Lighting Res. Technol. 2010; **42**: 345–360

Effects of dynamic lighting on office workers: First results of a field study with monthly alternating settings

YAW de Kort PhD and **KCHJ Smolders** MSc
Human Technology Interaction Group, Eindhoven University of Technology, Eindhoven, The Netherlands

Received 8 February 2010; Revised 12 June 2010; Accepted 20 June 2010

Dynamic lighting is designed to have positive effects on well-being and performance. In a field experiment we tested whether these effects are detectable and stable over time when employed in actual work settings. The study consists of two tranches, one following a monthly alternating experimental design, the other a yearly alternating one. This paper reports on the first tranche. In a dual balanced design, office workers experienced dynamic or static lighting according to an a-b-a /b-a-b scheme over three consecutive periods ($N = 142$, 90, 83). Questionnaire data suggest no significant differences for need for recovery, vitality, alertness, headache and eyestrain, mental health, sleep quality, or subjective performance, although employees were more satisfied with the dynamic lighting. Implications and limitations of the study are discussed.

1. Introduction

Although not always physically challenging, office work does take its toll on one's mental resources. Stress and attention fatigue are all too common in the office, so any environmental or ambient feature that holds the potential to revive office workers or help them recuperate from stress or fatigue throughout the day deserves our attention. In the current study we explore lighting as a potential environmental feature impacting office workers' well-being.

Recent research has indicated that lighting may have an impact on biological and psychological processes.[1–5] Dynamic lighting is an innovative lighting solution that aims to harness these potential effects of lighting characteristics such as colour temperature and illuminance. Artificial office lighting typically is constant in both illuminance and colour temperature, whereas natural light varies throughout the day as a result of weather conditions and the position of the sun. Begemann *et al.*[6] showed that preferences for artificial lighting vary with weather type, brightness and time of the day (in addition, they reported substantial interpersonal differences). With dynamic lighting, colour temperature and illuminance vary during the day according to a preset protocol, aiming to support or even enhance the natural rhythm of employees' alertness. A potential protocol, also applied in the present study, is presented in Figure 1. This particular protocol does not exactly emulate the natural pattern of daylight, but instead offers a higher illuminance and colour temperature in the morning and after lunchtime with lower and warmer white light during the late morning and afternoon. This is in line with preferences reported for overcast days in winter[6] and thus aims to

Address for correspondence: Yvonne de Kort, Human Technology Interaction, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands.
E-mail: y.a.w.d.kort@tue.nl

10.1177/1477153510378150

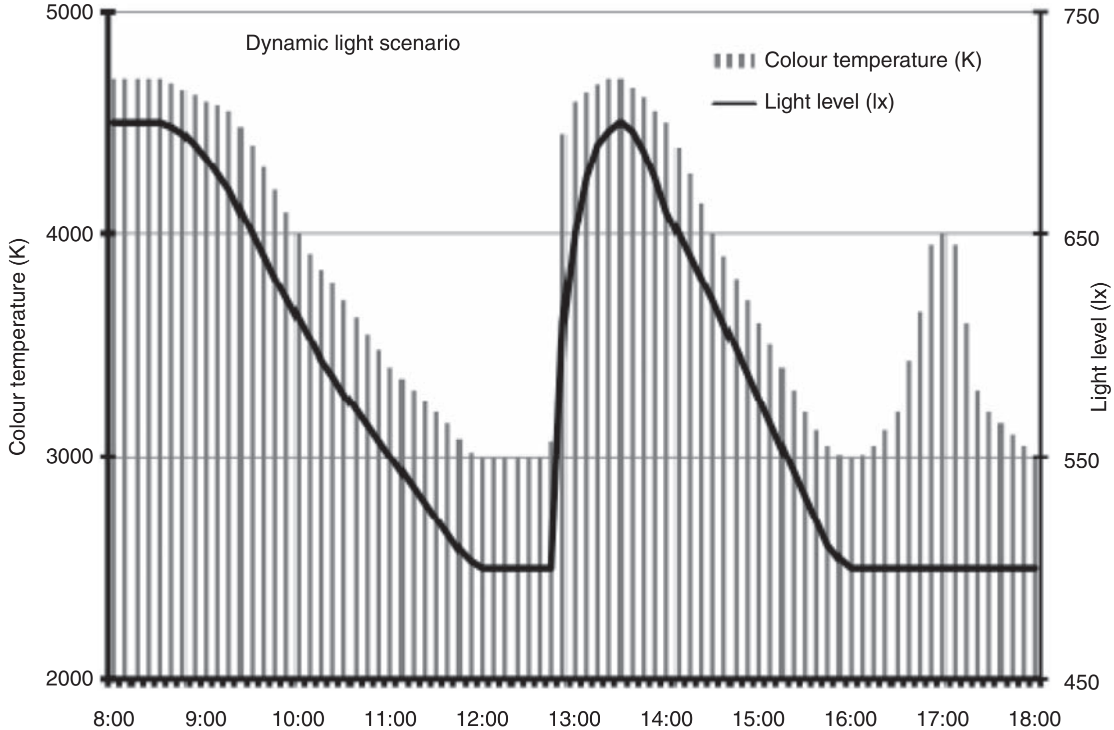

Figure 1 The dynamic lighting scenario: Illuminance and correlated colour temperature of the lighting plotted against time of day

stimulate workers during the work day, yet to also facilitate desirable relaxation around the lunch break.

