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Effect of changing room light on the productivity of permanent morning shift workers at industrial workstations

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Industrial workstations at Flextronics

Preface

People frequently ask about an increase in productivity in case of improved working conditions. Light is a decisive factor in this respect. For light not only causes an improvement of visual conditions, but it also has an effect on unconscious biological functions. Moreover, light is always an emotional factor.

In order to also provide scientifically sound evidence for an increase in productivity, not only production figures are analysed, for these cannot directly be attributed to good lighting.

Accordingly, in this study, much more comprehensive methods are applied to capture the effect of light on human beings.

It is noteworthy that even standard conditions allow the work tasks to be exercised impeccably and without any complaints. It is all the more pleasing that improved lighting has a positive effect on people's sleeping pattern during the night and on the reduction of unit lead times – and accordingly contributes to increase productivity.

Abstract

Within the scope of a field study, the psychophysiological and productivity-related effects of changing room lighting conditions for workers at the Althofen plant of Flextronics during the morning shift were recorded.

In the first study (preliminary study), two dynamic room lighting conditions were compared with each other. One scenario offered fewer but perceptible changes of light, another offered frequent, but imperceptible changes of brightness.

In the second study, two dynamic room lighting scenarios were selected for the main study by way of a pilot study, where 6 lighting scenarios were tested. These two dynamic scenarios were compared to standard lighting acc. to EN 12464-1 within the scope of a 9-week main study using multidisciplinary measuring methods (e.g. industrial psychology questionnaires, electrocardiography, actigraphy and recording of specific productivity ratios) in a season with low amounts of daylight.
Since the work process was subject to substantial interferences (e.g. change of working hours and of the team), various different sample sizes were included in the data analysis.
With the two dynamic room lighting scenarios, the vagal tone* of the workers increased in the first and last third of the morning shift, as compared to standard lighting. Moreover, a markedly improved quality of sleep was observed with these two room lighting scenarios.

Additionally, perceptible brightness changes in the production bay provided for increased well-being at the end of the shift. In contrast, physical activity during the morning shift featuring a room lighting scenario with imperceptible brightness changes was substantially lower.

In study 1, due to the sophisticated organisation of work, it was not possible at first to measure an influence of the room lighting on the productivity of the workers in a simple way. An evaluation of the relative mean unit processing time suggested a 4 % increase in productivity for the winter.

Overall, it may be said that changing room lighting conditions that go beyond standard lighting will have a positive effect on working people both during the morning shift and during the night. Finally, the present field study demonstrates that while capturing the influence of room lighting on the productivity of the workers in a modern production plant was massively blurred by the prevailing rigid organisation of work, it nevertheless has an impact in that tasks are performed more easily and quickly.

* Vagal tone: state of tension or excitation of the parasympathetic nervous system that is primarily influenced by the nervus vagus.

This research project was carried out within the scope of the k-Licht competence centre. Interdisciplinary partners were involved. k-Licht was subsidised by the federal government and the Austrian Laender (see last page).

The first examinations started in 2006. Upon completion of all examinations and outside the subsidised period, the enormous amount of data was analysed. A laboratory study (see study "Laboratory experiment on influencing productivity through dynamic lighting effects") was carried out subsequently. The results of the first study at Flextronics were published in the highly renowned scientific journal "Lighting Research & Technology".

1 Problem definition

In a production plant, information about productivity is an important indicator of performance. Measuring the increase in productivity due to the influence of lighting is not a simple task. Where an increase is observed, this may often be due to a variety of influences.

In the sphere of lighting, there are many possibilities to create good visual conditions, even through static lighting meeting standard requirements as a minimum. For dynamic brightness sequences, it is possible to modify the brightness or colour temperature of the lighting. The changes may be effected quickly or slowly, and accordingly they may be perceptible or imperceptible.

The effect on the workers may be assessed through various interviews and measurements. An interdisciplinary research approach with experts from the fields of psychology, ergonomics, medicine and lighting technology jointly applying a set of measuring instruments to describe and analyse the effects on well-being and stress, motivation and sleeping quality, the capacity to regenerate after work, as well as the quality of the lighting situation has proven to be useful.

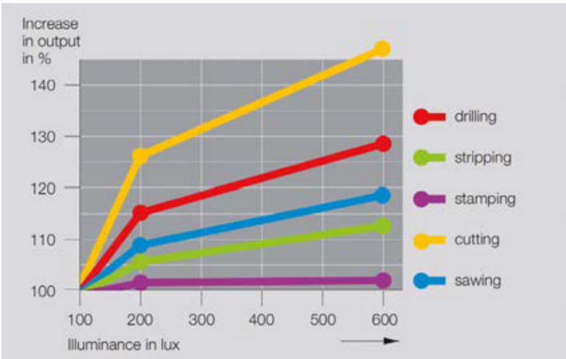
Finally, the company must be prepared to have the examinations carried out.

2 Scientific state of the art

Scientists agree that light has a decisive influence on the visual performance and the well-being of working people. Indirectly, therefore, good lighting quality has an influence on productivity. If illuminance levels are too low, the error rate is considerably higher /Völker/. For simple manual tasks, error rates will only decrease from illuminance levels of approx. 500 lx onwards. Juslén has shown that an increase of illuminance levels from 800 lx to 1 200 lx improves productivity by some 4.7 % during the morning shift in winter, while in summer no influence was observed /Juslén/. He has carried out his investigations in numerous industrial plants with different lighting installations.

Observing the effect of light on human beings is a topic that is addressed by various sciences such as psychology, medicine, ergonomics and lighting technology. Within the scope of a preliminary project by k-Licht, questionnaires, medical examinations, observations and measurements were compiled. This has resulted in a set of instruments to carry out a field study under real conditions in an industrial plant.

The analyses of the preliminary project at the k-Licht competence centre have demonstrated that dynamic general lighting has a positive influence on both the psychophysiology and the productivity of working people. In the process, the lighting effects of very slow brightness changes, as they may occur on a cloudless day, were recorded. Based on these research results, the question arose as to whether quicker brightness changes (within a few minutes up to a maximum of half an hour) with high differences in brightness (varying between 1 000 and 2 000 or 3 000 lx of horizontal illuminance in the task area) might again reinforce the lighting effect.



3 Research hypotheses

The aim of this project was to quantitatively record the influence of highly variable general lighting on the psychophysiological well-being and the productivity of workers in a production plant.

Variable light is room lighting that varies over the course of time with respect to:
– brightness (illuminance)
– light colour (spectrum)
– light distribution (luminance distribution in the room)

In this context, primarily the immediate effects of variable room lighting during the morning shift were to be measured. The data collection within the present study was deliberately effected in the darker season, because it was expected that the effects of artificial lighting on people would be more pronounced, since the natural influence of daylight outside working hours is very low during that season.

The basic task was to develop lighting conditions of varying degrees of dynamism that would meet the following two main requirements:

1. They should have psychophysiological effects, and
2. should be accepted by the employees.

In many papers on lighting effect research published so far, this has been an incompatible pair of opposites.

4 Research methods

4.1 Methods used

The examination was carried out in two phases, one pilot study and the main study.

