Voluntary Oculomotor Performance Upon Awakening After Total Sleep Deprivation

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Abstract: The potential impact of sleep inertia on measures of voluntary oculomotor control have been surprisingly neglected. The present study examined the effects of 40 hours of sleep deprivation on saccadic (SAC) and smooth pursuit (SP) performance, attentional/visual search performance (Letter Cancellation Task, LCT) and subjective sleepiness (Sleepiness Visual Analog Scale, SVAS) recorded immediately after awakening. Standard polysomnography of nine normal subjects was recorded for 3 nights (1 adaptation, AD; 1 baseline, BSL; 1 recovery, REC); BSL and REC were separated by a period of 40 h of continuous wakefulness, during which subjects were tested every two hours. Within 30 s of each morning awakening, a test battery (SAC, SP, LCT, SVAS) was administered to subjects in bed. For data analysis, mean performance obtained during the day preceding the sleep deprivation night was considered as "Diurnal Baseline" and compared to performance upon awakening from nocturnal sleep. As a consequence of sleep deprivation, SWS percentage was doubled during REC. Saccade latency increased and velocity decreased significantly upon awakening from REC as compared to the other three conditions (Diurnal baseline, AD awakening, BSL awakening); accuracy was unaffected. As regards SP, phase did not show any impairment upon awakening, while velocity gain upon awakening from REC was significantly lower as compared to the other conditions. Finally, number of hits on LCT upon awakening from REC was significantly lower and subjective sleepiness higher as compared to Diurnal Baseline. It is concluded that 40 h of sleep deprivation significantly impaired performance to SAC and SP tasks recorded upon awakening from recovery sleep. This performance worsening is limited to the measures of speed, while both SAC accuracy and SP phase do not show a significant decrease upon awakening. Since saccadic velocity has recently been found to negatively correlate with simulator vehicle crash rates, it is suggested that the adverse effects of sleep deprivation on sleep inertia magnitude should be avoided by any personnel who may have to perform critical tasks involving high oculomotor control immediately after awakening.

Key words: Sleep deprivation; sleep inertia; smooth pursuit; saccadic eye movements; awakening; oculomotor performance

INTRODUCTION

THE NEUROBEHAVIORAL CONSTRUCT OF "SLEEP INERTIA"[1] CAN BE CONCEPTUALIZED AS THE CARRYOVER OF SLEEP-RELATED PROCESSES INTO THE WAKING STATE THAT IMMEDIATELY FOLLOWS AWAKENING.[2] FROM A PHYSIOLOGICAL POINT OF VIEW, THE TRANSITION between sleep and wakefulness is characterized by a reduction in cerebral blood flow velocity,[3-5] a gradual and continued drop of theta and delta EEG power well into the first few minutes of wakefulness[6] and a general impairment of cerebral responsiveness as indicated by the decreased amplitude and increased latency of some components of visual evoked potentials.[7] This state of "functional deafferentation[7]" is probably responsible for the cognitive and behavioral performance impairment observed up to one hour after awakening from sleep.[8,9]

One of the most powerful sleep inertia modulating factors is the homeostatic pressure for sleep. Long periods of wakefulness, causing profound modification in sleep architecture and increasing sleep depth, dramatically exacerbate cognitive impairment upon awakening from recovery sleep (e.g., 10). It has been reported that cognitive decrements after abrupt awakenings from one and two hour naps show a linear relationship with SWS amount during the nap.[10,11] Some recent results suggest that this worsening of cognitive performance after sleep deprivation is correlated with changes in core body temperature,[12] as already hypothesized by Dinges.[13]

On the other hand, the available evidence for circadian modulation of sleep inertia can not be considered definitive. Conflicting evidence comes from studies of napping with and without previous sleep deprivation (e.g., 14—16), as well as from repeated awakenings during nocturnal sleep (e.g. 17—19). As an example, Bonnet & Arand[14] reported a worsening of sleep inertia effects following awakening at

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5:00 A.M., but some other studies showed greatest performance impairment upon awakenings placed in the first part of the night.[16, 20-21]

Moreover, the intensity of sleep inertia is influenced by the type of task used, highly demanding cognitive and attentional tasks being much more affected than simple motor ones (e.g., 2, 22-23).

As far as the sleep inertia time course is concerned, performance impairment upon awakening has been reported to persist for time periods ranging between 30 minutes and about two hours.[8, 9, 24] These large differences in sleep inertia duration may be due to methodological differences between these studies as well as to a possible differential sensitivity of the performance tasks used.

Performance impairment upon awakening also has relevant operational implications. In an increasing number of work settings, as in sustained military/peace-keeping operations, space flight preparation and launching, crisis and catastrophe management, sustained periods of continuous performance are often required.[25] In these work scenarios sleep inertia is a serious contraindication to the use of napping during quasi-continuous operations, especially if highly skilled and dedicated personnel may be required to perform complex tasks immediatly after sudden awakening at unpredictable times.[10]

Previous studies on the effects of sleep inertia have preferentially used performance tasks such as reaction time and arithmetic tasks,[2,10-11,22,26] while the potential impact of sleep inertia on measures of voluntary oculomotor control have been neglected. Some of these measures (e.g., eye blinking rate, mean saccade velocity, saccade rate, peak saccade velocity) have already been evaluated during simulation of different flight or driving tasks (e.g., 27-30) or after an acute shift of the sleep-wake cycle,[31] as possible indices of workload, fatigue, or sleepiness. The evaluation of the actual effectiveness of voluntary oculomotor performance upon awakening can have significant implications in some operational contexts (e.g., air traffic controllers, pilots) where the consequences of human error may be catastrophic.

For these reasons, as part of a larger research program,[32] in this study we tested saccadic and smooth pursuit eye movements, attentional/visual search performance, and subjective sleepiness upon morning awakening from undisturbed nocturnal sleep, as well as upon awakening from recovery sleep that followed 40 hours of continuous wakefulness. An impairment of oculomotor and attentional performance upon awakening is expected, as compared to a baseline level recorded during diurnal wakefulness. In addition, a further impairment after sleep deprivation is expected, as a consequence of increased sleep depth.