Light can influence the regulation of the biological clock, and the secretion of hormones such as melatonin and cortisol. During daytime the secretion of melatonin is low and therefore the influence of light on its suppression minimal.[1] Research has shown that the level of cortisol increases when exposed to high light levels in the morning, but not in the afternoon[1] or evening.[2] These biological effects are dependent on the colour temperature, light level, duration and timing of exposure as well as on the size and position of the light source[3,7,8] and probably have an influence on individuals' well-being, health and performance.[9] Scheer and Buijs[2] showed an increase in cortisol levels when participants were exposed to 800 lx 1 hour after awaking, compared to exposure to no light. However, light level had no effect on cortisol levels in the late evening. Rüger *et al.*[1] investigated the effect of bright light on cortisol levels, core body temperature, heart rate and sleepiness, fatigue and energy. Participants were exposed to a high light level (5000 lx) or a low light level (<10 lx) for 4 hours between noon and 4.00 pm in the first experiment and between midnight and 4.00 am in the second experiment. Participants were exposed to light levels below 10 lx before and after the 4 hours of light exposure. The results showed that light level had an effect on heart rate and core body temperature, but not on cortisol concentration. Light level also had a positive effect on subjective alertness/sleepiness, feelings of fatigue and energy: Participants felt more alert, less fatigued and more energetic in the bright light condition than in the dim light condition. The results of these two experiments show different patterns for the physiological measures and the psychological measures: Effects of lighting on physiological measures were time dependent whereas effects of lighting on psychological measures were independent of time of day. Bright light only increased heart rate and core body temperature during the nighttime exposure but not during daytime exposure to the high light level. The authors argue that the effect of lighting on subjective alertness and sleepiness is not fully mediated by the suppression of melatonin as melatonin levels are very low during daytime and suggest that there may be different mechanisms behind the physiological and psychological effects of lighting.[1]

Phipps-Nelson *et al.*[10] investigated the effect of a 5-hour light exposure to a high light level (1000 lx at eye level) on sleepiness and performance compared to less than 5 lx during daytime under a constant routine after two nights of sleep restriction. Results showed that exposure to 1000 lx had a significant effect on subjective sleepiness, performance and slow eye movements, but not on melatonin level. Participants were more alert, that is lower self-reported sleepiness and fewer short eye movements, and shorter reaction times on a vigilance test than in the 5 lx condition. There was no effect of lighting condition on melatonin level. In both conditions, melatonin levels were low as expected during daytime.

Aries[11] reported an inverse correlation between light level and employees' level of fatigue and sleep quality. In an earlier experiment by Grünberger *et al.*,[12] participants were exposed to either a high light level (2500 lx) or a lower light level (500 lx) for 4 hours between 9.00 am and 5.00 pm. The results showed that the higher light level had a positive effect on participants' alertness, their ability to concentrate and their mood, and resulted in a reduction of errors made on a performance test, compared to lower intensity lighting. Other studies have also shown positive effects of a high light level on people's well-being and performance.[1,13,14] It should be noted that in most of these studies the difference in light level between the high and low intensity lighting condition was large (>2000 lx).

Complementing studies employing artificial light, Kaida *et al.*[14] showed that indoor exposure to natural light (>2000 lx) for 30 minutes in the early afternoon had a direct effect on subjective alertness and EEG measures. No effect of light exposure on cognitive performance was found. Kaida *et al.*[15] also showed that 30 minutes exposure to natural light through a window (>2000 lx) increased feelings of pleasure and reduced feelings of sleepiness during the light exposure.

Research into the psychological effects of lighting suggests that both a high illuminance and a high colour temperature can have positive effects on people's well-being, health and performance. For instance, Fleischer *et al.*[4] showed that exposure to higher colour temperature lighting (5600 K) is more stimulating than warm white lighting (3000 K) although participants did indicate that they experienced the warm white lighting as more pleasant. Some smaller studies have also shown an activating effect of a higher colour temperature (6500–7500 K) compared to 3000 K lighting.[5,16] However, other studies have failed to demonstrate comparable effects[17,18] so, overall, the literature is still inconclusive. Employing even more extreme lighting conditions, Viola *et al.*[19] found an effect of high colour temperature (17 000 K) on workers' ability to concentrate, level of fatigue, alertness, daytime sleepiness and subjective performance compared to a lower colour temperature (2900 K). Lastly, Mills *et al.*[20] found comparable effects of colour temperature on well-being and performance of employees in a call centre.

Practically all of the rigorous scientific research into the biological and psychological effects of high intensity or high colour temperature office lighting has been performed in laboratories, where participants are exposed to – sometimes extreme – lighting conditions for only short periods of time – typically several hours. Moreover, other variables potentially impacting the effects of light are under the experimenters' control in contrast to the situation in real-world research. Studies into the effects of dynamic lighting are scarce both in the field and in the lab and often involve only small numbers of participants. One example of a more rigorous design is the recent study by Hoffmann *et al.*[21] They compared the effects of variable lighting (500–1800 lx, 6500 K) to those of static lighting (500 lx, 4000 K) on melatonin levels and subjective mood on three consecutive days. The variable lighting pattern, consisting of relatively short peaks in lighting level in the morning and early afternoon, showed modest positive effects on self-reported activity, while under static lighting, subjective ratings of deactivation and fatigue increased in the afternoon. Unfortunately, the findings did not point in the same direction unequivocally and although sulphatoxymelatonin levels decreased during the day, this pattern did not differ between static and dynamic light. It appears that melatonin levels were already low in the early morning and quickly decreased to their natural daytime minimum.[22,23] User evaluations in real-world projects have produced some anecdotal evidence for increased well-being and performance amongst office employees (e.g. Interpolis and Trigion in The Netherlands, VUB bank in Slovakia). Whether these effects are detectable and whether they are stable over time when actually employed in the work setting has not been thoroughly investigated to date.

The present paper reports the intermediate results of the first large-scale field test into the effects of dynamic lighting on office workers. The longitudinal study follows an experimental design in two tranches, in which four groups of about 100 to 200 employees each are alternately exposed to dynamic and static lighting. In one tranche, which we are reporting on here, lighting conditions change on a monthly basis during the winter months, according to a dual balanced design. In the second tranche the lighting conditions remain stable during winter, dynamic for one group, static for the other. Then during summer both groups switch to the alternate condition. The advantage of this design is that we can both explore the relatively short- and long-term effects of dynamic lighting compared to constant lighting. In addition, we can compare the two lighting conditions both between and within groups. In this paper, we describe the results of data gathered during the first winter for the two short-term groups (see Smolders and de Kort[24] for preliminary results of the second tranche).

2. Method

2.1 Design

The current study is a dual-balanced field experiment, with Lighting condition (dynamic vs. static) within, and Group (A vs. B) between groups, and three consecutive measurement periods (dynamic–static–dynamic and static–dynamic–static schemes respectively, in January, February and March). In the original design there were four measurement periods and the lighting condition would change three times. However, the study was delayed because complaints just before the start indicated that the calibration in some of the rooms was incorrect due to newly added furniture replacement (desks and tables with a white finish). All luminaires were checked and recalibrated where necessary. Therefore, it was not possible to have four measurement periods during the dark months. In the current dual balanced design two groups of participants were exposed to dynamic or static lighting, alternating on a 3-week basis, for three periods in a row.

