Bright light exposure during simulated night work improves cognitive flexibility

Erlend Sunde[a]*, Jelena Mrdalj[b], Torhild T. Pedersen[b], Bjørn Bjorvatn[c,d], Janne Grønli[b], Anette Harris[a], Siri Waage[a,d] and Ståle Pallesen[a,e]

[a]Department of Psychosocial Science, University of Bergen, Bergen, Norway; [b]Department of Biological and Medical Psychology, University of Bergen, Bergen, Norway; [c]Department of Global Public Health and Primary Care, University of Bergen, Bergen, Norway; [d]Norwegian Competence Center for Sleep Disorders, Haukeland University Hospital, Bergen, Norway; [e]Optentia Research Focus Arena, North-West University, Vanderbijlpark, South Africa

*Corresponding author: erlend.sunde@uib.no; Department of Psychosocial Science, University of Bergen, Christies gt. 12, 5015 Bergen, Norway

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Night work leads to sleepiness and reduced vigilant attention during work hours, and bright light interventions may reduce such effects. It is also known that total sleep deprivation impairs cognitive flexibility as measured by reversal learning tasks. Whether night work impairs reversal learning task performance or if bright light can mitigate reversal learning deficits during night work, is unclear. In this counterbalanced crossover study (ClinicaTrials.gov Identifier NCT03203538), young healthy individuals completed a reversal learning task twice during each of three consecutive simulated night shifts (23:00–07:00 h). The night shifts were performed in a laboratory under a full-spectrum (4000 K) bright light (~ 900 lx) and a standard light (~ 90 lx) condition. Reversal learning task performance was reduced towards the end of the night shifts (04:50 h), compared to the first part of the night shifts (00:20 h) in both light conditions. However, with bright light the reversal learning task performance improved towards the end of the night shifts, compared to standard light. The study shows that bright light may mitigate performance deficits on a reversal learning task during night work and implies that bright light interventions during night work may be beneficial not only for vigilant attention, but also for cognitive flexibility.

Keywords: cognitive control; decision making; reversal learning; working memory; task switch; sleep deprivation; light emitting diode; LED

Word count: 7245

Introduction

Night work is associated with sleepiness and impaired vigilant attention during work hours (Ganesan et al. 2019). These effects likely reflect circadian misalignment, i.e., work hours being in conflict with the workers' endogenous circadian rhythm (Åkerstedt 2003), and prolonged time awake especially on the first night shift (Santhi et al. 2007). The negative effects of night work and sleep deprivation/sleep loss on cognitive performance have been consistently shown on psychomotor vigilance tasks (PVTs), in terms of slowing of responses and increases in attentional lapses (Ganesan et al. 2019; Lim and Dinges 2008; Sunde et al. 2020). Notably, sleep deprivation differentially impacts cognitive tasks (Jackson et al. 2013). Complex cognitive tasks that require higher "executive" functions have been reported to be especially vulnerable to sleep loss (Harrison and Horne 2000; Jones and Harrison 2001; Satterfield and Killgore 2019). Still, the evidence of impaired performance on more complex tasks following sleep loss is less documented compared to more simple tasks (Lim and Dinges 2010).

Reversal learning tasks capture aspects of cognitive control, a feature of executive functions (Satterfield and Killgore 2019), and include elements similar to those present in many real-life settings. Here, decisions must be taken under time pressure as subjects have to quickly decide whether to respond or inhibit a response to stimuli. Moreover, the task requires cognitive flexibility as the subjects can adjust and update their behavioral choices based on feedback (Honn et al. 2019; Whitney et al. 2015). Studies show that sleep deprivation impairs performance on reversal learning tasks (Honn et al. 2019; Satterfield et al. 2018; Whitney et al. 2015). Particularly, after 55 h of wakefulness the ability to adapt to reversal of contingencies is impaired and salience of feedback to behavioral outcomes is reduced, i.e., "feedback blunting" (Whitney et al. 2015). Importantly, the impaired performance on reversal learning tasks seems to be related to problems with dynamic/flexible attentional control, which is diminished during sleep deprivation (Whitney et al. 2017), rather than the vigilant attention deficits evident during sleep deprivation (Honn et al. 2019; Lawrence-Sidebottom et al. 2020; Whitney et al. 2015). As night work normally implies sleep deprivation, it is thus important to investigate how to mitigate these effects during night work.

Bright light exposure has the potential to reduce the negative impacts of night work on cognitive performance, including vigilant attention, cognitive throughput (e.g., number of math calculations during 4 min) and logical reasoning (Campbell and Dawson 1990; Czeisler et al. 1990; Sunde et al. 2020). The favorable effects of light exposure can be attributed to improved circadian adaptation (Horowitz et al. 2001), as well as acute alerting responses (Cajochen 2007). These non-visual effects of light stem from a subset of intrinsically photosensitive retinal ganglion cells (ipRGCs), that convey signals to brain areas regulating circadian rhythms, as well as various brain regions involved in alertness and cognition (Vandewalle et al. 2009). Furthermore, light exposure is particularly potent when individuals perform tasks under high homeostatic and circadian sleep pressure (Vandewalle et al. 2011). While bright light exposure may be beneficial for some elements of night workers' cognitive performance, the impact of light exposure during night work on cognitive flexibility and reversal learning have not yet been considered.

With the development of light emitting diode (LED) technology, new opportunities for using light exposure as a cost-effective countermeasure against negative effects of shift work have emerged. In a recent study, a full-spectrum (4000 K) LED-based bright light (~ 900 lx) intervention, compared to a standard light (~ 90 lx), reduced subjective sleepiness and vigilant attention deficits (assessed by PVT) during simulated night work (Sunde et al. 2020). As expected, both slowing of responses and increase in attentional lapses were less pronounced during night shifts in bright light.

The present study aims to address whether the beneficial effects of the bright light intervention on vigilant attention during simulated night shifts, pertain also to cognitive flexibility using a reversal learning task. Further, the study investigates the effects of the bright light intervention on two complementary measures, a working memory (WM) scanning task and a task switching test. The WM scanning task allows for assessment of the ability to encode and maintain relevant information. Previously, it has been shown that 51 h of wakefulness led to less information being encoded, but not to impaired ability to maintain and search encoded information (Whitney et al. 2015). The task switching test involves executive control processes, and is considered as a measure of the ability to rapidly adjust behavior to changing environmental demands, which normally is reduced during sleep deprivation (Couyoumdjian et al. 2010).

It was hypothesized that three consecutive simulated night shifts in full-spectrum (4000 K) LED-based bright light (~ 900 lx), compared to a standard light (~ 90 lx), would improve performance on the reversal learning task, the WM scanning task and the task switching test.

Materials and methods

Participants and study design

Twenty-six participants (19–27 y of age; 20 females) completed the study. Participants were screened prior to enrollment and reported good health; normal vision; habitual sleep duration between 6–10 h daily; waking up between 06:00–10:00 h; no shift work or trans meridian travel during one month prior to the study; and were neither extreme morning nor extreme evening types (Adan and Almirall 1991). Female participants were not pregnant or breastfeeding. For one participant data from the last night shift was excluded due to illness, and one participant’s data from the whole second study period (three night shifts) was excluded due to sleep problems prior to the night shifts. The sample size follows recommendations, based on power analysis, for studies investigating alerting effects of light (Souman et al. 2018).

A counterbalanced crossover study design was used. The participants performed three consecutive simulated night shifts (23:00–07:00 h) in a laboratory under a full-spectrum (4000 K) bright light (photopic illuminance: ~ 900 lx; photon density: ~ 7.5 x 10^{14} photons/cm^2/s, reduced to ~ 200 lx from 05:00 h) and a standard light (photopic illuminance: ~ 90 lx; photon density: ~ 7.5 x 10^{13} photons/cm^2/s). Standard ceiling mounted LED-based luminaires were used, and the light characteristics were measured at each of eight similar workplaces, at eye level (vertical) while seated. About half of the participants started with bright light and the other half started with standard light. The two study periods were separated by 4 weeks. Participants went home to sleep ad libitum after the night shifts and had no restrictions concerning activities, including light exposure, during their spare time. However, the study was commenced at a high latitude where time of year (September to February) limited daylight exposure when commuting home after the night shifts. Thus, this laboratory study was conducted as a naturalistic night work experiment.

