

Sleep's Influence on a Reflexive Form of Memory That Does Not Require Voluntary Attention

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Study Objectives: Studies to date have examined the influence of sleep on forms of memory that require voluntary attention. The authors examine the influence of sleep on a form of memory that is acquired by passive viewing.

Design: Induction of the McCollough effect, and measurement of perceptual color bias before and after induction, and before and after intervening sleep, wake, or visual deprivation.

Setting: Sound-attenuated sleep research room.

Participants: 13 healthy volunteers (mean age = 23 years; age range = 18–31 years) with normal or corrected-to-normal vision.

Interventions: N/A.

Measurements and Results: Encoding: sleep preceded adaptation. On separate nights, each participant slept for an average of 0 (wake), 1, 2, 4, or 7 hr (complete sleep). Upon awakening, the participant's baseline perceptual color bias was measured. Then, he or she viewed an adapter consisting of alternating red/horizontal and green/vertical gratings for 5 min. Color bias was remeasured. The strength of the aftereffect is the postadaptation color bias relative to baseline. A strong orientation contingent color aftereffect was observed in all participants, but total sleep duration (TSD) prior to the adaptation did not modulate aftereffect strength. Further, prior sleep provided no benefit over prior wake. Retention: sleep followed adaptation. The procedure was similar except that adaptation preceded sleep. Postadaptation sleep, irrespective of its duration (1, 3, 5, or 7 hr), arrested aftereffect decay. By contrast, aftereffect decay was arrested during subsequent wake only if the adapted eye was visually deprived.

Conclusions: Sleep as well as passive sensory deprivation enables the retention of a color aftereffect. Sleep shelters this reflexive form of memory in a manner akin to preventing sensory interference.

Keywords: Adaptation, interference, plasticity, visual deprivation, aftereffect

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INTRODUCTION

Emerging evidence suggests that sleep plays a key role in the processes of learning and memory,^{1,2} which involve change at synaptic and cellular levels in the brain. A number of different learning tasks have been used over the years³⁻¹⁰ to illustrate this point. Together, these studies encompass both declarative and procedural forms of learning and plasticity.

Although different forms of memories were examined in the different studies, they all share certain key aspects. In every single study, the participant had to direct his or her attention to learning a skill or retaining a piece of information: the goal was to learn and retain as much as possible, and the extent to which this goal was achieved was measured. Thus, the learning in these studies was inextricably inseparable from reward-driven, attention-related, and goal-directed factors.

However, sleep may not have a monolithic influence on all memory. There are multiple forms of plasticity and the mechanisms in sleep that influence a particular form of memory could overlap but not be identical to the sleep-dependent mechanisms influencing a different form of memory. Thus, the influences of sleep on automatic, reflexive forms of plasticity and attention-

demanding, goal-oriented forms could differ. It is known from tasks that do not involve a learning component that sleep is critical for attention, and the lack of sleep substantially diminishes one's ability to sustain attention.¹¹ Therefore, if it could be shown that sleep improves or consolidates forms of memory that do not require attention, it would show that sleep aids learning in different ways and in ways that are independent of those that restore attention resources.

A second question is whether sleep before learning enables the encoding of memory. Does prior sleep help one acquire memories or learn skills more quickly and efficiently? If yes, it would mean that sleep makes brain circuits more plastic and more predisposed to learn new skills and commit new experiences to memory. In this regard, a recent study on motor skill learning found that prior sleep helps one learn a motor skill more quickly.¹² The task studied, which involved tapping a sequence of finger movements as quickly and accurately as possible, demanded attention. As discussed earlier, sleep could have a different effect on a more reflexive, nongoal-oriented form of plasticity. If sleep before reflexive learning causes a larger plastic change than would otherwise, then it would strengthen the idea that sleep renders brain circuits more plastic and predisposes one to learn more and better.

We asked if sleep enhances the encoding and consolidation of a reflexive form of plasticity: a form of visual adaptation known as the McCollough effect (ME). This form of memory does not require voluntary attention: ignoring the adapting stimulus does not affect the size of the ME; namely, the size of the color aftereffect (AE) remains the same whether or not the

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subject focuses their attention on the colored grating adapter.¹³ Knowing that overnight sleep restores attentional resources, if sleep were to enhance the encoding and consolidation of visual adaptation, it would have to be via a different mechanism.

To address the issues of whether sleep before and after the acquisition of a reflexive form of plasticity enhances the change, we studied sensory adaptation. Even a few seconds of exposure to a visual stimulus without demand on attention leads to the formation of a brief afterimage. A few minutes of exposure to an alternating sequence of colored, oriented gratings causes an AE to form in which the perceived color is contingent on the adapting orientation¹⁴ (the ME), and more importantly, is persistent for days to months after the induction of the adaptation.¹⁵ Note that we use induction of adaptation and adaptation interchangeably. We studied the effect of sleep on its induction and on its retention and found that sleep before adaptation had no effect on the strength of the resulting AE; sleep after adaptation preserved the AE, whereas wakefulness after adaptation did not; and sleep helped retain and stabilize the AE by “freezing” it. Our combined findings support the idea that plastic changes in the brain’s circuitry are initially fragile, sleep shelters the plastic change from interference, and sleep retains and stabilizes the memory by some mechanism other than memory replay. These findings are also discussed in relation to those from previous studies.

MATERIALS AND METHODS

Participants

Participants in different experiments of the study were chosen from a set of 13 healthy volunteers with normal or corrected-to-normal vision. Three of the participants were the authors; the rest were blinded to the purpose of the study. The study was conducted with the understanding and written consent of each participant and under a protocol approved by the University of Houston Committee for the Protection of Human Subjects.

Adaptation Procedure

The adapter alternated between two orientation patterns of identical spatial frequency (3.4 cycles/degree): a horizontal grating, consisting of red (Commission Internationale de l’Eclairage (CIE) coordinates, $x = 0.602$, $y = 0.344$, luminance = 12.7 cd/m²) and black stripes alternating with a vertical grating consisting of green (CIE coordinates, $x = 0.310$, $y = 0.572$, luminance = 12.7 cd/m²) and black stripes (Figure 1A, left panel). The two adapting patterns alternated every 10 s for a combined total duration of 5 min. Participants were required to maintain gaze on the screen although not to any specific point on the patterns. Adaptation was monocular, i.e., one eye was blocked from visual stimulation during the procedure.

Stimuli and Procedure

All experiments were performed on a Windows XP desktop computer (HP Pavilion, Palo Alto, CA) connected to a 21-inch-ViewSonic monitor (G225f) with a refresh rate of 75 Hz and a resolution of 1,280 × 1,024 pixels. Participants sat comfortably in a chair in front of the computer monitor during all components of the experiment. Viewing distance was 57 cm. Software was scripted in MATLAB (Mathworks, Inc., Natick, MA) uti-

lizing the psychophysics toolbox.^{16,17} The experimental room was dark (less than 0.01 cd/m²).

The experimental procedure consisted of two stages, separated in time by 8 or 12 hr (also described in the Conditions section). Adaptation on the color-oriented grating was conducted in the first stage. The first stage consisted of three components. In chronologic order, they are as follows: preadaptation test, adaptation, and postadaptation test 5 min after the adaptation. The second stage consisted of an intervening period consisting of sleep, wakefulness, or some combination thereof, followed by a retest.

Preadaptation and postadaptation tests

All tests (pretest, posttest, and retest) were identical in all respects. On each trial, vertical and horizontal grating patterns appeared side by side, randomly left or right of screen center (Figure 1A, center panel). The participant had to judge which of the two gratings (left or right) was more green and respond accordingly by pressing one of two adjacent keys on a computer keyboard. The key press ended the trial. No feedback was provided.