2.2 Participants

The Westraven building houses a substantial part of Rijkswaterstaat, which is the implementing body of the Ministry of Transport, Public Works and Water Management. Some 2000 people work in the Westraven building. For the current monthly alternating tranche, only departments located in the high-rise part of the building were selected. Departments with field-work employees were excluded from the study. Additional selection criteria for departments were that groups with similar tasks could be assigned to both experimental groups and that both experimental groups would approximately be of the same size. Scenarios were implemented on complete floors. Layout and furniture on each of the floors in the building were very similar, apart from the colour of the carpeting. Departments were distributed such that each colour of carpet was equally represented in both groups. Tasks of the recruited departments included administration, control, call-centre, ICT and purchasing. As stated above, each task was equally represented in each of the two groups. In total, the groups consisted of 414 office employees from seven departments. All members of the selected departments were recruited. *Post hoc* exclusion criteria were part-time contracts of less than 4 days, field jobs or substantial external services, reported illness during the measurement period, and filling in the questionnaire at home instead of in the office.[a]

Participants were aware that they were participating in a survey related to the effects of lighting, but were unaware of the exact lighting scenarios. The cover story was that various dynamic scenarios would be tested throughout the study, but the participants did not know we were testing static versus dynamic light.[b]

Employees worked on their own floors, but they may have occasionally briefly visited other floors. For lunch most employees would go down to the lunch restaurant; some may have gone for a brief walk outside occasionally. Of the participants in the first sample, 19.7% reported experiencing dry eyes to a moderate (12.7%) or severe (7%) extent, 16.9% experienced moderate to severe eye fatigue and 4.9% experienced moderate blurry vision.

In the first month of the field study 147 questionnaires were completed and returned (response rate: 35.5%). The data of five participants were removed because they indicated that they were only rarely at their workplace in the high-rise office building, that they were ill during the measurement period, or that they filled out the questionnaire at home. Of the remaining 142 participants (83 in the static and 59 in the dynamic condition), 111 were male and 31 female with a mean age of 45 years (standard deviation (*SD*): 10.23, range: 23–65 years). In the second measurement period, the questionnaire was again distributed and 96 employees (43 in the static and 47 in the dynamic condition) filled out the questionnaire completely (response rate: 23.2%). The data of six participants were removed because they indicated that they were only rarely at their workplace in the office or that they had filled out the questionnaire at home. Of the remaining 90 participants, 67 were male and 23 female with a mean age of 48 years (*SD* 9.73, range: 25–63 years). In the third measurement period, 84 employees (42 in the static and 41 in the dynamic condition) completed the

[a]Filling out the questionnaire at home was used as an exclusion criterion because of concern that conditions in the home office would confound the effects of office conditions.

[b]During the last month in the second year, we probed people's suspicion of the exact scenario on their floor (data not reported in this manuscript). The data indicated that most could not recognise the applied scenario and no differences emerged between the two conditions.

questionnaire (response rate: 20.3%). One participant filled out the questionnaire at home and his data was removed from the dataset. Of the remaining 83 participants, 68 were male and 15 female with a mean age 48 years (*SD*: 9.45, range: 25–65 years).

2.3 Procedure

The general procedure was such that employees experienced a certain lighting condition for 3 weeks. Data collection took place in the third week, after they had worked under these conditions for at least 2 weeks. The study formally started on Thursday, January 8. From that time on the lighting condition was dynamic for half of the participants (group A) and static for the others (group B). Two weeks later (again on Thursday) all potential participants received an e-mail with a hyperlink to an online questionnaire. The scenarios during this third week remained as they had been the 2 weeks before. A reminder was sent the following Tuesday. Data collection stopped 1 week after it had started; this was also the day that the conditions switched between groups. On Thursday January 29, the lighting condition was switched from dynamic to static and vice versa. Again, questionnaires were distributed 2 weeks after the new light scenarios had started (February 12). On February 19, the lighting condition was again switched, back to the same lighting conditions as in January. Data collection of this third phase started 2 weeks later (March 5) and ended on March 12. During the second and third measurement periods, the same procedure as in January was used. The selected timeline avoided national and popular holidays as well as the switch to daylight saving time (summertime, March 29). It took about 15 minutes to fill in the questionnaire. A Living Colors lamp from Philips was raffled every measurement period as an incentive for participants to complete the questionnaire.

2.4 Setting and lighting manipulation

The study was performed in a recently renovated high-rise office building, with a large daylight contribution (Figure 2), in which a flex-working concept is applied. The flex-working concept means that employees do not have their own desk but are free to select any desk on their department's floor throughout the day, week and year. All floors consist of a mix of meeting rooms, concentration cells and open-office space to facilitate the various tasks people perform throughout the day. The departments that were selected for the study were all in the high-rise part of the building, on various floors, with alternating conditions.

Recessed dynamic lighting luminaires (TBS375) were used, each holding 2 TL5 fluorescent lamps (light code 827 (2700K) and 865 (6500K)). The luminaire offers the possibility to change the colour temperature of the light between warm white (approximately 3000 K) and cool white (approximately 5000 K). After installation, every luminaire was calibrated in order to achieve the correct light levels on the desk below (measured horizontally). A central lighting control module controlled both the light level and the colour temperature according to the programmed scenario.

In the dynamic lighting condition, employees experienced a gradually changing lighting scenario (500–700 lx; 3000–4700 K) with a higher light level and colour temperature in the morning and after lunchtime (Figure 1). The static condition provided an illuminance of 500 lx at a colour temperature of 3000 K.

As complete floors of the building were used as the test site, light levels may have differed moderately between specific desks and locations on account of the non-perfect uniformity of the artificial lighting, and due to the varying daylight contribution over the department floors. Vertical illumination levels were not measured or calibrated but probably differed substantially, depending on

Figure 2 A view of the indoor environment

the specific location and viewing direction of the individual.

