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Research report

Shining light on memory: Effects of bright light on working memory performance

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HIGHLIGHTS

- We discuss a neurobehavioural view on non-image forming performance effects of light.
- Based on this view, we examined whether these effects depend on task difficulty.
- Illuminance level differentially affected easy vs. difficult digit-span performance.
- In the afternoon, bright light led to worse performance on two relatively difficult tasks.
- Bright light improved performance on the easier digit-span task in the afternoon.

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ABSTRACT

This study examined whether diurnal non-image forming (NIF) effects of illuminance level on cognitive task performance depend on task difficulty and time of day. We employed a balanced crossover design with two 60-min sessions of 200 vs. 1000 lux at eye level. Digit-span task difficulty was manipulated within subjects (forward (FDST) vs. backward (BDST) digit-span task), *n*-back task difficulty was manipulated between subjects ($n = 1$, 2, or 3). Bright light exposure improved FDST performance during the final measurement block, especially in the afternoon. In contrast, BDST performance deteriorated slightly under bright light in the afternoon. Two-back performance was significantly worse under bright light in the afternoon, while no effect of illuminance level was found on 3-back performance. Thus, the more difficult BDST was affected differently by light intensity as compared to the easier FDST. *N*-back accuracy, however, did not confirm this role of task difficulty. Future studies should investigate whether similar results hold for other types of tasks and how other variables (e.g., time of day, physiological arousal, or other task characteristics) may influence the direction and magnitude of NIF effects on performance.

1. Introduction

Via the non-image-forming (NIF) pathway, light can affect the circadian rhythm and induce acute alerting and activating effects throughout the 24-h day [1,2]. It is now well established that a third class of retinal photoreceptors, the so-called intrinsically photosensitive retinal ganglion cells (ipRGCs), are primarily responsible for these NIF effects of light [3–5]. A substantial amount of research has shown that high (as compared to low) illuminance levels can exert acute physiological as well as subjective alerting effects during the biological night [6–11] and day [10–14]. These acute alerting effects of bright light sometimes, but not always, translate into enhanced sustained attention and cognitive performance abilities [6,10–13,15,16]. On occasion even performance undermining effects are reported (e.g., [16]). The mechanisms that may explain these inconsistent effects of illuminance level on task performance are still unknown. Yet, if we aim to optimize cognitive performance through light intensity, it is essential to better understand these processes. Therefore, the focus of the current study was to further investigate the effects of illuminance level on cognitive task performance.

1.1. Cognitive performance under bright vs. dim light

During the biological night, exposure to bright light – as compared to dim light – either improves sustained attention and cognitive abilities, or leaves them unaffected [6,11,15,17–20]. For

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example, neither Campbell et al. nor Kretschmer et al. found an effect of bright vs. dim light on sustained attention, but they did report improvements on working memory and arithmetic abilities [15] as well as on logical reasoning [18]. In contrast, Boyce et al. did not find improvements on logical reasoning abilities but did report improvements on digit recall and grammatical reasoning [17]. Overall, no consistent pattern of bright light effects on task performance can be found in these studies. However, it should be noted that the lighting characteristics (such as illuminance level and correlated colour temperature (CCT)) as well as the timing and duration of the light exposure are quite different from one study to the other. This may partly explain why light exposure sometimes does, and at other times does not show positive effects on cognitive performance.

Fewer studies have focused on NIF effects of light on cognitive performance during the biological day. Those that have, however, revealed even more contrasting results, including not only positive and null effects, but also negative ones [11–14,16,21,22] Although Smolders et al. [13,16] and Phipps-Nelson et al. [12] reported improvements on sustained attention under bright light, results on a task requiring visual scanning revealed mixed effects and results on working memory and inhibitory abilities even showed performance-undermining effects of bright vs. dim light exposure [13,16]. Rüger et al. [11], on the other hand, showed performance improvements under bright light on visual search and arithmetic abilities, but no improvements on sustained attention. Again it should be noted that light exposure characteristics differed substantially between studies. In addition, subjects were light and/or sleep deprived prior to the light manipulation in the studies of Phipps-Nelson et al. [12] and Rüger et al. [11], which may have influenced subsequent effects of light exposure on cognitive task performance.