The tests used the method of constant stimuli. In other words, the amount of green in the two oriented patterns shown on a given trial randomly varied from trial to trial, so that each grating patch appeared to take on a perceived hue ranging from slightly green or greenish to slightly red or reddish. There were seven hue levels (from reddish to greenish) for each of two orientations and 30 trials for each condition, giving a total of 420 (= 7 × 2 × 30) trials per test. Step size, namely the distance in CIE coordinate space between two adjacent hue levels, averaged (Δx , Δy) = (0.0002, 0.0069). Hue levels were identical across all participants and experiments. Tests were conducted on each eye separately (the other eye was covered).

Conditions

The procedures were largely common among all experiments, i.e., in all experiments, the ME was induced, AE strength tested both before (baseline) and after the induction, and a manipulation performed either before or after the induction. However, there were differences, including the nature of the manipulation and its timing relative to the adaptation. Note that all experiments had a repeated measures design, i.e., the same participants were studied for all the different conditions of the experiment. The order of the various procedures and manipulation specific to each experimental condition is summarized in the following paragraphs.

Experiment 1 – AE induction versus total sleep duration (TSD): Each participant ($n = 5$) was expected to sleep, on separate nights, for 0 (wake), 1, 2, 4, or 7 hr (or complete sleep); actigraphy measurements (MiniMitter Inc., Bend, OR) found that our participant sample slept, on average, for 55 min ± 1 min; 1 hr, 52 min ± 2 min; 3 hr, 39 min ± 7 min; and 7 hr, 21 min ± 11 min on the 1-, 2-, 4-, and 7-hr TSD conditions, respectively. Planned contrasts using paired, 2-tailed t tests (0 versus 1 hr, 1 versus 2 hr, 2 versus 4 hr, and 4 versus 7 hr) confirmed that TSD values on the 4 different preadaptation nights differed statistically (all P s < 0.005). The order, namely 0, 1, 2, 4, or 7 hr TSD, was counterbalanced across participants. Immediately after waking up, the participants’ perceptual color bias was test-

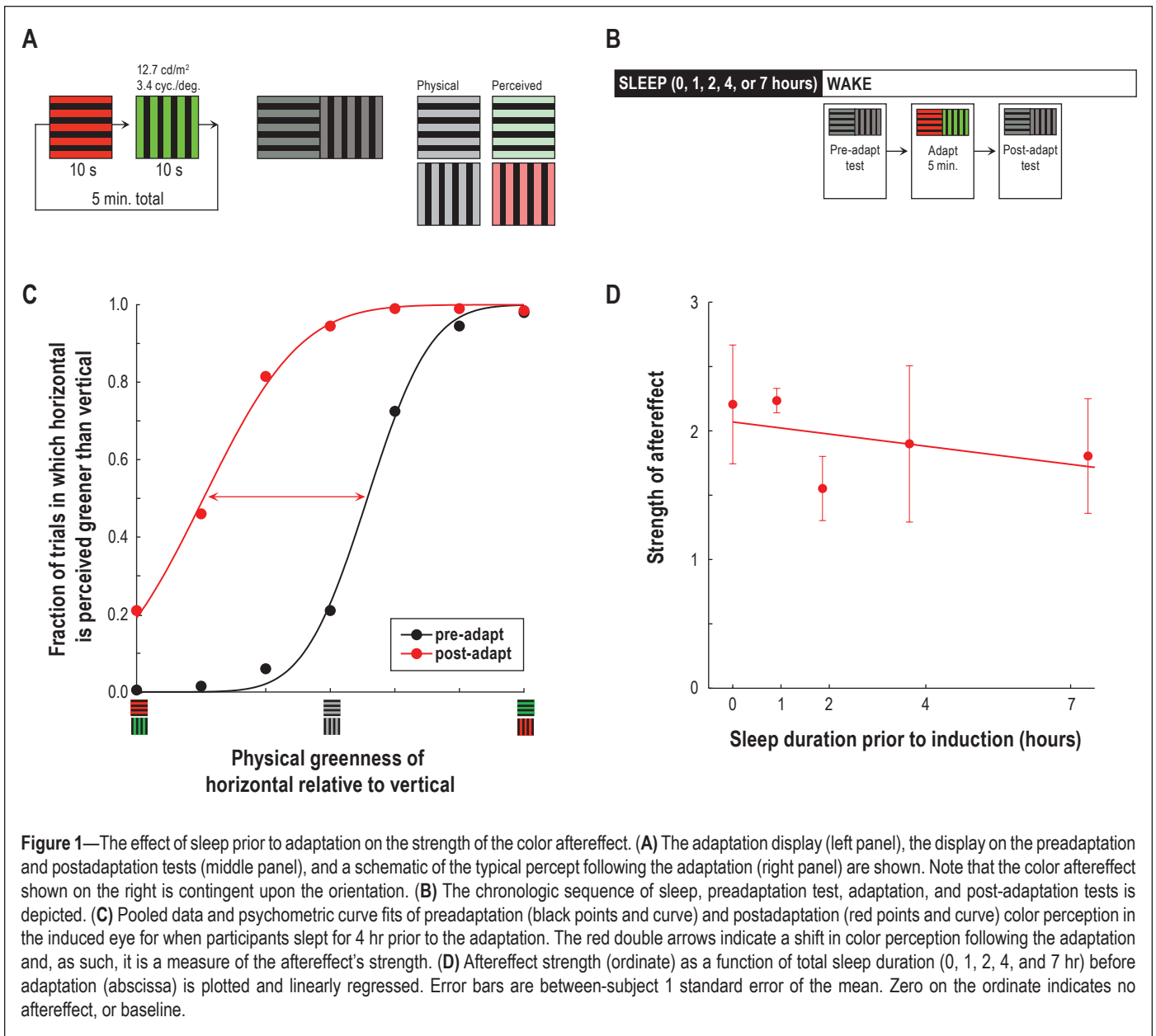


Figure 1—The effect of sleep prior to adaptation on the strength of the color aftereffect. **(A)** The adaptation display (left panel), the display on the preadaptation and postadaptation tests (middle panel), and a schematic of the typical percept following the adaptation (right panel) are shown. Note that the color aftereffect shown on the right is contingent upon the orientation. **(B)** The chronologic sequence of sleep, preadaptation test, adaptation, and post-adaptation tests is depicted. **(C)** Pooled data and psychometric curve fits of preadaptation (black points and curve) and postadaptation (red points and curve) color perception in the induced eye for when participants slept for 4 hr prior to the adaptation. The red double arrows indicate a shift in color perception following the adaptation and, as such, it is a measure of the aftereffect's strength. **(D)** Aftereffect strength (ordinate) as a function of total sleep duration (0, 1, 2, 4, and 7 hr) before adaptation (abscissa) is plotted and linearly regressed. Error bars are between-subject 1 standard error of the mean. Zero on the ordinate indicates no aftereffect, or baseline.

ed (pretest). The adaptation procedure followed immediately afterward. Five min after the induction, perceptual color bias was remeasured (posttest). The difference between posttest and pretest perceptual color bias yields the strength of the AE that results from the adaptation.