The aim of the pilot study was to have six different lighting sequences, each of them presented for one week, assessed with respect to acceptance and tolerance during everyday work.

Before the start of the pilot study, an ergonomic assessment of the workstations in place as well as a classification of these according to specific tasks was effected. Subsequently, those workstations were selected where psychophysiological data of employees were to be recorded within the scope of the pilot study and the main study.

The observations took place in summer and in winter.
24–29 female test subjects, 61 % of them over 40 years of age, participated in the study.

Concurrently with the ergonomic evaluation, the researchers worked out a concept for capturing production ratios at the workstations selected. The workstations were put together in groups (line production) working on the same product in each case. It turned out that from the number of units processed daily by each working group and from the time required for this, a relative lead time per unit can be calculated. This ratio illustrates the productivity of a working group in a representative manner.

Frequently, in studies on the biological effects of light, the persons exposed to the light are not questioned about the quality of the lighting. However, this is a decisive aspect with a view to the future applicability of indoor lighting systems and may cause visual, cognitive and physiological dysfunctions, especially in case of very quick brightness changes of the interior lighting.
The analysis of the interviews facilitated the development and/or selection of two lighting control algorithms for dynamic room lighting, whose psychophysiological effects were meant to be compared with a control lighting scenario in the main study.

As the employees were not meant to perceive when exactly the room lighting scenario was changed, the programming of the lighting control system in the room was modified every Saturday, i.e. outside working hours.

There are manifold influences on the study results that are not light-related and can hardly be controlled, or not controlled at all, such as diseases of employees, additional family-related stress outside working hours, unexpected new orders, damage to equipment or problems in the field of materials procurement. These effects superimpose to a large extent the psychophysiological effects achievable through general lighting. Since such incidents were minutely documented by the study manager on site, it was possible to filter the captured data accordingly before starting the analysis.

Before and after the main study, the **medical-physical status of the study participants and their status in terms of industrial psychology** was determined within the scope of an occupational health check of half an hour. This measure has provided for an exact control of employee-related disturbances of the study results.

A study design with **short-term repetitions of the measurements** was implemented to further reduce the disruptive factors. Thus, each of the three lighting scenarios was offered randomly three times for one week in each case.

A more frequent change of lighting conditions may carry another advantage: employees are not able to form a very strong opinion about the room lighting situation.

Overall, it may be said that a **randomised, controlled double-blind study** with a **3x3 cross-over design** was implemented. This type of study design is also frequently implemented in pharmacological effects research and is currently considered as one of the highest scientific standards with respect to investigation methods.

Apart from collecting subjective data by means of questionnaires, cardiac activity was recorded by means of an easily adjustable and user-friendly chest strap throughout the shift. Additionally, physical activity (even outside working hours) was continuously recorded via a monitoring system worn on the wrist (actigraph) from Monday before the start of the shift until Friday after the end of the shift.

The 15 monitoring systems and chest straps available were divided among the study participants such that a sufficient amount of cardiac and activity data were captured per lighting scenario in each case.

Every Saturday, the lighting scenario for the coming working week was programmed, so that the study participants were not able to fathom which lighting scenario had been set.

4.2 Test set-up

Room
The production company installed a new production bay. Concurrently, a new general lighting system was meant to be installed. A special feature of the interior finish of the production bay were the white walls and the floor. The choice of the colours of the room periphery was determined by the fact that in this industrial hall the image of a very clean working environment for the manufacture of medicinal products was meant to be created - this is particularly important for visits by clients of Flextronics.

Production bay shortly after installation of the lighting in 2005. The bay has not been fully furnished yet, and the sections of the bay are deliberately operated using two different lighting conditions for demonstration purposes, in order to illustrate the varying colour temperatures.

Room light intervention
In the production bay, TECTON RC 2/54 W luminaires with fluorescent lamps in the light colour 4 000 K (Ra > 80) and the "EMOTION Touch" lighting management system were used. The lighting installation complied with ÖNORM EN 12464-1 (e.g. glare control UGR < 19). Control was effected automatically, accordingly no intervention by the employees was possible. Only manually switching on and off before and/or after the shifts was possible.

At the windows (they are located on the northwestern side of the building), film screens with a transmission factor of 13 % were installed. In this way, visual interaction with the outdoor situation was maintained (the daylight factor was below or equal to 2 %) and the influence of variable quantities of daylight could be properly controlled. At the various workstations, therefore, daylight with only 30 to 150 lx of horizontal illuminance in the task area was measurable.

Timing
The present study breaks down into three phases. First, there was the development of the highly dynamic lighting sequences to be tested, followed by the pilot study of 6 selected dynamic lighting sequences.

In the pilot study, two goals were meant to be achieved in particular:

1. To check whether the new dynamic lighting conditions are accepted by the workers, and/or to determine which lighting conditions are accepted more fully.

2. To examine the productivity data captured with a view to their usefulness, to test the daily data transmission via the php server of Messrs. Bartenbach, and to develop an evaluation strategy.

Based on the results of the pilot phase, two of these six lighting sequences were selected and tested together with a reference lighting situation (standard lighting) in the main study.

Development of highly dynamic lighting sequences
The goal of development work was to design several lighting sequences with highly dynamic brightness changes some of which were meant to be perceived. This is due to the fact that consciously perceived changes of light will trigger certain expectations and accordingly are subjectively assessed in a different way than lighting changes that are not consciously perceived by the test subjects.

Within the scope of the present project, dynamic lighting situation means that not the light colour, but exclusively the illuminance level of the general lighting varies over time. The light colour of the primary light source (fluorescent lamp) was always around 4 000 K.

The lowest value of each dynamic lighting situation was the illuminance level of 1 000 lx prescribed in the relevant standard. The highest brightness levels in the dynamic sequence amounted to a mean horizontal illuminance of 3 000 lx in the task area.

Generally, both the duration, the point in time as well as the degree of dynamic brightness changes were subject to variations.

For the pilot study three highly dynamic lighting sequences were developed, one of them with imperceptible and two with perceptible brightness changes.

4.3 Assessment and measuring instruments

Based on the various disciplines, the instruments for data capture can be divided as follows:

Industrial psychology
Questionnaires regarding stress level, mental state, chronotype, sleep and alertness

Industrial medicine
Medical-physical status and social anamnesis, heart rate measurement, physical activity

Production
Individual recording of number of units processed and the respective time required

Ergonomics
Ergonomic workplace evaluation

Lighting technology
Lighting documentation, questionnaire on lighting quality

Based on the various disciplines, the instruments for data capture can be divided as follows:

Measuring parameters I

Questionnaire regarding current state

With this questionnaire, the influence of the lighting conditions studied on the current state and specific aspects of social interaction of the employees (e.g. sociableness, aggressiveness, etc.) was meant to be examined. Since the questionnaire was submitted three times per working day in each case, the changes over time of the studied parameters were also recorded.

Journal regarding sleeping quality and morning alertness

The journal was submitted daily before the start of the shift and consisted of two 7-grade rating scales for the sleeping quality of the past night and for the present feeling of alertness before the start of the shift. This journal was meant to show the longer-term effects of room lighting on sleep and regeneration during the night. Since the interview was effected daily, a weekly sequence can also be quantified.

