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WORKPLACE ILLUMINATION EFFECTS ON ACUITY, COGNITIVE PERFORMANCE AND WELL-BEING IN OLDER AND YOUNG PEOPLE

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Abstract

This study investigates how, in a simulated office environment, four different general lighting conditions (300-2700lux desk-illuminance) affect a group of 30yr-old (n=24) and 60yr-old (n=24) participants with respect to their alertness, mood, performance on a cognitive test-battery, vitality, lighting appraisal and visual acuity. Only for visual acuity and lighting appraisal significant effects of illuminance are found. Using a paper-based Landolt-C task, we demonstrate that acuity increases with illuminance in both age groups. A log-log plot of our acuity data against desk-illuminance shows a linear line with an intercept that significantly differs between the age groups, while the slope does not. Hence, in either age group, an illuminance reduction from 500 to 300 lux reduces visual acuity by 4.1%, while a threefold increase in illuminance augments acuity by 9.5%. Participants experience the 300lux condition as uncomfortably dim, especially in the 60yr-group. Both age groups experience the 2700lux condition as too bright.

Keywords: Workplace Lighting, Office Lighting, Human Centric Lighting, Vigilance, Visual Acuity, Lighting Comfort, Alertness, Mood, Cognitive Performance, Ageing, Elderly.

1 Introduction

Current recommendations for task lighting in offices prescribe 300-500 lux typically, and are predominantly based on visibility. They usually depart from a standard observer and do not address the particular light needs of the rapidly growing part of the workforce that is above 50 years of age and has to cope with gradually declining visual functions (Adrian, 1993; Akizuki and Inoue, 2004; Geerdinck et al., 2009; Owsley, 2011; Sagawa et al., 2003; van de Kraats and van Norren, 2007; Winn et al., 1994). Moreover, current lighting recommendations usually neglect non-visual effects of light, although our understanding of these effects is rapidly increasing. Recent research has demonstrated the importance of light as a critical biological signal that not only enables vision, but also strongly impacts our well-being and health. Light has acute effects on mood (Partonen and Lonnqvist, 2000; Wirz-Justice et al., 2004), alertness (Phipps-Nelson et al., 2003) and attention. Next to this, light is the strongest and most important regulator of our body clock. Every day again light exposure is needed to (re)adjust the timing and stability of our 24hr sleep-wake cycle, thus impacting our performance, physiology, immune responses, appetite and a variety of behaviours. The melanopsin-containing photosensitive ganglion cells in our retina play an important role in driving these non-visual effects of light, in addition to rods and cones (Lucas et al., 2014).

In new lighting installations and designs, light levels are frequently reduced in our surge to conserve energy. However, the illuminances used in these installations might become too low to meet the needs of the ageing workforce. Simultaneously, they leave little opportunity to realize health-, well-being- and performance-supporting non-visual effects of light. It may do more harm than good when we continue to overlook the influence of age and non-visual effects within our lighting-standards, -designs, and -installations.

The current study was designed to investigate which lighting levels are needed to provide the elder and younger part of the workforce with a healthy and comfortable office environment. We specifically focused on the different lighting needs that were expected between both age groups. The potential effects of different illuminance levels (ranging from 300-2700 lux) were

measured with a set of objective as well as subjective measures targeting people's visual and cognitive performance, comfort, appraisal and mood.

2 Method

2.1 Study set-up and participants

The study was executed in Eindhoven, The Netherlands, during October 2013 - March 2014. Forty-eight healthy participants were split in a 30yr-old and a 60yr-old subgroup with a mean age($\pm$ SD) of 30.8($\pm$ 1.6) and 59.9($\pm$ 2.4), respectively. All participants had normal sight (visual acuity >0.8), or corrected-to-normal sight. In a "within-subject" study design, participants were instructed to keep a regular sleep schedule during the 6 week period in which they underwent four different lighting conditions during four visits to a simulated office room. A participant always visited in a group with the same four individuals, from 3PM-4.30PM, and on the same day of the week (Tue-Fri). The order of the light conditions was balanced across all participant groups.