MATERIALS AND METHODS

Subjects

Nine normal male subjects were selected as paid volunteers for the study (mean age=23.2 years). Subjects were selected if they usually went to sleep between 11.00 and 12.00 P.M. and if they usually slept 7—8 hours per night. Other requirements for inclusion were: no daytime nap habits, no excessive daytime sleepiness, no other sleep, medical or psychiatric disorder, as assessed by a one-week sleep log and by a clinical interview. Participants were unaware of the purpose of the experiment and signed an informed consent; their rights were protected through the entire course of the experiment.

Procedure

The protocol of the study was reviewed and approved by the local Institutional Review Board. Participants slept for three nights in a sound-proof, temperature controlled room: 1) Adaptation (AD); 2) Baseline (BSL); 3) Recovery (REC).

To avoid a progressive improvement of performance during the experiment due to a practice effect, all the subjects familiarized with the oculomotor tests in the evening that preceded the adaptation night by performing them at least three times each. In addition, with regard to the Letter Cancellation Task (LCT), they were trained to asymptotic performance levels during the whole day preceding the baseline night, by performing an LCT every two hours starting at 10 A.M. after the awakening from the adaptation night. For this reason, performance upon awakening on the adaptation night was excluded from the LCT data analysis (see below).

Every night, sleep recording started at 11.30 P.M. (±15 min) and ended after 7.5 hours of accumulated sleep (i.e., sleep duration was kept constant within and between subjects). In the adaptation and baseline nights, subjects arrived at the sleep laboratory and, after electrode and ear mold[1] montage, their undisturbed sleep was recorded. A 40 hour schedule of sleep deprivation began on morning awakening following the baseline night. Subjects remained in the sleep laboratory together with at least one experimenter throughout the whole course of the 40 hours of continuous wakefulness. During the sleep deprivation period, every two hours oculomotor performance (saccadic eye movements - SAC -, smooth pursuit eye movements - SP - and optokinetic nystagmus - OKN -) was recorded, as a possible indicator of sleepiness, in the above-mentioned sound-proof, temperature controlled bedroom. During the testing period, subjects were sitting in bed leaning their back against the headboard. The oculomotor performance

[1]In this experiment middle-ear muscle activity (MEMA) during sleep was recorded by a pressure-sensitive transducer encased in silicone ear molds fitted to the individual external auditory canals (for more details see Ref. 32).

was assessed in the dark. Each subject was requested to position his head to a predetermined height, to insure that the bar (see below) was exactly located in front of his eyes. Furthermore, variations of attentional/visual search performance and of subjective sleepiness were assessed respectively by means of a Letter Cancellation Task (LCT), and of a Sleepiness Visual Analog Scale (SVAS). The duration of each testing session was about 30 minutes. The mean of performances recorded during the day preceding the sleep deprivation night (seven testing sessions, from 10 A.M. to 10 P.M.) has been considered in the present study as "Diurnal baseline."

When not involved in testing sessions, subjects were allowed to carry out their own preferred activities, such as reading, writing, listening to music, watching TV, or playing games, always under the direct supervision of at least one experimenter. Lying down, sleeping and vigorous physical activity were not permitted. Meals were provided to subjects at 8.30, 14.30, and 19.30. Non-scheduled light snacks were permitted, while caffeinated beverages, chocolate, alcohol, and medications that can induce sleepiness were not allowed during the deprivation protocol. Time information was available to subjects, and light exposure was not strictly controlled for (although the laboratory was constantly illuminated by four neon lamps, blinds only in part attenuated the light coming from the outside).

Results on performance and vigilance during the sleep deprivation period will be presented elsewhere. The 40-hour schedule of sleep deprivation ended at 10.00 P.M.; the recording of the recovery night began at 11.30 P.M. (±15 min). Subjects were awakened after 7.5 hours of accumulated sleep. Within 30 seconds of each morning awakening, a shorter version of the above-mentioned test battery was again administered (OKN was omitted) to subjects sitting in bed in the same conditions as in the diurnal testing. The first test (SAC) was given about 30 seconds after awakening; the second test (SP) after about three minutes after awakening; the third one (LCT) five minutes after awakening and the SVAS 10 minutes after awakening. The tests were always administered in the same order.

Saccadic Eye Movement Recording

The test stimulus was a visual target (a red dot of light) moving, once each 1-1/4 seconds, on a horizontal bar located at 1.2 meters from the subject's eyes. The subject was asked to fix his gaze on the target at the center of the bar without moving his head, and then to visually follow the target which moved horizontally through a series of stepwise jumps of pseudo-random amplitude (5 to 30 degrees), within a range of ± 20° of the visual field. For each session, about 100 saccadic eye movements were elicited in a time interval of two minutes. Eye movements were recorded with an electronystagmographic (ENG) technique by two electrodes placed about 1 cm from the medial and lateral canthi of the dominant eye; a bipolar recording (AC, time constant: 15.9 sec) was carried out with an Automated ENG MASTR Package (ICS Medical Corporation), installed on a Bull Micral 200 computer. This system controlled the stimulus administration and calibration, and also performed automatic saccade analysis after detection and rejection of eye movements considered as artifacts.

Latency of saccadic eye movements, their accuracy and their peak velocity (limited to the saccades between 10° and 16°) were considered as dependent variables for data analysis. Latency was computed as the time between stimulus movement and the first eye movement of more than 90°/second. Accuracy is the amplitude of the first saccade (not considering other possible correcting saccades) divided by the amplitude of target movement, and expressed as a percentage. Peak velocity is the maximum velocity reached in each saccadic movement as measured over an 18.75 msec period. Finally, the algorithm of the analysis software rejected as artifacts eye movements that occurred too early (250 msec before through 75 msec after target movement), too late (more than 600 msec after target movement), or in the wrong direction.

Smooth Pursuit Eye Movement Recording

The test stimulus was a red dot of light moving on a horizontal bar located in front of the subject at eye height and at a distance of 1.2 meters. The subject was asked to look at the center of the bar without moving his head and to fix his gaze on the dot of light which moved horizontally in a sinusoidal pattern for a total amplitude of 33.4° of the visual field. Six different stimulus frequencies were used: 0.2, 0.3, 0.4, 0.5, 0.6, 0.7 Hz, which corresponded respectively to a peak velocity of 21, 31.5, 42.5, 52.5, 63 and 73.5 degrees per second. Six cycles were recorded with each stimulus frequency. The whole sequence was repeated twice. Eye movements were recorded with the same ENG technique and system used for the SAC. This system controlled the stimulus administration and calibration, the recording and automatic analysis of SP eye movements.

