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Laboratory experiment regarding impact on productivity through dynamic lighting

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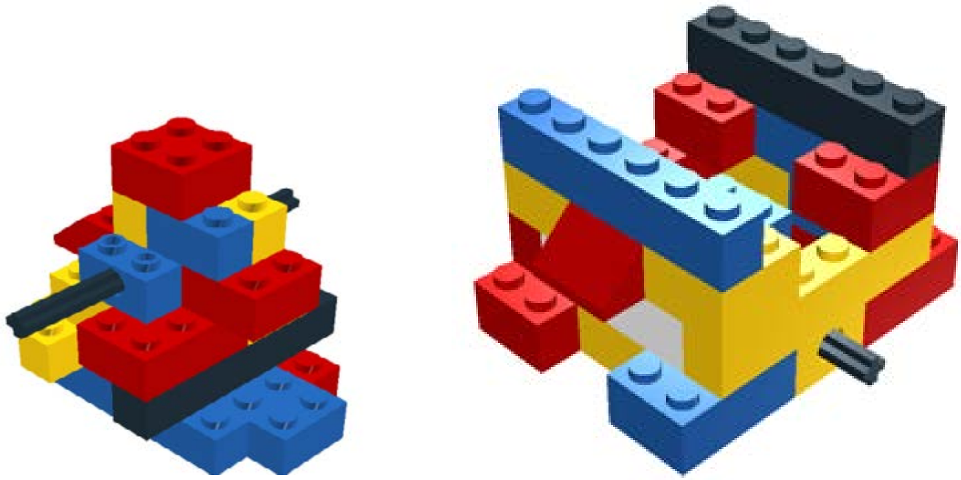


Foreword

This laboratory study was aimed at comparing the performance-related, subjective and physiological effects of two highly dynamic types of room lighting with the effects of standard lighting for production work.

While most studies dealing with the physiological effects of light stimuli refer to circadian rhythms, the effect of dynamic lighting rhythms in the range of seconds and minutes has hardly ever been the subject of scientific research so far. Accordingly, the particular focus of the research project carried out between January and March 2011 with 29 participants was the assessment of production-related and physiological influences of relatively fast dynamic changes of brightness (duration of periods: 10 seconds with brightness variation between 500 and 680 lux or 30 minutes with brightness variation between 500 and 2 000 lux).

Within the scope of the laboratory study, no significant changes of productivity due to highly dynamic room lighting were measured. However, with both dynamic room lighting scenarios, immediate lighting effects were recorded. For one thing, the test subjects experienced dynamic brightness variations based on 10-second periods as less tiring, as well as more interesting and stimulating – although these dynamic changes were not perceptible. On the other hand, there were physiological effects that were measurable until far into the night. This high-frequency room lighting had an activating, stimulating effect during the day, while it resulted in more quiet sleep during the night; room lighting based on dynamic changes of brightness over 30-minute periods had a relaxing effect during work.

Abstract

Already in 2010, a field study carried out by Zumtobel, Bartenbach GmbH and other multidisciplinary partners at the electronics company Flextronics demonstrated the positive impact of dynamic lighting on the psychophysiological condition and the productivity of the employees. Now, the goal of the present laboratory study is to deepen and specify the insights obtained in the previous study.

Most studies on the physiological effect of light stimuli refer to circadian or longer ultradian rhythms. However, the effect of dynamic lighting rhythms in the range of seconds has hardly ever been the subject of scientific study so far. Accordingly, the focus of the research project carried out between January and March 2011 with 29 participants was on the assessment of the influences of relatively quick dynamic changes (duration of periods: 10 seconds), but also relatively low amounts of light (500–680 lux) on the ultradian rhythms of people. For this purpose, production processes – some of them simple, others more complex – were simulated under controlled laboratory conditions with four participants per week in each case, with said simulations taking place in one constant or two different dynamic lighting scenarios.

With horizontal illuminance of constantly 500 lux and a light colour of 4 000 K, the room lighting condition “control light” complied with the standard lighting required under the EN 12464-1 lighting standard for production plants. For "sawtooth" test lighting, the illuminance level was – imperceptibly – increased from initially 500 lux in a linear manner to 2 000 lux and reduced again to 500 lux within a period of 30 minutes. For the dynamic brightness scenario “breathing light” – equally imperceptible and studied for the first time in this trial – illuminance was increased from 500 lux to 680 lux and reduced again to 500 lux within a period of ten seconds. Variations of colour temperature or the spectral composition of the light were not used in any of the three lighting scenarios.