All in all, it can be concluded that the collective results of studies examining the NIF effects of light intensity on cognitive task performance are quite equivocal. Possible explanations for these contrasting findings may be partly found in differences in lighting characteristics (e.g., illuminance level or CCT) or timing characteristics (timing and duration of the light exposure) (see [1] for a review). However, there are also studies reporting differential effects of illuminance level on task performance within one study paradigm [6,11,16,17,21]. In these studies, various tasks were performed under the same light manipulation, but differences in the direction and magnitude of NIF effects of light on cognitive performance were found. These results suggest that task characteristics may play an important role in the effect illuminance level on cognitive performance.

1.2. Mechanisms underlying daytime performance effects

Recent neuroimaging studies provide evidence for mechanisms that may explain diurnal acute alerting effects of light, as well as light's differential effects on cognitive task performance [14,23,24]. These studies indicate that bright and/or monochromatic blue light exposure modulates activation of brain areas related to alertness and regulation of physiological arousal levels. More specifically, these results revealed light-induced activation in subcortical brain areas related to bodily arousal regulation such as the thalamus and the locus coeruleus (LC) [14,25]. Activation of the LC may in turn affect bodily state arousal levels via changes in the noradrenergic system [26]. These changes in arousal level have been found to influence task performance as described by The Yerkes–Dodson Law (YDL) [27]. The YDL explains that the relationship between arousal levels and task performance may be moderated by task difficulty. It suggests that for easier tasks (i.e. tasks needing only focused attention on a restricted range of stimuli), performance improves with increasing arousal levels in a dose-dependent manner following a logistic function. However, for more difficult tasks (i.e. tasks requiring divided attention (multitasking) and/or higher executive functions) an inverted U-shape relationship between performance and arousal was found. This relationship showed lower performance levels under low (i.e. when a person feels sleepy, drowsy and/or bored) and high (i.e. when a person is stressed or anxious) arousal levels, and optimal performance levels under intermediate arousal levels.

In this line of reasoning, previous research revealed that, as compared to relatively low illuminance levels (≤500 lux at eye level), high illuminance levels (≥1000 lux at eye level) increase physiological arousal levels as measured by heart rate, skin conductance and muscle sympathetic nerve activity [10,28,29]. Therefore, it is possible that acute light-induced activation of the brainstem (especially the LC) affects cognitive performance via changes physiological arousal levels. However, although the YDL is commonly accepted and empirical support for the YDL does exist [30–33], it is also criticized on methodological issues in the original study as well in later studies replicating the YDL. Points of discussion are the precise conceptualization of arousal and how to properly change physiological arousal levels in human subjects [34–37]. Therefore, it can only be speculated that illuminance level affects cognitive performance in a task-dependent manner by changing arousal levels.

The studies of Vandewalle et al. [24] also revealed light-induced brain activation in cortical areas related to attention regulation such as the dorsolateral prefrontal cortex, the intraparietal sulcus (IPS) and the superior parietal lobe [14,23,38]. Moreover, they found light-induced activation in cortical areas related to higher executive functioning and working memory abilities such as the IPS, the middle frontal gyrus and the supramarginal gyrus [25,38]. These increases in brain activation under bright and blue light were found during performance on a working memory task. However, although changes in brain activation in regions related to arousal and cognitive functioning were observed, these studies did not reveal differences in participants' actual cognitive performance abilities under the different lighting conditions. It therefore remains unclear whether light-induced brain modulation may (partly) explain differences in performance under different lighting conditions. A limitation of these neuroimaging studies is that the light exposure duration was relatively short (maximum of 20 min). Vandewalle et al. [24] hypothesized that modulation of brain networks may temporarily enhance cognitive performance when the duration of the light exposure period is extended. Obviously, additional studies employing longer light exposure durations are needed to investigate whether changes in brain activation can explain light-induced changes in cognitive performance.

1.3. The current study

It can be concluded that there is considerable evidence that illuminance level can exert acute NIF effects on alertness and performance during the biological day. However, findings regarding NIF effects of light on cognitive task performance are quite inconclusive and the underlying mechanisms through which these effects are manifested are largely unknown. As explained previously, the effect of physiological arousal on task performance may be moderated by task difficulty. Because bright light exposure has been found to enhance physiological arousal levels [10,28,29], optimal light exposure for cognitive task performance may depend on task difficulty. That is, optimal performance levels for more challenging tasks are expected to occur at lower illuminance levels (lower physiological arousal) as compared to optimal performance levels for easier tasks. In order to investigate this hypothesis, we compared cognitive performance under two illuminance levels (200 and 1000 lux at eye level) on two working memory tasks, which were manipulated in difficulty level. In addition to task