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Acute sleep loss induces signs of visual discomfort in young men

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Abstract

Acute sleep loss influences visual processes in humans, such as recognizing facial emotions. However, to the best of our knowledge, no study till date has examined whether acute sleep loss alters visual comfort when looking at images. One image statistic that can be used to investigate the level of visual comfort experienced under visual encoding is the slope of the amplitude spectrum, also referred to as the slope constant. The slope constant describes the spatial distribution of pixel intensities and deviations from the natural slope constant can induce visual discomfort. In the present counterbalanced crossover design study, 11 young men with normal or corrected-to-normal vision participated in two experimental conditions: one night of sleep loss and one night of sleep. In the morning after each intervention, subjects performed a computerized psychophysics task. Specifically, they were required to adjust the slope constant of images depicting natural landscapes and close-ups with a randomly chosen initial slope constant until they perceived each image as most natural looking. Subjects also rated the pleasantness of each selected image. Our analysis showed that following sleep loss, higher slope constants were perceived as most natural looking when viewing images of natural landscapes. Images with a higher slope constant are generally perceived as blurrier. The selected images were also rated as less pleasant after sleep loss. No such differences between the experimental conditions were noted for images of close-ups. The results suggest that sleep loss induces signs of visual discomfort in young men. Possible implications of these findings are discussed.

KEYWORDS
aesthetical pleasantness, amplitude spectrum, natural scene statistics, psychophysics, total sleep deprivation

1 | INTRODUCTION

The average duration of sleep in the Western world has decreased over the last 50 years (Bixler, 2009), with many adults today not managing to sleep the minimum recommendation of 7 hr per day (Watson et al., 2015). Although chronic sleep loss has been shown to be harmful to well-being (Åkerstedt et al., 2018; Gallicchio & Kalesan, 2009), there is growing evidence that even acute episodes of sleep loss can worsen health and performance, including impaired cognitive functioning (Cedernaes et al., 2015; Krause et al., 2017; Lim &

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Dinges, 2010; Rångtell et al., 2019; Yoo, Hu, Gujar, Jolesz, & Walker, 2007). In recent years, evidence has emerged to suggest that acute sleep loss may also compromise visual functions, including difficulty in recognizing facial emotions (Van Der Helm, Gujar, & Walker, 2010), reduced visual task performance (Jackson et al., 2008) and impaired visuospatial perception (Killgore, 2010). However, no study to date has examined whether human subjects perceive images as more or less aesthetically pleasing and comfortable when experiencing sleep loss. This is an important area of research, as it could suggest that sleep debt – from an aesthetical perspective – may modulate the way we see the world. To fill this gap, the present within-subject, counterbalanced crossover study recruited 11 young men with normal or corrected-to-normal vision. Subjects participated in two conditions: one night of sleep loss and one night of sleep. In the morning after each night, subjects were presented a set of images with a randomly chosen initial slope constant on a computer. Specifically, we examined whether the slope constants of the amplitude spectrum and the perceived pleasantness of natural scenes and close-ups differed between the two sleep conditions.

During the last few decades, the use of image statistics has attracted researchers from many different fields (Azzopardi & Petkov, 2012; Clark et al., 2014; Graham, Schwarz, Chatterjee, & Leder, 2016; Isherwood, Schira, & Spehar, 2017; Simoncelli & Olshausen, 2001). Image statistics are useful as they provide a method for quantifying photographs of natural and manmade scenes, thereby providing tools for understanding the link between the environment and the design of biological visual systems (Barlow, 2001). Image statistics can thus be used for defining the sensory input that is essential for performing a specific visual task and to apply this knowledge under more controlled conditions in the laboratory when performing electrophysiological or behavioural experiments (Fitzgerald & Clark, 2015; Geisler, 2008; Leonhardt et al., 2016).