The quantification of the study results was effected by analysing production ratios and subjective perceptions, but also by measuring the subjects’ heart rate variability and their level of activity after work and during the night.

Over the course of weeks, substantial learning and training effects were observed. In spite of taking account of this performance increase, and in spite of the careful checking of intervening variables, as well as the systematic variation of lighting scenarios, no significant differences in productivity were observed between the three lighting situations. Nevertheless, there were immediate responses to both test lighting situations during work. For one thing, the test subjects experienced “breathing light” as less tiring, as well as more interesting and stimulating – although it was not even perceptible. On the other hand, there were physiological effects that were measurable until far into the night. High-frequency light (breathing light) had an activating, stimulating effect during the day, while it resulted in more quiet sleep during the night; low-frequency light with higher illuminance (sawtooth) had a relaxing effect during work.

So far, biologicial effects of light were achieved primarily by using high luminous intensity levels, associated with high investment and operating costs. This laboratory study shows that such effects can be obtained with only slightly increased amounts of light by means of dynamic lighting control systems.

1 Problem definition

Already in 2010, a field study carried out by Zumtobel, Bartenbach GmbH and other multidisciplinary partners at the electronics company Flextronics demonstrated the positive impact of dynamic lighting on the psychophysiological condition and the productivity of the employees. The goal of the present laboratory study is to deepen and specify the insights obtained in the previous study and to achieve more marked effects on measurable production ratios by increasing the biological effectiveness of light.

First, any disturbance variables resulting from operational routines and work organisation were to be eliminated – for instance, at Flextronics people worked in production lines, impeding individual performance evaluation. Second, the visual, biological and emotional effects of dynamic light, especially also at lower doses of light, was to be examined – due to the complexity of activities in the field study, even standard lighting had an illuminance level of 1 000 lux. Third, dynamic lighting rhythms with substantially shorter periods were to be compared with Flextronics, in order to reflect important human ultradian rhythms even more closely. The starting point of the present research project is the question of the extent to which such inner rhythms that may get lost or may change under the stresses of workaday life can be restored through dynamic lighting control.

2 Scientific state of the art

Human physiology is profoundly affected by circadian and ultradian rhythms. Sleep-wake rhythm, hormonal balance and body temperature, among others, are some of the circadian rhythms that approximately recur every 24 hours. Ultradian rhythms determine, for instance, sleep cycles, heart rate, breathing, blood pressure, but also neural impulses. The duration of ultradian cycles may amount to hours, minutes, seconds, but also just a few milliseconds.

Phenomena of chronobiology, i.e. the timing of physiological processes in human beings, animals and plants, have been studied since the middle of the 20^{th} century. One of the fathers of modern chronobiology and chronomedicine was the industrial physiologist Gunther Hildebrandt, who studied, among other things, pulse and breathing rate, blood pressure and perfusion in humans and discovered that during the night, these physiological parameters are related to each other in varying, but always integral proportions. Another important cycle over the course of the day is the Basic Rest Activity Cyle (BRAC) that was described for the first time by sleep researcher Nathaniel Kleitman. The latter found out in the 1960s that the REM and non-REM phases of sleep are protracted into the day – as rhythms defining phases of performance and regeneration with a duration of some 90 minutes.

It has been known for quite some time that the synchronisation of the “inner clock” is also effected to a substantial degree by light acting as a “timer”; this has been demonstrated in numerous studies on the effects of exogenous light stimuli on human endogenous rhythms. For instance, researchers have found out that by stimulating certain retinal cells in the eye, light flickering in the 10-Hertz range (synchronous with the brain’s alpha activity) has a positive effect on people’s capacity to learn. Thus, it was demonstrated in studies that elderly people with mild cognitive deficiencies, who were learning under these specific lighting conditions, were able to memorise more information than the persons in the control group who had been working without this type of light. In another research project, the sleep researcher Charles Czeisler demonstrated that even extremely short light stimuli may have physiological effects. In experiments during the night, he exposed his test subjects to ultra-short blue LED light flashes (2 milliseconds) to show that in this way, the release of melatonin, also known as the “sleep hormone”, can be modified.

Most experiments regarding the physiological effect of light stimuli refer to circadian or longer ultradian rhythms, while the effect of dynamic light rhythms in the range of seconds and minutes has hardly ever been the subject of scientific research so far.