Three days prior to the first night shift, in the afternoon, an enrollment session at the laboratory was commenced. This included practice of the cognitive tests (each test practiced once) administered during the night shifts, ensuring familiarization with the procedures and tests, hence reducing aptitude and practice effects. Practice of tests was only performed before the first study period. Participants' sleep was monitored and verified by wrist actigraphy for three days prior to the night shifts. The sleep patterns prior to the night shifts were similar for the first and second study period, with a mean (SD) duration of sleep episodes of 480 min (82 min) and 480 min (93 min), respectively. The mean (SD) "out of bed"/rise times were 8:35 h (1:13 h) and 8:40 h (1:25 h), respectively. Still, there were some individual differences in the rise times before the first and second study period, as six participants' rise time was > 30 min later and five participants' rise time was > 30 min earlier, at the second study period compared to the first. More details about the study design, laboratory, light conditions, and procedures have been reported previously (Sunde et al. 2020).

Two test sessions were performed during each night shift. Session 1, in the first part of the night shift, started with the WM scanning task at 00:10 h, followed by the reversal learning task at 00:20 h and the task switching test at 00:40 h. The WM scanning task took around 8 min to complete, whereas the reversal learning task and the task switching test both had a duration of approximately 6 min. Thus, participants had short breaks between the tests to prepare and get ready for the next. Session 2, towards the end of the night shift, started with the WM scanning task at 04:40 h, the reversal learning task at 04:50 h and the task switching test at 05:10 h. The tests were administered on a desktop computer with stimuli appearing in the center of the screen. Up to eight participants were present in the laboratory at the same time, each designated to a fixed workplace/desk. The workplaces were separated by partition walls that reduced disturbance during test sessions. In addition, participants used noise cancelling headsets (BOSE QuietComfort 25, BOSE corp., USA) during testing, and were instructed to remain quiet and seated until all had completed the tests, as indicated by the researcher. A researcher was present in the laboratory during the night shifts to ensure that the protocol was followed.

The study was approved by the Norwegian Regional Committee for Medical and Health Research Ethics (No. 2016/1903), and all participants provided written informed consent. The study was preregistered with ClinicaTrials.gov Identifier NCT03203538.

[Figure 1 near here]

Reversal learning task

The reversal learning task (Figure 1A) is basically a *go/no-go* task where subjects are instructed to respond to stimuli they identify as *go* stimuli and inhibit responses to stimuli they identify as *no-go*. The feedback provided during the test allows subjects to learn which stimuli are in the *go* and the *no-go* sets. Stimuli were presented in trial blocks with eight two-digit numbers in a randomized order. Four of the stimuli were assigned to the *go* set, and four were assigned to the *no-go* set. After presentation of a stimulus, subjects had a 750 ms window in which they had to decide to respond (by pressing the space bar) or withhold their response. Accuracy feedback ("Correct!" or "Wrong!"), including hypothetical monetary reward ("+50 NOK") or punishment ("-50 NOK"), lasted 2500 ms after each trial. The temporary reward balance (e.g., "Sum = 750 NOK") was also included in the feedback. After 48 or 56 trials (i.e., six or seven trial blocks), the stimulus-response sets were reversed without warning. Based on the feedback, subjects had to update their response sets during the following 40 trials (5 trial blocks) in the post-reversal phase (Whitney et al. 2015). As the task was administered repeatedly, several unique versions with different stimuli (two-digit numbers) sets were used, ensuring that participants did not recall the *go* or *no-go* stimulus-response sets from previous administrations.

For both the pre- and post-reversal phase, the hit rate and false alarm rate were calculated in total, and for each trial block. The hit rate, or fraction of hits, reflects the probability of responding to *go* stimuli, while the false alarm rate comprises the probability of responding to *no-go* stimuli. Based on the hit rates and false alarm rates, calculation of discriminability (*d'*) and criterion (*c*) values were made, in accordance with signal detection theory (Stanislaw and Todorov 1999). The *d'* value provides a measure of the subjects' ability to discriminate between the *go* and the *no-go* stimuli, whereas the *c* value is a measure of response bias (Stanislaw and Todorov 1999). Both pre- and post-reversal *d'* and *c* were used as dependent variables in the main analyses.

Working memory (WM) scanning task

The WM scanning task (Figure 1B) was based on a test used in a previous sleep deprivation study (Whitney et al. 2015). The stimuli set in the WM scanning task consisted of 156 nouns drawn from the lexical database “Norwegian Words” (Lind et al. 2015). The word length was between three and seven letters with the frequency of use, and the imageability (how easily the word triggers a mental sensory image), categorized as medium to high (Lind et al. 2015). Three different stimuli set with unique words were used to reduce re-using of words. The test consisted of three blocks with 24 trials in each block (i.e., 72 trials in total). Each trial began with a start-of-set signal (“##start##”), followed by a memory set of six words, presented serially for 500 ms each, before an end-of-set signal (“##end##”) appeared. After the end-of-set signal, a probe word was presented, with half of the probe items coming from the memory set. Thus, there were six positive probe items for each of the serial positions (i.e., the position of the probe item within the memory set). The order of words and the valence (positive or negative trials) of the trials, was randomized. Subjects were instructed to respond as quickly and accurately as possible by pressing “1” if the probe item was part of the memory set, and “2” if the probe item was not part memory set. The probe item was presented for 5000 ms, or until a response was provided, followed by feedback (“Correct!” or “Wrong”) lasting 1500 ms. If no response was registered within 5000 ms, “No response registered” was provided as feedback, accompanied by a sound to alert the subject before the next trial. The mean accuracy proportion and mean response time (RT) were calculated for negative trials (i.e., the probe item was not part of the memory set) and for each serial position (positive trials), with the accuracy and RTs for positive trials used as dependent variables in the main analyses.

Task switching test

The task switching test (Figure 1C) was designed using a “task-cueing procedure”, similar to the switching tasks used in a previous sleep deprivation study (Couyoumdjian et al. 2010), and in a study assessing effects of napping and bright light in the afternoon (Kaida et al. 2013). Each trial started with a blank screen for 300 ms, followed by a cue, either a diamond (Task A) or a square (Task B), for 500 ms. Based on the cue, the task was to distinguish between odd and even numbers (Task A), or identify if the stimulus was a number higher or lower than 5 (Task B). The stimulus, a number from 1–9 (excluding 5), appeared in the middle of the cue for 5000 ms or until a response was made. The cue remained on the screen until completion of the trial. The next trial started immediately following a correct response. If the response was incorrect or no response was detected within 5000 ms, “XXX” in red was presented for 500 ms before the next trial began. If no response was detected, the feedback included a sound to alert the subject. There were 10 trial blocks consisting of eight “Task A” and eight “Task B” trials. Thus, there were 16 possible task-stimuli combinations within each trial block (i.e., 160 trials in total). Each trial was randomly replaced with one of the remaining task-stimuli combinations in the trial block, and each test started with 16 random practice trials.

In the task switching test the task may change from one trial to the next (switch trial), or the task may be repeated (repetition trial). For both repetition- and switch trials the mean RTs and the proportion of errors were calculated, and used as dependent variables in the main analyses. In addition, the “switch cost”, calculated by subtracting the mean RT for switch trials from the mean RT for repetition trials, was used as a dependent variable. The switch cost is considered an operational measure of executive control (Couyoumdjian et al. 2010; Monsell 2003), and higher switch cost indicates poorer performance (i.e., reduced executive control). Similarly, the “pure switch cost”, was calculated using only the repetition- and switch trials with alternating stimulus and alternating response from one trial to the next.

Statistical analysis

Data was analyzed using Linear Mixed Model (LMM) analyses. For dependent variables a null model, a main effects model, and an interaction effects model were computed, with participant included as a random effect in all models. In the main effects model, Light (bright light vs. standard light), Night (night shift 1, 2 and 3), and Session (1 vs. 2) were entered as fixed factors. For the WM scanning task, Serial position (1, 2, 3, 4, 5 and 6) was also included as a fixed factor in the model. In the interaction effects model, the interactions for all the main factors were also entered as fixed factors. Only statistically significant ($p < .05$) interaction effects were retained in the final model. Model fit was assessed using a likelihood ratio test, by comparing the difference in -2 times the log of the likelihood between the models, following a chi-square distribution. The degrees of freedom used was equal to the difference between the number of parameters between the compared models. The normality of the residuals from the final models were assessed with normality plots. Post-hoc comparisons for significant main and interaction effects were conducted using Bonferroni corrections (applying constant alpha = .05), and the estimated marginal means (EMMs) and standard errors (SEs) are reported. The percentage variance explained by the final model was calculated by assessing the proportion of reduction in variance of the residuals compared to the null model. Statistical analyses were performed using IBM SPSS Statistics, version 25 (IBM Corp., USA).