A common image statistic used to describe the visual environment is the amplitude spectrum, which describes the spatial distribution of pixel intensities (Tolhurst, Tadmor, & Chao, 1992; Torralba & Oliva, 2003). This follows a power law, so that when plotted on a log-log scale, there is a linear relationship between the average amplitude spectrum (A) and the spatial frequency (f), of the following function:

$$A(f) = c / f^{\text{alpha}}$$

This relationship allows us to describe a large two-dimensional amplitude spectrum with a single value (alpha) referred to as the slope constant (Dyakova & Nordström, 2017; Field & Brady, 1997), facilitating comparisons between images (Graham & Field, 2007; Pouli, Cunningham, & Reinhard, 2011; Redies, Hasenstein, & Denzler, 2007; Tolhurst et al., 1992; Torralba & Oliva, 2003).

Artificially increasing the slope constant of an image leads to this being perceived as more blurry (Tadmor & Tolhurst, 1994). In addition, the distance between the camera and the object affects the slope constant, where, for example, close-up photos have higher slope constants than distant scenes (Torralba & Oliva, 2003). However, even among images obtained from similar distances, the slope constant may vary: photos of fields, clouds and coasts have higher slope constants, with more signatures in the lower spatial frequencies, whereas photos of mountains or forests have lower slope constants, with more signatures in the higher frequencies (Torralba & Oliva, 2003). Nevertheless, the slope constants across a range of natural scenes have been found to typically be close to 1–1.2 (Dyakova & Nordström, 2017; Tolhurst et al., 1992).

Based on previous findings suggesting that acute sleep loss modulates visual functions (e.g., Jackson et al., 2008; Killgore, 2010; Van Der Helm et al., 2010), we hypothesized that one night of sleep loss would alter the slope constants perceived as most natural. To investigate this hypothesis, we recruited 11 healthy young men for a counterbalanced crossover design study, with one night of sleep loss versus one night of sleep.

2 | MATERIALS AND METHODS

2.1 | Participants

Eleven men aged 20–25 years (mean ± *SEM*, 22.6 ± 0.5 years), with normal BMI (23.0 ± 0.77 kg/m^2) and normal or corrected-to-normal vision, were included in the present study. The participants reported no sleep disorders, and no nicotine, alcohol, drug or caffeine addiction. None of the participants was jet lagged, experienced shiftwork or had sleep deprivation during the month leading up to the experiment. All participants were scored as having intermediate, moderate morning or moderate evening chronotypes, with a mean (±*SEM*) score of 51.2 (±3.2) on the Morningness–Eveningness Questionnaire (MEQ, Horne & Ostberg, 1975). The study was conducted according to the Declaration of Helsinki, all participants provided written informed consent and the study was approved by the regional ethics office (Regionala etiksprövingsnämden, 2016/278).

2.2 | Experimental procedure

Each subject took part on two separate occasions, spaced apart on average by 5 days: one night of sleep loss versus one night of sleep. The two study nights were allocated using a counterbalanced crossover design (first session/second session: sleep/sleep loss and sleep loss/sleep; n = 6 and 5, respectively). In each experimental session, participants arrived at the laboratory between 20:00 and 21:00 hours to perform baseline tests. In the sleep condition, participants wore a wrist actigraphy monitor to measure their sleep at home (wActiSleep+, ActiGraph, LLC, Pensacola, FL). Subjects were instructed to remain fasting, with the exception of drinking water, and to be in bed approximately between 23:00 and 07:00 hours (actigraphy-estimated total sleep duration, mean ± *SEM*: 7 hr, 13.5 ± 15 min). Subjects returned to the laboratory the next morning. In the sleeploss condition, participants stayed in the laboratory. They were allowed to spend their time with a selection of movies, games and books and were continuously monitored by a female experimenter to ensure that they