3 Research hypotheses

The goal of the study is to demonstrate that inner rhythms that are changed through stress during the day may be stabilised by means of dynamic lighting effects and more or less synchronised with the inner clock, and that this also entails significant changes of a person's general condition and productivity.

The special focus of research is primarily on the assessment of influences of relatively low doses of light (500–680 lux) and of relatively quick dynamic changes (duration of periods 10 seconds) on ultradian rhythms. For this purpose, production processes were simulated under controlled laboratory conditions, using one constant and two variable dynamic lighting scenarios. Quantifiable effects of dynamic light were expected with respect to the following factors in particular:

- Subjective effect of light:
  subjective condition and perception of lighting quality

- Production-related effect of light:
  production ratios such as "lead time per unit" or "average daily error rate"

- Biological effect of light:
  responses of the autonomic nervous system of the workers during work (heart rate variability) and in the following night (actigraphy)

4 Research methods

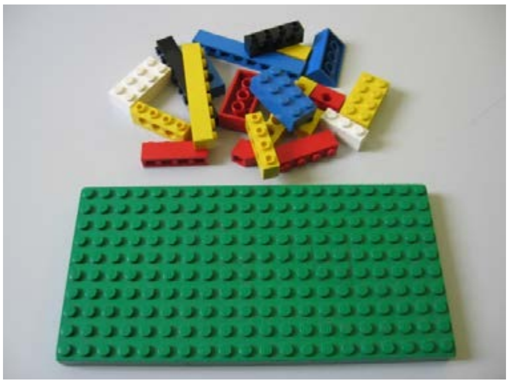
Test set-up and test procedure
This study was carried out with a total of 29 participants (15 men and 14 women) at the Bartenbach GmbH in Aldrans. The months of January, February and March 2011, with very little daylight, were chosen as the study period in order to keep the impact of daylight before and after the date of the study as low as possible. Every week, from Monday to Saturday, four test subjects were simultaneously staying in a room with individual workstations that were screened from each other. The allocation of the test subjects to the workstations was effected just as randomly as the allocation of the lighting scenarios.

Selection of/requirements with respect to the participants
With a view to the results being as sustainable and comparable as possible, only healthy individuals were admitted to the study, without any physical complaints, disposing of a normal stress level, who were neither extreme early-morning persons nor extreme evening persons in chronobiological terms.

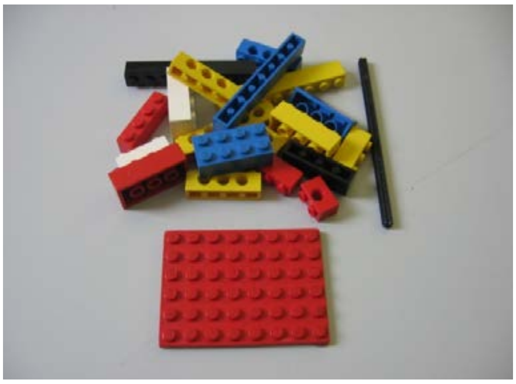
In order to possibly exclude any external influences during the entire week of the study, any excessive consumption of tobacco and caffeine as well as the intake of pharmaceutical drugs were to be avoided as was the consumption of alcohol during and after work. Additional restrictions on the test subjects' everyday lives resulted from the requirement to keep the stress situation during production and regeneration phases on the same level if possible. For this reason, the test subjects were generally meant to sleep between 11:00 p.m. and 6:30 a.m. – which was verified by measuring their level of activity. Equally, the test subjects were meant to refrain from doing any sports during this period, since this may have a strong biological effect on sleeping quality.

Workstations of the four test subjects in the laboratory.

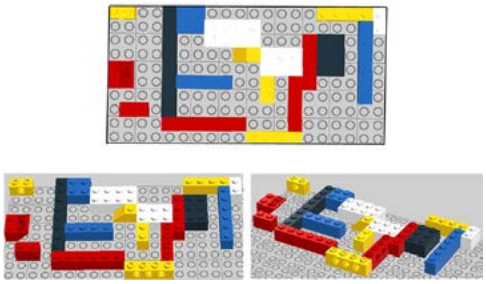
The task of the test subjects was to assemble as many simple two-dimensional and/or complex three-dimensional objects from LEGO bricks as possible within six days, while being exposed to three different lighting scenarios, working a whole day long in each case. After completion of assembly (taking some two minutes), the objects to be assembled according to templates had to be photographed from two perspectives using a webcam, then disassembled completely and finally assembled again. To ensure that the objects had actually been disassembled completely, two different simple or complex tasks had to be completed by turns. The webcam photos were analysed by the investigator to obtain precise values regarding production times and error rates. Both incorrectly assembled objects and instances of exceeding the (generous) time limits were considered as errors.