For both the static and the dynamic scenario daylight responsive dimming was implemented. Sensors mounted near the luminaires close to the windows measured the light levels on the desks underneath. Whenever levels exceeded the target value (e.g. 500 lx for the static or 700 lx for the dynamic scenario) on account of the daylight contribution, the system would dim down to a 0 lx artificial lighting contribution. Estimates of the daylight factor with a simulation of a floor in Dialux produced an average daylight factor of 4.88 on the desks of the employees (daylight factors on individual desks ranged from 2.74 to 6.88). Of course, the measurements were performed in the darker months of the year (January–March). Investigation of the weather in the first, second and third measurement period – weekdays of the 2 weeks before and 1 week during the survey – showed that during January there were more sun hours than in February and March (approximately 60, 35 and 40 hours, respectively).[25]

2.5 Measures

The questionnaire consisted of measures of the need for recovery (i.e. the need to recuperate from attention fatigue and stress), vitality, alertness, headache and eyestrain, mental health, sleep quality and subjective performance. Subjective evaluations of lighting conditions were also assessed. In addition, attitudes towards the job and work environment and personal characteristics were included as control variables. Objective measures such as days of sick leave and coffee consumption were collected on a department level to corroborate subjective findings.

2.5.1 Need for recovery

Need for recovery was measured with a behaviour-based scale consisting of 34[c] items describing behaviours at office employees' discretion to recover from mental strain, psychological distress, motivational deficits

[c]The original scale consists of 35 items. The item 'I take care of plants in the office' was dropped due to lack of variance as it was not allowed to have plants in this office.

and/or mental fatigue,[26] combined with 11 evaluative statements created by Van Veldhoven and Broersen.[27] Examples of such restorative behaviours are 'I go to the toilet even though I do not need to', 'I go home earlier than planned', 'I take an extra, short break', 'I look outside for a moment'.[d] This scale has been tested for reliability, convergent and predictive validity in earlier research.[26] Some of these items had 5-point response scales ranging from (1) 'never' to (5) 'very often' or from (1) 'never' to (5) 'at least once a day'. Other items had dichotomous response scales with either (1) 'It happens never or rarely' and (2) 'It happens sometimes or often' as response options, or with (1) 'yes' and (2) 'no' options. The evaluative statements are dichotomous items with (1) 'yes' and (2) 'no' as response options. Separation reliability of the scale was 0.83 in each consecutive month. The separation reliability matches a classical definition of reliability; it represents the ratio between the true and estimated variance of people's recovery needs.[28] The reliability score of this scale thus indicates that scale's internal consistency is satisfactory.

2.5.2 Mental health and vitality

Mental health and vitality were assessed using two subscales from the Dutch version of the SF-36 Health Survey (RAND-36).[29] The mental health subscale consists of five items, such as 'Have you been a very nervous person?' and had an internal consistency between $\alpha = 0.75$ and $\alpha = 0.81$. The vitality subscale consists of four items (e.g. 'Did you have a lot of energy?') with Cronbach's alpha between $\alpha = 0.76$ and $\alpha = 0.87$. The response options of both subscales ranged from (1) never to (5) very often.

[d]The reference 26 is in Dutch, but the scale and a report on the validity and reliability in English are available upon request from the authors. A manuscript has been submitted to the Journal of Occupational and Organizational Psychology (JOOP).

2.5.3 Headache and eyestrain

Headache and eyestrain were measured with eight items taken from Viola *et al.*,[19] which describe symptoms, such as 'headache' and 'eye fatigue', with response options ranging from (1) 'absent' to (4) 'severe'. The scale had an internal reliability ranging from $\alpha = 0.84$ to $\alpha = 0.89$.

2.5.4 Alertness and sleep quality

Alertness was assessed with the Karolinska Sleepiness Scale (KSS)[30] with 'today' instead of 'at this moment' as a time frame. The response options ranged from (1) 'extremely alert' to (9) 'extremely sleepy–fighting sleep'. Sleep quality was measured with the Pittsburgh Sleep Quality Index[31] consisting of 18 items concerning subjective sleep quality, sleep latency, sleep duration, sleep efficiency, sleep disturbances, sleeping medication and daytime dysfunction. The scale has an internal consistency between $\alpha = 0.61$ and $\alpha = 0.70$.

2.5.5 Subjective performance

Subjective performance was measured with the question 'On a scale from 0 to 10, how would you rate your performance on the days you worked during the last 2 weeks?' derived from the World Health Organization Health and Work Performance Questionnaire (WHO-HPQ).[32]

2.5.6 Subjective evaluations

Subjective evaluations of lighting conditions concern pleasantness of the lighting, experienced light level, experienced disturbances of the artificial lighting and of daylight and satisfaction with the lighting. Pleasantness of the lighting was measured with two semantic differential adjective items (pleasant–unpleasant, comfortable–uncomfortable). These items were internally consistent with Cronbach's alpha ranging from $\alpha = 0.79$ to $\alpha = 0.90$. Experienced light level was measured with three items about light level (artificial light and daylight) on the workplace, on the screen and in the office space from Hellinga and de Bruin-Hordijk.[33] The response scale ranged from (1) 'too little light' to (5) 'too much light' and the scale was internally consistent with alphas ranging from $\alpha = 0.72$ to $\alpha = 0.84$. Experienced disturbance of the artificial lighting was assessed with two items adopted from Hellinga and de Bruin-Hordijk.[33] The two items probed hindrance from direct light and from reflections (glare) of artificial light. The 5-point response scale ranged from (1) 'never' to (5) 'very often' and these items had an internal consistency ranging from $\alpha = 0.75$ to $\alpha = 0.91$. Experienced disturbance of daylight was measured with similar items. This scale was internally consistent with alpha ranging from $\alpha = 0.69$ to $\alpha = 0.77$. Satisfaction with the lighting was assessed with the question: 'How satisfied are you with the lighting at your workplace?' with response options ranging from (1) 'very dissatisfied' to (5) 'very satisfied'.