2.2 Experimental settings and lighting conditions

The simulated office room measured 6.8x3.5x2.6 m (LxWxH). Each short side of the room had two artificial windows that mimicked an outdoor view without any influence of daylight on the lighting conditions within the room. The room had four desks and was equipped with two lines of LED-fixtures providing direct down-lighting and indirect up-lighting, both with 4000K. Each line of fixtures was suspended lengthwise above two desks, see Figure 1.

Between 3.15PM and 4.15PM one of the four lighting conditions shown in Table 1 was present. In the 15 minutes directly before and after this time interval, the 500 lux condition was applied. The four light conditions differed in (horizontal) desk-illuminance and had a very homogeneous light distribution. Consequently, the ratio of the vertical to the (horizontal) desk-illuminance was virtually constant between the conditions. The artificial windows had a very modest and limited contribution to the lighting conditions, see Table 1. A vertical illuminance (E_v , measured at the eye position of a person sitting at the desk) of 36 lux results when only the PC monitors in the room are activated (i.e., deactivating all luminaires and artificial windows).

2.3 Measures

Throughout each lab visit, the same test-battery was administered several times. The test-battery contained a visual acuity test, an auditory Psychomotor Vigilance Task (PVT), a typing task and some more complex cognitive tasks involving executive function (GoNoGo, Stroop, typing). Subjective alertness was assessed by means of the Karolinska Sleepiness Scale (KSS) (Akerstedt and Gillberg, 1990) and the Global-Vigor and -Affect (GVA) scale (Monk, 1989) was used to probe mood. Additional questionnaires (Eklund and Boyce, 1996) were used to probe comfort and appraisal of the lighting conditions.

Table 1 – Characteristics of the four lighting conditions (all 4000K luminaires on, all artificial windows on, all monitors off) used in the study.

The table gives: the horizontal illuminance on the desk (E_h); the vertical illuminance (E_v) at the eye position of a participant sitting at the desk; the luminance (L_{Landolt}) of the vertically mounted, paper-based visual acuity test; the luminance of the two long walls (L_{wall}); the peak luminances that result when a subject sitting at the desk is looking directly to the ceiling (L_{ceiling}) or the luminaires ($L_{\text{luminaire}}$); the luminance ($L_{\text{paper desk}}$) of a white paper lying on the desk. The bottom row (only A_{win}) gives the light characteristics that result when only using the artificial windows, deactivating all monitors and luminaires in the room.

Lighting condition	E_h [Lux]	E_v [Lux]	E_h/E_v	L_{Landolt} [Cd/m ²]	L_{wall} [Cd/m ²]	L_{ceiling} [Cd/m ²]	$L_{\text{luminaire}}$ [Cd/m ²]	$L_{\text{paper desk}}$ [Cd/m ²]
300 lux	292	159	0.54	32	32	127	1861	70
500 lux	500	264	0.53	57	55	253	3414	128
1400 lux	1405	742	0.53	157	147	710	10440	359
2700 lux	2690	1427	0.53	296	279	1374	19690	681
only A_{win}	15	15	1.03	4		1	1	18



Figure 1 – Left: Photograph of the simulated office room in which four participants were seated at a desk in front of a monitor. The desk on the left was used by the test leader. Two artificial windows are visible in the rear wall. Right: Photograph of the paper-based Landolt-C visual acuity test set-up used.

We used an auditory Psychomotor Vigilance Task (PVT) to measure reaction times. The PVT consisted of a sequence of 88 beeps, interleaved by a random period between 4.25s-9.75s after a response was given. In case no response was given, the task would not continue until a response was detected. The participants heard the beeps via headphones connected to a PC and responded by pressing the space bar of the keyboard. Participants were asked to keep their eyes open during the task and fixated on a '+'-sign in the middle of the PC screen.