Assessment of the test data

For the reversal learning task, the pre-reversal hit rates and false alarm rates were inspected prior to the main analyses, to ensure that participants performed as expected by acquiring the initial (pre-reversal) stimulus-response set. Four test results, from the first session on the first night shift, were excluded as the false alarm rate was higher than 75%, and two test results were excluded as the hit rate was lower than 25%. This indicated that the participants had not learned, or forgot, how to perform the task despite the practice session.

For the WM scanning task, one set of test data with very low mean accuracy (< 0.20) was excluded prior to the main analyses, as low accuracy indicated that the subject fell asleep or did not engage properly in performing the task.

For the task switching test, descriptive statistics and inspection of the raw data indicated that some tests were not performed adequately. Prior to the main analyses, data from three tests were excluded as many trials (39, 56 and 84) were timed out, indicating that the participants fell asleep or did not engage in the task. Data from five tests were excluded, having a proportion of errors of 25% or more in total (n = 1), or in either repetition- (n = 1) or switch trials (n = 3), considered to indicate lack of engagement. Analysis of the residuals from the final model of mean RT on repetition trials, identified data from three tests as outliers. One test had very slow RTs (this was the first session on the first night shift) compared to the other tests by this subject. Two tests (from the same subject) had a relatively large number of timed out trials (n ≥ 15), indicating that the subject was not able to respond in a timely manner. These tests were removed before LMM analyses were repeated.

Results

Reversal learning task

Table 1 includes the results for the fixed factors included in the final LMM analyses for both pre- and post-reversal discriminability (*d'*). In session 1 (at 00:20 h, in the first part of the night shifts), participants performed equivalently in the two light conditions (Figure 2A; top) and were able to discriminate the *go* and *no-go* stimulus sets both pre-reversal (*p* = .845) and post-reversal (*p* = .934). In the pre-reversal phase at session 1, participants gradually improved their performance with trial blocks, as the hit rate and false alarm rate increased and decreased, respectively (Figure 2B; top). As expected, the reversal of contingencies disrupted performance, which then again gradually improved during the post-reversal phase. Pre- and post-reversal *d'* did not differ significantly between the three night shifts at session 1.

[Table 1 near here]

In session 2, (at 04:50 h, towards the end of the night shifts), participants' performance differed with light condition (Figure 2A; bottom), as *d'* was improved with bright light, compared to standard light, both pre-reversal (p = .002) and post-reversal (p = .001). Thus, participants were better at discriminating the *go* and *no-go* stimulus sets with bright light, compared to standard light. In the pre-reversal phase, the hit rate increased and the false alarm rate decreased, with trial blocks within both light conditions (Figure 2B; bottom). As Figure 2B shows, the performance appears to be better with bright light, particularly in terms of hits on night shift 3. Likewise, in the post-reversal phase (Figure 2B; bottom), the improved performance of the hit rate with trial blocks, was shown to be higher with bright light on night shift 2 and 3. Pre-reversal *d'* improved with consecutive night shifts, with EMM of 1.33 (SE = 0.11) and 1.89 (SE = 0.11) on night shift 1 and 3 (p < .001), respectively. Also, post-reversal *d'* in session 2 was improved with consecutive night shifts, with EMM of 0.91 (SE = 0.14) and 1.62 (SE = 0.14) on night shift 1 and 3 (p < .001), respectively. The main effect of Night showed that *d'* gradually improved from night shift 1 to 3, and as indicated by the Night by Session interaction, this improvement was mainly due to changes in session 2.

[Figure 2 near here]

As shown in Figure 3, pre-reversal *d'* with bright light was similar in session 1 (00:20 h) and session 2 (04:50 h) (p = .436). With standard light, pre-reversal *d'* was significantly lower in session 2, compared to session 1. Post-reversal, for both light conditions, *d'* was lower in session 2, compared to session 1. However, as noted previously, *d'* in session 2 was significantly higher with bright light, compared to standard light.

[Figure 3 near here]

Analyses of the hit rates and false alarm rates for each trial block, indicated that the effects on *d'* were mainly due to decreases in hits, and not increases in false alarms, as can be noted from the pattern in Figure 2B. Analyses of the criterion scores, *c* (response bias), was conducted similarly as for *d'*, resulting in only one significant main effect of Session ($F_{1,271}$ = 12.41, *p* = .001) for pre-reversal *c*, with EMMs of -0.179 (SE = 0.05) and -0.072 (SE = 0.05) for session 1 and 2, respectively. Note that negative *c* indicates a bias towards *go* responses (i.e., pressing the space bar). There were no other statistically significant main effects or interactions concerning pre- and post-reversal *c*. Hence, the effects of night shifts in different light conditions on the reversal learning task, particularly evident in the post-reversal phase in session 2, were mainly attributable to differences in the ability to discriminate the *go* and *no-go* stimulus-response sets, rather than changes in response bias.

Working memory (WM) scanning task

The results from the LMM analyses of accuracy and mean RTs for positive trials, that is, trials were the probe item occurred in the memory set, are given in Table 1. Figure 4 shows the accuracy on the WM scanning task by serial position for the two light conditions, and for each night shift.

[Figure 4 near here]

The general pattern of performance on the WM scanning task, indicated that accuracy was best for the most recent memory set items. Accuracy gradually improved from the first to the last serial position.

The Light by Session interaction showed that in session 1, in the first part of the night shifts (00:10 h), performance was similar for both light conditions (*p* = .333), with EMMs of 0.86 (SE = 0.02) and 0.87 (SE = 0.02) for bright light and standard light, respectively. However, towards the end of the night shifts (session 2; 04:40 h), performance was better with bright, compared to standard light (*p* < .001), with EMMs of 0.88 (SE = 0.02) and 0.82 (SE = 0.02), respectively.

Analysis of the RTs on the WM scanning task revealed a pattern similar to the accuracy data, albeit reversed, with lower accuracy accompanied by longer RTs (Figure A1). As seen in Figure 4, in session 2, the general pattern of performance differences for the two light conditions implied that accuracy was 5–10% lower with standard, compared to bright light, at each serial position. Thus, there were no evident growing disparity from the most recent to the least recent serial positions, indicating no differences between light conditions in terms of participants' ability to maintain information that reached WM.

Performance on the WM scanning task declined with consecutive night shifts, from EMM of 0.88 (SE = 0.02) on night shift 1 to 0.82 (SE = 0.02) on night shift 3 (*p* < .001). This decline was apparently independent of light condition. The Night by Session interaction indicated that for session 1, performance on night shift 3 was poorer than on both night shift 1 (*p* < .001) and 2 (*p* = .021), while for session 2, performance was poorer on night shift 3 only, compared to night shift 1 (*p* = .028).

Task switching test

Table 1 includes the results from the LMMs for the mean RT on both repetition- and switch trials, the mean switch cost, and the proportion of errors for repetition- and switch trials. The analyses of pure switch cost revealed no significant main- or interaction effects. Figure A2 shows the mean RTs and the mean switch cost for each light condition, session and night shift.

[Figure 5 near here]

The general pattern of performance on the task switching test revealed that RTs for switch trials were slower than for repetition trials, as can be seen by the patterns in Figure 5A and 5B. Thus, the participants were faster when the task was repeated, compared to when the task switched, from one trial to the next. For repetition trials, the RTs did not differ statistically ($p = .168$) between bright light and standard light. However, for switch trials, the RTs differed with light condition and were faster with bright light compared to standard light ($p = .036$). Performance gradually improved with consecutive night shifts (Figure 5B), and as shown in Figure 5C, the mean switch cost was reduced on night shift 2 and 3, compared to night shift 1. The analyses of the proportion of errors revealed that, for both repetition- and switch trials the proportion of errors was lower with bright light, compared to standard light. For switch trials, the Light by Session interaction indicated that in session 1, proportion of errors was similar ($p = .308$) for bright light (6.6% errors) and standard light (7.1% errors), with EMMs of 0.066 (SE = 0.008) and 0.071 (SE = 0.008), respectively. However, in session 2, proportion of errors was reduced ($p < .001$) with bright light (5.8% errors), compared to standard light (6.6% errors), with EMMs of 0.058 (SE = 0.008) and 0.066 (SE = 0.008), respectively.