Phase (accuracy of eye movement measured in angular degrees of leading or lagging with respect to target movement) and velocity gain for right and left eye movements (peak velocity of eye movement/peak velocity of target movement) were considered as dependent variables after elimination of saccadic eye movements (defined as movements faster than the stimulus by 15 deg/s). As regards the former variable, the phase of the fundamental frequency of the eye movement is computed by the computerized system from a Discrete Fourier Transform, and compared to the phase of the stimulus. If phase shift is greater than 3° leading or more than 20° lagging, the cycle is rejected as an artifact. For computing gain, the velocity of the stimulus over its fastest 250 milliseconds is compared to the eye-movement over the same period.

Letter Cancellation Task

This task required subjects, in a five-minute period, to search and sign sequentially (from left to right and from top to bottom), as fast and as accurately as possible, three target letters within a 36x50 matrix of capital letters (fonts: New York, 12") printed on an A4 paper sheet.[33] Every target appeared 100 times in a random sequence; for each matrix, 300 hits were possible. Number of hits was considered as dependent variable.

Sleepiness Visual Analog Scale (SVAS)

The SVAS required subjects to provide a graphic evaluation of their sleepiness by making a point, corresponding to the intensity of their feeling, on a 100 mm long line. The line was anchored at the left end with "extremely sleepy" and at the other end with "extremely wide awake." The distance of the point from the right end of the line was considered as the dependent variable.

Sleep recording

A VEGA 24 (Esaote Biomedica, Firenze) polygraph set at a paper speed of 10 mm/s was used for polygraphic recordings. EEG (C3-A2 and C4-A1) was recorded with an AC time constant of 0.3 s and a low pass filter set at 30 Hz.

Bipolar horizontal and vertical eye movements were recorded with a time constant of 1 second. Bipolar horizontal EOG was recorded from electrodes placed about 1 cm from the medial and lateral canthi of the dominant eye,[2] and bipolar vertical EOG from electrodes located about 3 cm above and below the right eye pupil.

Submental EMG was recorded with a time constant of 0.03 seconds as a standard measure of electromyographic activity during sleep. Supplemental bipolar EMGs with a time constant of 0.03 seconds were recorded by the right and left masseter muscles and by laryngeal surface electrodes.[3] Electrode impedance was kept below 5 KOhms.

Data Analysis

Left central EEG (C3-A2), EMG, and horizontal and vertical EOG were used to visually score sleep stages, according to the standard criteria (35). With regard to SWS scoring, the amplitude criterion (>75 μV) was strictly followed.

As regards SAC, latency and accuracy of saccadic eye movements were submitted to a one-way repeated measure ANOVA with Condition (Diurnal baseline, AD, BSL, REC), while velocity was submitted to a two-way repeated measure ANOVA Amplitude (10°, 11°, 12°, 13°, 14°, 15°, 16°) by Condition (Diurnal baseline, AD, BSL, REC).

As regards SP, phase and velocity gain for right and left eye movements were submitted to two-way repeated measure ANOVAs Frequency (0.2, 0.3, 0.4, 0.5, 0.6, 0.7 Hz) by Condition (Diurnal baseline, AD, BSL, REC).

As regards LCT, number of hits was submitted to a one-way repeated measure ANOVA with Condition (Diurnal baseline, BSL, REC); in this case, performance upon awakening on the adaptation night was excluded from the analysis, since subjects were trained to asymptote during the day preceding the baseline night (see Procedure section).

Finally, as regards SVAS, subjective evaluation of sleepiness was submitted to a one-way repeated measure ANOVA with Condition (Diurnal baseline, AD, BSL, REC).

Post-hoc comparisons of means (Fisher PLSD) were carried out where needed.

RESULTS

Polysomnography

These results have been published in detail elsewhere (32). Briefly, as a consequence of sleep deprivation, recovery nights were characterized by a decrease of stage 1, stage 2, and intra-sleep wake. SWS percentage was doubled (from 10.94 to 22.12 percent), the sleep efficiency index increased, and percentage of REM sleep was unaffected. The latencies of all NREM sleep stages were shortened.