Experiment 2 – AE retention versus TSD: The perceptual color bias of each participant ($n = 5$) was measured on each night. This is the baseline measurement for the particular combination of participant and TSD. The participants then adapted to the stimulus sequence for 5 min, as described in the previous section, Adaptation Procedure. Perceptual color bias was measured after adaptation to yield the strength of the resulting post-adaptation, pre-sleep AE. Then, the participant went to sleep, on separate nights, for approximately 1, 3, 5, or 7 hr (complete sleep); actigraphy measurements found that our participant sample slept, on average, for 1 hr, 28 min \pm 10 min; 3 hr, 4 min \pm 20 min; 4 hr, 37 min \pm 31 min; and 6 hr, 48 min \pm 27 min on the 1-, 3-, 5-, and 7-hr TSD conditions, respectively. Planned contrasts showed that actual TSDs among the 4 TSD condi-

tions were significantly different (all $P_s < 0.02$). TSD order was counterbalanced. Immediately after waking up, participants' perceptual color bias was re-measured to estimate the postsleep AE strength and to compare with presleep AE strength.

Experiment 3 – AE retention across sleep versus wake: In this experiment, retention across an extended period of wakefulness was examined. In the wake condition, participants ($n = 10$) tested and adapted to the inducers in the morning (09:00) were then retested in the evening (21:00) after 12 hr of awake, natural visual experience. In the sleep condition, participants tested and adapted in the evening (21:00) were then retested in the morning (09:00) after a similar 12-hr period that included a night of sleep (on average, participants slept for approximately 7.5 of 12 hr). The same set of participants participated in both conditions, separated by a period of 1 wk. The order of wake and sleep conditions was counterbalanced.

Experiment 4 – Wake (visual deprivation): As in the wake condition of Experiment 3, participants ($n = 10$) tested and adapted in the morning (09:00) and were retested for AE re-

tion after a period lasting several hours. However, in this condition, the adapted eye was deprived of visual stimulation during the intervening period. An eyepatch (Bernell Corp., Mishawaka, IN) was placed in front of one eye that deprived the patched eye of visual stimulation while the person stayed awake. Selection of eye was counterbalanced across the set of participants. For a given participant, the same eye was occluded during adaptation and testing. Participants were then retested in the evening (21:00, 12-hr retention, $n = 5$), or in the afternoon (approximately 17:00; 8 hr retention; $n = 5$). Participants were monitored during the retention period for arousal state with actigraphy. All remained awake throughout this period, during which they conversed, surfed the Internet, and/or worked on examinations and projects in the laboratory.

Extinction procedure

Short exposure to an achromatic grating of the same spatial composition (i.e., orientation, spatial frequency) as the adapter washes out the AE,¹⁸ resulting in veridical perception. After retest, the participant viewed an alternating sequence of achromatic horizontal and vertical gratings of the same composition as the adapters for a period of 5 min. This washed out the AE, as confirmed later on the pre-adaptation test of the subsequent condition. The extinction procedure was instrumental in allowing us to use nearly the same set of participants on all four experiments.

Analysis

Psychometric functions

Test performance for each participant and testing condition was fitted with a cumulative normal distribution function. The two free parameters—the mean (μ) and the standard deviation (σ) of the distribution—were estimated by a least-squares criterion (function *nlinfit* in MATLAB) and the parameter μ determined the point of subjective equality (PSE) or threshold estimate. The PSE represents the physical hue at which both test orientations are perceived to be of identical hue (greenness). Shifts in the PSE indicate a change in color perception in the current study.

Statistical analysis

One-way and 2-way repeated measures analyses of variance (ANOVAs) were used to compare group color AE strengths across four or five different values of TSD in Experiments 1 and 2. The effect of TSD on the induction of adaptation or on AE retention was linearly regressed (AE strength versus number of hours of sleep) and the slope of the least-squares fit was statistically compared to zero using a 2-tailed *t* test. Two-tailed paired *t* tests were also performed to compare within-subject percentage changes in PSE across the various manipulations in Experiments 3 and 4. The *t* tests were also used to confirm above-chance AE strength, or to compare sleep durations measured with actigraphy.

The bootstrap method¹⁹ was used to test the significance of the difference in the preadaptation and postadaptation, pre-sleep and postsleep, and premanipulation and postmanipulation points of subjective equality (PSEs) on pooled data (pooled means data from individual participants is combined and aver-

aged before fitting the pooled averaged data with a psychometric function) from Experiments 3 and 4. Computer simulations using this method enumerated all possible pairs of psychometric functions from the pooled distribution and weighted them by their binomial probability. Each of the possible pairs of psychometric functions yielded a pair of PSE estimates. The difference in PSE between the two psychometric functions ($PSE^{pre} - PSE^{post}$) was compared with the distribution of the PSE differences between the pairs of psychometric functions generated by the bootstrapping method. The upper and lower PSE difference values of the distribution that would exclude the upper and lower 2.5% of the bootstrapped population, respectively, were taken as the 95% confidence limits.

RESULTS

Sleep Before Adaptation Does Not Lead to a Stronger AE

A question is whether sleep just before the induction of adaptation leads to a stronger AE, i.e., an AE that is of larger magnitude. We addressed this issue in two related ways. First, we compared whether wakefulness versus sleep just prior to induction influenced AE magnitude. Second, we explored if the strength of the AE varied systematically with the amount of sleep prior to induction. We hypothesized that if prior sleep enhanced plasticity, AE strength would be greater after sleep than wake. Furthermore, if sleep in general, regardless of sleep stage, augments plasticity, then AE strength would increase with prior sleep duration. Alternatively, if early but not late sleep is responsible for the plasticity enhancement, then AE strength would be largest after 1 or 2 hr of sleep but not after 4 or 8 hr. Note that in healthy sleepers, as our participants were, early sleep (1 hr) typically consists almost exclusively of non-rapid eye movement (REM) sleep, which has been implicated in enhancing a number of different memories.

Our results were unequivocal: Sleep before adaptation did not enhance AE strength. Figure 1 summarizes the results. Figure 1A, right panel, is a schematic diagram of the orientation-contingent color AE: after the adaptation procedure, participants ($n = 5$) perceived a physically achromatic horizontally oriented pattern to be greenish and an achromatic vertically oriented pattern to be reddish. Figure 1B, which is a timeline of the experiment, shows that the adaptation and all tests occur only after the participant wakes up (or is woken up) from sleep. Figure 1C shows the adapted eye's pooled data ($n = 5$ participants) and psychometric curve fits before (black curve) and after (red curve) the adaptation procedure for a representative condition: 4 hr of sleep. The shift between the two curves (double arrow) shows the shift in perceived color and is a measure of AE strength. For all five sleep durations that we tested (0, 1, 2, 4, or 7 hr of sleep), the 5-min-long adaptation procedure yielded a strong orientation-contingent color AE: 2-tailed *t* tests (corrected for multiple comparisons using the false discovery test²⁰ – FDR.m in MATLAB) confirmed the presence of a statistically significant AE after the adaptation procedure for all five sleep durations tested. However, AE strength did not vary in proportion with the actual amount of previous sleep: as Figure 1D shows, the slope of the linear regression of AE strength as a function of TSD was statistically indistinguishable from zero ($R = -0.142$, 95% confidence interval = $[-0.508$,

