J Neural Transm (2007)
DOI 10.1007/s00702-006-0621-4
Printed in The Netherlands

Journal of Neural Transmission

Rapid communication

Blue light improves cognitive performance

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Received: August 14, 2006 / Accepted: December 18, 2006 / Published online: January 25, 2007

Summary A newly discovered system of photoreceptors for circadian rhythms works non-visual and responds to blue light (460 nm). We report a longitudinal study in 44 adults, showing that a significant increase in alertness and speed of information processing could be achieved by blue light as compared to normal light.

Keywords: Blue light, circadian rhythm, cognitive efficiency, alertness, speed of information processing

Introduction

Brainard et al. (2001) and Thapan et al. (2001) reported a non-visual photoreceptor system in humans, that is closely interlinked with circadian rhythms. It works independently of the scotopic and photopic photoreceptor systems and is intact in some individuals with amaurosis as well as with red–green color blindness (Lockley et al., 2006). The circadian photoreceptor system responds most sensitively to blue light with a wave length at approximately 460 nm (Berson et al., 2002; Brainard and Hanifin, 2005). Blue light needs much less energy to influence circadian rhythms than light waves in the scotopic or photopic spectrum (Lockley et al., 2003).

These findings have successfully been used in clinical practice to improve sleep-wake disturbances in old patients with and without Alzheimer's disease (Figueiro and Rea, 2005; Figueiro et al., 2003). Changes in the circadian rhythms due to different light have been expected to occur after hours or even days. Changes in body temperature have been found to occur after a 2 hour delay (Cajochen et al., 2005). However, exposing oneself to a blue environment or looking at a blue picture leads to the subjective impression of an immediate change in one's alertness. This experience led us to the hypothesis, that effects of blue light may occur even after seconds and should lead, compared to light with a lower frequency, to an increase in alertness. If this hypothesis is true, a change in mental fitness should occur also during seconds, according to the activation model of Yerkes and Dodson (1908). If so, probands in a relaxed mood should experience an increase in cognitive efficiency when exposed to blue light, while subjects with an already elevated activation may suffer from increased emotional tension. We report a longitudinal pilot study evaluating this hypothesis.

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Methods

We conducted an open longitudinal study with adults attending a lecture ("Brain weeks", University of Erlangen-Nuremberg) entitled "light and mind". After a short introduction the participants were asked to take part anonymously in an harmless experiment. Its objective and first results would be presented in the end of this lecture. Actually, the audience learned the expectations of the experimenters and the preliminary results in the end of the lecture.

Participants were exposed to different illuminations for 20 sec each and had to judge their degree of alertness on a 7 step rating scale (further information is summarized in the legend of Table 1) and were asked to keep it

Table 1. *Characteristics of study items*

n	Condition	m	md	sd	Minimum	Maximum	Wilcoxon (p)
Alertness[a]							
42	room light 0′	3.5	3.5	1.1	2.0	5.0	
43	yellow 2′	3.6	3.0	1.2	1.0	6.0	
42	blue 4′	3.8	4.0	1.2	2.0	6.0	
44	white 6′	3.8	4.0	1.1	2.0	6.0	
42	blue 8′	3.7	4.0	1.2	1.0	7.0	
40	yellow 10′	3.3	3.0	1.1	1.0	6.0	
Mean*	yellow (2′ + 10′)/2	3.4	3.5	1.0	1.0	6.0	
	blue (4′ + 8′)/2	3.7	4.0	1.2	1.5	6.5	
Difference*	$m_{blue} - m_{yellow}$	0.3	0.5	0.2	−3.0	4.5	0.023**
C (bit/sec)							
40	room light 0′	17.9	17.5	5.0	8.8	31.3	
42	yellow 2′	18.3	18.1	5.1	7.5	31.3	
42	blue 4′	19.6	18.8	4.5	10.0	31.3	
43	white 6′	18.5	17.5	5.2	8.8	31.3	
41	blue 8′	19.9	20.0	5.1	10.0	31.3	
44	yellow 10′	19.1	18.8	4.8	11.3	31.3	
Mean*	yellow (2′ + 10′)/2	18.7	18.4	4.3	10.6	28.8	
	blue (4′ + 8′)/2	19.8	20.0	4.7	10.0	31.3	
Percentual change***	$m_{blue} - m_{yellow}$	4.9	3.3	1.9	−15.0	32.1	0.020**

C = Speed of information processing (bit/sec) = 5 bit × number of letters read/reading time; *individually measured, **exact, one-sided, ***100 $(m_{blue} - m_{yellow})/m_{yellow}$; [a]1 = very drowsy, 2 = drowsy, 3 = relaxed, but awake, 4 = fully awake, 5 = little tensed, 6 = very tensed, 7 = panic.

in mind. Ten seconds later using the same illumination, a measure of the speed of information processing was performed during 4 sec. Immediately afterwards normal room light was switched on again and participants were asked to write down the last two letters they had read and the degree of alertness they had estimated.