2.5.7 Job and work-related evaluations

Job-related questions concern evaluation of the work atmosphere, job satisfaction, commitment to the company, work diversity, decision authority and job demands. To assess work atmosphere, four evaluative statements were employed, such as 'The work atmosphere is good.' The response scale was a 5-point scale from (1) 'never' to (5) 'very often'. The internal consistency of the four statements ranged from $\alpha = 0.81$ to $\alpha = 0.83$. Three dichotomous (yes/no) statements were employed to assess job satisfaction ('I am satisfied with my job'), commitment to the company ('I feel committed to the company') and work diversity ('my work is diverse'), respectively. Decision authority and job demands were measured with two subscales of the Job Content Questionnaire.[34] Decision authority was assessed with three statements, such as 'I have freedom to make decisions about my job'. The subscale is internally consistent with alpha ranging from $\alpha = 0.64$ to $\alpha = 0.69$. Job demands were measured with four statements, such as 'My job requires I work fast'. This subscale had an internal consistency between $\alpha = 0.68$ and $\alpha = 0.76$. Both subscales had a 4-point response scale ranging from (1) 'totally disagree' to (4) 'totally agree'.

Work-condition-related questions concerned the impression of the office environment, pleasantness of the indoor climate and satisfaction with the indoor climate. Impression of the office environment was assessed with nine adjectives, such as 'pleasant', 'orderly' and 'quiet' from Aries.[11] The unipolar response options ranged from (1) 'not at all to' (5) 'extremely'. The internal consistency of the nine adjectives ranged from $\alpha = 0.78$ to $\alpha = 0.91$. Pleasantness of the indoor climate was measured with two semantic differential adjective items (pleasant–unpleasant, comfortable–uncomfortable). This scale was internally consistent with alpha values ranging from $\alpha = 0.84$ to $\alpha = 0.92$. To assess satisfaction with the indoor climate two items concerning satisfaction with the temperature and ventilation at the workplace were employed with response options ranging from (1) 'very dissatisfied' to (5) 'very satisfied'. This scale was internally consistent with alpha between $\alpha = 0.73$ and $\alpha = 0.77$.

2.5.8 Personal characteristics

Questions regarding personal characteristics concerned gender, age, light sensitivity and mean number of working hours per week. Light sensitivity was measured with the items 'How much trouble do your eyes give you when you are exposed to bright light?' and 'How much do you suffer from headaches when you are exposed to bright light?' on a 5-point scale from (1) 'not at all' to (5) 'extremely'. The reliability of this scale ranged from $\alpha = 0.73$ to $\alpha = 0.78$.

2.6 Analyses and hypotheses testing

The aim of the study was to test whether the dynamic lighting scenario installed in this building would show positive effects on

Table 1 Main dependent variables and background measures: Means and (standard deviations) per experimental condition and phase

Phase Condition	January		February		March	
	Static	Dynamic	Static	Dynamic	Static	Dynamic
N	83	59	43	47	42	41
Need for recovery	−0.97 (0.71)	−0.92 (0.81)	−0.59 (0.67)	−0.69 (0.75)	−0.88 (0.81)	−0.68 (0.70)
Vitality	14.4 (2.6)	14.4 (2.4)	14.2 (2.6)	14.3 (2.6)	14.8 (2.2)	14.2 (3.4)
Alertness (KSS)	3.40 (1.36)	3.76 (1.75)	3.70 (1.83)	3.70 (1.55)	3.71 (1.37)	3.71 (1.68)
Mental health	20.7 (2.4)	20.5 (2.1)	20.0 (2.6)	20.4 (2.7)	20.9 (1.6)	20.9 (2.4)
Headache and eyestrain	12.3 (3.8)	12.1 (3.7)	12.4 (2.6)	12.8 (4.0)	12.1 (4.1)	12.0 (4.4)
Sleep quality	4.68 (2.22)	4.84 (2.26)	5.20 (2.06)	5.34 (2.95)	4.19 (2.18)	4.69 (2.49)
Subjective performance	7.59 (0.74)	7.43 (0.84)	7.44 (0.73)	7.43 (0.74)	7.45 (0.63)	7.44 (0.92)
Age	44.3 (10.7)	48.0 (9.1)	50.4 (8.8)	46.5 (10.3)	47.1 (9.7)	49.1 (9.2)
Light sensitivity	2.02 (0.79)	2.01 (0.87)	2.07 (0.91)	2.18 (0.99)	2.01 (0.97)	1.91 (0.79)
Work atmosphere	4.01 (0.60)	3.92 (0.66)	3.97 (0.63)	4.03 (0.60)	4.08 (0.51)	4.01 (0.73)

well-being and performance. The main hypotheses therefore were that in dynamic conditions, employees would report higher vitality and alertness, and lower need for recovery than under static lighting conditions. In addition, effects on subjective performance, mental health, sleep quality and headache and eyestrain were explored. Moreover, potential mediation and/or moderation by individuals' light sensitivity, impression of the office and work atmosphere were investigated.[e] Linear mixed model (LMM) analyses were employed to enable the inclusion of covariates in a repeated measures design. Moreover, this analysis enabled us to deal with the fact that some employees would participate three times, whereas others filled in the questionnaire only once or twice.

3. Results

To investigate the effect of lighting condition (dynamic vs. static lighting) on employees' well-being, health and performance, LMM analyses were performed on the need for recovery, vitality, mental health, alertness, headache and eyestrain, sleep quality and subjective performance (separate LMM analyses for each dependent variable), with Lighting condition and Month as fixed factors and participant as a random factor. Light sensitivity, impression of the office and work atmosphere were included as covariates.[f]

Means and standard deviations for the dependent variables are reported in Table 1, per experimental condition and per month, as are descriptive statistics for the most relevant background variables. These data were then analysed as specified above. The results showed that there was no significant effect of lighting condition on need for recovery, vitality, mental health, alertness, headache and eyestrain, global sleep quality and subjective performance (all $F<1$, except for alertness, $F=1.31$, NS). In Table 2, the F-statistics for Condition and Month are shown. Table 3 shows the estimated marginal means for all dependent variables in both the static and the dynamic condition.

The factor Month did show an effect on need for recovery [$F(2,153)=13.27$; $p<0.001$]. Pairwise comparisons indicated that workers'

[e]For the sake of clarity and brevity, we will only report on background variables in as far as they showed significant differences or relations.

[f]We first assessed the Pearson's correlations between potentially confounding variables and dependent variables and added only those covariates that had significant correlations with the dependent measures for well-being, health and performance.