Discussion

This naturalistic night work experiment investigated how a bright light (~ 900 lx) intervention during three consecutive simulated night shifts, compared to a standard light (~ 90 lx), affected young healthy participants’ performance on a reversal learning task. Bright light improved performance on the reversal learning task towards the end of the night shifts (session 2, 04:50 h), compared to standard light. Specifically, a better discriminability (a higher *d’*) between *go* and *no-go* stimuli was shown in the bright light intervention. Thus, the hypothesis of improved performance on the reversal learning task during night shifts with bright light was supported. In addition, independent of light exposure, performance was poorer towards the end of the night shifts than in the first part of the shifts (session 1, 00:10 h). Hence, the impaired cognitive flexibility previously reported in sleep deprivation studies (Honn et al. 2019; Whitney et al. 2015), also seem to pertain to simulated night work.

There was a higher hit rate in bright light, especially after reversal of contingencies towards the end of night shift 2 and 3, explaining the improved discriminability, compared to standard light. Short-term (during the test) for both light conditions, the pattern of performance suggested that the hit rate increased and the false alarm rate decreased, hence discriminability gradually improved. The unannounced reversal of contingencies caused an abrupt performance deficit that was again gradually improved with further trial blocks. Towards the end of the night shifts, the increase in hit rates and decrease in false alarm rates was lower than in the first part of the night shifts, resulting in lower discriminability. For bright light this was evident only for the post-reversal phase (after reversal of contingencies), while pre-reversal discriminability was maintained at similar levels throughout the night shifts. In standard light discriminability was reduced towards the end of the night shifts both pre- and post-reversal. In general, the pattern of performance on the reversal learning task was similar to that reported previously (Honn et al. 2019; Whitney et al. 2015). In the study by Whitney et al. (2015), after 55 h of sleep deprivation, participants were basically unable to adapt to reversal of contingencies, with discriminability levels close to zero. As can be expected, the same severity of impairment was not found during simulated night shifts. In the study by Honn et al. (2019), performance impairment was reported after 30.5 h of sleep deprivation with discriminability levels similar to the current study. However, Honn et al. (2019) used a reversal learning task version with only four two-digit stimuli, implying lower burden on WM maintenance resources compared to the current study where eight two-digit stimuli were used.

Long-term performance was improved, as discriminability towards the end of the night shifts improved from night shift 1 to 3. Thus, in line with previous findings, prior experience with the test seemed to be beneficial for performance (Whitney et al. 2015). While Whitney et al. (2015) found that sleep deprivation interfered with improvement, the current study found that improved performance was mainly driven by changes towards the end of the night shifts. There was no significant Light by Night interaction for discriminability. However, assessment of the hit rates and false alarm rates towards the end of the night shifts (session 2), indicated that improvement with consecutive night shifts was mainly due to increased hit rates with bright light, especially in the post-reversal phase. In Whitney et al. (2015), participants were severely sleep deprived, hence comparison with night work is somewhat problematic and underlines the observed differences from the current study. Furthermore, the current study commenced a practice session a few days prior to the first night shift, hence participants' performance was already at a heightened level when starting the simulated night shifts.

A working memory (WM) scanning task was administered as a complementary measure to assess if the night shifts and the bright light intervention affected the ability to encode and maintain relevant information. Performance in bright light, compared to standard light, was improved towards the end of the night shifts (session 2), and the general pattern indicated improvement for all serial positions. Hence, the hypothesis of improved WM task performance with bright light was supported. The results followed the expected response pattern, revealing a recency effect with accuracy improving from the first to the last serial position. The finding of improved WM scanning task performance in bright light is in accordance with previous studies, mainly using n-back tests, reporting that light interventions during night work can improve performance on WM tasks (Kretschmer et al. 2011; Motamedzadeh et al. 2017). However, there seems to be lack of previous studies reporting effects of light exposure during night work on WM scanning tasks. After 51 h of sleep deprivation, one study found 20% lower accuracy than for well-rested individuals at all serial positions (Whitney et al. 2015), and another study, using a similar type of WM scanning task, reported impaired performance in terms of RTs, accuracy and errors of omission (Tucker et al. 2010). In the current study, there was no clear reduction in accuracy towards the end of the night shifts (session 2), compared to the first part of the night shifts (session 1), but a clear pattern of longer RTs in session 2, compared to session 1, emerged. Taking into account that the simulated night shifts entail less severe sleep deprivation, and that session 1 commenced at 00:10 h, the results were overall considered to be in line with the previous studies.

Towards the end of the night shifts with bright light, more information was encoded into WM than with standard light. However, as there was no growing disparity with serial position, participants could maintain and search the encoded information similarly in both light conditions. This indicates that WM scanning efficiency, considered as an executive component, was not affected by the bright light intervention. Rather, the improved performance on the WM scanning task in bright light, was apparently related to non-executive components of the task. Importantly, these findings indicate that the beneficial effects of bright light on the reversal learning task, cannot be explained by differences in the ability to maintain and search information in WM. Similarly, although not investigating the effects of light, Tucker et al. (2010) and Whitney et al. (2015), found that the performance deficits on a WM scanning task after 51 h of sleep deprivation was mainly due to effects on non-executive components of the task, while the executive component (i.e., scanning efficiency) was not affected by sleep deprivation.

Lapses of attention are thought to account for the lower accuracy on the WM scanning task (Whitney et al. 2015). Previously, it was reported that the number of attentional lapses in the later parts of the night shifts were significantly lower with bright light, compared to standard light (Sunde et al. 2020). Hence, lapses of attention likely contribute to the overall lower WM scanning task performance with standard light. As such, lapses of attention could result in information acquisition failures, i.e., failures to acquire information from stimuli and feedback, also on the reversal learning task. However, previous studies simulating information acquisition failures in well rested individuals, have altogether shown that lapses of attention cannot explain the distinct deficits in reversal learning performance during sleep deprivation (Honn et al. 2019; Lawrence-Sidebottom et al. 2020; Whitney et al. 2015). Still, lapses of attention and slowing of responses may have had some impact on the reversal learning performance. For instance, as participants had only a 750 ms window to decide whether to respond or inhibit a response, it is plausible that a non-response actually represented a lapse of attention and not a deliberate decision not to respond. However, lapses of attention could happen at any time of the task, and considering that the criterion scores, *c* (response bias), were largely unaffected, it appears that attentional lapsing cannot fully account for reversal learning task performance. Another possibility is that a general slowing of responses led to fewer responses regardless of type of stimuli, hence explaining the decrease in hits with no clear increase in false alarms, as seen with standard light on night shift 2 and 3. Whitney et al. (2015) reported that effects on discriminability were due to both decreases in hits and increases in false alarms. Nonetheless, the improved reversal learning task performance with bright light in the current study implies that bright light interventions during night work may be beneficial not only for vigilant attention, but also for cognitive flexibility.

The task switching test was administered as a complementary measure capturing elements of cognitive control and flexibility. The results followed the expected pattern with slower RTs on switch trials than on repetition trials. There was a pattern of improved performance with repeated administrations, as reported also in previous studies (Couyoumdjian et al. 2010; Kaida et al. 2013). The switch cost seen on the task switching test is considered a measure of executive control, and Couyoumdjian et al. (2010) reported that sleep deprivation increased the switch cost. However, in the current study there were no evidence of increased switch cost during the simulated night shifts. Also, the bright light intervention did not affect the switch cost in either session 1 or session 2 during the night shifts. Hence, in terms of switch cost, the hypothesis of improved task switching performance with bright light was not supported. In the study by Couyoumdjian et al. (2010), participants were tested at 10:00 h, after a night with sleep deprivation, hence they had been awake for a longer period than in the current study. In the current study, performance during session 2 (05:10 h) was compared to session 1 at 00:40 h. Thus, participants' performance could already be compromised at session 1. On the other hand, a recent study showed that the switch cost did not increase after 24 h of sleep deprivation (Nakashima et al. 2018). Using neuroimaging, Nakashima et al. (2018) indicated increased activation in several brain regions, including the frontoparietal system, which was considered to reflect compensatory responses. It was further suggested that the compensatory response may signal involvement of executive functions that can mitigate the effects of sleep deprivation on the switch cost (Nakashima et al. 2018). Thus, such compensatory mechanisms may explain the limited effects of night work, and light exposure, also in the current study.