The following modes of illumination, that changed every two minutes, were used (cf. to Fig. 1): room light (0″–20″), yellow light (580 nm; 2′0″–2′20″), blue light (455 nm; 4′0″–4′20″), white light (6′0″–6′20″), blue light (8′0″–8′20″) and finally yellow light (10′0″–10′20″). We used fluorescent lamps with an energy of 18 W (1.400 lumen). When lamps were turned on, the room was otherwise darkened until probands were asked to write. Probands were sitting between 3 and 14 m away from the lamps. They were distributed over the anterior rows of seats in the lecture hall because, due to limited time, they had to be investigated simultaneously.

The speed of information processing (C) was measured as previously described (Lehrl and Fischer, 1990). Briefly, a line with 25 light grey and stochastically different letters (16 cm of height) was projected to a screen with a dark background on demand. Example:

r m d l i n s d v b k p e f r t z r n u v e a l g

These letters shall be read as fast as possible from left to right, like if they were read out to somebody. Full binary decisions are needed to recognize a letter. They are 4.7 bit → 5 bit (repertoire with 26 letters = $2^{4.7}$). The C can be calculated as follows:

Speed of information processing C (bit/s) = 5 bit × number of letters read/reading time. The reading time equalled 4 sec in each presentation.

C is closely related to one's level of fluid intelligence. Due to it's adjustment in adults, it can be directly connected with the IQ (Lehrl and Fischer, 1990).

Statistical analyses were done using non-parametric methods (Spearman's correlation and the Wilcoxon's test for dependent samples). *p*-Values were adjusted for multiple comparisons where appropriate *p*-values less than 0.05 were considered statistically significant. All analyses were done using the Statistic Package for the Social Science, version 12 (SPSS Inc., Chicago, IL).

The experiment was scheduled to raise the audience's motivation and insight into the topic. Since, additionally, the short exhibition to very weak light was not believed to leave any damages, an approval by an ethical committee was not provided.

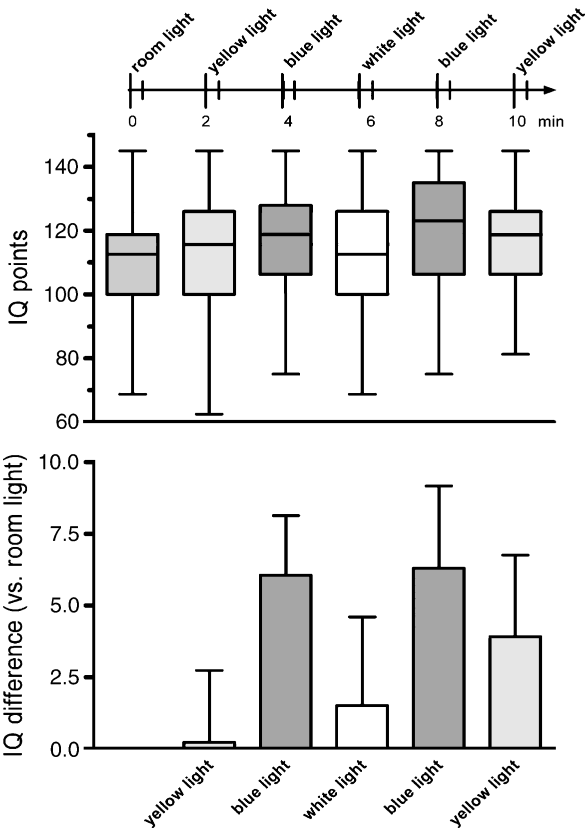

Fig. 1. Boxplots of fluid intelligence (IQ) with different modes of illumination. Below: Bar graphs and mean quartiles of IQ differences compared to room light. Different modes of illumination (changed every 2 min): room light (0″–20″), yellow light (580 nm; 2′0″–2′20″), blue light (455 nm; 4′0″–4′20″), white light (6′0″–6′20″), blue light (8′0″–8′20″) and finally yellow light (10′0″–10′20″). Significantly increased IQ points under exposure with blue light, statistical details are summarized in the results section

Results

44 of 45 participants of the lecture agreed to participate in the study. In four cases, some data were missing. The remaining data was used for analysis. Age ranged from 17 to 79 years (median: 63.5 years); 17 (38.9%) of the participants were male.