The GoNoGo task resembled the PVT, but used a beep that was either of a high or a low frequency. Participants were instructed to press the spacebar of the keyboard only in response to beeps with the low frequency. The higher frequency beeps were to be ignored. Outcome measures were the number of incorrect presses, the reaction time to the target and the number of missed targets. The task consisted of 240 beeps of which 75% had a low frequency (target beeps) and 25% a higher frequency (distractor beeps), presented in a random order. Each next stimulus was presented 1.5-2.5s (randomly varying) after a response was given.

A computerized version of a Stroop-like task (Zysset et al. 2001) was used. Participants were instructed to indicate whether the colour of the characters of the upper word (appearing 0.1 s prior to the lower word) matches the meaning of the word below (printed in white), as quickly and accurately as possible. The 'N' and 'M'-keys of the keyboard were used to respond,

referring to 'Non-matching' and 'Matching'. The Stroop task used consisted of 12 times a set of 14 stimuli.

The visual acuity (VA) test consisted of an A3-piece of paper with 96 Landolt-C's, printed in four orientations. The print had a contrast of 0.93 and a reflectance factor of 0.84. Behind the paper, one centimeter below each Landolt-C, a low-intensity red LED was mounted. These LEDs were used as a computer-randomized pointer. Participants were instructed to indicate the open side of the Landolt-C directly above the activated LED by pressing the appropriate key ($\uparrow$, $\downarrow$, $\rightarrow$ or $\leftarrow$) as quickly and accurately as possible. In each test, all 96 stimuli were used twice, in a random order, where each next stimulus was presented as soon as a response has been entered. The test was placed vertically and a chin-rest was used to fix the viewing distance to 53 cm (see Fig. 1). Each participant used one single personalized Landolt-C chart. The twelve different Landolt-C sizes on this chart were equidistant on a $\log(VA)$ scale. Moreover, the center of the scale was chosen so that, in the 500 lux condition, the participant gave 62.5% correct entries, simultaneously ensuring that the two smallest and largest ring sizes of the scale resulted in approximately 25% and 100% correct entries.

A lighting appraisal and comfort questionnaire was administered in Dutch, via computerized surveys. The questionnaire contained the Office Lighting Survey (Eklund & Boyce, 1996) for which a 7-point Likert scale (1=highly disagree, 7=highly agree) was used. The same scale was applied to assess participants' satisfaction with the lighting. Moreover, participants were asked to rate the lighting on a 10-point scale (1=very bad, 10=excellent).

3 Results

The light condition did not have a distinct, statistically significant effect on mood (GVA), alertness (KSS), and on various aspects of reaction times in the GoNoGo, PVT and Stroop tasks.

The Landolt-C test was analyzed by plotting the percentage correct answers against the log of the Landolt-C size used. For every light condition one plot was made per participant, and a sigmoidal curve fit was used to obtain that point on the curve above which the participant entered the right Landolt-C orientation in at least 62.5% of the cases. The Landolt-C size of this point defines the visual acuity (for that particular light condition) according to:

$$VA = 2.1851 / C_{size} \quad (1)$$

where

VA is the visual acuity as assessed with a Landolt-C test that is printed on white paper with 72 points per inch and uses a viewing distance of 530 mm;
 C_{size} is the size (in points) of the Landolt-C ring.

A linear mixed model (LMM) was used to analyze how the logarithm of visual acuity from Eq. (1) depended on age and light condition, treating light as a continuous predictor via the logarithm of illuminance. A linear relationship with a common slope for both age groups was selected as the best model; more complex models did not give a significantly better fit. The best model is given by Equation (2), a graphical presentation is provided in Fig. 2.

$$\log(VA) = A + B * \log(E_h) + C * young \quad (2)$$

where

$\log(VA)$ is the mean value of the $^{10}\log$ of the visual acuity from the paper-based Landolt-C test;
 A equals -0.275 (95%CI: -0.359 to -0.191);
 B equals 0.0822 (95%CI: 0.0681 to 0.0963);
 $\log(E_h)$ is the $^{10}\log$ of the horizontal desk illuminance (300-2700 lux);
 C equals 0.193 (95%CI: 0.091 to 0.296);
 young is an indicator function that equals 1 for the 30yr-group and 0 for the 60yr-group.