Measuring parameters II

Questionnaires regarding lighting quality

To record the lighting quality, questionnaires were submitted once after the end of the shift on Wednesdays and Fridays. The questionnaires were to show the extent to which the dynamic lighting conditions studied influence room lighting quality in a season with low amounts of daylight, as compared to standard lighting. The acceptance of brightness sequences in working contexts has not been examined yet, and accordingly was meant to be explored for the first time in a field study.

24-hour recording of physical activity and light exposure

To capture physical activity and daily light exposure, a measuring system in the form of a high-usability "watch" (e.g. impact-resistant, waterproof) worn on the wrist was used.

This made the continuous, non-invasive recording of both variables possible from Monday 5:45 a.m. until Friday 2:00 p.m. It was shown in many research projects on the effects of light that these two variables may clearly illustrate an immediate effect of light on human beings.

Apart from the continuous recording of daytime activity of the study participants during the shift, we were also interested in their activity after the shift (which is considered a disruptive factor with respect to the influence of room light in the production bay). Moreover, using this monitoring system, it was possible to record very precisely nighttime activity as an indicator of sleeping quality (time of falling asleep/waking up, waking up during the night, overall activity during the night).

Apart from physical activity, the daytime-based quantity of light was recorded as a second variable. In this way, it was possible to record the exposure to light during breaks outside the production bay, after work (i.e. additional daylight exposure) and during the night as potential disruptive factors of the study.

Heart rate measurement

During shift work, the heart rate was recorded over a period of 24 hours with comfortable chest straps. This made it possible to measure the influence of the room lighting situation on the autonomic regulation of study participants.

Production ratio – lead time

By recording the lead time, the influence of room lighting on a major production ratio was meant to be demonstrated. Changes in productivity due to room lighting interventions might be the best argument for higher investment amounts and higher operating costs for the investor.

Disruptive factors

Questionnaire regarding chronic stress level

This questionnaire was submitted to the study participants before the beginning and after completion of the main study, in order to record their work-related chronic stress. Ideally, the scores of this questionnaire would remain fairly constant per person for the two measurements.

Questionnaire on sleeping quality

Since sleeping quality has a decisive impact on the psychophysiological effects of various light exposures, this aspect was investigated by means of a standardised questionnaire immeidately before and after the main study. This investigation in turn did not serve to exclude employees from participation in the study (due to increased scores), but to demonstrate that their sleeping quality did not change significantly in the period of data collection.

Questionnaire on working conditions

This questionnaire was submitted to the study participants before the beginning and after completion of the main study, in order to record their task area-related working conditions. Ideally, the scores of this questionnaire would remain fairly constant for all test subjects in both measurements.

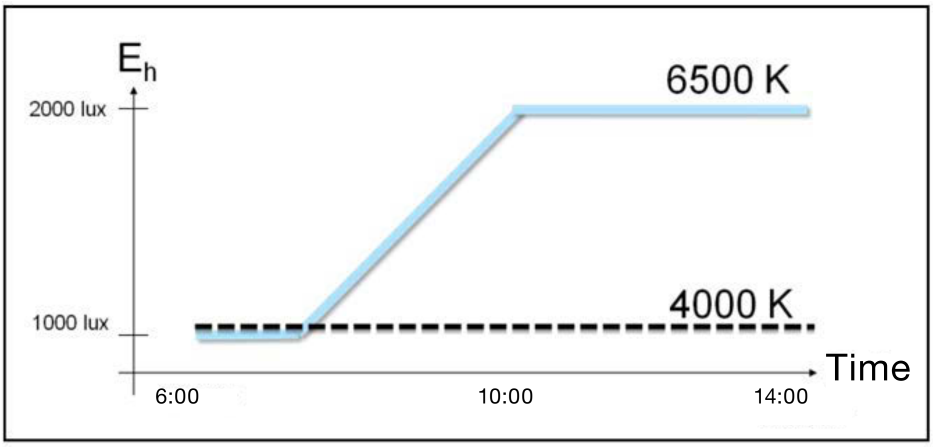
Overall, the following interview and measuring instruments were used for the industrial psychology, labour medicine, ergonomic and lighting investigations:

- Questionnaire “Betriebliche Analyse der Arbeitsbedingungen” (analysis of working conditions at the company) (IMPULS)
- Questionnaire “Trierer Inventar zum chronischen Stress” (Trier chronic stress inventory) (TICS)
- Questionnaire “Befindlichkeitsskalierung” (mental state score) (BSKE)
- Questionnaire “Pittsburgh Sleeping Quality Index” (PSQI)
- Weekly journal on “Schlafqualität und zum Gefühl des morgendlichen Wachseins” (sleeping quality and feeling of alertness in the morning) (FBWTB)
- Lighting quality questionnaire (FQL 2)
- “Morningness–Eveningness Questionnaire” (MEQ-SA)
- Production ratios
- Monitoring system to capture physical activity and exposure to light
- Recording of the activity of the autonomic nervous system
- Ergonomic evaluation by inspection

4.4 Test implementation

In the preliminary project of k-Licht, already published in Lighting Research and Technology, the psychophysiological effects of light of two room lighting conditions were compared with each other. One was constant light with horizontal illuminance of 1 000 lx in the task area with a light colour of 4 000 K; the second lighting situation had a primary light colour of 6 500 K with a dynamic brightness sequence.

Accordingly, horizontal illuminance of 1 000 lx prevailed in the task area between 6:00 a.m. and 8:00 a.m. Subsequently, over the course of two hours (i.e. imperceptibly), the brightness in the production bay was doubled. This increased brightness was then maintained until the end of the morning shift. The brightness sequence just described is based on the idea to use artificial lighting to simulate the brightness sequence of daylight with a clear sky in the production bay.



Lighting situation A: standard lighting, 4 000 K (with 3 859 K on the eye)
Lighting situation B: test lighting, 6 500 K (with 6 398 K on the eye) in the preliminary project

In the preliminary project, the psychophysiological effects of light of each of the two lighting conditions were measured for one month in summer and one month in winter in each case.

In the course of data analysis, an improvement of productivity in winter was observed with dynamic lighting (reduction of lead time by 4 %). Moreover, it was demonstrated for the winter months again that both the physiological regeneration while sleeping and the state of the shift workers at the end of the shift were significantly improved with dynamic lighting as compared to standard lighting conditions.

Lighting conditions of the pilot study
The six lighting conditions of the pilot study can be divided into three groups:

– room lighting with imperceptible dynamic brightness changes
– room lighting with perceptible dynamic brightness changes
– constant room lighting

Several short and imperceptible changes of brightness ("sawtooth")

Changes of brightness within thirteen 30-minute cycles (15 minutes of increasing brightness and 15 minutes of decreasing brightness) during the morning shift. The fluctuations in brightness were not perceptible.