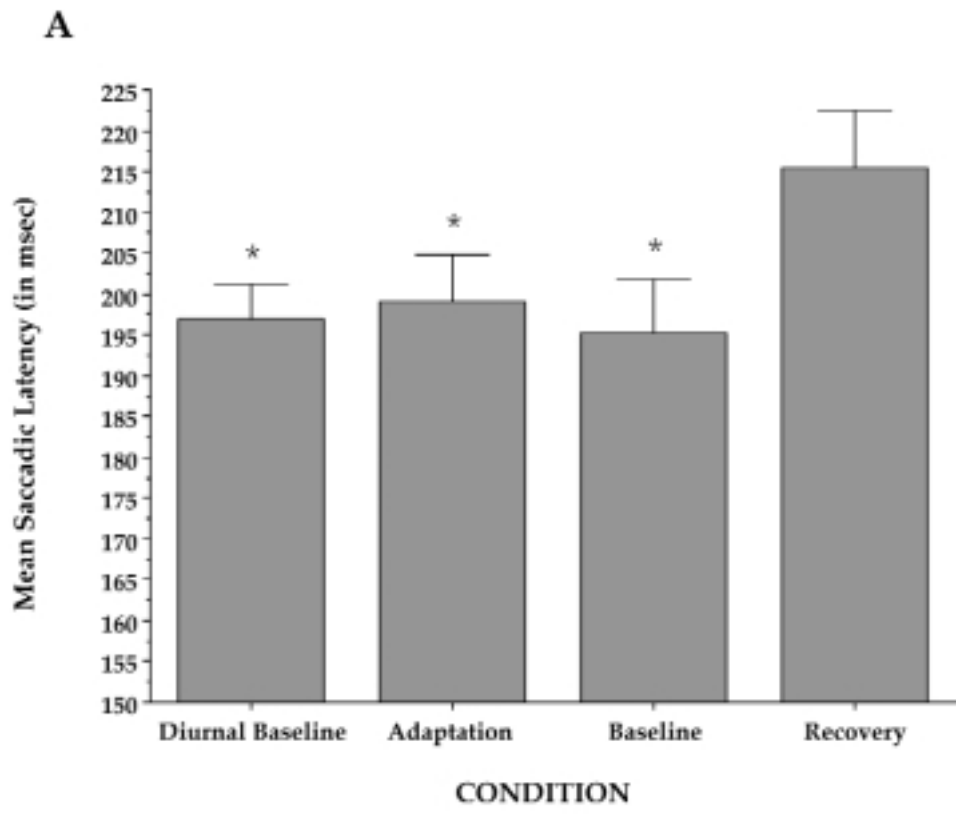
Saccadic Eye Movements

Latency of saccadic eye movements. One-way ANOVA was significant ($F_{3,24}=7.01$; $p=.001$; Figure 1a). Saccadic latency was negatively affected by the increased depth of recovery sleep; as a matter of fact, post-hoc comparisons of means indicated that latency increased significantly upon awakening on REC night as compared to the other three conditions (see Fig. 1a). However, a significant increase of saccadic latency was not evident upon awakening from adaptation and baseline nights, as compared to Diurnal Baseline.

Velocity of saccadic eye movements. Two-way ANOVA showed a significant main effect for Condition ($F_{3,24}=7.33$; $p=.001$; Figure 1b). Also in this case, saccadic velocity was negatively affected by the increased depth of recovery sleep. Post-hoc comparisons showed that mean saccadic velocity upon awakening on REC is significantly lower as compared to the other three conditions (see Fig.

[2] Eye dominance, a behavioral measure of lateral preference, was evaluated by a seven-item questionnaire.[34]

[3] Supplemental EMG deviations were due to the need to discriminate between endogenous MEMA (see footnote 1) and middle-ear variations evoked by motor activity (i.e., subvocalizations, mouth opening, swallowing, teeth clenching, and head turning). Furthermore, we monitored the subject's head movements by means of a strain gauge connected to the ear mold, and monitored the sound level in the sleep room by means of a microphone placed at the level of the subject's head.[32]



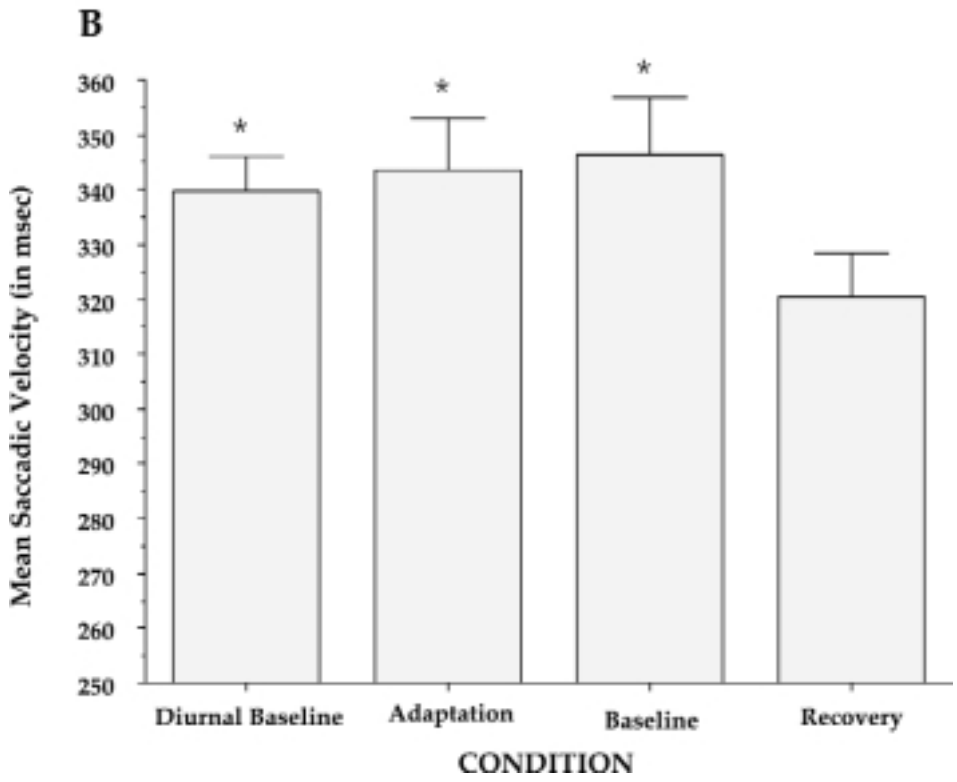


Figure 1—Panel A reports mean latency (+1 SEM) of saccadic eye movements (in msec) in the Diurnal Baseline and upon awakening from the three experimental nights (Adaptation, Baseline and Recovery). Asterisks indicate significant differences (REC vs. Diurnal Baseline: p=.001; REC vs. AD: p=.003; REC vs. BSL: p=.0005). **Panel B** shows mean velocity (+1 SEM) of saccadic eye movements (in msec) in the Diurnal Baseline and upon awakening from the three experimental nights (Adaptation, Baseline and Recovery). Asterisks indicate significant differences (REC vs. Diurnal Baseline: p=.005; REC vs. AD: p=.0009; REC vs. BSL: p=.0003).