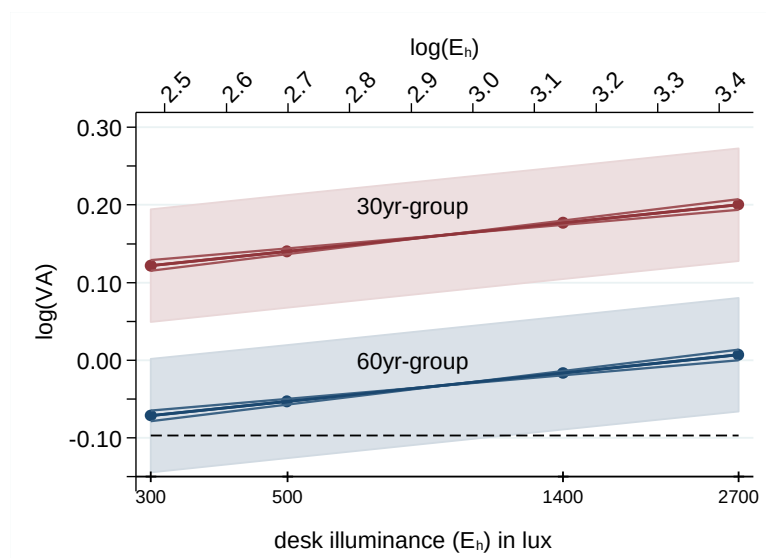


Figure 2 – Graphical representation of the dependence of the mean value of the logarithm of visual acuity (VA) as predicted by the LMM model of Eq. (2). The middle dark-red line represents the 30yr-group whereas the middle dark-blue line represents the 60yr-group. The shading indicates the 95% confidence interval of the mean $\log(VA)$ within each age group; the lighter lines with varying steepness indicate the 95% confidence interval of the mean slope of the middle dark lines.

The selected model of Equation (2) has a constant difference in average $\log(VA)$ between the 60yr- and 30yr-group. This difference does not depend on the light condition used. Equation (2) shows that, within the 300-2700 lux range studied, the visual acuity of the 60yr-group always is 36% (95%CI: 19-49%) below that of the 30yr-group. Moreover, the visual acuity in both subgroups improves by 9.5% (95%CI: 7.8-11.1%) when increasing the illuminance by a factor of 3. When reducing the illuminance from 500 to 300 lux visual acuity drops by 4.1% in both age groups.

The medians of the Office Lighting Survey (OLS) questions on lighting distribution, deep shadows, reflections, flicker, and unnatural skin tones indicated that participants did not experience any issues with these topics for any of the lighting conditions, as expected. For the other OLS questions and for the lighting satisfaction and rating questions the results are shown in Table 2.

Table 2 - Median scores for the four light conditions on some of the OLS questions (1=highly disagree, 7=highly agree) and on the lighting appraisal and rating questions for which a clear and significant effect of light was found (Friedman p-values are given, NS is used when $p>0.05$). The corresponding post-hoc analysis results are also given to show which light condition pairs are significantly different.