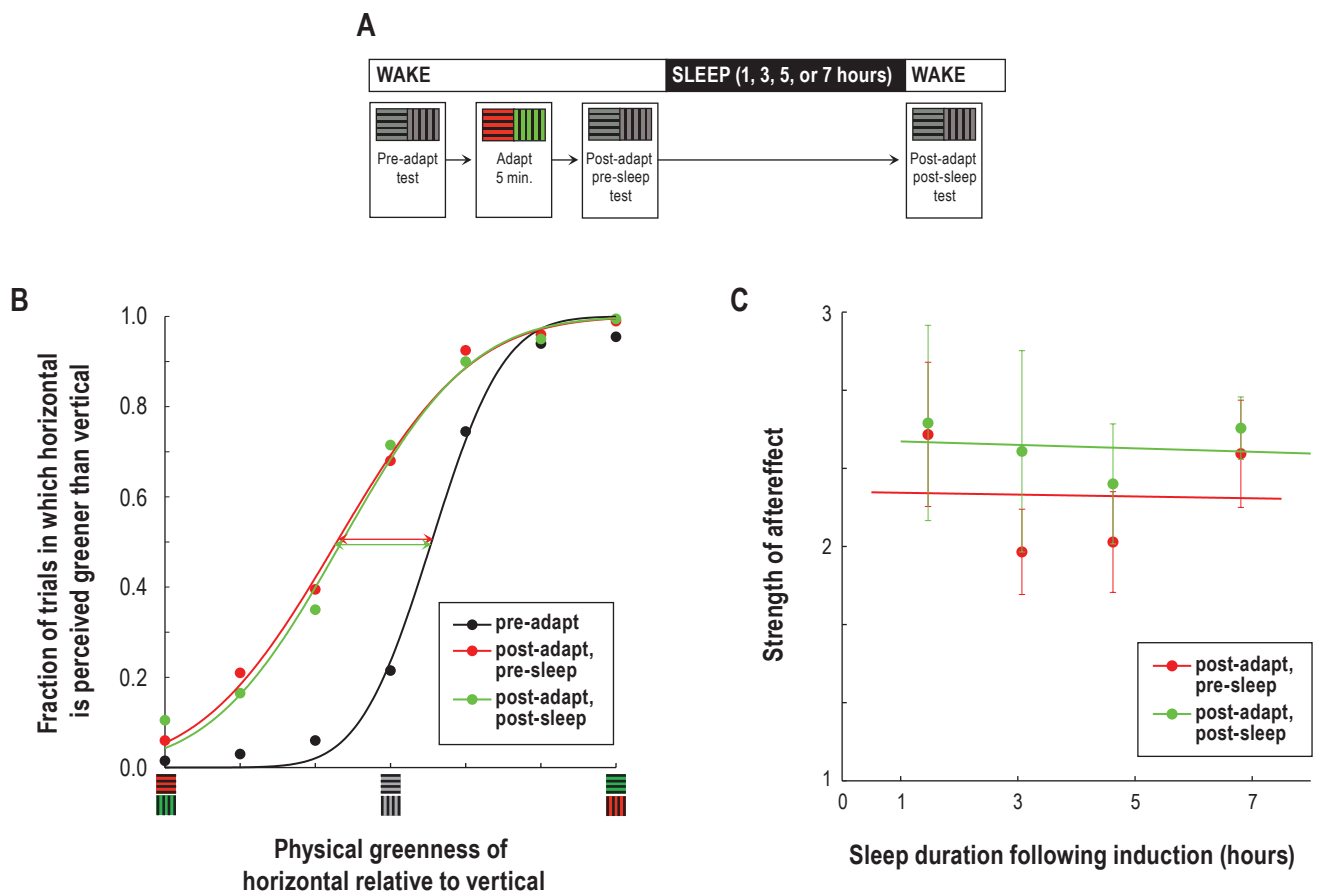


Figure 2—The effect of sleep after adaptation on the strength of the color aftereffect. **(A)** The chronologic sequence of adaptation and tests is depicted with respect to the occurrence of sleep. Sleep duration is varied across different nights. **(B)** Pooled data and psychometric curve fits are shown of preadaptation baseline (black points and curve), post-adaptation, presleep (red points and curve), and postadaptation, postsleep (green points and curve) color perception in the adapted eye for when participants slept for approximately 5 hr immediately after the adaptation. The red double arrows measure the presleep perceptual color shift and the green arrows measure the postsleep perceptual color shift relative to preadaptation baseline levels. Note that the red and green double arrows are of similar length, indicating that aftereffect magnitudes were unaffected across the approximately 5 hr sleep period. **(C)** Presleep (red points and line) and postsleep (green points and line) aftereffect strengths in the adapted eye, normalized to the corresponding measures in the unadapted eye, are plotted as a function of total sleep duration (1, 3, 5, and 7 hr) after the adaptation. The lines represent the respective optimal least-squares fits. Error bars are between-subject standard error of the mean.

0.269]; $P = 0.500$). A 1-way repeated measures ANOVA with TSD as the factor also revealed no effect ($F(4, 16) = 0.686$, $MS_e = 0.598$, $P = 0.612$). In summary, the magnitude of the AE was no different whether one had slept (1-, 2-, -, or 7-hr TSD) or stayed awake (0 hr TSD) just before the induction, and AE strength was not significantly affected by the amount of sleep before the induction either.

Sleep Duration Does Not Modulate Color AE's Strength

TSD prior to adaptation does not affect the strength of the AE. But does TSD after adaptation affect the strength of the AE? Encoding and consolidation are different stages of the memory process, and sleep has been shown to affect the consolidation of a variety of goal-oriented, attention-demanding memories. In the case of motor and visual skill learning in particular, overnight sleep has been found to not just retain but enhance the memory.² We reasoned that if sleep were to enhance AE strength, sleep duration would modulate AE strength. In other words, if sleep, regardless of stage, enhances the visual AE,

additional sleep ought to enhance the AE more, which would mean a monotonic increase in AE strength with postadaptation sleep duration. However, if deep, slow-wave sleep (SWS) is mainly responsible for enhancing the AE, then the AE strength ought to increase between 1 and 3 hr of postadaptation sleep, and exhibit small, perhaps negligible, additional increases over longer sleep durations (5 and 7 hr).

The results did not support either hypothesis: AE strength measured right after sleep, irrespective of its duration, was indistinguishable from that before sleep, indicating that sleep “freezes” the AE that was formed in preceding wake, or maintains it without loss. Figure 2 shows the results. Figure 2A is the timeline. For illustration, Figure 2B shows pooled data ($n = 5$ participants) from the 5-hr condition, which is representative of our findings at all sleep durations tested. The black curve and points are the baseline, i.e., before sleep and before adaptation. The red curve and points are the shift in perceptual color bias, i.e., the color AE after the adaptation procedure but just before the participant goes to sleep. The green curve and

points are the AE after the adaptation and after sleep. Adaptation clearly results in an AE, as indicated by the shift of the red curve relative to baseline (black curve), and 5 hr of sleep leaves the AE intact with little attenuation, as indicated by the lack of a noticeable shift of the green curve relative to the red one in Figure 2B. This lack of a shift induced by sleep was true across all 4 values of TSD tested: 1, 3, 5, and 7 hr (Figure 2C): 2-tailed *t* tests, corrected for multiple comparisons²⁰ revealed AE strength above zero after the adaptation procedure at each of the four TSDs tested. As Figure 2C further shows, there was little change in AE strength across sleep (compare red versus green lines), irrespective of sleep duration: A 2-way repeated measures ANOVA (factors: presleep/postsleep and TSD) found an insignificant change across sleep ($F(1, 28) = 0.563, P = 0.495$) indicating that intervening sleep has negligible effect on AE strength, an insignificant effect of TSD ($F(3, 28) = 0.652, P = 0.597$) arguing against the two hypotheses previously discussed, and, an insignificant interaction between the two factors ($F(3, 28) = 0.653, P = 0.596$), indicating that the lack of change across sleep was, by and large, independent of TSD. A 1-way repeated measures ANOVA on postsleep AE data alone also revealed no effect of TSD ($F(3, 12) = 0.217, MS_e = 0.158, P = 0.883$). Furthermore, as illustrated in Figure 2C, the slope of the linear regression of postsleep AE strength as a function of TSD was statistically indistinguishable from zero ($R = -0.034, 95\%$ confidence interval = $[-0.470, 0.415]; P = 0.887$). Combined, these results suggest that sleep fails to enhance an already existing color AE but does, however, arrest its decay (for as long as one sleeps).