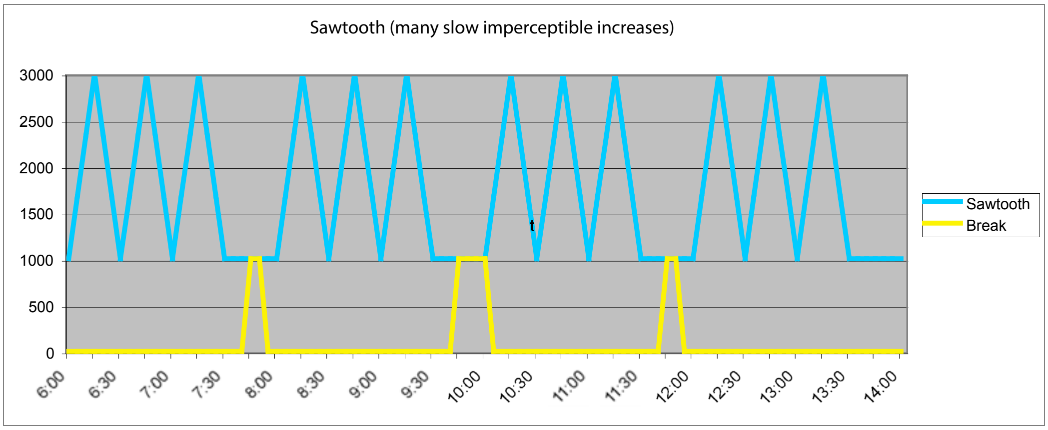


Fig. 01: Lighting situation "sawtooth" of the pilot study

Two perceptible changes of brightness (“alertness”)

At the beginning and towards the end of the morning shift, there was a quick increase of brightness in the task area. This change in brightness was perceived by the employees and served the purpose to increase the employees’ alertness at the start of work and to reduce the employees’ fatigue towards the end of the morning shift by perceptibly changing brightness.

Each of the two quick brightness changes lasted for a total of 90 minutes, with very high brightness levels prevailing for 30 minutes after the quick increase, subsequently reducing the brightness to the original level imperceptibly over 60 minutes. Since this reduction of brightness took place slowly and imperceptibly, it may be assumed that the employees maintained an impression of very high brightness levels (3 000 lx) for over 30 minutes.

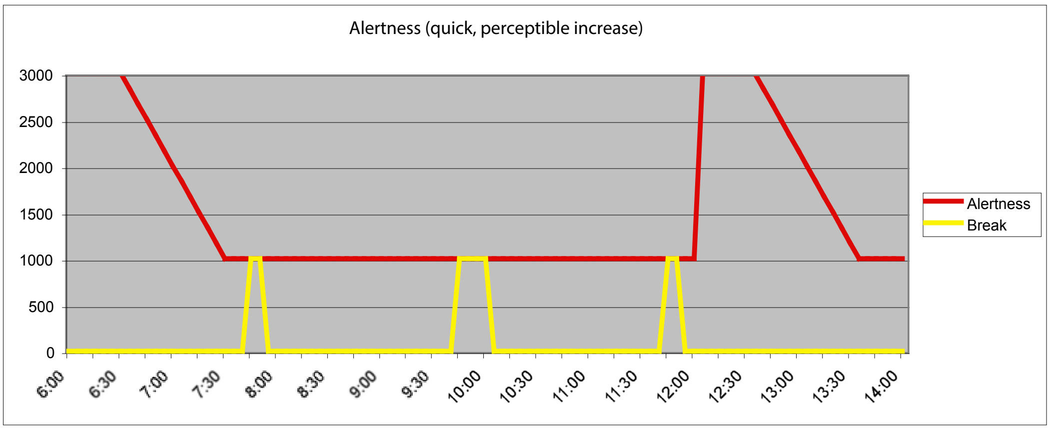


Fig. 02: Lighting situation “alertness” of the pilot study

Several perceptible changes of brightness (“alertness²”)

Five times the brightness level was quickly increased in the production bay during the morning shift. As opposed to the lighting situation “alertness”, the change in brightness only lasted for 45 minutes, primarily consisting in a brightness increase within 3 minutes and a reduction of brightness over 35 minutes. The distribution of these highly dynamic brightness changes was chosen in such a way that at the start of work two changes of brightness (halfway through the working hours after the 15-minute break one brightness change, and after the last short break (respectively towards the end of the morning shift) again two changes of brightness were automatically effected via room lighting control.

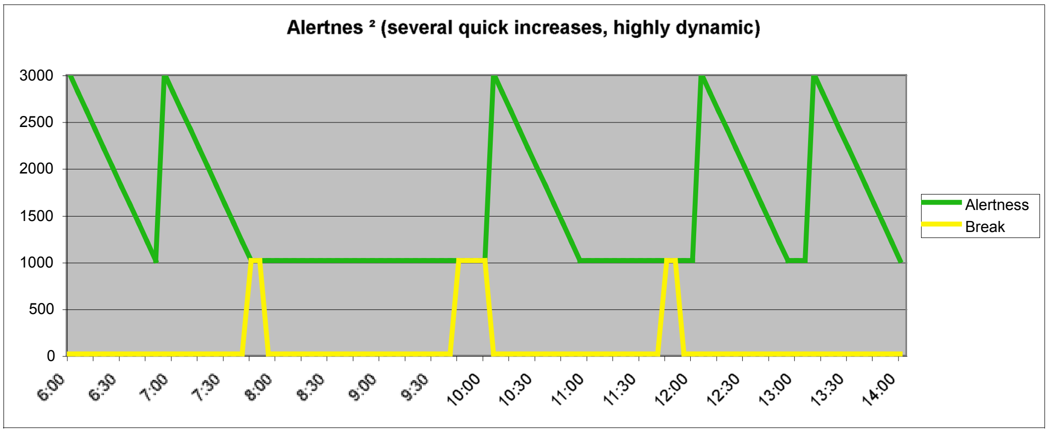


Fig. 03: Lighting situation “alertness²” of the pilot study

Constant room light at 2 000 lx (“standard²”):

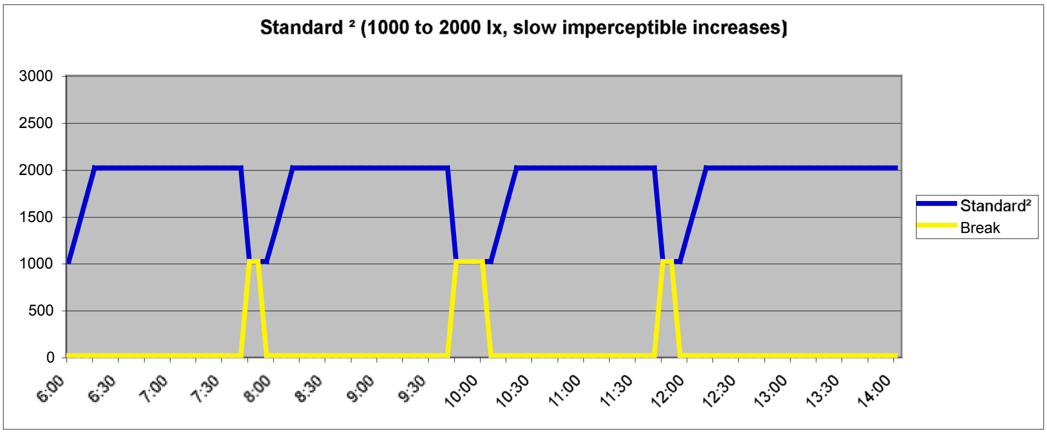


Fig. 04: Lighting situation “standard²” of the pilot study (the areas marked in yellow are breaks; shortly before and after a break, the room light was dimmed to 1 000 lx, so that a change of room was possible without visual disruptions)