Another study also reported no effects of bright light on switch cost Kaida et al. (2013), but the findings are not directly comparable as participants in that study were not exposed to night shifts or sleep deprivation. Current analysis of the RTs for the switch and repetition trials separately, showed some evidence of beneficial effects of bright light for switch trials only. Similarly, for the proportion of errors, there were beneficial effects of bright light, however only a small proportion of the variance in performance on the task switching test was explained. The task switching test in session 2 commenced at 05:10 h, few min after the bright light had been changed to ~ 200 lx. It is conceivable that the task switching performance was slightly reduced due to the changed lighting. Taken together, task switching performance was affected to a limited degree by the night shifts and the bright light intervention. Thus, the hypothesis of improved task switching performance with bright light received limited support. The task switching test is considered to reflect cognitive control, as such shows some similarity with the reversal learning task. However, the current study indicates that the two tasks capture distinct elements of cognitive control that seem differentially impacted by night work and bright light exposure.

The overall beneficial effects of bright light on the reversal learning task can be explained by both improved circadian adaptation and acute effects of light exposure (Cajochen 2007; Horowitz et al. 2001). Previously, it was reported that the participants' circadian rhythm was phase delayed with the bright light intervention, and that improved daytime sleep indicated that sleep occurred at a more favorable circadian time (Sunde et al. 2020). Thus, the bright light appears to have improved the circadian adaptation to the night work schedule. Also, as the daytime sleep duration was increased with bright light (Sunde et al. 2020), the accumulated sleep loss in course of the three consecutive night shifts was reduced with the bright light intervention. The pattern of improved fraction of hits with bright light on night shift 2, and especially night shift 3, fit well with the evidence suggesting a circadian adaptation and improved sleep with the bright light intervention. On the other hand, it is also conceivable that acute effects of bright light exposure improved performance on the reversal learning task. Performance on the reversal learning task rely on the prefrontal cortex

(PFC), specifically the orbitofrontal cortex and associated pathways (Frank and Claus 2006). Light exposure is known to modulate brain activity (task-dependent) during engagement in cognitive tasks, including activation of PFC areas (Vandewalle et al. 2009). Hence, it is conceivable that light exposure also has the potential to improve performance on tasks such as the reversal learning task.

The specific underlying mechanisms explaining the observed effects of reduced cognitive flexibility during night work, and the beneficial effects of bright light exposure is not clear. Previously, reduced efficacy of feedback to direct and modify behavioral choices, i.e., feedback blunting, have been found during sleep deprivation (Whitney et al. 2015). It has been suggested that the feedback blunting results from the required acquisition of a novel choice pattern in the pre-reversal phase, interfering with the ability to use new feedback information to update the choice pattern in the post-reversal phase (Honn et al. 2019). Apparently, the bright light intervention affected both these factors, as discriminability was improved with bright light both pre- and post-reversal.

The current study was commenced as a naturalistic night work experiment, and as noted earlier (Sunde et al. 2020), there are several factors that may have affected the results. However, the generalizability to real-life settings, i.e., ecological validity, can be improved using such a naturalistic approach. Few requirements were put on participants outside the laboratory, and differences in terms of e.g., exposure to daylight, sleep habits, and other behavioral factors may have had an impact on the participants' performance during the night shifts. Still, a set of criteria concerning inclusion of participants were used, e.g., good health, refrain from alcohol and tobacco, normal sleep and no extreme chronotypes. Hence, the trial was conducted on a selected sample of participants and is thus not directly comparable to actual night workers in a real-life setting. Previously, large individual differences in the responses to light exposure have been reported (Phillips et al. 2019), hence individual differences may have affected the current results. Furthermore, individual differences regarding effects of sleep deprivation on reversal learning task performance have been shown. Satterfield et al. (2018) found that, based on a genetic polymorphism (Val158Met) of catechol-O-methyltransferase (COMT), subjects vary substantially in their vulnerability to the performance impairment in the post-reversal phase during sleep deprivation. Carriers of the Val (valine) allele are particularly vulnerable to the performance deficits on the reversal learning task, while the Met (methionine) allele provides resilience. Interestingly, this genotype effect was not seen for vigilant attention measured with a PVT (Satterfield et al. 2018). Genotype was not assessed in the current study and the effects of light exposure for the different genetic polymorphisms remain to be investigated. While there are differences and uncontrolled factors that may have affected the results, the crossover design did control for several of such factors and ensured comparability across the two light conditions. The participants were relatively young adults, mainly female students, hence other age groups and gender distributions should be investigated in future studies. Also, trials at actual workplaces involving night work are needed, and different light conditions (e.g., illuminance level, irradiance level, spectral distribution) should be investigated.

In conclusion, the current findings have important implications showing that a bright light intervention during night work has the potential to mitigate performance deficits on a reversal learning task. This task captures elements of cognition that are highly important in real-life settings, e.g., workplaces where dynamic situations require cognitive flexibility and the ability to adapt to changes in events. Similar LED-based light equipment can easily be installed at various workplaces and may improve performance and reduce the risk of errors during night work.

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Disclosure statement

The authors declare no competing interests.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Erlend Sunde http://orcid.org/0000-0002-3982-5486
Jelena Mrdalj http://orcid.org/0000-0003-2180-0341
Torhild T. Pedersen http://orcid.org/0000-0003-4313-3711
Bjørn Bjorvatn http://orcid.org/0000-0001-7051-745X
Janne Grønli http://orcid.org/0000-0002-2781-3533
Anette Harris http://orcid.org/0000-0003-0799-8304
Siri Waage http://orcid.org/0000-0001-9891-6348
Ståle Pallesen http://orcid.org/0000-0002-5831-0840