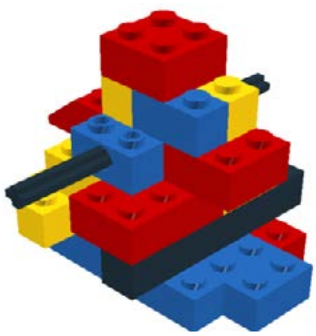
Working material – simple activity



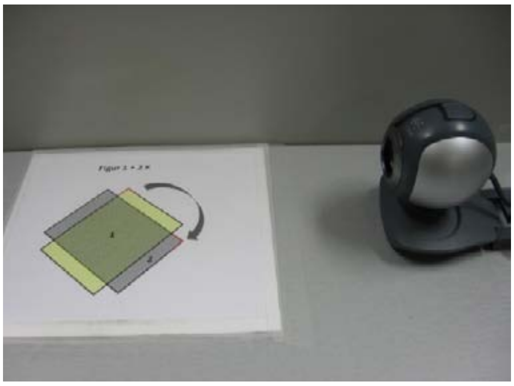
Working material – complex activity



Option 1: Assembly instruction – simple



Option 2: Assembly instruction – complex



Quality control: Template and webcam

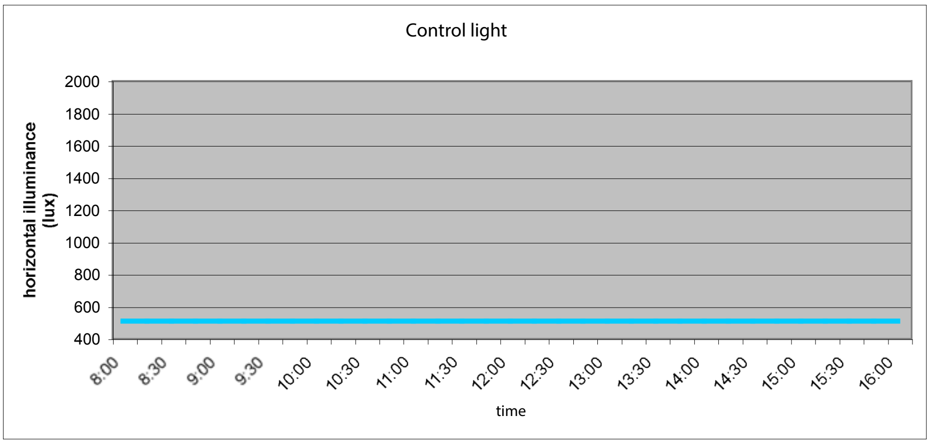
First of all, the finished product was placed on the yellow rectangle and photographed using the webcam (release on the PC).
Then the object was rotated to position 2 and a second photo was taken.

Working hours were between 8:00 a.m. and 4:00 p.m., with three breaks of 5, 20 and 5 minutes in analogy to the Flextronics field study.

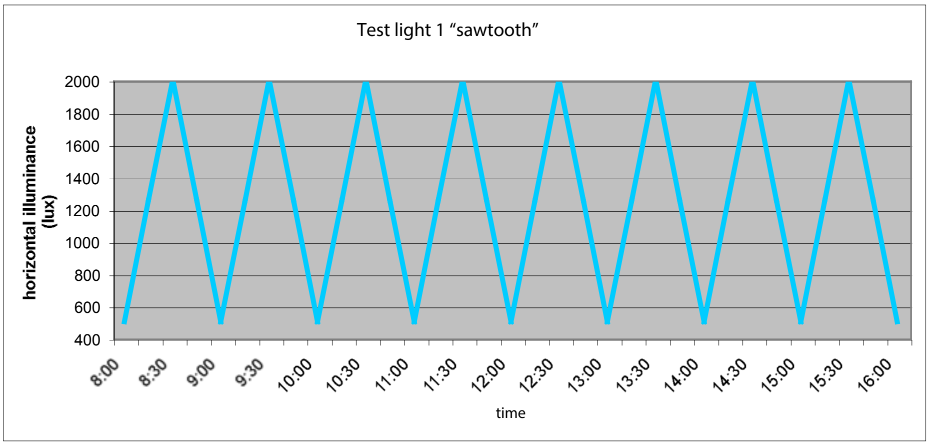
Lighting technology/lighting scenarios
Basically, all tasks had to be fulfilled under dimmable ambient lighting provided by luminaires with with a specular reflector optic, with illuminance of at least 500 lux and a constant light colour of 4 000 K, in line with standard requirements. In none of the test set-ups, the dynamic lighting sequences were meant to be perceptible as such, in order to exclude that the participants consciously perceived them as a stress factor. Moreover, the test subjects were informed neither about the prevailing lighting scene nor about the purpose of this study. Variations of the colour temperature or spectral composition of the light were not used in any of the three lighting scenarios.