Constant room light at 3 000 lx (“standard³”):

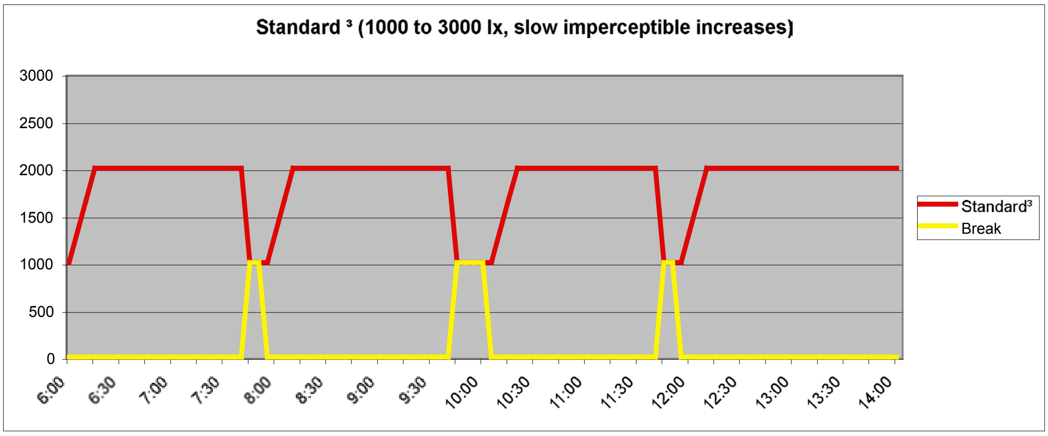


Fig. 05: Lighting situation “standard³” of the pilot study

Lighting conditions of the main study

1. Upon conclusion of the pilot study, the lighting quality questionnaires were analysed. All lighting conditions with a prevailing horizontal illuminance level of 3 000 lx received clearly negative evaluations with respect to room lighting quality. The maximum horizontal illuminance level was accordingly fixed at 2 000 lx.

2. The lighting quality of imperceptible and perceptible brightness changes was evaluated highly differently. Therefore, perceptible and imperceptible brightness changes as lighting conditions were also meant to be examined in the main study.

3. A control lighting situation (“standard”) to compare the psycho-physiological lighting effects with the lighting effects of the other lighting situations.

Thus, a total of three lighting situations were included in the main study:

– Perceptible lighting changes (see Fig. 02 and 03)
– Imperceptible lighting changes (see Fig. 01)
– Control situation “standard”: 1 000 lx, 4 000 K

Several imperceptible changes of brightness (“sawtooth”)
Within 30 minutes, the brightness in the task area is increased from 1 000 lx to 2 000 lx and reduced again to 1 000 lx. This imperceptible change of brightness was effected without interruption 15 times in total within the morning shift. The intention of this highly dynamic room lighting was to achieve continuous stimulation of cortical arousal centres. Due to the fact that this stimulation through light was effected without the study participants being aware of it, it was possible to measure the purely biological lighting effect and to exclude “psychological” lighting effects superimposing the former.

Two perceptible changes of brightness (“alertness”)
At the beginning of the shift and towards its end, the brightness level was increased perceptibly from 1 000 lx to 2 000 lx in the task area within 3 minutes, then maintained at this level for 2 hours, and subsequently reduced again to 1 000 lx within 30 minutes. As with the lighting situations “alertness” and “alertness²” of the pilot study, this dynamic room lighting scenario also intends to provide a wake-up impulse to the employees at the beginning and towards the end of the morning shift.

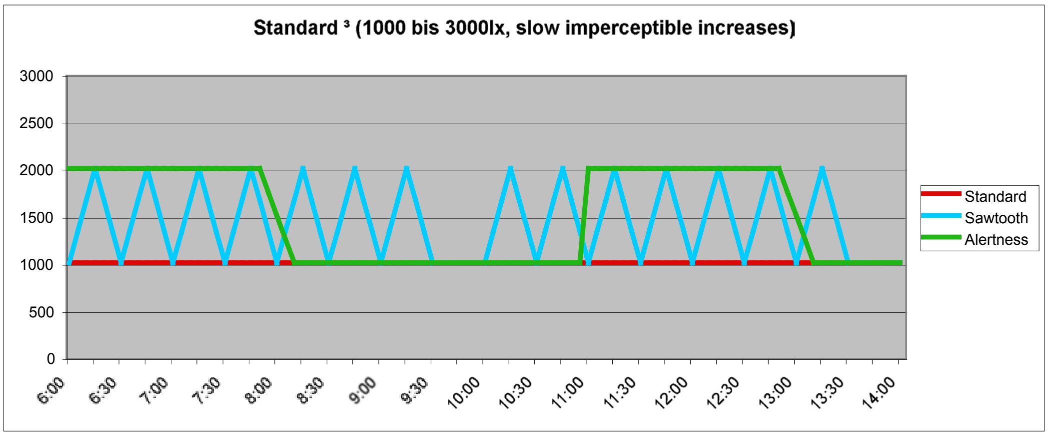


Fig. 06: Lighting conditions of the main study

Finally, it should be stated that the daily amount of light of both dynamic room lighting scenarios was 50 % higher than the amount of light under standard conditions.

5 Results

From the main study, the results of the actigraphic data analysis are presented. Subsequently, the analyses of the heart rate data, of the mental state questionnaires, of the lighting quality questionnaires and of productivity follow.

Analysis of actigraphic data
The actigraphic data covering the working period extended from 7:00 a.m. to 1:00 p.m.

The actigraphic data covering the working period during the night extended from 11:00 p.m. to 3:00 a.m. This period was clearly identified as a period of sleep for all test subjects involved (note: the usual time of falling asleep was 10:30 p.m. and the time of waking up 4:00 a.m.).

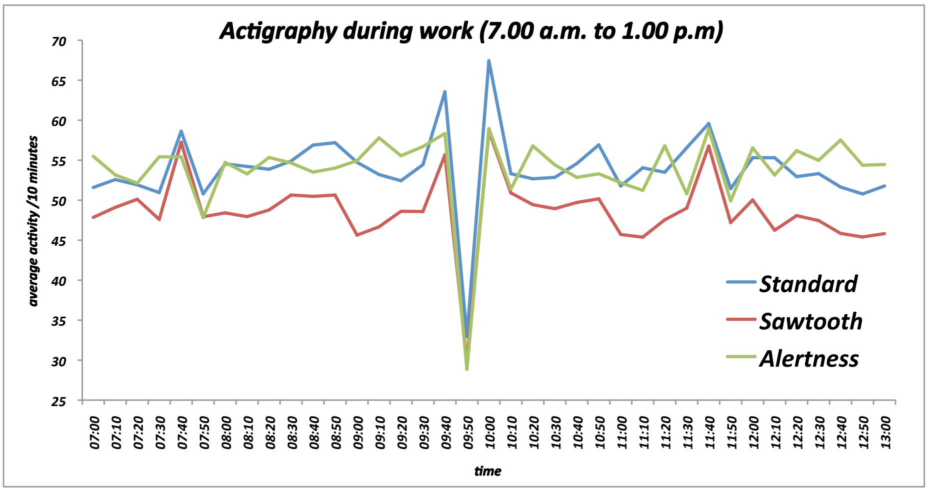


Fig. 07: Physical activity (actigraphy)

By way of summary it may be said that under “sawtooth” conditions clearly reduced physical activity was recorded. Interestingly, this contradicts the original hypothesis that frequent changes of brightness (resp. “sawtooth”) have a more pronounced activating effect – and are accordingly associated with a higher level of physical activity – than less frequent changes of brightness (resp. “alertness”).