The Color AE is Retained Across Sleep, But Not Across Wake

Sleep after adaptation does not enhance the AE but, as the previous experiment showed, it helps retain the AE and prevents it from dissipating. However, is sleep necessary to retain the AE or could the AE be maintained across a period of wake? To answer this question, we compared AE strengths across a 12-hr retention period of wakefulness alone and a period of identical duration, that included a night of sleep (Figures 4A and 4B illustrate the respective timelines in the two conditions—12 hr wake and 8 hr sleep + 4 hr wake).

The results were clear: The AE dissipated across wakefulness in the intervening period but significantly less across an intervening period that included sleep. Figures 3C and 3D show the pooled data and psychometric curves for baseline (black), postadaptation, presleep (red) and post-adaptation, postsleep (green) tests. There was a dramatic decline in AE strength across a 12-hr period of wakefulness (compare length ratio of green double arrows to red double arrows in 12 hr wake versus 8 hr sleep + 4 hr wake; this yields the fraction of pooled AE retained across each intervening period). Bootstrapping tests statistically confirmed the AE was differentially retained across the two 12-hr periods ($P < 0.001$). For each individual participant, we fitted their baseline, preintervening and postintervening period data with psychometric curve fits and obtained PSEs. From this, we obtained the ratio of the post-12-hr intervening period AE to the pre-12-hr period AE

(i.e. $\frac{\text{post} - 12 \text{ hour PSE} - \text{baseline PSE}}{\text{pre} - 12 \text{ hour PSE} - \text{baseline PSE}}$) for each participant,

which yields the proportion of the AE that is retained across the intervening 12-hr period. Ratio means for the two periods are shown in Figure 3E (% AE retained across the 12-hr wake period was $20.3 \pm 9.6\%$, but $84.5 \pm 20.3\%$ across the 8-hr sleep + 4-hr wake period). Again, there was a significant difference in the retained AE ratios between the two intervening periods ($t(16) = 2.86, P = 0.011$). In summary, sleep shelters the AE from interference and helps retain the change in the adapted visual pathway, whereas the AE decays over a period of intervening wake.

Absence of Visual Stimulation While Awake Helps Retain AE

It could be that some physiologic property of sleep, e.g., REM sleep, SWS, spindles, lack of external visual stimulation, protects the ME from dissipating. Here, we investigate the last of the candidates listed. In the previous experiment, participants went about their daily activities while awake. As a result, their visual pathway was continuously being stimulated by the external environment. Could this stimulation during wake interfere with the AE stored in the visual pathway and hasten its decay? To address this issue, we ran tests on participants ($n = 10$) while they stayed awake but one of their eyes was deprived of visual stimulation (Figure 4A shows the timeline of the visual deprivation experiment). The orientation-contingent color AE is monocular^{14,21}; i.e., the AE can be induced and retained in one eye independent of the other. On this basis, we deprived the adapted eye of stimulation over the wake retention period. Five participants were retested after a 12-hr period of monocular visual deprivation, so as to have similar retention period durations as in the previous experiment. A different set of five participants was retested after an 8-hr period of monocular visual deprivation, so as to parallel in duration a normal period of sleep. There was no statistical difference in the preadaptation baselines (bootstrap test, $P > 0.5$), the postadaptation, predeprivation AE strengths ($P > 0.5$), or the postdeprivation AE strengths between the 8-hr and 12-hr subgroups ($P > 0.25$; see Figure S1 for a comparison between the 8-hr and 12-hr subgroups). Therefore, we combined data from both subgroups (all 10 participants) for further analysis.

Our analysis showed that visual deprivation in the wake period by and large prevented the color AE from dissipating. The results are illustrated in Figures 4B and 4C. Figure 4B shows the pooled data and psychometric curves. As expected, adaptation yielded a robust AE that did not dissipate at all across the wake period during which the adapted eye was deprived of visual stimulation (compare lengths of green and red double arrows in Figure 4B). Bootstrapping tests also showed that the AE strengths before and after the deprivation did not differ ($P > 0.25$). As in the previous experiments, we measured the extent to which the color AE was retained across the deprivation period, which is the ratio of the postdeprivation and

predeprivation AEs ($\frac{\text{post} - \text{deprive PSE} - \text{baseline PSE}}{\text{pre} - \text{deprive PSE} - \text{baseline PSE}}$). Us-

ing this measure, we found that the mean AE retained across our 10 participants was 87.8%, which is statistically indistinguishable from 100% retention or zero decay ($P = 0.72$) and furthermore, is statistically comparable to the mean AE retained across sleep, as Figure 4C depicts. In summary, depriv-