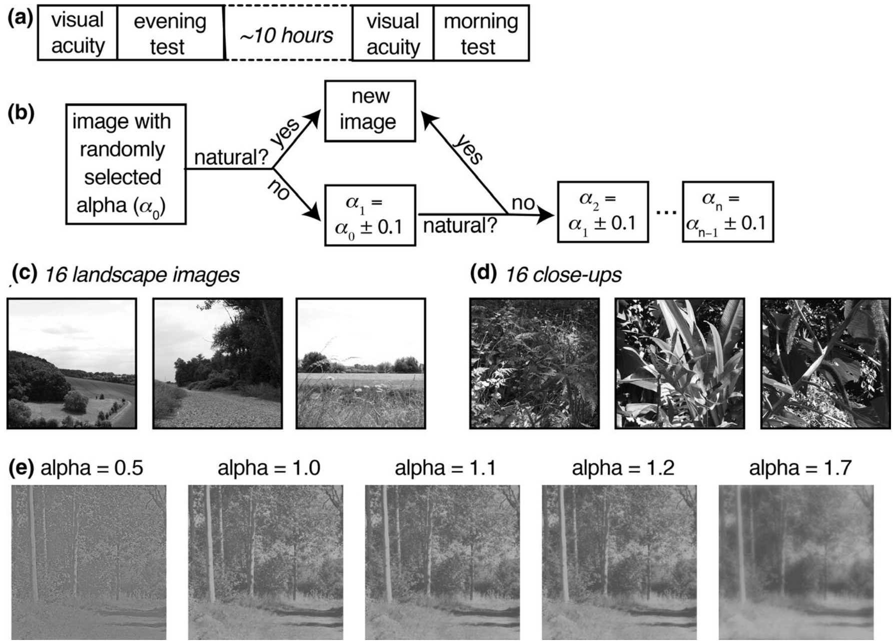

FIGURE 1 Experimental design. (a) Schematic overview of the experiments, with a visual acuity test and a psychophysics test in the evening and in the morning, with approximately 10 hours in between. During the 10 hours of the night, the participants were either kept awake under supervision or were asleep at home, monitored by using wrist actigraphy (~23:00–07:00 hours). (b) Schematic description of the psychophysics experiment. Each participant was shown a randomly selected image with a randomly selected slope constant. By pressing the right or left arrow on the keyboard, the image's slope constant increased or decreased in steps of 0.1. This continued until the most natural looking image was chosen. (c) Examples of images depicting natural scenes. The contrast and brightness of the images shown here are adjusted for display purposes. (d) Examples of the images depicting close-ups of natural objects. (e) Examples of a scene with manipulated slope constants (alpha as indicated)

remained awake (Chapman, Benedict, & Schioth, 2018). In order to account for the increased energy expenditure during the night, in the sleeploss condition, research participants were given a sandwich (~320 kcal) at ~02:00 hours (as in Greer, Goldstein, & Walker, 2013). Participants were allowed to drink water *ad libitum* but no caffeinated beverages.

In each of the experimental conditions, participants' perception of the slope constant (Figure 1, task description below) was measured in the evening, not later than 22:00 hours, and the following morning, approximately 10 hours later (Figure 1a). To test for peripheral effects such as oculomotor muscle fatigue, or lens accommodation issues, a visual acuity test was performed immediately before the evening session and immediately before the morning session (Figure 1a). All research participants had 20/20 vision.

2.3 | Psychophysics tests

Each subject was placed in a dark room in front of a linearized 13-inch monitor (Retina MacBookPro), with each image displayed in its centre, surrounded by a black background, at a viewing distance of ~30 cm, with no head or eye fixation. Subjects had unlimited time to observe each presented image, and the test lasted no longer than 45 min in total. The images were presented in a random order to each subject, and so was the initial slope constant (alpha) of each image. Note that the initial slope constant would most often lie outside the underlying slope constant of each image (i.e., before image manipulation). Subjects were instructed to press the left or right arrow on the keyboard until they perceived each image as most natural looking. The right arrow increased alpha by 0.1, up to a maximum of 1.7, and the left arrow decreased alpha by 0.1, down to a minimum of 0.5 (Figure 1b). Once subjects had chosen the slope constant that they perceived as most natural looking, they indicated the pleasantness of the "final" image on a visual analogue scale from 0 to 100, where 0 is absolutely unpleasant and 100 is extremely pleasant. Then, the next randomly selected image appeared, which initiated the next trial.