Alertness was significantly higher when comparing blue light against yellow light. The median difference equalled 0.5 points on the alertness-scale (Table 1). Under the conditions of room light and yellow light, alertness was in the "relaxed" range and was elevated by blue light into the range of "full alertness" (Table 1).

To examine the possibility that there is a trend for the alertness to rise in any illumination case independent from color of light, we compared the first three illuminations (incl. room light) to the latter three conditions (incl. white light) by the Wilcoxon-test: $p = 0.966$. This result does not support the suggestion of a trend.

Analogous to alertness, C increased after switching from yellow to blue light (+3.3%) corresponding to an increase of about 5 IQ-points (Fig. 1).

Changes in C and alertness were significantly correlated (Spearman's rho = 0.34, $p = 0.016$; 1-sided). Examining only those cases, that were not already "fully alerted" under yellow light, the correlation was even stronger (Spearman's rho = 0.50; $n = 26$; $p = 0.004$; 1-sided).

We found no association between age and changes in C or alertness, neither for all grades of alertness, nor analyzing the cases with low baseline alertness only. Gender was correlated with alertness but not with C, showing a tendency of men for higher increase in alertness under blue light condition (rho = 0.36; $n = 42$; $p = 0.019$).

Discussion

To our knowledge, this is the first report showing an increase of alertness combined with an enhanced speed of information processing after blue light but not after yellow light exposure. Both, alertness and speed of information processing are important determinants of fluid intelligence whereby this type of intelligence is active when the central nervous system (CNS) is at its physiological peak. Thus, the present results hint to linkage between blue light exposure and cognitive performance.

These findings are in line with recent studies showing that exposure to short-wavelength (blue) light was associated with lower subjective sleepiness and ability to sustain attention (Lockley et al., 2006).

It is well known that light exposure is associated with acute physiological and alerting effects in humans. For example, it has been indicated that this sensitivity of the human alerting response to light and its thermoregulatory sequelae are blue-shifted relative to the three-cone visual photopic system (Cajochen et al., 2005). Ocular photoreceptors with a peak sensitivity around 460 nm have been found to regulate circadian rhythm function which was associated with melatonin suppression and phase shifting. Furthermore, no suppression of melatonin occurred by light exposure when the eyes are covered (Czeisler et al., 1995). Melatonin has sleep-improving effects and reduces alertness (Gubin et al., 2006). Thus, it is feasible that a blue light induced decrease of melatonin is associated with an enhanced alertness and its associated improvement of speed of information processing.

Although in the literature blue light is predominantly associated with a decrease of melatonin. Its levels seem to change in a time frame of many minutes or hours and not in the range of seconds that have been investigated here. Therefore, we believe that different transmitters have to be considered to explain our results. Conceivable are dopamine and nor-epinephrine. In-depth-going analyses have to be undertaken elsewhere.

Remarkable is the high IQ of the subjects. It may be caused by the interests for the demanding lessons in the milieu of the university, and by the intellectually elevated population of Erlangen in which more than the half of the employees have university exams (Siemens research laboratories and university are the predominating employers). Could the results differ in less highly gifted persons? There is no theoretical indication of less validity on other levels of intelligence. The post hoc analysis of the data confirms this hypothesis because the level of IQ, measured under room light at the beginning of the experiment does neither monotonically correlate (Spearman rank) with the difference of alertness ($\rho = 0.12$; $p = 0.487$, 2-sided) nor speed of information processing ($\rho = 0.06$; $p = 0.707$, 2-sided) under blue compared to yellow light.

In general, we postulate that blue light is beneficial for learning processes, especially in male individuals who are known to have a lower grade of alertness (Eysenck and Eysenck, 1985).

Further controlled studies including the measurement of biological markers (i.e. dopamine, nor-epinephrine, and melatonin levels) and possible side effects of prolonged blue light exposure (i.e. macula alteration) are needed to verify these initial findings.

In the given study a subjective scale for alertness, that had been developed in close relation to EEG-parameters (Haider, 1969), has been selected because of its practicability. The here presented results confirm its validity. Nevertheless, more objective markers for alertness, however, may be considered in future studies.

Acknowledgement

We gratefully acknowledge the technical support by Katrin Kokocinski (Haus der Gesundheit, Erlangen) and Elektro-Schröpf Company (Erlangen).

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