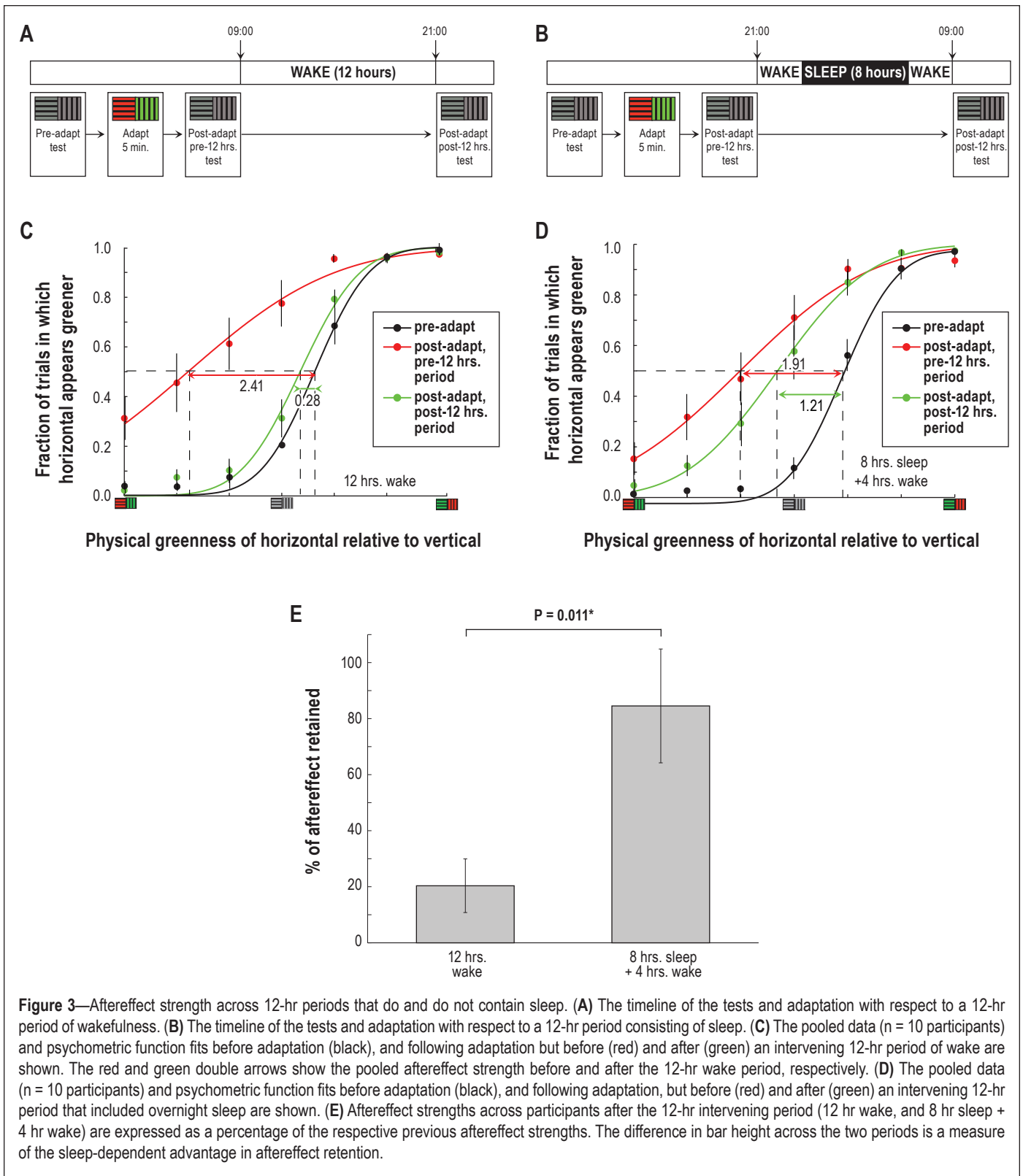
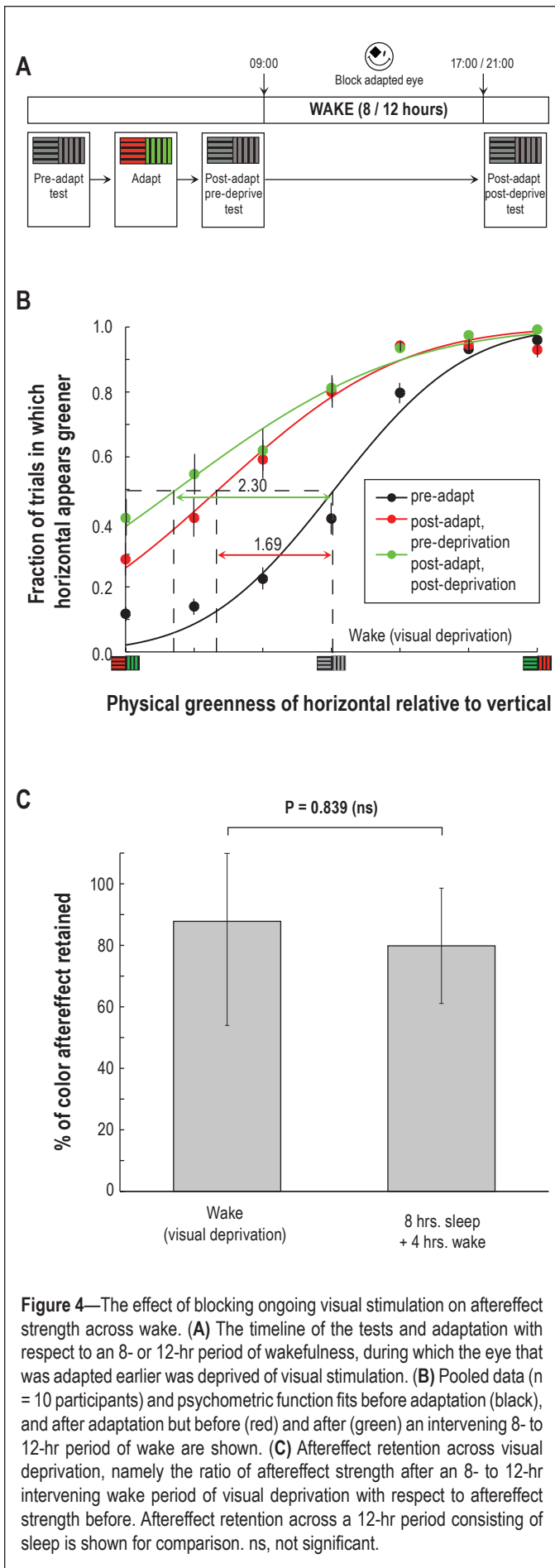


Figure 3—Aftereffect strength across 12-hr periods that do and do not contain sleep. **(A)** The timeline of the tests and adaptation with respect to a 12-hr period of wakefulness. **(B)** The timeline of the tests and adaptation with respect to a 12-hr period consisting of sleep. **(C)** The pooled data ($n = 10$ participants) and psychometric function fits before adaptation (black), and following adaptation but before (red) and after (green) an intervening 12-hr period of wake are shown. The red and green double arrows show the pooled aftereffect strength before and after the 12-hr wake period, respectively. **(D)** The pooled data ($n = 10$ participants) and psychometric function fits before adaptation (black), and following adaptation, but before (red) and after (green) an intervening 12-hr period that included overnight sleep are shown. **(E)** Aftereffect strengths across participants after the 12-hr intervening period (12 hr wake, and 8 hr sleep + 4 hr wake) are expressed as a percentage of the respective previous aftereffect strengths. The difference in bar height across the two periods is a measure of the sleep-dependent advantage in aftereffect retention.

ing the visual pathway of external visual stimulation during wakefulness is sufficient to arrest the dissipation of the AE that was otherwise observed across regular (nondeprived) wakefulness (Figure 3E). The absence of decay in AE strength across a period of visual deprivation is reminiscent of a similar finding across a period of sleep, although the mechanisms underlying each could be different, which we will discuss in the following paragraphs.

DISCUSSION

Approximately 30 to 35 yr ago, MacKay and colleagues studied the effects of sleep on the ME.²²⁻²⁴ MacKay et al.'s studies were conducted on at most three participants (some on just one participant), whereas our study includes up to 10 participants and thus is a more rigorous investigation of the effect of sleep on the ME. Some of our findings confirm and extend theirs, but others diverge from theirs in important ways.



Sleep's Function in AE Induction?

Our findings on the role of sleep in the induction of adaptation diverge substantively from a past study conducted by Lund and MacKay,²² who studied whether sleep before adaptation enhanced the size of the ME in 3 participants, one of whom is an author of this article. They claimed that if sleep duration exceeded 6 hr on the night before the induction ME strength increased with sleep duration, so that ME strength was greatest after approximately 8 hr of sleep; on the other hand, ME strength was diminished by the same amount for all durations of 6 hr or less. We did not find the same result: ME strength was not affected by prior sleep duration, statistically or numerically (Figure 1). We do not know the exact reason for the discrepancy in finding but we highlight some key differences between the respective experimental procedures. Adaptation duration was 5 min in our study, but 15 min in theirs. Thus, their ME is likely to be stronger than ours but will also last for a longer duration, perhaps for weeks. This is problematic because MEs resulting from inductions a few days apart accumulate and interact. Unlike in our study, MacKay and colleagues did not wash out the ME and did not report the color bias before induction (Figure S2 shows there is no bias before adaptation at any of the sleep durations for our participants in Experiments 1 and 2, and that the preadaptation bias is statistically indistinguishable from zero.). Moreover, unlike MacKay and colleagues, at the start of each experiment, we measured the amount of preexisting color bias in both eyes, and normalized for it in our analysis. Thus, there were a number of procedural differences between the two studies that could account for the discrepancy in finding.