2.4 | Images

The participants were shown 32 images; 16 depicted natural landscape scenes (examples in Figure 1c) and 16 represented close-ups of natural objects (Figure 1d). The images were captured using a full-frame digital single-lens reflex Nikon D700 or Canon Ixus 230 HS camera. Each image was cropped to a 1024 × 1024 square and converted to greyscale using the Matlab function *rgb2grey* (Mathworks). To manipulate the slope constant, we used previously described approaches (Dyakova, Lee, Longden, Kiselev, & Nordström, 2015; Tadmor & Tolhurst, 1994; Tolhurst & Tadmor, 1997). Briefly, we first performed a two-dimensional Fourier transform and calculated the orientation-averaged amplitude as a function of spatial frequency. We next divided the Fourier-transformed image by its amplitude spectrum to get a flat one (i.e., where alpha = 0). By multiplying the result with the coefficient $(1+k*f^{-alpha})$, where k is a constant, we generated images with the desired alpha. Then, by performing an inverse Fourier transform, we recreated the images, but now with the selected alpha (examples in Figure 1e).

We generated manipulations of all images with slope constants between 0.5 and 1.7 in increments 0.1. We used *imadjust* (Matlab) to maximally increase the image contrast and next set the image RMS contrast to 0.1 and the mean brightness level (from 0 to 255) to 127. The RMS contrast was defined using the equation:

$$\text{Contrast} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \frac{1}{n-1}\sum_{i=1}^{n}x_i)^2},$$

where n is the number of pixels, x_i is the brightness level (from 0 to 255) of pixel i and x is the mean brightness of the image.

2.5 | Statistical analysis

All statistical analyses were performed in Prism version 7.0d (GraphPad Software, San Diego, CA, USA). The data in the text are given as mean ± *SEM*, unless otherwise stated. Significant differences between the two sleep conditions ($p < 0.05$) were investigated using Wilcoxon matched-pairs signed rank tests with Bonferroni correction for multiple comparisons. Bonferroni-corrected p-values are given in the text. Correlation was investigated using the Pearson correlation coefficient.

3 | RESULTS

3.1 | Acute sleep loss alters the slope constant of natural scenes but not close-ups

After a night of sleep loss, subjects selected higher slope constants for natural scenes than they did after a full night of sleep ($p = 0.0064$, Figure 2a). For images of close-ups, the slope constant chosen as looking most natural was similar to the one following sleep loss ($p = 0.96$, Figure 2b). Importantly, no differences in slope constants between the experimental conditions were observed at baseline (i.e., in the evening before the sleep intervention) (both $p = 1$, Figure 2c, d).

3.2 | Sleep loss reduces the visual comfort of viewing natural scenes but not close-ups

Natural scenes were perceived as less pleasant following sleep loss compared with a night of sleep (59.8 ± 1.8 versus 64.0 ± 1.6; $p = 0.0024$, Figure 3a). In contrast, no such difference in pleasantness was seen for close-ups (sleep loss versus sleep: 45.0 ± 1.7 versus 47.8 ± 2.0; $p = 0.74$, Figure 3b). Importantly, no differences in