The following three lighting scenarios were examined:

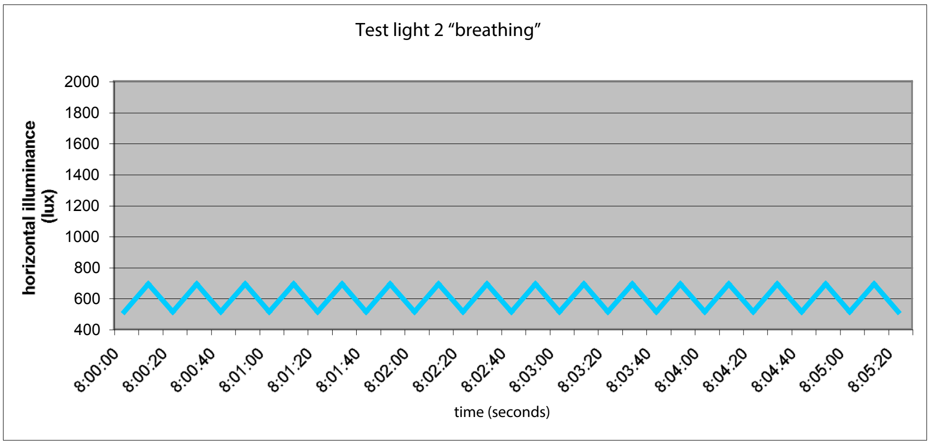
- Control light:
  With an illuminance level of constantly 500 lux and a light colour of 4 000 K, this room lighting condition complied with the standard lighting required under the EN 12464-1 lighting standard for production plants.



– Test light 1 “sawtooth”:
illuminance was – imperceptibly – increased from initially 500 lux in a linear manner to 2 000 lux and reduced again to 500 lux within a period of 30 minutes. These very slow rhythms correspond to one of the scenarios in the Flextronics field study.



– Test light 2 “breathing”:
For the dynamic brightness scenario “breathing light” – equally imperceptible and studied for the first time in this trial – illuminance was increased from 500 lux to 680 lux and reduced again to 500 lux within a period of ten seconds.



Measuring techniques

For one day in each case, all 29 test subjects were processing simple and/or complex tasks under all three lighting scenarios. The capture of data during the winter months, with a low level of daylight, was essential to be able to control the amount of light during the trial period in the best possible manner. To take account of learning effects, but also of difficulties to get started in the morning or of afternoon fatigue, the first and the last half hour were excluded from data analysis.

All data obtained with respect to sociography, productivity, as well as physiological regulation and/or actigraphy were first analysed descriptively and then subjected to an inferential statistics analysis. In the process, the researchers determined a level of significance of 5 %, with the probability of error for trends with respect to differences ranging up to 10 %.

The following measuring techniques were applied:

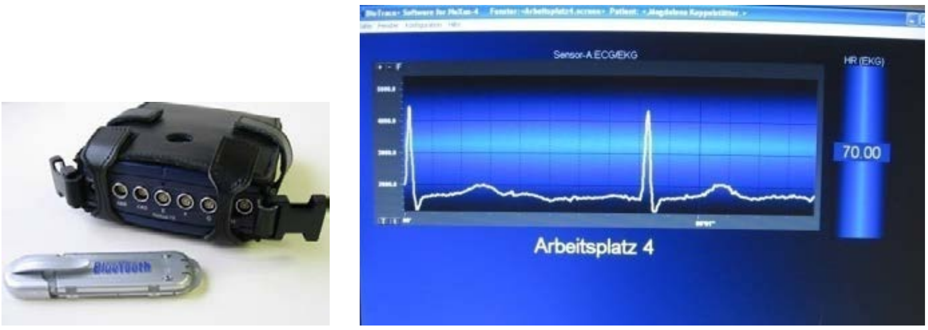
- Questionnaire data:
  MEQ – Morningness-Eveningness Questionnaire (chronotype analysis before the study)
  PSQI – Pittsburgh Sleep Quality Index (subjective quality of sleep; once before data capture)
  TICS – Trierer Inventar zum chronischen Stress (Trier chronic stress inventory; once before data capture)
  FBL – Freiburger Beschwerdenliste zu körperlichen Beschwerden (Freiburg list of physical complaints; once before data capture)
  BSKE – test of personal condition during data capture (in the morning, at noon, in the evening)
  Weekly journal – last night's sleeping quality, current condition (in the morning)
  Questionnaire regarding lighting situation - subjective perception of lighting conditions (in the evening)

- Productivity ratios:
  Within the scope of the study, learning and training effects were to be expected over the entire course of the study weeks. In order to still be able to provide information on productivity changes resulting from test lighting scenarios, only the data captured between 12:30 p.m. and 3:30 p.m. were included in the calculation of the production ratios.

- Heart rate analysis:
  The heart rate of the study participants was permanently measured while they were staying at the laboratory using the Nexus 4 or Nexus 10 biofeedback system (sampling rate 1024 Hz) and analysed using the ANS-Explorer software (http://www.neurocor.de/produkte_ansexplorer_de.html).

- Actigraphy:
  After work until and including start of work the next day, the study participants had a Daqtometer (http://daqtix.com/products/daqtometer) on the wrist of their non-dominant hand to measure their level of activity. The motion data thus obtained were summarised as a mean value of five minutes of activity in each case.

Screenshot of the display at the test subject's PC – green: production is within time limit; yellow: "Attention, please try to come to an end"; red: photo was only taken after expiry of the time limit – counts as an error



Nexus 10 with Biotrace software screenshot (http://www.mindmedia.nl/CMS/de.html)

Daqtometer for measuring physical activity

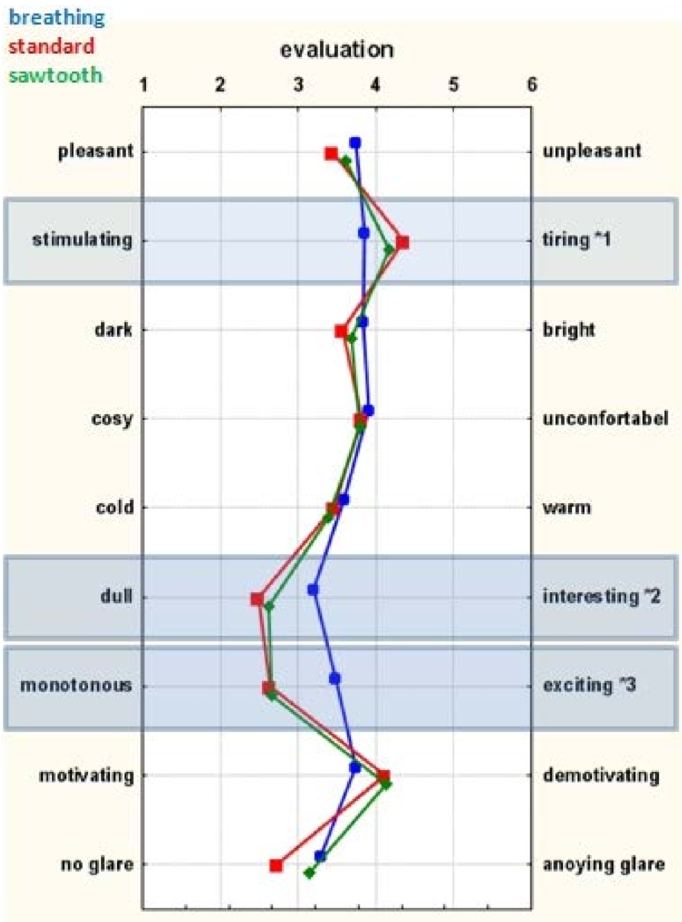
5 Results

Questionnaire data

The analysis of all sociographic and questionnaire data shows that the laboratory study comprised 29 individuals between 20 and 64 years of age (average age 30 years) being a healthy sample – without any above-average physical complaints, with normal stress level and healthy sleep. Overall, in relation to the break-down according to chronotypes, there were 62 % normal types, 21 % moderate evening persons and 17 % moderate morning persons.