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Appendices

Figure A1

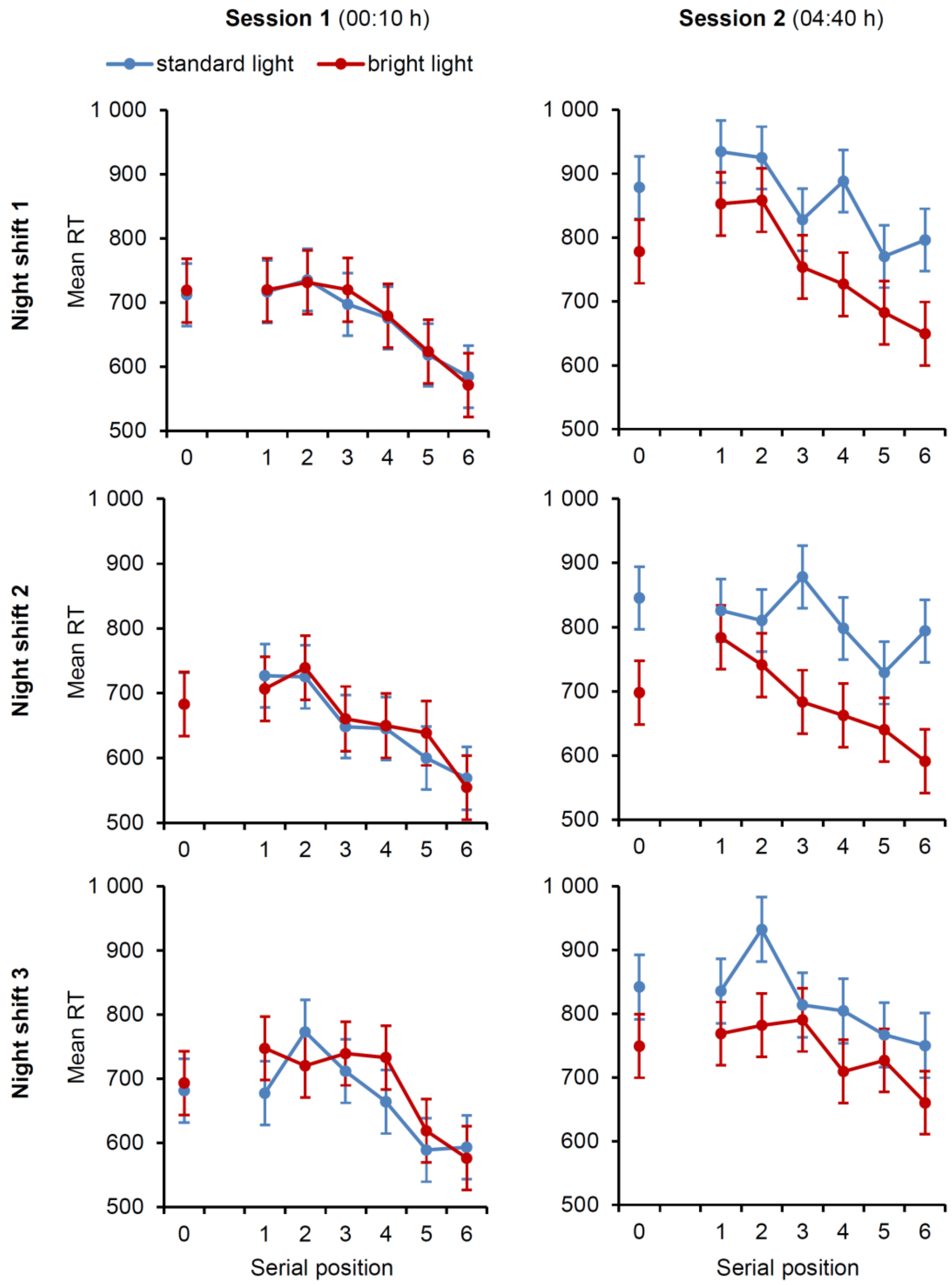

Figure A1. Performance on the working memory (WM) scanning task given as estimated marginal means and standard errors (bright light: ~ 900 lx; 4000 K, standard light: ~ 90 lx; 4000 K). Response time (RT) shown for each serial position (i.e., position of the probe item within the memory set). Serial position 0 indicates negative trials where the probe item was not in the memory set.

Figure A2

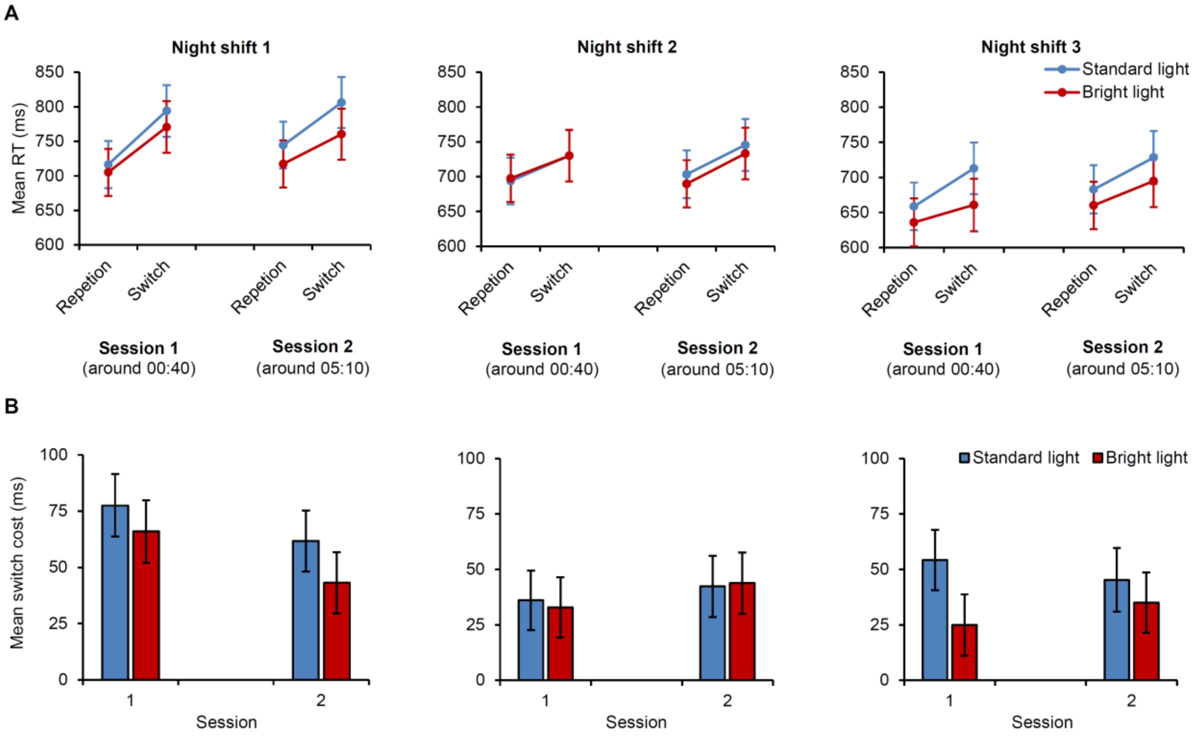

Figure A2. Performance on the task switching test given as estimated marginal means and standard errors (bright light: ~ 900 lx; 4000 K, standard light: ~ 90 lx; 4000 K). Session 1 (00:40 h) and session 2 (05:10 h). **(A)** Response times (RTs) on repetition- and switch trials. **(B)** Switch cost, i.e., the difference in ms between repetition- and switch trials.

Table

Table 1. Linear mixed model analyses for performance tasks completed twice (first part of the night shift vs. towards the end of the night shift), during each of three consecutive simulated night shifts in bright light vs. standard light. Statistics for the fixed factors included in the final models.

	Bright light	**Standard light**	***Light***		***Night***		***Session***		***Serial position***		***Light*Session***		***Night*Session***		***Night*Session*Serial position***		***Explained variance***
	EMM (SE)	*EMM (SE)*	*F (df)*	*p*	*F (df)*	*p*	*F (df)*	*p*	*F (df)*	*p*	*F (df)*	*p*	*F (df)*	*p*	*F (df)*	*p*	
Reversal learning task (n tests = 297)																	
pre-reversal *d'*	1.90 (0.08)	1.76 (0.08)	4.20 (1,272)	.041	11.89 (2,269)	<.001	11.88 (1,269)	<.001	-		5.49 (1.269)	.020	4.47 (2,269)	.012	-		10.5%
post-reversal *d'*	1.67 (0.12)	1.50 (0.12)	5.22 (1,273)	.023	9.88 (2,271)	<.001	28.91 (1,271)	<.001	-		5.87 (1,271)	.016	9.07 (2,271)	<.001	-		12.5%
Working memory scanning task (n tests = 303)																	
Accuracy	0.87 (0.02)	0.85 (0.02)	12.32 (1,1798)	<.001	26.91 (2,1792)	<.001	3.84 (1,1792)	.050	74.01 (5,1792)	<.001	24.20 (1,1792)	<.001	5.85 (2,1792)	.003	2.13 (25,1792)	.001	18.3%
Mean RT	701.68 (25.55)	748.64 (25.49)	19.74 (1,1798)	<.001	5.44 (2,1792)	.004	108.60 (1,1792)	<.001	21.16 (5,1792)	<.001	29.85 (1,1792)	<.001	-		-		10.2%
Task switching test (n tests = 293)																	
Mean RT repetition	684.31 (29.24)	699.84 (29.22)	1.91 (1,268)	.168	10.25 (2,267)	<.001	1.80 (1,267)	.181	-		-		-		-		2.5%
Mean RT switch	724.98 (31.20)	752.49 (31.17)	4.45 (1,268)	.036	13.94 (2,267)	<.001	0.80 (1,267)	.373	-		-		-		-		3.8%
Mean switch cost	40.88 (8.25)	52.71 (8.24)	2.80 (1,271)	.095	4.66 (2,268)	.010	0.23 (1,268)	.631	-		-		-		-		3.1%
Error proportion repetition	0.05 (0.01)	0.06 (0.01)	11.55 (1,268)	<.001	1.34 (2,267)	.265	2.21 (1,267)	.139	-		-		-		-		1.4%
Error proportion switch	0.06 (0.01)	0.08 (0.01)	19.01 (1,268)	<.001	0.89 (2,267)	.413	1.05 (1,267)	.306	-		9.25 (1,267)	.003	-		-		2.8%

Bright light, ~ 900 lx; 4000 K. Standard light, ~ 90 lx; 4000 K. Explained variance, equals the proportion of reduced residual variance from the null model to the final model. EMM, estimated marginal means. SE, standard error. df, degrees of freedom. d', discriminability. RT, response time.