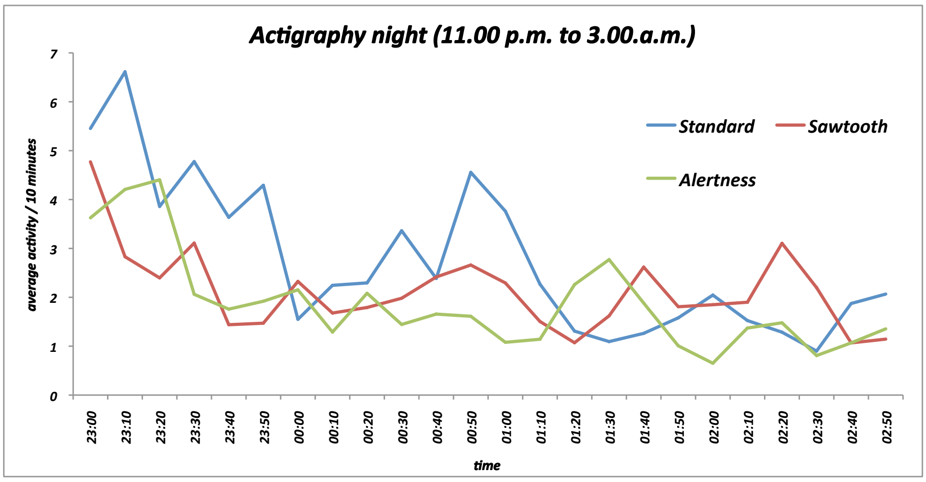


Fig. 08: Actigraphy / night

For the nightly motion data, it was found that dynamic room lighting with light exposure per working day increased by 50 %, regardless of whether there were perceptible or imperceptible dynamic changes of brightness, has a significant influence on physical rest while sleeping at night. Such a result was already obtained in the previous project based on the physiological data (heart rate variability analysis). The present result underpins the effect of specific, higher amounts of light during work on subsequent nightly sleep.

Analysis of heart rate data

Within the scope of the main study, heart rate data was exclusively recorded during working hours. Just as for the actigraphic data, heart rate data were only included in the further statistical analysis for the period between 7:00 a.m. and 1:00 p.m.

Considering all detailed results of the HRV analysis during work, it may be stated that the two dynamic lighting situations at the start and towards the end of work had the most marked effect on the autonomic nervous system. In the medium third of the shift, there are no significant differences between standard lighting and the two dynamic room lighting scenarios.

Analysis of mental state questionnaires

To record the employees' present state, a mental state questionnaire was submitted to them every Wednesday (i.e. in the middle of the working week) before the start of the shift, during a 15-minute break at 9:50 a.m. and immediately after the end of the shift. This questionnaire allows for an assessment of the currently perceived positive state (with subscores motivation, mental balance, extraversion and elevated mood) and negative state (with subscores for anxiety, demotivation, excitement and tenseness).

Overall, it may be said that the dynamic lighting conditions studied had a minor but demonstrable influence on the perceived mental state of the test subjects. At the end of the shift, a change of state was observed in the category "positive mental state" under "alertness" (perceptible changes of brightness).

Analysis of weekly journals

All test subjects had to make an entry in a journal regarding the restfulness of last night's sleep and the current feeling of alertness before the start of the shift at around 5:45 a.m.

Contrary to expectations, there were no lighting effects either for the subjectively perceived quality of sleep or for the present alertness at the beginning of the shift. This result is remarkable, since actigraphic data showed that the test subjects' nights had been significantly more quiet and that they had very short periods of sleep on average under the two dynamic lighting situations. This clearly puts into question the subjective assessment of nightly sleep and of alertness at the start of the shift as being very positive. It must be assumed that either the self-assessment of the test subjects was inaccurate or the responses in the journal represent (socially) desirable answers.

Questionnaire regarding lighting quality

Within the scope of the pilot study and the main study, six questions regarding lighting quality were asked:

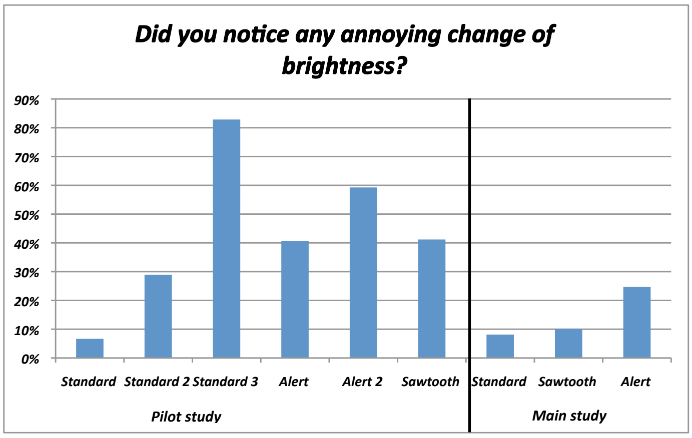


Fig. 09: Question 1 (vertical axis: relative proportion of test subjects)

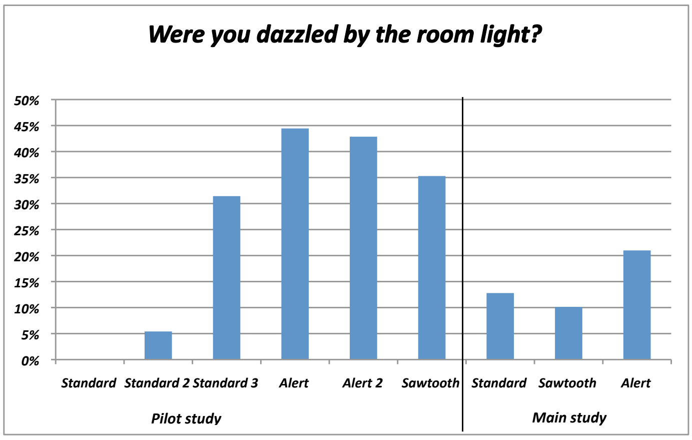


Fig. 10: Question 2 (vertical axis: relative proportion of test subjects)