Among other things, it was derived from the lighting situation questionnaires, in which the subjectively perceived lighting quality had to be assessed using a semantic differential of 9 pairs of adjectives, that the breathing light tended to be perceived as less tiring as well as much more interesting and stimulating.

With respect to the persons' subjective condition, no significant differences were observed between the three lighting scenarios. Independent of the room lighting conditions, fatigue increased with increasing exposure towards the afternoon. What was remarkable, however, was the fact that in spite of varying lighting levels the lighting scenes were not described as brighter or darker etc.



Productivity ratios
Over the course of weeks, substantial learning and training effects were observed. In spite of taking account of this increased performance, and in spite of the careful monitoring of intervening variables as well as the variation of lighting scenarios, no significant differences in productivity were observed between the three lighting situations and two levels of complexity – neither with respect to the error rate nor relating to the relative lead time.

Heart rate analysis
With respect to heart rate variability, marked physiological effects were demonstrated for the two dynamic lighting situations. It was shown, for instance, that in comparison to constant control-light conditions, the slow dynamics of the sawtooth test light significantly contribute to activating the parasympathetic nervous system, that part of the autonomic nervous system that regulates the regeneration of the body. It was also observed that the breathing light primarily addresses the sympathetic nervous system, which is responsible for performance increases in the organism.

Actigraphy
The analysis of the motion data did not reveal any clear differences between the two lighting conditions in relation to activity in the evening and while sleeping. Thus, under breathing light, there was demonstrably increased activity in the afternoon and early in the evening, as compared to sawtooth or control-light conditions. In the “sleeping time” interval, however, an opposite effect was demonstrated. Here, breathing light caused a significantly reduced level of activity as compared to sawtooth light, and tended to cause lower median activity levels as compared to control-light conditions.

Abstract
In none of the two dynamic lighting scenarios, any significant influences on the test subjects' productivity were demonstrated. Nevertheless, there were immediate responses to both test lighting situations during work. For one thing, the test subjects experienced dynamic lighting (breathing light) as less tiring, as well as more interesting and stimulating – although it was not even perceptible to them. On the other hand, there were physiological effects that were measurable until far into the night. High-frequency light (breathing light) had an activating, stimulating effect during the day, while it resulted in more quiet sleep during the night; low-frequency light with higher illuminance (sawtooth) had a relaxing effect during work.

Ultimately, this laboratory study proves that biologically effective light reduces work-related psychophysiological stress. At the same time, it also shows that employees experiencing a lower level of stress do not necessarily perform better – at least not during the relatively short study period of six days in total.

6 Discussion and outlook

So far, biological effects of light were achieved primarily by using high luminous intensity levels, associated with high investment and operating costs. This laboratory study shows that such effects can be obtained with only slightly increased amounts of light by means of dynamic lighting control systems.

Apart from the periods of 10 seconds that were studied for the first time within the scope of the dynamic breathing light, there are other ultradian stimulation frequencies that might be examined in future studies. Further insights may also be gained by integrating somnology, by limiting the study to one specific type of task or by selecting longer examination periods. Possibly, biological lighting effects may also be obtained by varying the light colour or beam pattern at other frequencies. Independent of these possibilities for deepening our knowledge, the findings obtained in this laboratory study already now contribute to driving the development of future standards in relation to the non-visual effect of light on people.

7 Literature

G. Hildebrandt, M. Moser & M. Lehofer:
Chronobiologie & Chronomedizin. (Chronobiology & Chronomedicine) Hippokrates Verlag 1998

Study regarding Industry and engineering/productivity Flextronics

Bartenbach

Markus Canazei, head of the psychology of perception department of Bartenbach GmbH since 2004, has essentially managed this study on behalf of Zumtobel. Moreover, he is a lecturer for “Visual Perception” at the academy of light.

He has a teaching degree from Klagenfurt university for mathematics and PPP (pedagogics, psychology, philosophy), technical mathematics and psychology. He also studied psychotherapeutic science at Donau-Universität Krems and concurrently completed the training to become a psychotherapist.

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