' preferences and trends in their behaviour, which seem to be based on conscious decisions either to improve their comfort or to save energy. But natural human laziness favours the development of automatic controls since it seems that the desire for good comfort is not strong enough to overcome the reluctance to make the personal effort needed for frequent manual adjustment of lights and blinds. These automatic controls should be well accepted, as long as they are discreet, logical and offer the possibility of override.

A major difficulty is raised by the method of experimentation. This stands in the way of extension of the results to configurations with characteristics other than those described in the paper, in particular, to different lighting installations (the experimentation was conducted with indirect luminaries) or to installations equipped with blinds with colours other than those used in the experiment.

Questions remain with regard to the optimum tilt angle of the blind slats, the role of the external obstructions as well as the acceptability of sunlight penetration when the relative azimuth angle of the sun with respect to the façade is high.

It would be useful to have the opinion of the authors on these aspects.

Comment 2 on 'Monitoring manual control of electric lighting and blinds' by CF Reinhart and K Voss

Dr Takashi Inoue (Department of Architecture, Tokyo University of Science, Chiba, Japan)

This is an extremely interesting article covering issues related to the control of lighting and solar-shading in the office environment. The control of lighting is the more subtle of the two, and appropriate consideration must be given to elements of cultural and educational background. On the other hand, the control of solar-shading devices, particularly with regard to which situations require shading of solar radiation, is a little less complicated, and the differ-