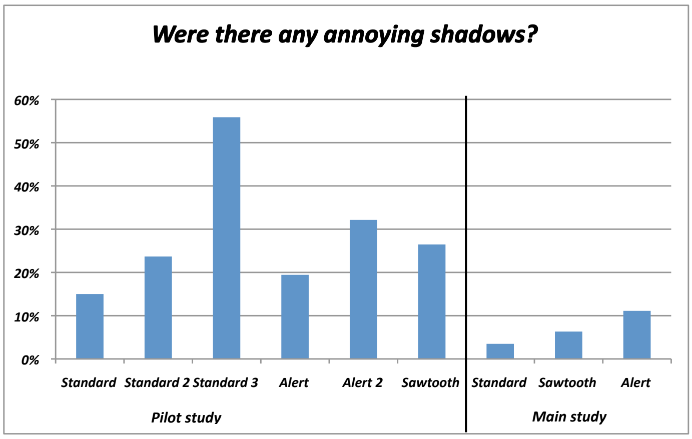


Fig. 11: Question 3 (vertical axis: relative proportion of test subjects)

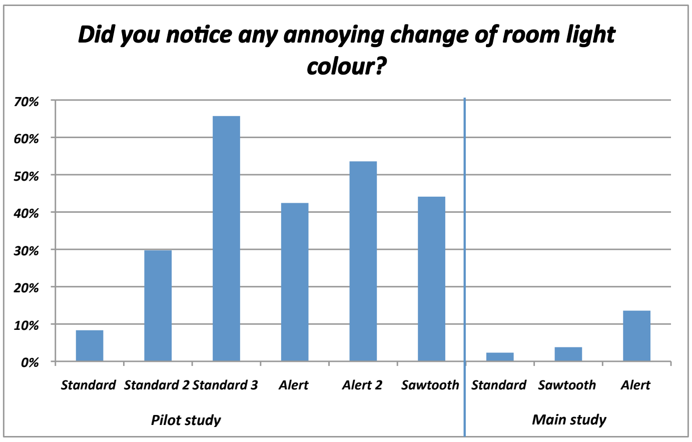


Fig. 12: Question 4 (vertical axis: relative proportion of test subjects)
Note: The light colour was not changed at all, accordingly these answers suggest how often the answers were “guessed”.

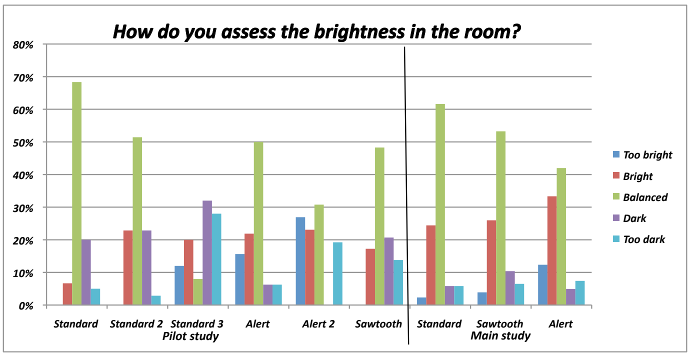


Fig. 13: Question 5 (vertical axis: relative proportion of test subjects)

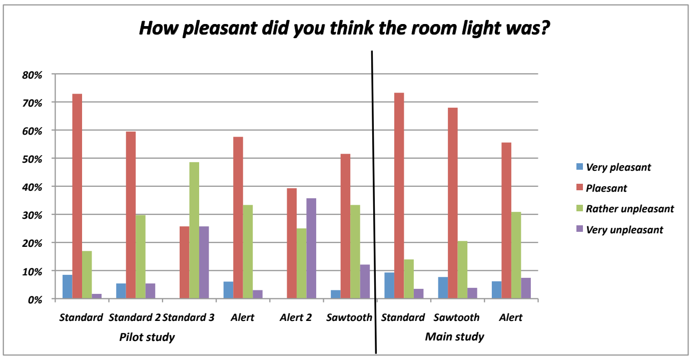


Fig. 14: Question 6 (vertical axis: relative proportion of test subjects)

The primary result of the analysis of questionnaire data regarding the lighting conditions in the pilot study was that both perceptible and imperceptible brightness changes from 1 000 lx to 3 000 lx were clearly rejected by the test subjects due to their glare effect and annoying variation of brightness.
Furthermore, it may be said by way of summary that the three lighting situations of the main study only differed with respect to the assessment of annoying brightness changes. However, they were assessed as equally pleasant, equally bright and generally equivalent with respect to the formation of shadows and glare effect.

The following table schematically shows the subjectively perceived lighting quality in relation to the parameters “perceptibility of dynamic brightness changes”, “variation of brightness” and “frequency of brightness variation”. On the one hand, it becomes clear that horizontal illuminance in the task area should be limited to 2 000 lx. On the other hand, frequent perceptible brightness changes, frequent imperceptible brightness changes and infrequent perceptible brightness changes with a pronounced variation of brightness (from 1 000 lx to 3 000 lx) equally appear to decrease subjectively perceived lighting quality in general.

Reference is made here to the results of study 1.

Dynamic change of brightness	Variation of brightness	Frequency of brightness variation	Perceived lighting quality
Perceptible	1 000 – 2 000 lx	Rare	++
Perceptible	1 000 – 2 000 lx	Frequent	- (hypothetical)
Imperceptible	1 000 – 2 000 lx	Rare	++
Imperceptible	1 000 – 2 000 lx	Frequent	++
Imperceptible	1 000 – 3 000 lx	Rare	+ (hypothetical)
Imperceptible	1 000 – 3 000 lx	Frequent	--
Perceptible	1 000 – 3 000 lx	Rare	--
Perceptible	1 000 – 3 000 lx	Frequent	--

Fig. 15: Summary of subjectively perceived lighting quality.

Analysis of productivity data
The lead time per unit, qualified according to the specifications, was used to assess productivity.

The results of study 1 show that in summer, the lead time is basically shorter than in winter. In summer, no differences with respect to lead time are observable.

In winter, the lead time is generally longer. With dynamic changes of the lighting, it decreases by some 4 %.

	Mean value			
Static control lighting (summer)	90.06 %		+ 9 % (static summer – static winter)	
Dynamic room lighting (summer)	90.53 %			+ 4.5 % (dynamic summer – dynamic winter)
Static control lighting (winter)	99.08 %	+ 4 % (static winter – dynamic winter)		
Dynamic room lighting (winter)	95.07 %			

100 % ... lead time according to specification.

Due to the highly specific organisation of work in the production bay (i.e. line production, KAIZEN organisation, 6 Sigma programme), no other typical ratios for productivity (e.g. error rate, sick leaves) could be quantified.

For a total of 14 test subjects, it was possible to carry out a statistical analysis of relative lead time; with these persons, neither a change of workstation nor of work tasks, of daily target lots, nor assistance by a colleague to achieve the target nor any technical failure occurred during the observation period of 3 weeks.

The statistical analysis did not indicate any influence on productivity figures.

The available working hours are intuitively used in a uniform manner. Study 1 shows that dynamic lighting changes allow unit lead times to be reduced individually and accordingly to create more “space” in workaday life overall. This explains the positive effects on improved well-being at the end of the shift.