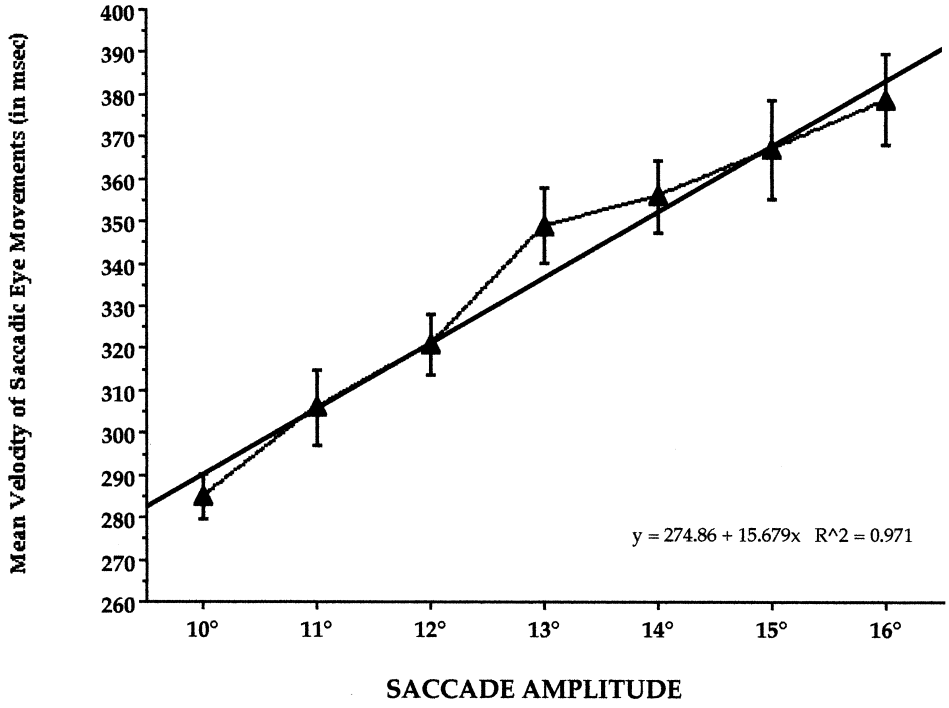


Figure 2—Mean velocity (±1 SEM) of saccadic eye movements (in milliseconds) for each considered amplitude. The interpolate curve indicates a linear increase of saccade velocity as a function of the increasing saccade amplitude.

1b). Again, a decrease of saccadic velocity was not detected upon awakening from adaptation and baseline nights.

The main effect for Amplitude was also significant (F6,48=52.57; p=.000000), indicating the physiological increase of eye movement velocity as a function of the amplitude of saccades (Figure 2).

The Amplitude x Condition interaction was not significant (F18,144=1.48; p=.10).

Accuracy of saccadic eye movements. One-way ANOVA was not significant (F3,24<1), indicating that fairly stable levels of saccadic accuracy were maintained upon awakening from sleep. Increased sleep depth during recovery sleep did not affect saccadic accuracy.

Smooth Pursuit Eye Movements

Velocity gain of SP rightward (RVG) and leftward (LVG) eye movements. Two-way ANOVA showed a significant main effect for Condition for both RVG (F3,24=3.20; p=.04) and LVG (F3,24=5.12; p=.007, Figure 3). Globally, SP velocity gain was impaired by the increased depth of recovery sleep. Post-hoc comparisons showed that RVG upon awakening from REC is significantly lower as compared to the other three conditions (see Fig. 3). Moreover, LVG upon awakening from REC is significantly lower as compared to Diurnal Baseline and to performance upon awakening from BSL (see Fig. 3), while the difference between REC and AD only approached significance (p=.06). For both RVG and LVG no significant differences were found between Diurnal Baseline and performance upon awakening from adaptation and baseline nights, indicating that these variables are negatively affected only when sleep follows a period of sleep deprivation.

The main effect for Frequency was also significant for both RVG (F5,40=21.78; p=.00000) and LVG (F5,40=24.68; p=.00000), indicating a worse performance at the highest frequencies (Figure 4a).

The Frequency x Condition interaction was not significant (RVG: F15,120=1.24; p=.25; LVG: F15,120<1).

Phase of SP eye movements. Two-way ANOVA showed a significant main effect for Frequency (F5,40=28.08; p=.00000), indicating the negative effect of increasing target frequencies on SP responses (Figure 4b).

The main effect for Condition (F3,24=2.30; p=.10) and the Frequency x Condition interaction (F15,120=1.15; p=.32) were not significant.

Letter Cancellation Task[4]

Number of hits. One-way ANOVA was significant

[4] The Letter Cancellation Task and Sleepiness Visual Analog Scale were completed by eight out of nine subjects

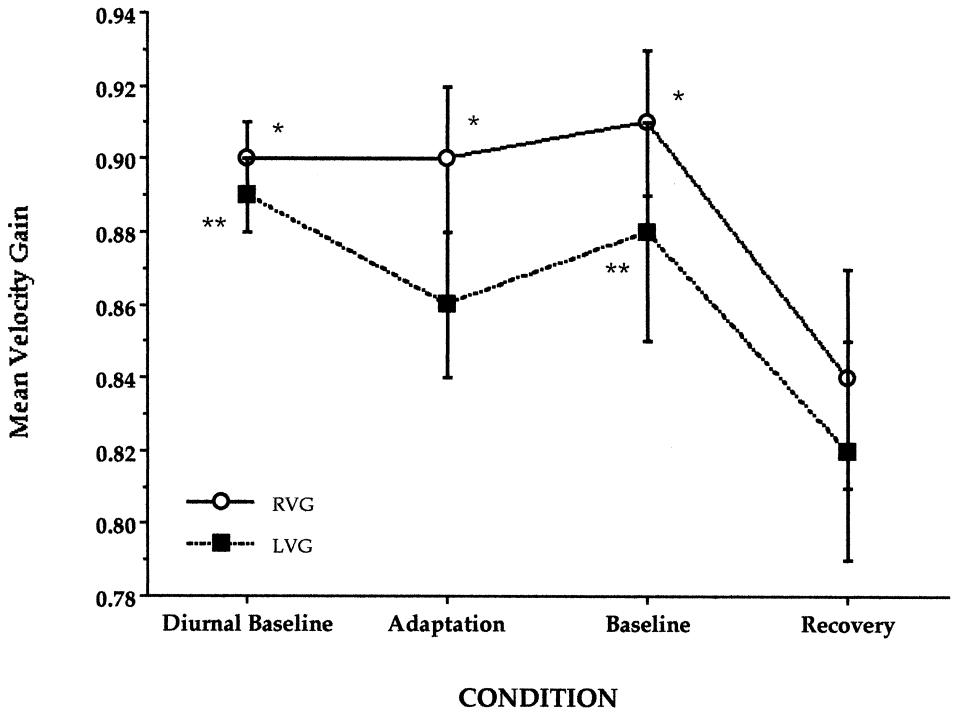


Figure 3—Mean Velocity Gain (±1 SEM) of Rightward (RVG) and Leftward (LVG) Smooth Pursuit (SP) Eye Movements in the Diurnal Baseline and upon awakening from the three experimental nights (Adaptation, Baseline and Recovery). Values closer to 1 indicate a better performance. Asterisks indicate significant differences between Conditions for RVG (REC vs. Diurnal Baseline: p=.02; REC vs. AD: p=.03; REC vs. BSL: p=.01). Double asterisks indicate significant differences between Conditions for LVG (REC vs. Diurnal Baseline: p=.001; REC vs. BSL: p=.007).