Active Versus Passive Models of Sleep Function in AE Retention

In contrast, we confirmed and extended MacKay and MacKay's finding that the ME did not diminish across a night of (approximately 8 hr) sleep;²³ we found that the ME does not change strength across sleep, irrespective of whether the person slept 1, 3, 5, or 7 hr after the induction (Figure 2). Although we did not conduct polysomnographic recordings, it is well known that early sleep in healthy sleepers consists primarily of deep, non-REM sleep (mostly SWS), and late sleep consists primarily of REM sleep.²⁵ Had SWS played a major role in arresting AE decay, one would expect that the ME would be larger over 3 hr of sleep than 1 hr, because of the greater amount of SWS accumulated across the additional 2 hr, but no further changes in ME strength would occur over longer sleep durations, because SWS constitutes a small portion of late sleep. Had REM sleep played the major role instead, the ME would diminish over short sleep durations (1 or 3 hr) that are dominated by non-REM sleep, but that there would be no further loss or even a compensatory gain in ME strength over longer sleep durations (5 or 7 hr). However, our results do not support any of these hypotheses: AE strength remains unaffected by subsequent sleep, irrespective of sleep duration.

The hypotheses mentioned presuppose that sleep, via active mechanisms unique to sleep, helps retain the ME. On the other hand, our study lends support to the hypothesis that sleep passively maintains the ME. During both REM and non-REM sleep the eyes remain shut, precluding external sensory interference. The passive model is in line with our finding that the ME decays during regular wakefulness^{23,24} (Figure 3) and

blocking retinal stimulation during wakefulness arrests the decay^{23,24} (Figure 4). Nevertheless, although the passive, permissive model provides a parsimonious account of experimental data to date, we have no data that actually eliminate the active model. Sleep could, via active mechanisms unique to it, avert ME decay and achieve the same result as sensory interruption. Perhaps the only way to truly test (and prove) the active model of sleep is a gedanken experiment: during sleep, bombard the retina with patterned visual stimuli; the ME decay caused by experimentally induced sensory interference is counteracted by putative, active sleep-dependent mechanisms; ME strength after sleep will still be greater than that across an equivalent period of wakefulness (with identical manipulation).

Sensory Exposure and Sleep

Studies have shown that sleep shelters declarative memories,²⁶ and face recognition memories,²⁷ from sensory interference. Depending on the form of memory in question, the sheltering effect of sleep is passive and temporary, as has been shown for face recognition memory,²⁸ or endures beyond the duration of sleep, as has been shown for verbal memory.²⁹ Memory for new word associations and new faces is typically best right after learning them. During the course of a typical day, one sees and recognizes scores of faces and listens to and speaks countless words, which interferes with newly laid memory traces. Sleep shelters these memories by suppressing sensory stimulation. Thus, the sheltering effect of sleep appears to be quite general across different forms of memory. Therefore, it is not unreasonable to expect that the sheltering effect of sleep demonstrated here for a passive form of visual learning shares some commonalities in terms of underlying mechanism with analogous sheltering effects observed for attention-demanding, goal-oriented, reward-driven forms of memory.

Adaptation as an Account of Our Findings

We explore an account of our findings on the sheltering effect of sleep from sensory interference based on local synaptic adaptation/fatigue. Adaptation is an integral component of an account of sleep function in visual and motor skill learning. Experiments have shown that performance on a visual discrimination task saturates, and sometimes deteriorates, over the course of a day's overtraining but sleep arrests the decline and reverses it³⁰; similarly, performance on a motor skill task saturates over the course of a day's training but then shows a marked improvement immediately following sleep.^{31,32} Such findings of sleep altering the trajectory of performance have led one of us to hypothesize that intensive training on a procedural skill triggers two opposing processes—learning and local synaptic fatigue³³ (similar arguments were proposed later by Censor et al.,³⁴ using the term adaptation in place of synaptic fatigue/burnout). As training progresses, learning continues unabated, but the consistently intense attentional demands cause the cell assemblies and synapses tuned for the task to “burn out” or fatigue. To compensate, the brain recruits circuits and cells that are increasingly less tuned to the task. Depending on the moment-by-moment balance between the two processes, behavioral performance either saturates or dips. Sleep helps the brain recover from the local synaptic burnout, which allows for the learning to manifest more completely. The behavioral outcome

of this recovery is the enhancement in overnight performance observed in experiments.

Applying somewhat simplistically the previously discussed ideas of local synaptic adaptation to the current study on visual adaptation, one might argue that the sleeping brain ought to “recover” from the adaptation that occurred earlier during wake. Because of our data demonstrating that the ME remains intact across sleep, this finding cannot account for our data (for that matter, the synaptic homeostasis hypothesis posits that the synaptic strength of acquired memories must change across sleep,³⁵ which is contradicted by current data as well). This is because the dual process account applies to certain kinds of memories that demand attention during acquisition and visual adaptation is not one of them, because visual adaptation places no demands on voluntary attention.¹³ In brief, the synaptic fatigue/burnout is not applicable here.

If Sleep Equals Sensory Deprivation

Nonetheless, the remarkable convergence of sensory deprivation and sleep in sheltering the ME begs for an explanation. If sleep works via sensory deprivation in sheltering certain memories from sensory interference, it could have important implications for how neuronal activity during sleep in visual areas is affected by this type of adaptation. Studies suggest that the hippocampus plays a crucial role in the consolidation of declarative memories,³⁶⁻³⁸ which are initially formed in the hippocampus. However, adaptation is not a form of memory whose neural substrate is the hippocampus but rather the early visual pathway, and therefore, it is not unreasonable to expect that the memory mechanisms underlying each are different. Activation by an ongoing barrage of external stimuli of the neural substrate storing the ME is sensory interference; sensory deprivation prevents sensory interference by precluding activation of the cell assemblies that store the AE, thereby preserving the memory as is.

The explanation is somewhat simplistic, however. Neurons slowly oscillate at a rate < 1 Hz between quiescent and bursting states in stage 2 sleep and SWS,^{39,40} whereas waves of activity continuously propagate through the thalamus and visual cortex in REM sleep.²⁵ Put another way, the brain is not shut down during either REM or non-REM sleep. An alternative explanation must be explored in light of this fact: the cell assemblies in the visual pathway that constitute the neural substrate of the ME (neurons that are tuned to the orientation, spatial frequency and color of the adapting patches) get activated in sleep but at the same rate and phase as the neighboring cell assemblies that are not part of said substrate; this means no local differences in activity level to trigger activity driven change in synaptic strength from prior wake. This results in preserving the ME as is. Our account is speculative but testable.

A Role for Sleep in Reflexive Learning

The previous discussion brings us back to a point we made at the outset. Nearly all sleep-dependent forms of learning examined to date are active, i.e., attention to the stimulus is required for improved performance, and goal-directed, i.e., overnight improvement, is rewarded, explicitly or implicitly. In contrast, attention is not required to adapt: visual adaptation merely requires visual exposure. Adaptation is not explicitly goal-driven: retaining an AE carries no reward or conceivable benefit to the

organism. Perceptual judgments of color cannot be ascribed a utility value in terms of success or failure, and adaptation is not an error but rather a recalibration of the system in response to the most recent visual environment. Controversies regarding account notwithstanding, the current findings do reveal that sleep, or more precisely the lack thereof, influences reflexive forms of synaptic plasticity that do not demand attention.