Figures

Figure 1

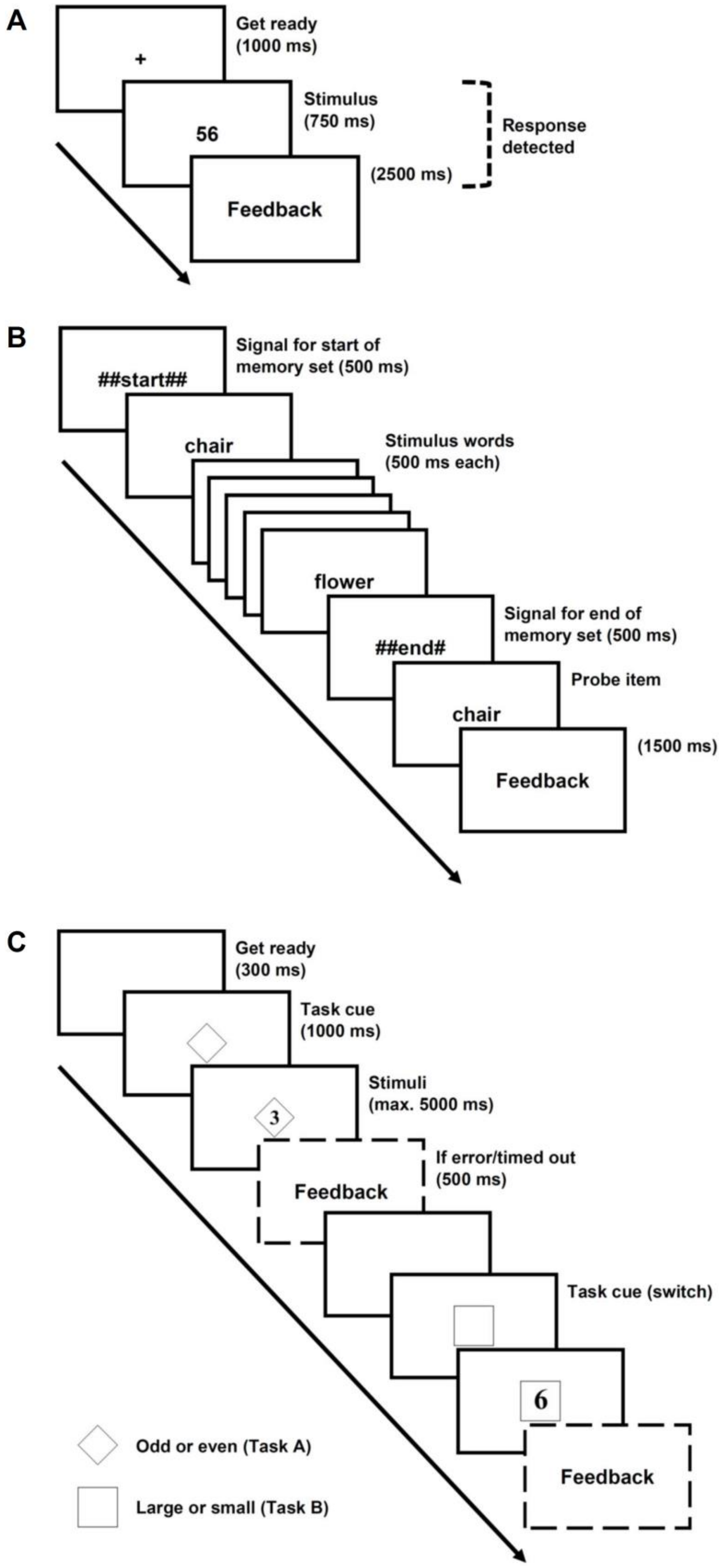

Figure 2

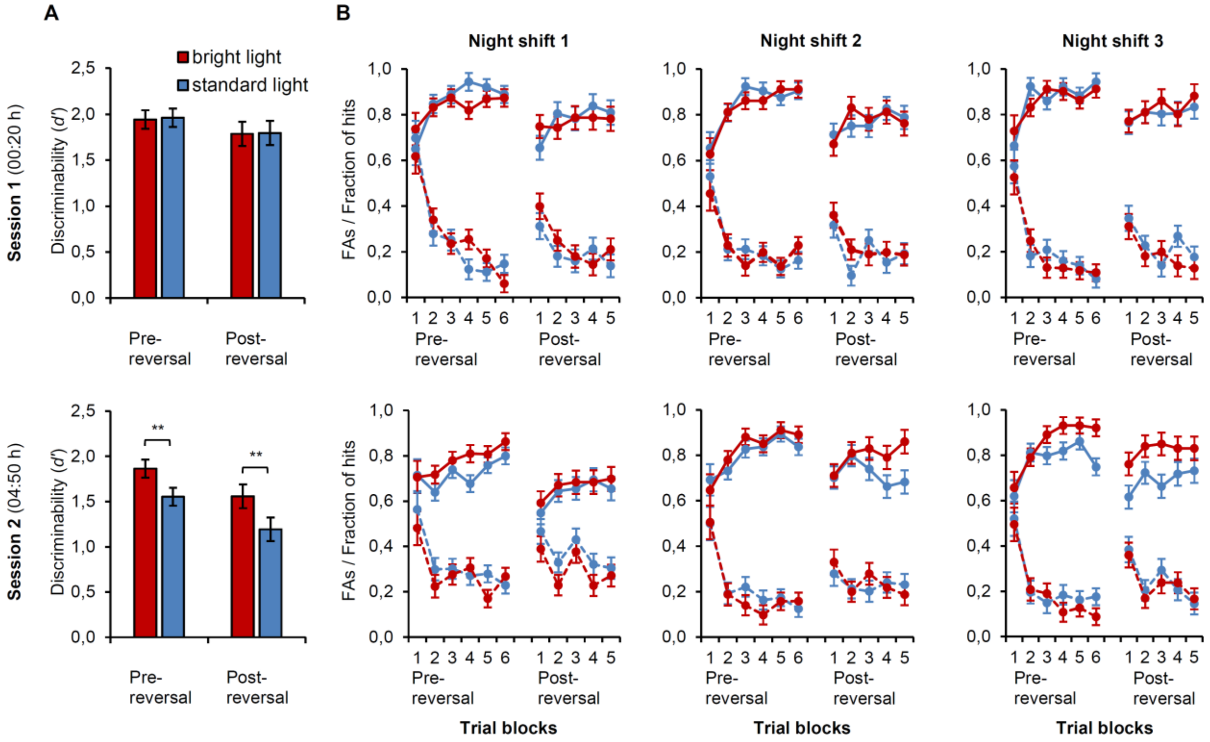
A
B
🟥 bright light
🟦 standard light
Session 1 (00:20 h)
Session 2 (04:50 h)
Discriminability (d')
2,5
2,0
1,5
1,0
0,5
0,0
**
**
Pre-reversal
Post-reversal
Night shift 1
Night shift 2
Night shift 3
FAs / Fraction of hits
1,0
0,8
0,6
0,4
0,2
0,0
1 2 3 4 5 6
1 2 3 4 5
Trial blocks

Figure 3

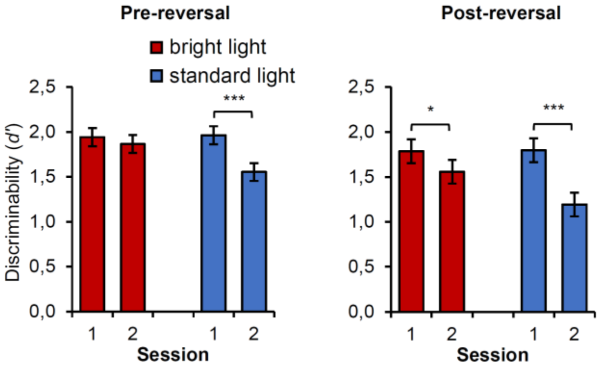
Pre-reversal
Post-reversal
bright light
standard light
Discriminability (d')
2,5
2,0
1,5
1,0
0,5
0,0
***
*
***
1
2
1
2
Session
Session