Table 2 Results of LMM analyses: *F*-statistics for well-being, health and performance measures ($N = 315$)

	Lighting condition			Month		
	F	*df*	*p*	*F*	*df*	*p*
Need for recovery	0.06	(1,167)	0.81	13.27	(2,153)	<0.001
Vitality	0.08	(1,190)	0.78	0.34	(2,169)	0.71
Mental health	0.01	(1,179)	0.92	2.56	(2,154)	0.08
Headache and eyestrain	0.00	(1,193)	0.95	0.45	(2,172)	0.64
Alertness	1.31	(1,202)	0.25	1.01	(2,180)	0.37
Sleep quality	0.63	(1,151)	0.43	2.81	(2,135)	0.06
Subjective performance	0.35	(1,210)	0.56	1.19	(2,190)	0.31

Table 3 Estimated marginal means (EMM) and standard errors (SE) of well-being, health and performance measures for static and dynamic conditions ($N = 315$)

	Dynamic		Static	
	EMM	SE	EMM	SE
Need for recovery	−0.76	0.05	−0.77	0.05
Vitality	3.59	0.04	3.58	0.04
Mental health	4.10	0.03	4.10	0.03
Headache and eyestrain	1.53	0.03	1.53	0.03
Alertness	3.74	0.12	3.59	0.11
Sleep quality	4.98	0.18	4.84	0.17
Subjective performance	7.42	0.06	7.46	0.06

recovery needs were lower in January (mean (*M*): −0.95; *SD*: 0.77) than in February (*M*: −0.64; *SD*: 0.71) and March (*M*: −0.78; *SD*: 0 .76) with $p < 0.01$ for both contrasts. There was no difference in recovery needs between February and March ($p = 0.16$). The effects of Month on the remaining dependent variables did not reach statistical significance. To get an impression of effect sizes, partial correlations were computed between Lighting condition and the dependent variables, and Month and the dependent variables, respectively (correlations were controlled for Month and the dependent variables, respectively; in addition, the correlations are controlled for the covariates: Light sensitivity, impression of the office and work atmosphere). The only correlation that was significant was between Month and the need for recovery ($r = 0.134$, $p = 0.02$).

We also performed LMM analyses with scales probing the subjective evaluation of the lighting as dependent variable, Lighting condition and Month as fixed factors, participant number as random factor, and light sensitivity, impression of the office environment and work atmosphere as covariates. The results of these analyses showed that Lighting condition had a statistically significant effect on satisfaction with the lighting [$F(1, 211) = 5.16$; $p = 0.02$]. Office workers were more satisfied with the lighting in the dynamic lighting condition (*M*: 3.69; *SD*: 0.87) than in the static condition (*M*: 3.53; *SD*: 0.91). In addition, Lighting condition had a significant effect on the experienced disturbances of artificial lighting [$F(1,196) = 4.44$; $p < 0.04$]. Unexpectedly, workers reported fewer disturbances of artificial lighting in the static condition (*M*: 1.71; *SD*: 0.72) than in the dynamic lighting condition (*M*: 1.80; *SD*: 0.78). Note that disturbances were measured on a 5-point scale, thus office employees in both conditions, on average, never (1) or rarely (2) experienced disturbances of the artificial lighting. There was no significant effect of Lighting condition on experienced disturbances of daylight [$F < 1$, $p = 0.34$]. In addition, the Lighting condition had no significant effect on the evaluation of pleasantness of the lighting [$F(1, 242) = 1.87$; $p = 0.17$]. The effect of Lighting condition on experienced light level showed a non-significant trend [$F(1, 247) = 3.01$; $p = 0.08$]: indicating a trend for employees to evaluate the lighting as brighter in the dynamic lighting condition (*M*: 3.06; *SD*: 0.48) than in the static condition (*M*: 2.98; *SD*: 0.52). Table 4 reports the *F*-statistics for Lighting condition and Month concerning the subjective evaluation of the lighting; Table 5 reports the estimated marginal means on all subscales for both experimental conditions.

Month had a significant effect on disturbances of daylight [$F(2, 192) = 4.98$; $p = 0.01$]. Pairwise comparisons indicated that workers

Table 4 Results of LMM analyses: *F*-statistics of subjective evaluation of the lighting condition ($N=315$)

	Lighting condition			Month		
	F	*df*	*p*	*F*	*df*	*p*
Pleasantness of lighting	1.87	(1,242)	0.17	1.09	(2,220)	0.34
Satisfaction with lighting	5.16	(1,211)	0.02	0.21	(2,192)	0.81
Light level	3.01	(1,247)	0.08	2.28	(2,223)	0.11
Disturbances of daylight	0.93	(1,215)	0.34	4.98	(2,192)	0.01
Disturbances of lighting	4.44	(1,196)	0.04	1.31	(2,178)	0.27

Table 5 Estimated marginal means (EMM) and standard errors (SE) of the subjective evaluations of static and dynamic lighting conditions ($N=315$)

	Dynamic		Static	
	EMM	SE	EMM	SE
Pleasantness of lighting	3.66	0.06	3.55	0.06
Satisfaction with lighting	3.73	0.07	3.57	0.06
Light level	3.06	0.04	2.97	0.04
Disturbance of daylight	2.64	0.07	2.56	0.07
Disturbance of lighting	1.82	0.06	1.69	0.06

experienced more disturbances of daylight in January (*M*: 2.69; *SD*: 0.91) than in February (*M*: 2.54; *SD*: 0.91) and March (*M*: 2.52; *SD*: 0.82) with $p=0.022$ and $p=0.004$, respectively. There was no significant difference between February and March concerning disturbances of daylight ($p=0.55$).

4. Discussion

We employed a three-phase dual-balanced ABA/BAB experimental design to investigate the effect of dynamic lighting compared to static lighting on workers' well-being, health and subjective performance in a longitudinal field study. In this paper, the results of linear mixed model analyses on the data of the short-term groups are reported (first tranche). The results showed no significant differences in workers' need for recovery, vitality, sleep quality, mental health, headache and eyestrain, or subjective performance as a result of the dynamic versus the static lighting condition, controlled for relevant personal, job and work-related characteristics.