Finally, the positive effect is also evident outside working hours, in that the measured quality of sleep improves with dynamically changing lighting situations.

By way of summary, it may be said that the lighting has a measurable influence on the employees.
However, the comprehensive, interdisciplinary study also shows that measurements with test subjects are very complex, and that currently there are no generally and easily applicable methods yet.

Good, standard-compliant lighting in itself allows to fulfil the work tasks. The positive perception of lighting quality shows that no deficiencies and complaints are to be expected.

Together with its partners, Zumtobel ensures the sound design and implementation of lighting installations based on compliance with the familiar standards, in particular EN 12464-1. Great attention is paid to lighting quality features, not only to comply with illuminance levels, but also to create uniform illumination, to avoid glare and reflexions, and to obtain good cylindrical and vertical lighting components that guarantee visibility and perceptibility.

Pasticceria La Baita srl, Caselle Torinese | IT

RSD Electronic, Naturno | IT

Technogym, Cesena | IT

7 Discussion and outlook

The comprehensive study provides three essential insights:

1. Light has an influence on working people.
The interdisciplinary application of methods shows that measuring the effect of lighting on human beings is complex. If no results are obtained, that does not mean that there is no effect, but that the instruments of observation and measurement have not been optimally used. Further efforts are required to improve the measuring instruments.

2. Changing lighting conditions show an effect as opposed to static lighting, especially in winter. An individually reduced unit lead time and accordingly an increase in productivity by 4 % was demonstrated (see Fig. 16) and should not be considered under the aspect of increased productivity, but rather attributed to the reduced level of stress during work. This is also suggested by the results that indicate improved well-being towards the end of the shift and improved sleep after work. Both the employees and the plant equally benefit from this. Accordingly, the meaning of "productivity" should be defined in a wider sense.

3. Positive effects on people can be obtained by increasing static illuminance or through varying sequences of light. Changing sequences of light have a considerably lower energy requirement and are accordingly to be preferred for economic reasons alone. The way the light should be varied still needs to be explored. In this study, a few dynamic lighting scenarios were examined by way of example. However, the full scope to define an "optimal" sequence has not been exploited yet.

Another positive aspect of the Flextronics study should be mentioned: the plant is regularly visited by international clients with a view to obtaining contracts. The option of cool white lighting with 6 500 K and high illuminance levels of up to 2 000 lx has been successfully implemented several times already, in order to present a bright, clean and efficient production bay to visitors.

Overall, many arguments in favour of improving the efficiency of industrial plants and the well-being of their employees have been derived from this long and comprehensive interdisciplinary study.

In combination with various studies compiled by Juslén (see Fig. 16), it turns out that even at high illuminance levels, effects on productivity can be obtained.

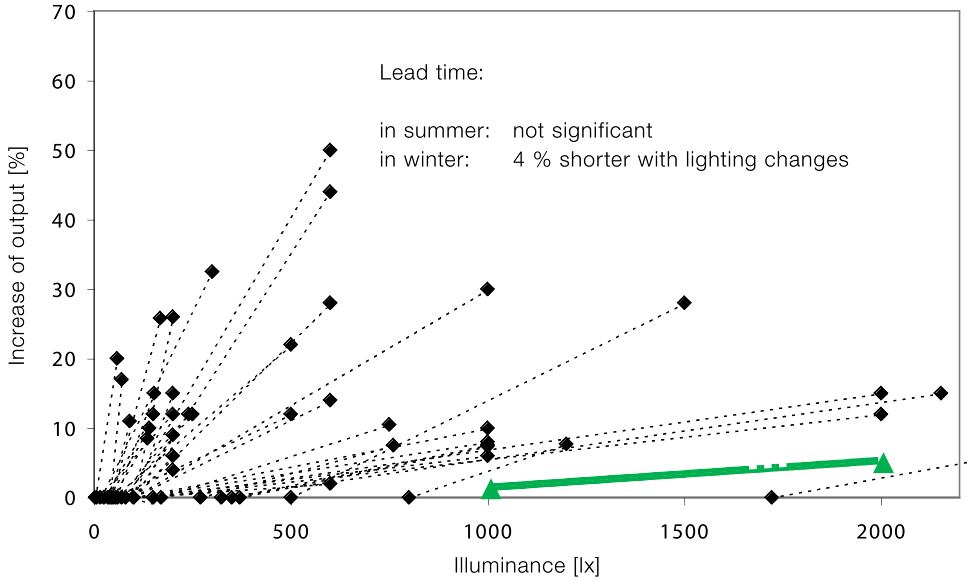


Fig. 16: In various studies compiled by Juslén, an "increase of output" and/or an improvement of unit lead time was observed. The largest potential for improvements is found in very low illuminance levels (often clearly below standard requirements). The Flextronics study (green line) already started with control lighting at a high, standard-compliant level. Nevertheless, an increase by some 4 % was achieved through lighting variations.

8 Literature

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Brief portrait of the partners

Zumtobel Lighting, Dornbirn: Peter Dehoff, Alexander Berger
Field of work: lighting technology, project owner
Supplier of high-grade lighting solutions

BLL: Bartenbach GmbH, Aldrans: Markus Canazei, Siegfried Mayr, Siegmund, Staggl, Julia Wörgötter
Field of work: psychophysical studies, lighting technology, analyses
The fields of activity of Bartenbach GmbH are daylight-based and artificial lighting design, starting from the initial concept through to monitoring of the building. Moreover, product developments, competition consultancy, workshops and expert opinions. Together with our specialised staff in the fields of planning, research and development, psychology of perception and model construction, optimal solutions can be worked out.

Flextronics, Althofen plant, Carinthia: plant manager Bergner
Field of work: study location
Flextronics International Ltd. is an internationally leading supplier of EMS (Electronic Manufacturing Services) with establishments in 30 countries.

Ergonomiezentrum Tyrol, Innsbruck: Ing. Walter Ambros,
Partner: Dr. Kurt Seipel
Field of work: ergonomic assessment

Management and organisation consultancy, personality development, ergonomically sound and economically efficient organisation of work and health promotion.

Team Prevent, Zentrum Klagenfurt, Dr. Juvan
Field of work: medical examinations (industrial medicine)
With our solutions in the field of industrial safety and health protection, we are the leading provider of consultancy in the fields of industrial medicine and safety engineering, who is also able to offer transnational service packages and to provide our clients with competent, targeted advice.

ABoVe, Gießen: Charlotte Sust, Prof. Dieter Lorenz
Field of work: psychology, interviews
We are preoccupied with people in modern systems of work, aiming at high productivity, efficacy and efficiency on the one hand, as well as high performance, motivation, health and well-being on the other hand.

AUVA, Allgemeine Unfallversicherungsanstalt, Vienna: Michael Wichtl
Field of work: ergonomics, sponsoring partner
AUVA is the social accident insurance company for 3.2 million gainfully employed people, 1.3 million pupils and students, numerous volunteer organisations and life savers.

k-Licht, Aldrans/Dornbirn: Peter Hein
Coordination of project and subsidies

Research partner

Sponsor

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FFG

Tirol
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WIRTSCHAFTS STANDORT
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SFG
Im Auftrag des Wirtschaftslandesrates

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