Appraisal/Comfort Question	Age group	300 lux	500 lux	1400 lux	2700 lux	Friedmann p-value	post-hoc
OLS1) Overall the lighting is comfortable	60yr	3	4	5	5	<0.01	300≠1400
	30yr	4.5	5.5	5	3	<0.05	500≠2700
OLS2) Lighting is uncomfortably bright for tasks I perform	60yr	3	3	2.5	5	NS	
	30yr	2	2.5	5	5	< 0.01	300≠2700 500≠2700
OLS3) Lighting is uncomfortably dim for the tasks I perform	60yr	5	4	2	1	< 0.01	300≠1400 300≠2700 500≠1400 500≠2700
	30yr	5	2	2	1	< 0.01	300≠1400 300≠2700 500≠2700
OLS7) Fixtures are too bright	60yr	2	2	4	6	< 0.01	300≠1400 300≠2700 500≠2700
	30yr	2	2	5	6	< 0.01	300≠1400 300≠2700 500≠1400 500≠2700
A) How satisfied are you with this office lighting? (1=very unsatisfied, 7=very satisfied)	60yr	2	4	5	6	<0.05	300≠1400 300≠2700
	30yr	3	5	5	3	NS	
B) Rate this lighting on a scale from 1(very bad) to 10(excellent)	60yr	5	6	8	7	<0.01	300≠1400
	30yr	5.5	7	6	4.5	<0.05	300≠500

Based on the findings reported in Table 2 the following observations can be made:

- OLS1: the 60yr-group experienced 300 lux as least comfortable (too dim) and 1400 lux as most comfortable. Moreover, the data also indicate that the 30yr-group experienced 2700 lux as uncomfortable (too bright). Using the Wilcoxon Rank Sum test, the difference in comfort between the 30yr- and 60yr-group was statistically significant for 300 lux [$W = 160.5$, $p = 0.033$] and for 2700 lux [$W = 368.5$, $p = 0.044$]:
 - the 60yr-group experienced 300 lux as significantly less comfortable than 30yr-group (median 60yr-group=3, median 30yr-group=4.5),
 - the 30yr-group experienced 2700 lux as significantly less comfortable than 60yr-group (median 60yr-group=5, median 30yr-group=3).
- OLS2: There was no significant effect of light on this question in the 60yr-group. However, in the 30yr-group, a significant effect of light occurred and post hoc tests indicated that the 2700 lux condition differed from the 300 lux and 500 lux conditions. The median scores in

both age groups indicated that each group slightly agreed with the statement that the lighting of the 2700 lux condition was uncomfortably bright.

- OLS3: Both age groups did slightly agree with the statement that the lighting was uncomfortably dim in the 300 lux condition.
- OLS7: Both age groups agreed that the fixtures were too bright in the 2700 lux condition. The 30yr-group also experienced the fixtures as slightly too bright in the 1400 lux condition.
- Question-A: The median score on the satisfaction question indicated that the 60yr-group (i) was unsatisfied with the 300 lux condition, (ii) was quite satisfied with 1400 lux condition and (iii) was satisfied with the 2700 lux condition. The 30yr-group was slightly unsatisfied with both the 300 and the 2700 lux condition.
- Question-B: On a 10-point lighting-rating scale (1=very bad, 10=excellent), significant differences were found between the 300 and the 1400 lux condition in the 60yr-group, with medians of 5 and 8 respectively. The 30yr-group displayed a significant difference between the 300 and the 500 lux condition, the median ratings were 5.5 and 7 respectively.
- The outcomes on questions OLS1, A and B correlate with each other (for all pairs the Spearman correlation coefficient was above 0.70 and $p < 0.001$).

4 Discussion

In the current experiment, visual acuity is studied while changing the general lighting conditions (and illuminance) in the room, rather than just changing the background luminance of the visual acuity task. Moreover, visual acuity was investigated by means of a novel computer-controlled paper-based Landolt-C test. Two age groups relevant to the working population were tested: a 30yr-group and a 60yr-group. Furthermore, the horizontal versus vertical illuminance ratio in this study was set to a constant value of 0.53. Hence, the horizontal and vertical values of the illuminances and luminances in this study are roughly linearly related across all lighting conditions used, see Table 1. This means that the B and C values of Eq. (2) apply to describe the relationship between VA and (il)luminance within this study, irrespective whether one expresses the light exposure in Eq. (2) as E_h , E_v , L_{paper} , or L_{Landolt} .