Interestingly, in spite of us not finding the beneficial effects that were hypothesised, workers in the dynamic lighting condition did report being more satisfied with that lighting condition, although at the same time they reported being disturbed by direct light or reflections of the lighting more often than did workers in the static lighting condition.

Need for recovery showed a significant effect of month of measurement, with employees reporting a lower need in January than in February and March. A lower need for recovery indicates a lesser degree of attention fatigue and stress. This is in line with weather reports, indicating more hours of sun on the workdays during the measurement period in January than in February and March, but may also be related to the fact that most employees had taken time off in December on account of the holidays. The higher number of disturbances of daylight in January may also be explained by the fact that there were more hours of sun in the first measurement period than in the other two.

The question we now need to address is what conclusions could or should be drawn from these data. For this we must consider not only the data, but also the methodology. We had hoped to conduct the study in four consecutive months, running four full-month measuring periods. Yet instead we saw ourselves compelled to cut one period and shorten the remaining periods from 4 to 3 weeks. This, unfortunately, is the reality of doing field studies. However, considering the fact that in the questionnaires participants were always asked to reflect on the last 2 weeks, the procedure still worked well in the three-times-3-week period compromise that resulted. Moreover, we did manage to uphold a sound experimental design. The dual-balanced ABA/BAB design is a statistically efficient design: It exploits the fact that in each time period we have both treatments and effects are tested within groups, as both groups experienced both lighting conditions. Furthermore, we employed a range of measurements, none of which showed significant beneficial effects of dynamic lighting. Power analyses indicated that participant numbers were such that minimal detectable differences of, for instance, vitality and need for recovery were around 0.3 and 0.4 units, respectively, in the single between-groups test alone. Sensitivity for the repeated and within-groups comparison was even higher. All scales repeatedly showed good reliability and had been successfully used in earlier studies and, although response rates were only modest, participant samples were still large enough to enable testing of these effects. Yet in spite of the robust design, methodology and procedure, we were not able to establish beneficial effects of dynamic lighting when compared to static lighting.

One possible reason why we did not find the expected effects was the substantial daylight contribution in the renovated building used in our study. Dynamic lighting is said to be most effective in situations with a low daylight contribution,[35] yet the building in our study has large daylight openings and appears very light. A high proportion of daylight could potentially have undermined the differences between the static and dynamic lighting cycle, especially in combination with the daylight responsive dimming. On the other hand, the study was performed during the darker months of the year (January–March). Nevertheless, on very sunny days the light level on desks close to the windows may have occasionally risen above the targeted level. Since in those instances, the artificial light was dimmed until only the daylight contribution remained, on very sunny days this may have resulted in similar light levels for people near the windows, whether they were working on floors with the static or the dynamic scenario.

A second consideration is that the specific dynamic pattern of the lighting employed here may have attenuated the findings. As was stated in the introduction, very little research exists on psychological effects of dynamic lighting. The pattern employed in the current study dictates fairly subtle changes in illuminance and colour temperature, especially in comparison to changes outdoors or the manipulations applied in laboratory-based studies.[1,12–15,19–21] These design choices have been based on state-of-the-art insights into human alertness curves, yet we are still far from fully understanding light's effects on humans' psychological and physiological states. Moreover, they were dictated by the maximum capacity of the installed lighting system and requirements for energy efficiency. The exact maximum of colour temperature and intensity of the lighting, the exact timing and shape of the curve and the range of wavelengths for an optimal curve are still under investigation. From the current findings one would certainly recommend more extreme values in terms of light intensity – values higher than 2000 lx or even 2500 lx have been shown to successfully influence psychological variables[1,12–15] – or colour temperature – values over 5600 K or even 6000 K have shown similar effects.[4,5,16] From the present study we conclude that the light levels employed in the dynamic scenario were too low to induce benefits on relevant psychological variables such as need for recovery, vitality and subjective alertness that are measurable in real-world conditions.

We conclude that in the first tranche of this longitudinal research we have not been able to establish beneficial effects of dynamic lighting on individuals' need for recovery, vitality, sleep quality, mental health, headache and eyestrain, or subjective performance, although office workers did report higher satisfaction with the dynamic than the static lighting. In the second tranche of the current project we will explore such long-term effects in groups that experienced static versus dynamic lighting during two consecutive years (AB/BA design). In addition, we will replicate the study performed in this first tranche. Additional measures will be included to investigate potential effects of views to the outside and to explore interpersonal differences, for example, related to chronotype. As yet, it remains unclear whether beneficial effects of dynamic lighting may emerge in more long-term applications, in environments with very limited or no daylight contribution, or when more pronounced or differently shaped curves are applied in terms of intensity and/or colour temperature.

Acknowledgement

We are grateful to Rijkswaterstaat, the Rijksgebouwendienst, Philips and Ariadne Tenner for facilitating and supporting this project. We would also like to thank Martine Knoop for her comments on an earlier version of this paper. Lastly, we would like to thank the two anonymous reviewers for their thoughtful and constructive feedback.

References

1 Rüger M, Gordijn MCM, Beersma DGM, de Vries B, Daan S. Time-of-day-dependent effects of bright light exposure on human psychophysiology: Comparison of daytime, night time exposure. *American Journal of Physiology – Regulatory, Integrative and Comparative Physiology* 2006; 290(5): 1413–420.

2 Scheer FA, Buijs RM. Light affects morning salivary cortisol in humans. *Journal of Clinical Endocrinical Metabolism* 1999; 84(9): 3395–3398.

3 Morita T, Tokura H. The influence of different wavelengths of light on human biological rhythms. *Applied Human Science* 1998; 17: 91–96.

4 Fleischer S, Krueger H, Schierz C. *Effect of brightness distribution and light colours on office staff, results of the 'Lighting harmony' project: Proceedings of Lux Europa 2001*, Reykjavik, Iceland, 2001.

5 Musea H, Sato M. The effect of color temperature of lighting sources on the autonomic nervous functions. *The Annals of Physiological Anthropology* 1992; 11: 533–538.

6 Begemann SHA, van den Beld GJ, Tenner AD. Daylight, artificial light and people in an office environment, overview of visual and biological responses. *International Journal of Industrial Ergonomics* 1997; 20: 231–239.

7 van Bommel WJM. Non-visual biological effect of lighting and the practical meaning for lighting for work. *Applied Ergonomics* 2006; 37(4): 461–466.