CONCLUSIONS

In healthy human adults, sleep prior to encoding did not facilitate acquisition of a visual AE. In contrast to wake, sleep after adaptation did shelter the AE from decay, although the sheltering effect was mimicked during wake by precluding visual interference. There are two widely accepted canons in the literature concerning the role of sleep in neural plasticity based on a number of studies of goal-directed, attention-demanding forms of memory: sleep has an irreplaceable role in memory retention and plasticity and, when sleep does help stabilize or retain a memory, the mechanism by which it does is memory trace reactivation. The current findings on sensory adaptation argue that these views do not generalize to sleep's influence on reflexive forms of learning that do not demand attention.

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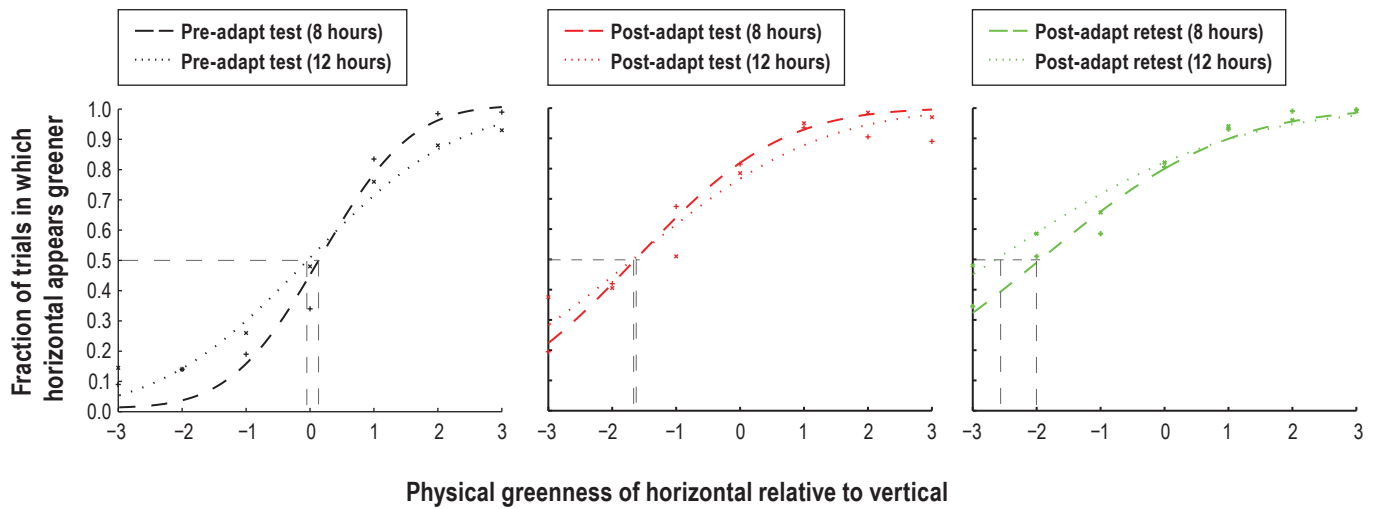


Figure S1—Pooled data and psychometric curve fits of pre-adaptation (left), post-adaptation, pre-deprivation (middle), and post-adaptation, post-deprivation (right) data are shown comparing the 12 hr (dashed lines) deprivation and 8 hr (solid lines) deprivation sub-groups ($n = 5$ participants in each). Bootstrap tests showed that the two sub-groups did not differ statistically in either the pre-adaptation ($P > 0.5$), the pre-deprivation ($P > 0.5$), or the post-deprivation tests ($P > 0.25$). The lack of a statistical difference at any level between the 8 hr and 12 hr visual deprivation sub-groups justified our combining both for analysis.

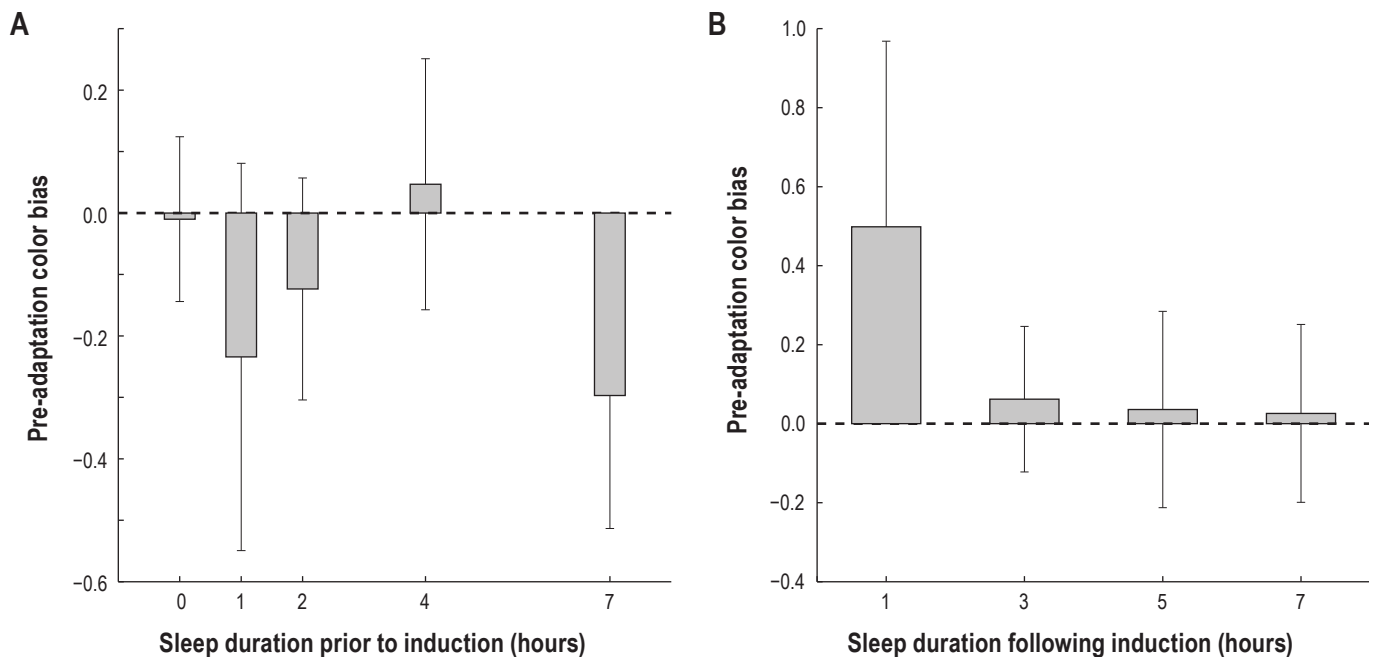


Figure S2—Perceptual color bias before adaptation **(A)** Pre-adaptation color bias versus total sleep duration prior to the tests is shown. A repeated measures ANOVA performed on the data with TSD as the main factor found that the bias was largely unaffected by prior sleep duration ($F(4, 16) = 0.66$, $MS_e = 0.159$, $P = 0.626$). Furthermore, one-sample t-tests found that the bias at each of the five TSD values tested was statistically indistinguishable from zero (all five $P_s > 0.2$). This shows that our participants' initial pre-adaptation color perception at all five TSD values was not biased, which strongly suggests that our extinction, or wash-out, procedure is effective. **(B)** Pre-adaptation color bias versus total sleep duration after the test. Once again, note that there is little difference in bar heights among the different TSD values. This is borne out by the data showing that pre-adaptation bias at all four TSD values is statistically indistinguishable from one another ($F(3, 12) = 0.81$, $MS_e = 0.323$, $P = 0.511$). As before, one-sample t-tests comparing individual bias with zero did not find differences from zero at any of the TSD values (all $P_s > 0.3$). Once again, these data confirm the effectiveness of our wash-out procedure and indicate that there is no bias before adaptation in our sample.