Various studies have shown that visual acuity increases when the background luminance of the acuity task increases, and explored this relationship for different age groups (Akizuki et al., 2008; Akizuki & Inoue, 2004; Sagawa, et al., 2003). All these studies demonstrate that visual acuity decreases with increasing age. Simultaneously, visual acuity has a tendency to saturate to a plateau value at high background luminances. Typically this occurs above 300 Cd/m^2 .

In the current study a linear relationship is found between $\log(\text{VA})$ and $\log(E_h)$, see Eq. (2), without any sign of a saturation effect. The linear relationship applies for a Landolt-C test luminance range of 32-296 Cd/m^2 , see Table 1. Within this luminance range previous studies also indicate that an approximately linear relationship occurs between $\log(\text{VA})$ and $\log(\text{luminance})$, and the slope of this relationship appears to be quite independent of age (Sagawa, et al., 2003; Akizuki & Inoue, 2004). The latter observation is confirmed by the results of the present study, see Fig.2. In the (il)luminance range of typical office settings, as studied here, the logarithm of visual acuity increases linearly with the logarithm of light intensity. The steepness of this increase is identical for the 30 and 60 year old group. Moreover, within this (il)luminance range, visual acuity does not saturate with increasing light level, see Fig. 2. This is in good agreement with previous studies; typically these demonstrate that visual acuity usually only reaches saturation at luminances well above 300 Cd/m^2 .

Regarding lighting appraisal, both age groups experience the 2700 lux condition as too bright. The 30-yr group also felt that the 1400 lux condition was slightly too bright, whereas the 60yr-group highly appreciated this condition (best median rating in Table 2). Both age groups experience the 300 lux desk-illuminance condition as uncomfortably dim. Lowering workplace desk-illuminance from 500 to 300 lux compromised visual performance and comfort especially

in 60yr-old people. This disadvantage might outweigh potential energy savings, in particular when placed into the perspective of the ageing workforce.

The current study did not show any benefits of extra light exposure with respect to alertness, mood and cognitive task performance of participants. The light intensity range (300-2700lux), light exposure duration (60 minutes) and exposure timing (by 3PM) as used in the current study might have been insufficient to strongly induce non-visual effects of light. More research is needed to establish under what circumstances such effects can be achieved in an office context.

5 Conclusion

The visual acuity in the 60yr-group is 36% below the visual acuity of the 30yr-group, irrespective of the light condition. Increasing the desk illuminance from 500 to 1400 lux improves visual acuity by 8.8%, again irrespective of age, and makes the lighting more comfortable for the 60yr-subgroup. Both age groups felt that the lighting condition with a 2700 lux desk-illuminance was slightly too bright. Simultaneously, the 30yr-group experienced the 2700 lux condition as significantly less comfortable than the 60yr-group;

An illuminance reduction from 500 to 300 lux compromises visual acuity by 4.1%, irrespective of age. Both age groups agree with the statement that the lighting condition with a desk-illuminance of 300 lux is uncomfortably dim. The 60yr-group experienced the 300 lux condition as significantly less comfortable than the 30yr-group.

The study results indicate that lowering desk-illuminance in workplace settings from 500 to 300 lux compromises satisfaction with the lighting, lowers visual acuity and compromises comfort, in 60yr-old more strongly than in 30yr-old, and this disadvantage might outweigh potential energy savings, in particular when placed into the perspective of the ageing workforce.

In the current study no convincing and statistically significant effects of light on subjective mood (GVA), subjective alertness (KSS) and reaction times of various cognitive tasks were found. More research is needed to establish the impact of lighting and its (acute and circadian) non-visual effects on performance, (visual) comfort, and well-being in the general population, and within the rapidly ageing workforce.

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