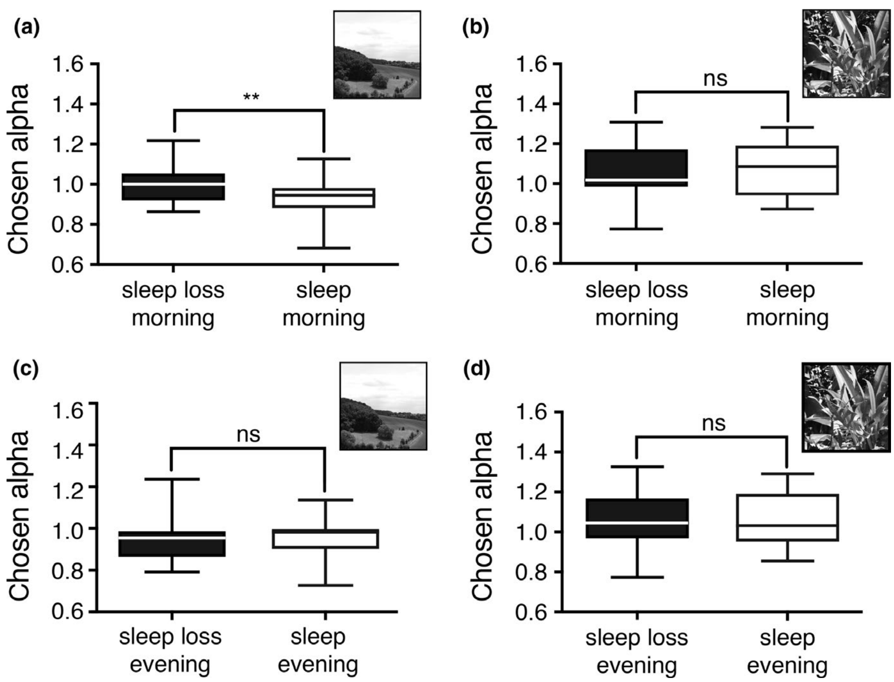

FIGURE 2 Acute sleep loss alters the slope constant of natural scenes. (a) Slope constant (alpha) chosen as most natural looking when viewing images of natural scenes after a night of sleep loss or a night of sleep. (b) Slope constant (alpha) chosen as most natural looking when viewing close-ups after a night of sleep loss or a night of sleep. (c) Slope constant chosen as most natural looking when viewing natural scenes at baseline (i.e., in the evening before each sleep intervention). (d) Slope constant chosen as most natural looking when viewing close-ups at baseline (i.e., in the evening before each sleep intervention). For each image, we averaged the slope constants chosen by each participant. In each panel, the central mark of each boxplot shows the median, the edges of the box the 25th–75th percentiles of the data, and the whiskers extend from the minimum to maximum of the data. **$p < 0.01$, ns = $p \geq 0.05$

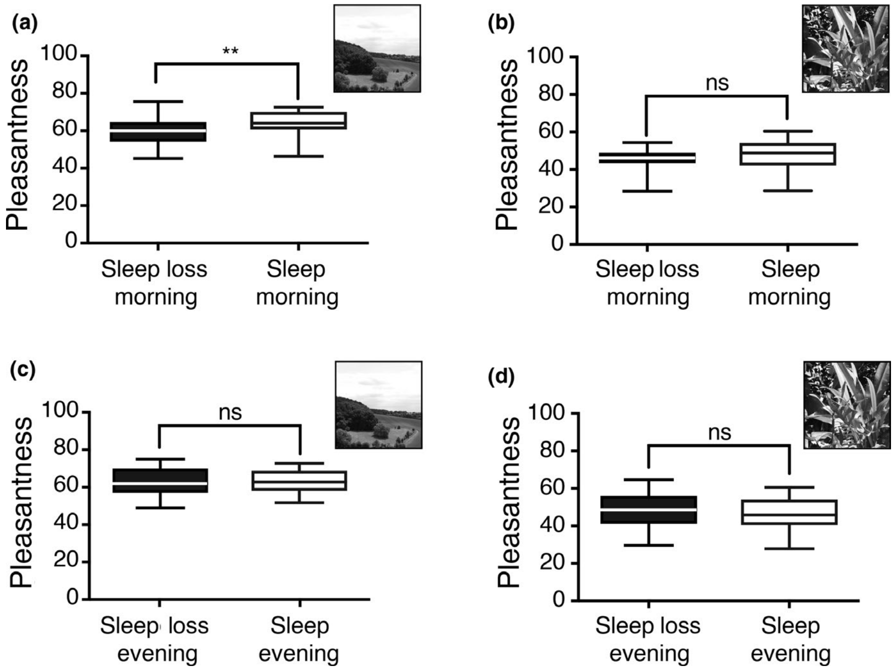

FIGURE 3 Sleep loss reduces the visual comfort of viewing natural scenes. (a) Subjective pleasantness for images of natural scenes following either a night of sleep loss or a night of sleep. Pleasantness was ranked on a scale from 0 to 100. (b) Subjective pleasantness for images of close-ups following sleep loss or sleep. (c) Subjective pleasantness for images of natural scenes at baseline (i.e., on the previous evening). (d) Subjective pleasantness for images of close-ups at baseline (i.e., on the previous evening). In all panels we show variations across images after averaging the results across participants, with the central mark of each boxplot showing the median, the edges of the box the 25th–75th percentiles of the data, and the whiskers extending from the minimum to maximum of the data. $^{**}p < 0.01$, ns = $p \geq 0.05$