8 Rea MS, Figueiro MG, Bullough JD. Circadian photobiology: An emerging framework for lighting practice and research. *Lighting Research and Technology* 2002; 34(3): 177–190.

9 van Bommel WJM, van den Beld GJ. Lighting for work: A review of visual and biological effects. *Lighting Research and Technology* 2004; 36(4): 255–269.

10 Phipps-Nelson J, Redman JR, Dijk D-J, Rajaratman SMW. Daytime exposure to bright light, as compared to dim light, decreases sleepiness and improves psychomotor vigilance performance. *Sleep* 2003; 26(6): 695–700.

11 Aries MBC. *Human lighting demands, healthy lighting in an office environment*. PhD thesis. Eindhoven: Eindhoven University of Technology, 2005.

12 Grünberger J, Linzmayer L, Dietzel M, Saletu B. The effect of biologically-active light on the noo- and thymopsyche and on psychophysiological variables in healthy volunteers. *International Journal of Psychophysiology* 1993; 15(1): 27–37.

13 Badia P, Myers B, Boecker M, Culpepper J. Bright light effects on body temperature,

alertness, EEG and behavior. *Physiology and Behavior* 1991; 50(3): 582–588.
14 Kaida K, Takahashi M, Otsuka Y. A short nap and natural bright light exposure improve positive mood status. *Industrial Health* 2007; 45(2): 301–308.
15 Kaida K, Takahashi M, Haratani T, Otsuka Y, Fukasawa K, Nakata A. Indoor exposure to natural bright light prevents afternoon sleepiness. *Sleep* 2006; 29(4): 462–469.
16 Deguchi T, Sato M. The effect of color temperature of lighting sources on mental activity level. *The Annals of Physiological Anthropology* 1992; 11: 37–43.
17 McColl SL, Veitch JA. Full-spectrum lighting: A review of its effects on physiology and health. *Psychological Medicine* 2001; 31: 949–964.
18 Veitch JA, McColl SL. A critical examination of perceptual and cognitive effects attributed to full-spectrum fluorescent lighting. *Ergonomics* 2001; 44: 255–279.
19 Viola AU, James LM, Schlangen LJM, Dijk D-J. Blue-enriched white light in the workplace improves self-reported alertness, performance and sleep quality. *Scandinavian Journal of Work, Environment and Health* 2008; 34(4): 297–306.
20 Mills PM, Tomkins SC, Schlangen LJM. The effect of high correlated colour temperature office lighting on employee wellbeing and work performance. *Journal of Circadian Rhythms* 2007; 5(2): 2–10.
21 Hoffmann G, Gufler V, Griesmacher A, Bartenbach C, Canazei M, Staggl S, Schobersberger W. Effects of variable lighting intensities and colour temperatures on sulphoatoxymelatonin and subjective mood in an experimental office workplace. *Applied Ergonomics* 2008; 39: 719–728.
22 Cajochen C, Kräuchi K, Wirz-Justice A. Role of melatonin in the regulation of human circadian rhythms and sleep. *Journal of Neuroendocrinology* 2003; 15: 432–437.
23 Zee PC, Turek FW. Role of melatonin in the regulation of sleep. In: Turek FW, Zee PC. (eds), *Regulation of Sleep and Circadian Rhythms*. New York: Marcel Dekker, 1999: 181–196.
24 Smolders KCHJ, de Kort YAW. *Light up my day: A between-group test of dynamic lighting effects on office workers' wellbeing in the field: Proceedings of Lux Europa*, Istanbul, Turkey, 2009.
25 Klimatologie – Maand en Seizoensoverzichten. Retrieved 27 April 2009 from http://www.knmi.nl/klimatologie/maand_en_seizoensoverzichten/index.html.
26 Smolders KCHJ, de Kort YAW, Kaiser FG. *Behoefte aan restoratie in kantoren : de ontwikkeling en validatie van een gedragsgebaseerde schaal om de psychologische effecten van (dynamische) verlichting te meten [Need for Recovery in Offices: Development and validation of a behavior-based scale to measure psychological effects of lighting]*. MSc thesis. Eindhoven: Technische Universiteit Eindhoven, 2008. Retrieved 17 June 2010, from http://alexandria.tue.nl/extra2/afstversl/tm/Smolders%202008.pdf.
27 Van Veldhoven M, Broersen S. Measurement quality and validity of the "Need for Recovery" scale. *Occupational Environmental Medicine* 2003; 60(suppl 1): 3–9.
28 Bond TG, Fox CM. *Applying the Rasch Model: Fundamental Measurement in the Human Science*. Mahwah, NJ: Erlbaum, 2001.
29 Van der Zee KI, Sanderman R. *Het meten van de algemene gezondheidstoestand met de RAND-36, een handleiding*. Groningen: Rijksuniversiteit Groningen, 1993.
30 Åkerstedt T, Gillberg M. Subjective and objective sleepiness in the active individual. *International Journal of Neuroscience* 1990; 52(1): 29–37.
31 Buysse DJ, Reynolds CF, Monk TH, Berman SR, Kupfer DJ. The Pittsburgh Sleep Quality Index: A new instrument for psychiatric practice and research. *Psychiatry Research* 1989; 28(2): 193–213.
32 Kessler RC, Barber C, Beck A, Berglund P, Cleary PD, McKenas D, Pronk N, Simon G, Stang P, Ustun TB, Wang P. The World Health Organization Health and Work Performance Questionnaire (HPQ). *Journal of Occupational Environmental Medicine* 2003; 45(2): 156–174.
33 Hellinga HIJ, de Bruin-Hordijk GJ. *The influence of daylight and view out on the visual*

comfort of workplaces: Proceedings of Balkanlight, Ljubljana, 2008: 233–242.

34 Karasek R, Brisson C, Kawakami N, Houtman I, Bongers P, Amick B. The Job Content Questionnaire (JCQ): An instrument for internationally comparative assessments of psychosocial job characteristics. *Journal of Occupational Health Psychology* 1998; 3(4): 322–355.

35 Schriek MHJ. *Dynamic lighting – energy savings by use of atypical daylight responsive lighting control*. MSc thesis. Eindhoven: Eindhoven University of Technology, 2007.