(F2,14=4.71; p=.03, Figure 5a). Also performance on this attentional/visual search task revealed to be impaired upon awakening, but only after a sleep period characterized by increased sleep depth. In fact, post-hoc comparisons showed that the number of hits scored upon awakening from REC is significantly lower as compared to Diurnal Baseline (see Fig. 5a), while no performance impairment was detected upon awakening from baseline sleep.

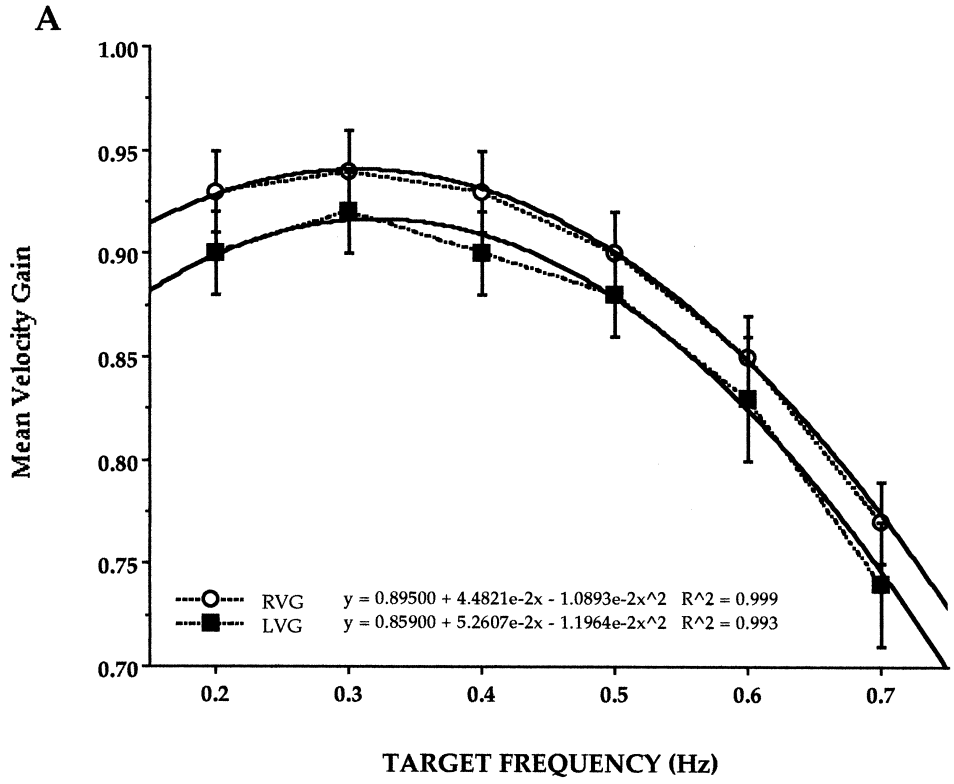
Sleepiness Visual Analog Scale

One-way ANOVA was significant (F3,21=3.17; p=.04, Figure 5b). Also subjective sleepiness was unaffected by sleep inertia upon awakening from adaptation and baseline nights. Post-hoc comparisons showed that only subjective sleepiness upon awakening from REC is significantly higher as compared to Diurnal Baseline (see Fig. 5b).

DISCUSSION

Some speed and accuracy measures of voluntary saccadic and smooth pursuit performance, recorded respectively 30 seconds and 3 minutes after awakening, do not show a significant deterioration after baseline nocturnal sleep episodes. On the contrary, the measures of both saccadic and smooth pursuit speed are strongly impaired by the increased sleep depth during the recovery night following 40 hours of sleep deprivation. This result is paralleled by a worsening of attentional/visual search performance and by an increase of subjective ratings of sleepiness upon awakening from the recovery night. It has also to be stressed that oculomotor performance worsening upon awakening from recovery sleep is limited to the measures of velocity, while both saccade and smooth pursuit accuracy are maintained at adequate levels.

The lack of any sleep inertia effect on the whole oculomotor parameters considered upon awakening from baseline sleep was quite unexpected. However, although performance decrements upon awakening have been demonstrated with a wide array of tasks, comprising simple motor tasks, sensory-motor tasks and cognitive tasks (for a review see 13), we recently reported that behavioral performance upon awakening was, in some cases, at the same level as the pre-sleep baseline.[22] As an example, the 10% fastest reaction times on an auditory reaction time task assessed upon morning awakening from baseline sleep did not differ from presleep wakefulness levels. It is possible that the cerebral down-regulation during the sleep-wake transition does not affect the possibility to give some simple motor response as fast and accurately as possible. Although sleep inertia is a transient phenomenon, its duration depending on the variable measured, we believe that the short delay between each awakening and the oculomotor task administration (between 30 seconds and 3 minutes) may have