pleasantness between the experimental conditions were observed at baseline (i.e., in the evening before the sleep intervention) ($p = 1$ and $p = 0.79$, respectively; Figure 3c, d).

3.3 | Correlational analysis

In the next step, we investigated the correlation between the slope constant ratio for natural scenes and pleasure rating ratio for natural scenes. The slope constant ratio was defined as the average slope constant in the sleep-loss condition divided by the average slope constant for the same individual in the sleep condition. The pleasure rating ratio was defined as the average pleasure rating score in the sleeploss condition divided by the average pleasure rating score in the sleep condition for the same individual. This analysis showed a weak correlation for natural scenes ($R^2 = 0.39$, $p = 0.04$; Figure 4a) but not for close-ups ($R^2 = 0.19$, $p = 0.18$; Figure 4b).

4 | DISCUSSION

The present counterbalanced crossover design psychophysics study examined whether a night of sleep loss, in contrast to a night with regular sleep, would alter the visual perception of images of natural scenes and close-ups by young men. To this aim, we measured the slope constant and assessed subjects' pleasantness when viewing the images. The slope constant describes the spatial distribution of pixel intensities (Tolhurst et al., 1992), and a slope constant within the natural range is perceived by both naïve and experienced human observers as more aesthetically pleasing and comfortable to view (Graham & Redies, 2010; O'hare & Hibbard, 2013; Redies, Brachmann, & Wagemans, 2017).

The main finding of our study was that acute sleep loss increased the slope constant of natural scenes (i.e., blurrier representations of distant landscapes were perceived as most natural looking) and lowered the visual comfort when viewing these images. These sleeploss-induced changes were also weakly correlated. In contrast, acute sleep loss neither affected the slope constant nor pleasure ratings of images of close-ups. Studies have shown that natural scenes regulate emotions in a positive way (Johnsen & Rydstedt, 2013; Joye & Bolderdijk, 2015). Indeed, one can improve people's directed-attention abilities and increase their positive emotions by placing them in a natural environment, or even simply making them view natural scenes (Berman, Jonides, & Kaplan, 2008; Berman et al., 2012; Nisbet & Zelenski, 2011). In addition, images with naturalistic slope constants are more pleasant to human observers (Graham & Field, 2007; O'hare & Hibbard, 2013; Redies et al., 2007). With all this in mind, an important area of future research is to investigate whether getting less pleasure from viewing natural scenes could play a role in the connection between long-term sleep loss and conditions hallmarked by anhedonia, such as depression (Bao et al., 2017; Fernandez-Mendoza