Figure 4

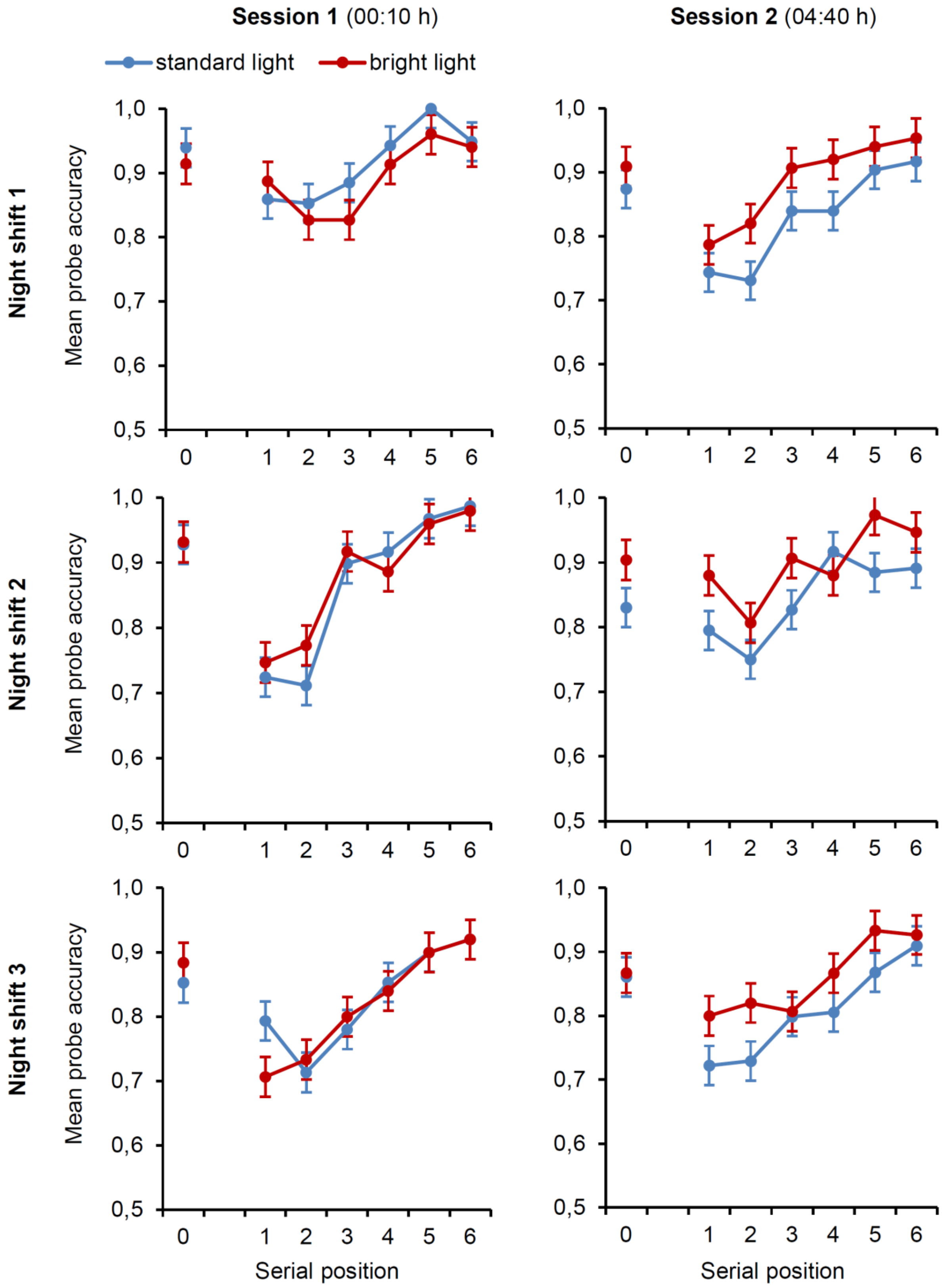
Session 1 (00:10 h)
Session 2 (04:40 h)
standard light
bright light
Night shift 1
Night shift 2
Night shift 3
Mean probe accuracy
1,0
0,9
0,8
0,7
0,6
0,5
0
1
2
3
4
5
6
Serial position

Figure 5

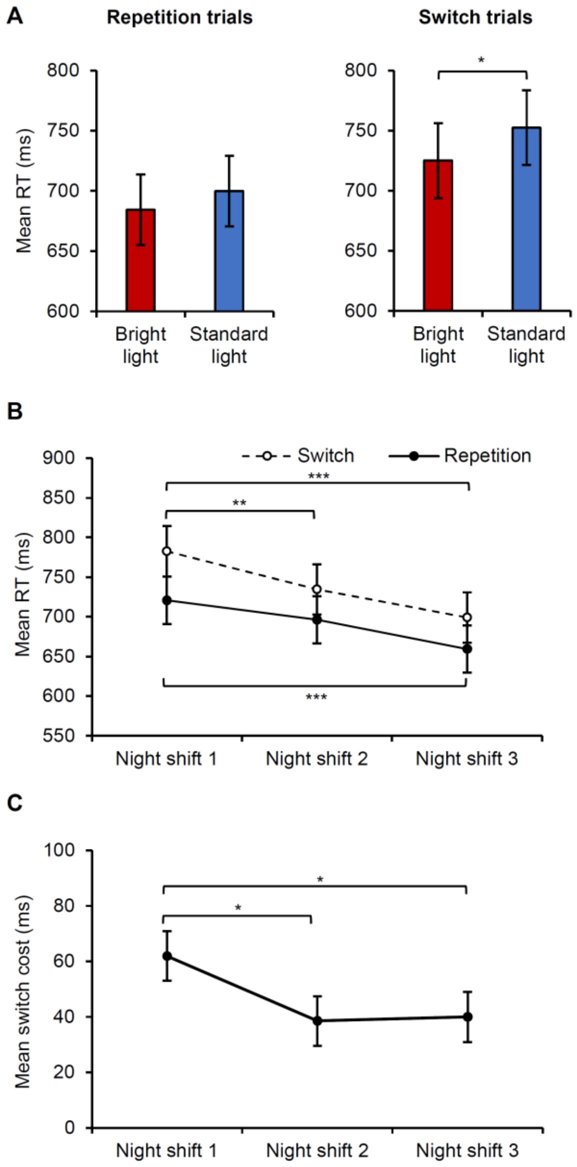
A
Repetition trials
Switch trials
Mean RT (ms)
800
750
700
650
600
Bright light
Standard light
*
B
Switch
Repetition
900
850
800
750
700
650
600
550
***
**
***
Night shift 1
Night shift 2
Night shift 3
C
Mean switch cost (ms)
100
80
60
40
20
0
*
*

Figure captions

- Figure 1. Examples of the performance task trials. **(A)** Trial schematic for the reversal learning task. Feedback included accuracy and hypothetical monetary reward or punishment based on accuracy, and temporary reward balance. **(B)** Trial schematic for the working memory scanning task. Feedback included accuracy. **(C)** Trial schematic for the task switching test. Feedback on accuracy was provided if the response was incorrect.

- Figure 2. Performance on the reversal learning task given as estimated marginal means and standard errors (bright light: ~ 900 lx; 4000 K, standard light: ~ 90 lx; 4000 K). Upper panels for session 1 (00:20 h), and lower panels for session 2 (00:50 h). **(A)** Discriminability (*d'*) pre- and post-reversal of the stimulus-response sets for the three night shifts combined. Brackets with asterisks indicate statistically significant differences (**; $p < .01$). **(B)** Fraction of hits (upper solid lines) and false alarms (FAs; lower dotted lines) for each of the pre- and post-reversal trial blocks, both light conditions and each night shift.

- Figure 3. Performance on the reversal learning task given as estimated marginal means and standard errors (bright light: ~ 900 lx; 4000 K, standard light: ~ 90 lx; 4000 K). Discriminability (d') pre- (left panel) and post-reversal (right panel) of the stimulus-response sets for the three night shifts combined. These are the same data as shown in Figure 2, but with comparison of the differences between session 1 (00:20 h) and session 2 (04:50 h) within each light condition. Brackets with asterisks indicate statistically significant differences (*; p < .05, ***; p < .001).

- Figure 4. Performance on the working memory (WM) scanning task given as estimated marginal means and standard errors (bright light: ~ 900 lx; 4000 K, standard light: ~ 90 lx; 4000 K). Accuracy proportion shown for each serial position (i.e., position of the probe item within the memory set). Serial position 0 indicates negative trials where the probe item was not in the memory set.

- Figure 5. Performance on the task switching test given as estimated marginal means and standard errors. Brackets with asterisks indicate statistically significant differences (*; p < .05, **; p < .01, ***; p < .001) **(A)** Response times (RTs) on repetition- and switch trials for bright light (~ 900 lx; 4000 K) and standard light (~ 90 lx; 4000 K).

(B) RTs on repetition- and switch trials for each night shift. Brackets above and below the markers for switch- and repetition trials, respectively. **(C)** Switch cost, i.e., the difference in ms between repetition- and switch trials, for each night shift.