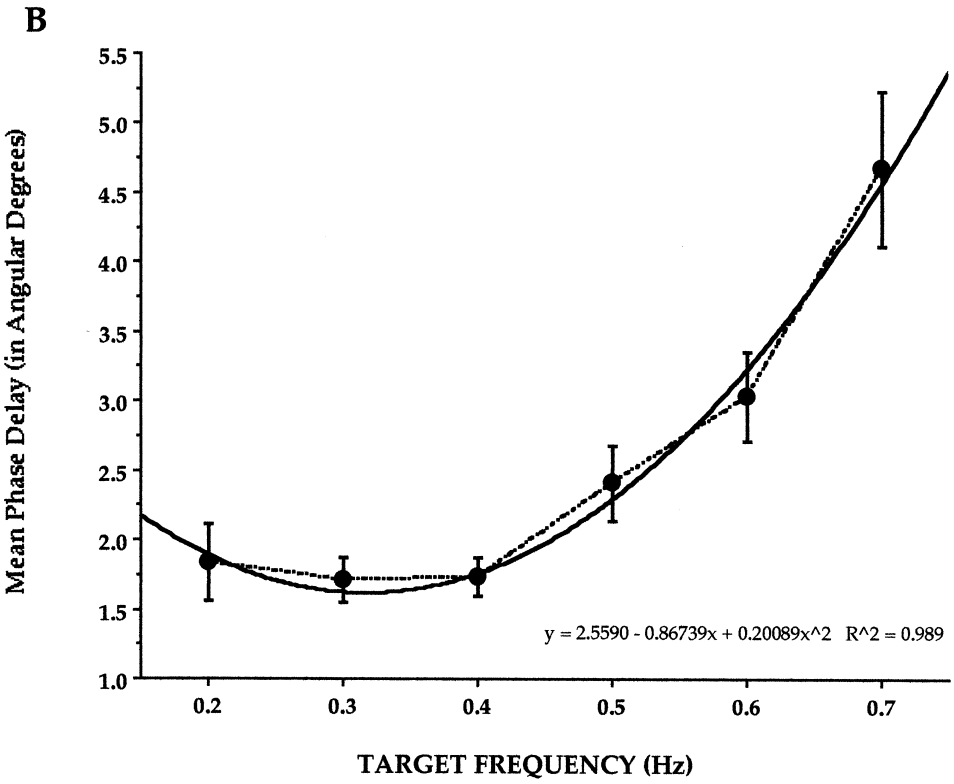
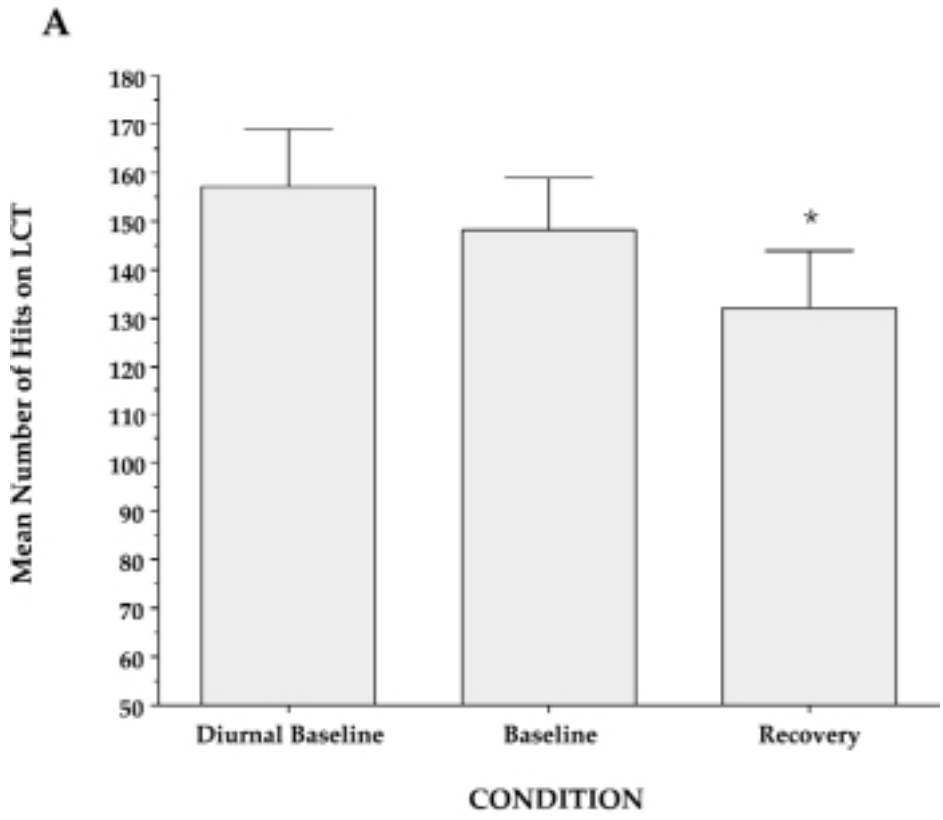


Figure 4—Panel A shows mean velocity gain (±1 SEM) of rightward (RVG) and leftward (LVG) smooth pursuit eye movements at each target frequency. Values closer to 1 indicate a better performance. The interpolate curves indicate a quadratic trend of decreasing gain as a function of increasing target frequency.
Panel B shows mean phase delay in angular degrees (±1 SEM) of smooth pursuit eye movements at each target frequency. The interpolate curve indicates a quadratic trend of increasing delay as a function of target frequency.