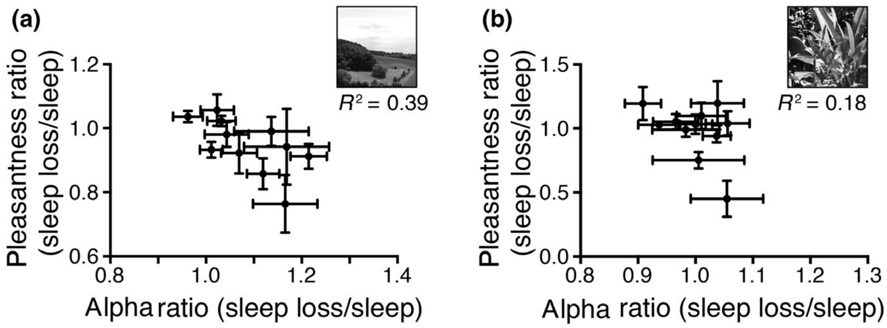

FIGURE 4 Correlation between the slope constant and perceived pleasantness. (a) The pleasantness ratio, defined as the ratio between the pleasantness chosen after a night of total sleep loss (TSD) and the pleasantness chosen after a night of sleep, as a function of the alpha ratio, defined as the ratio between the slope constant chosen after sleep loss and the slope constant chosen after sleep. For natural scenes, there was a weak correlation ($R^2 = 0.39$; $p < 0.05$). (b) The pleasantness ratio as a function of the alpha ratio when viewing close-ups ($R^2 = 0.19$; $p > 0.05$). In both panels we show variations across participants after averaging the results across images, with the data indicated as mean ± *SEM*

et al., 2015). Conversely, it could also be speculated that perceiving blurrier representations of natural scenes as more natural but less pleasant may underlie the change in creativity experienced by some artists when pulling an all-nighter, also referred to as insomnia creativity. In this context, it is worth mentioning that emotions, including negative ones, and art are strongly correlated (Palmer & Alfano, 2017; Silvia, 2005).

Another undesirable effect of experiencing lower visual comfort when viewing distant scenes under sleep loss conditions might be that humans are less motivated to switch attention to the variations in their visual environment. Of note, sleep-deprived subjects in driving simulators have reduced peripheral attention (Jackson et al., 2008) and reduced ability to process peripheral signals (Rogé, Pébayle, El Hannachi, & Muzet, 2003). Gaze orientation, which reflects attention, is also affected by sleep deprivation, being less synchronised and slower (Tong et al., 2016). This is important because selective attention gives us the ability to focus on a particular part of the visual surround. After sleep deprivation, there is thus not only a reduced suppression of irrelevant information (Poh & Chee, 2017), but also a negative effect on selective attention, likely to be caused by a reduction in top-down biasing of information processing in the sensory cortex (Chuah & Chee, 2008; Tomasi et al., 2009). Attention deficits are particularly serious when considering real-world errors (Dinges, 1995) because attention facilitates perception (Ungerleider, 2000).

Several limitations apply to our study. Our study should be seen as a pilot study, as it is based on a small sample of young men. Hence, our main findings must be followed-up by studies with large samples, including women as well as subjects of other ages. It is also unclear whether the observed effects of acute sleep loss on the slope constant and pleasure rating of images of natural scenes would be seen at later time-points in the day. Moreover, no conclusions can be drawn regarding the extent to which other types of sleep problems, such as sleep apnea, partial sleep loss and mistimed sleep, may affect measures of visual comfort. Notwithstanding these limitations, our study is the first to suggest that a single night of sleep loss is sufficient to alter aesthetical aspects of natural scenes. Importantly, the observation that sleep loss altered the slope constant of images of landscapes but not close-ups suggests that our findings are unlikely to be a result of oculomotor muscle fatigue or an inability of the lens to focus because of sleep loss. Also, pleasantness ratings for the close-ups were not affected by sleep loss, indicating that a general lowering in mood is not what is driving the effect of a perceived lower pleasantness for the natural scenes. Rather, the changes in visual perception driven by sleep loss seem to be specific to the type of image, in this case landscapes. In line with this, it has, for instance, been shown that sleep loss increases the brain reward response when viewing images of food in a functional magnetic resonance imaging setting (e.g., Benedict et al., 2012). This specificity in brain response to different types of visual scenes after sleep loss may be mediated by the physiological consequences of sleep loss; for example, the body is trying to compensate by reallocating the use of energy in order to cope with a higher metabolic stress.

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CONFLICT OF INTEREST

The authors are unaware of any affiliation, funding or financial holdings that might be perceived as affecting the objectivity of this manuscript. The authors declare that there is no biomedical financial interest or potential conflict of interest.

AUTHOR CONTRIBUTIONS

All authors designed the study; OD and KN wrote the protocol; OD collected the data; OD and KN conducted the analyses. All authors interpreted the data and all authors contributed to writing. All authors have approved the final manuscript.

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