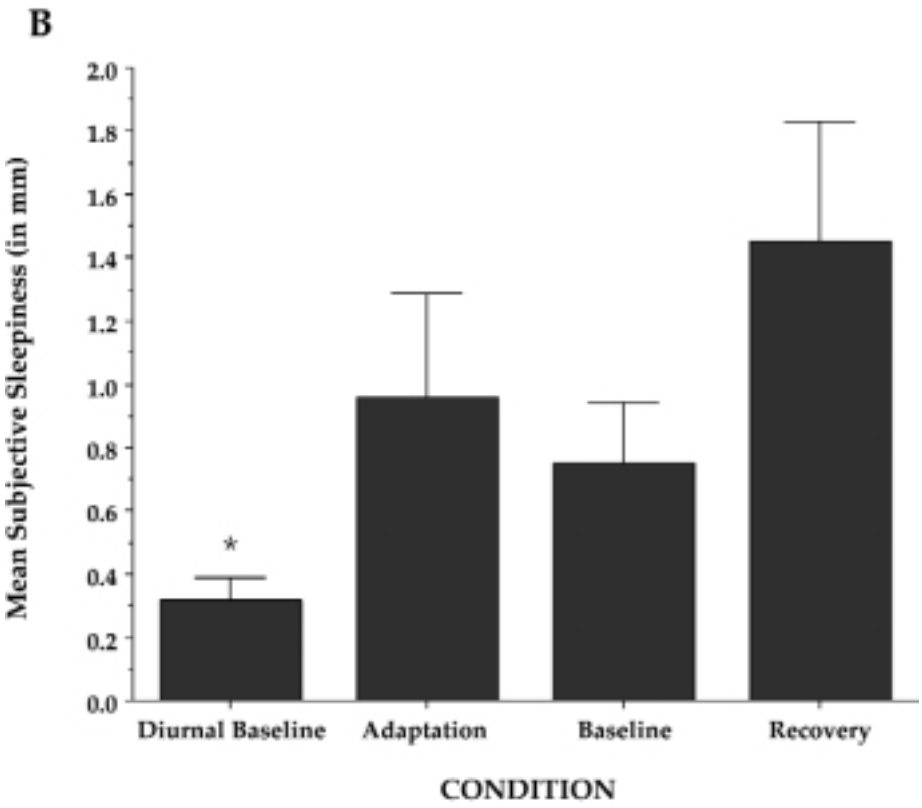


Figure 5—Panel A reports mean number of hits (+1 SEM) on Letter Cancellation Task in the Diurnal Baseline and upon awakening from Baseline and Recovery nights. Asterisk indicates the only significant difference (REC vs. Diurnal Baseline: p=.009).
Panel B shows mean values of subjective sleepiness expressed in millimeters (+1 SEM) on the Visual Analog Scale in the Diurnal Baseline and upon awakening from the three experimental nights (Adaptation, Baseline and Recovery). Asterisk indicates the only significant difference (REC vs. Diurnal Baseline: p=.006).

caused only a minimal decrease of sleep inertia magnitude. In fact, LCT performance and subjective sleepiness ratings, recorded 5 and 10 minutes after awakening, respectively, turned out to be impaired in a very similar way as the oculomotor tasks, regardless of the experimental night.

More surprisingly, both saccadic and smooth pursuit accuracy showed no impairment even after recovery sleep. A previous study[31] reported that saccadic accuracy significantly deteriorated only when very high levels of fatigue and sleepiness interacted with circadian factors (i.e., at 6.00 A.M. after a night of sleep deprivation preceded by a daytime sleep). The present study confirms the stability of saccadic performance accuracy by showing that it is maintained at adequate levels also during the sleep-wake transition, and extends this finding to the accuracy of smooth pursuit eye movements.

On the other hand, we confirmed that both the velocity and accuracy of smooth pursuit eye movements are deteriorated at higher target frequencies (e.g., 36). Similarly, the physiological linear increase of saccadic velocity as a function of eye movement amplitude in the 10°—16° range was confirmed (e.g., 37).

Interestingly, we found saccadic velocity, as well as smooth pursuit velocity gain, to be significantly impaired upon awakening from the recovery night as compared to both the baseline waking level and the mean velocity recorded upon the other two experimental awakenings. Saccadic velocity has been already considered as a sensitive indicator of the alertness state (e.g., 38). Velocity of saccades decreases when the subject's level of alertness lowers,[37] moreover, this parameter is sensitive to the effects of drugs that impair the state of alertness, such as benzodiazepines (e.g., 39), as well as to cumulative partial sleep deprivation.[30] In the latter study, Russo and co-workers reported that saccadic velocity decreased significantly during seven consecutive nights of sleep restricted to three or five hours. Since this oculomotor parameter was negatively correlated with simulator vehicle crash rates during the same partial sleep deprivation paradigm, the authors suggested the potential usefulness of saccadic velocity to evaluate alertness also in environmental contexts or in field studies (i.e., in sleep restricted drivers). In the present study, this parameter of saccadic performance turned out to be sensitive also to the decreased levels of arousal upon awakening, but only when sleep depth/pressure was increased by 40 hours of continuous wakefulness.

The present results are in line with those found evaluating the trend of oculomotor performance during the 40 hours of wakefulness.[40] As a matter of fact, in that case saccadic and smooth pursuit performance were negatively affected by increasing levels of sleepiness during prolonged wakefulness; however, performance worsening was limited to the measures of speed, while accuracy was maintained at adequate levels even at the end of the deprivation period. These results are however in partial disagreement with other data reported by our group in a study on the effects of selective SWS deprivation upon awakening.[2] In that case a measure of cognitive performance accuracy (i.e., the ratio: correct responses/number of responses on a subtraction task) was impaired more than speed (i.e., total number of responses) upon awakening from recovery night. The different outcomes can be due to the different experimental manipulation of sleep pressure (selective vs. total sleep deprivation), as well as to the completely different performance measures used in the two studies.

The saccadic and smooth pursuit performance worsening upon awakening found in the present study is probably due to the increased depth of the recovery sleep, testified by the concurrent increase of SWS amount.[32] According to Dinges,[13] the increased depth of recovery sleep should induce an enhancement of the physiological lowering of body core and brain temperature. The ensuing drop in brain metabolic activity and, more generally, in brain activation state, would make it extremely difficult for a person to perform well shortly after the awakening. Some recent results seem to confirm this hypothesis, by showing that cognitive impairment due to sleep inertia is worse after sleep deprivation, and that cortical arousal upon awakening is correlated with changes in core body temperature.[12] Although it has been reported that cognitive decrements after awakenings from one and two hour naps show a linear relationship with SWS amount during the nap,[10,11] we found very low correlations between each of the oculomotor performance variables and SWS amount during the recovery night[5]. However, performance upon awakening could also be related to other sleep variables not yet evaluated, such as spectral power density of the delta band (0.5—3.5 Hz), more than to SWS amount.

In conclusion, even though oculomotor performance accuracy is maintained at baseline levels upon awakening from a night of undisturbed baseline sleep, both saccadic and smooth pursuit velocity show a significant sleep inertia effect upon awakening from recovery sleep following 40 hours of sleep deprivation. Since a measure of oculomotor performance velocity has been recently found to negatively correlate with simulator vehicle crash rates in a cumulative partial sleep deprivation study,[30] the present results also gain a significant operational relevance. From a sleep logistics perspective, it is suggested that the adverse effects of sleep deprivation on sleep inertia magnitude should be avoided (e.g., by planning prophylactic naps before accumulating sleep debt) by any personnel who may have to perform complex or critical tasks involving high oculomotor control immediately after awakening.

[5] Pearson's r coefficients were never significant and explained little percentages of variance.

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