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Differences in sensory reweighting due to loss of visual and proprioceptive cues in postural stability support among sleep-deprived cadet pilots

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ABSTRACT

Background: Sleep deprivation is known to diminish postural control.
Research question: We investigated whether sleep deprivation affects sensory reweighting for postural control due to loss of visual and proprioceptive cues.
Methods: Two cohorts of cadet pilots were deprived of sleep for 40 h. Variabilty in force-platform center of pressure was analyzed based on the whole path length (WPL); circumference area (CA); mean of displacement along x and y axes and corresponding standard deviations (SDx, SDy); and frequency of body-sway intensity, all of which were recorded while the cadets stood with eyes open (NEO), eyes closed (NEC), and eyes closed on a foam platform base (FEC) A sleepiness index (SUBI) based on principal component analysis of selected Cohort 1 data (n = 37) was used to compare Cohort 2 data (n = 29) with scores for the Stanford Sleepiness Scale (SSS) and Pittsburg Sleep Quality Index (PSQI).
Results: Balance began to deteriorate at 16 h for NEO and at 28 h for NEC and FEC ($p < 0.05$). At 40 h, WPL, CA, and SDy of COP for NEO indicated balance deteriorated further while WPL and SDy for NEC and WPL, CA, SDx, and SDy for FEC indicated balance incrementally improved. Frequency bias of body-sway differed between NEO, NEC, and FEC. In Cohort 2, the SUBI correlated significantly with SSS ($p < 0.05$), but not with PSQI.
Significance: Effects of sleep deprivation were mitigated over time, suggesting that compensatory mechanisms influenced sensory reweighting for NEC and FEC between 28 and 40 h of sleep deprivation, but not for NEO. Frequency bias of body-sway suggested that sensory reweighting in the absence of visual cues differed from that in the absence of both visual and proprioceptive cues.

1. Introduction

The effects of sleep deprivation have been shown to be associated with a higher risk of motor vehicle accidents [1], and sleep loss has also been shown to be a major contributor to declining performance among commercial airline pilots [2]. Given the greater cognitive demands on pilots, compared with that of operators of wheeled motor vehicles, the effects of sleep-deprivation-related fatigue among pilots is, therefore, an important public safety concern for the air transportation industry.

Sleep deprivation affects both postural stability and adaptation to changes in environmental stimuli, with more severe impairment in both functions occurring when sleep-deprived subjects close their eyes [3], which suggests that sensory reweighting in the absence of visual cues is altered by sleep deprivation. Likewise, the perturbation of proprioceptive stimuli has a greater effect on sleep-deprived subjects than well-rested subjects [3]. Differences in methods of proprioceptive perturbation can also affect the extent to which sensory reweighting of proprioceptive cues is affected by sleep deprivation [3,4]. Therefore, it remains unclear whether fatigue has equal effects on the roles that balance, vision, and proprioception play in sensory reweighting for postural control in sleep-deprived subjects.

2. Methods

2.1. Participants

A total of 66 male cadet pilots from a single military aviation academy in Beijing, China were enrolled in our study. Thirty-seven cadets were randomly enrolled in Cohort 1 (age: 23.3 ± 2.03 y; BMI: 21.4 ± 3.00 kg/m^2). Twenty-nine cadets were randomly enrolled in

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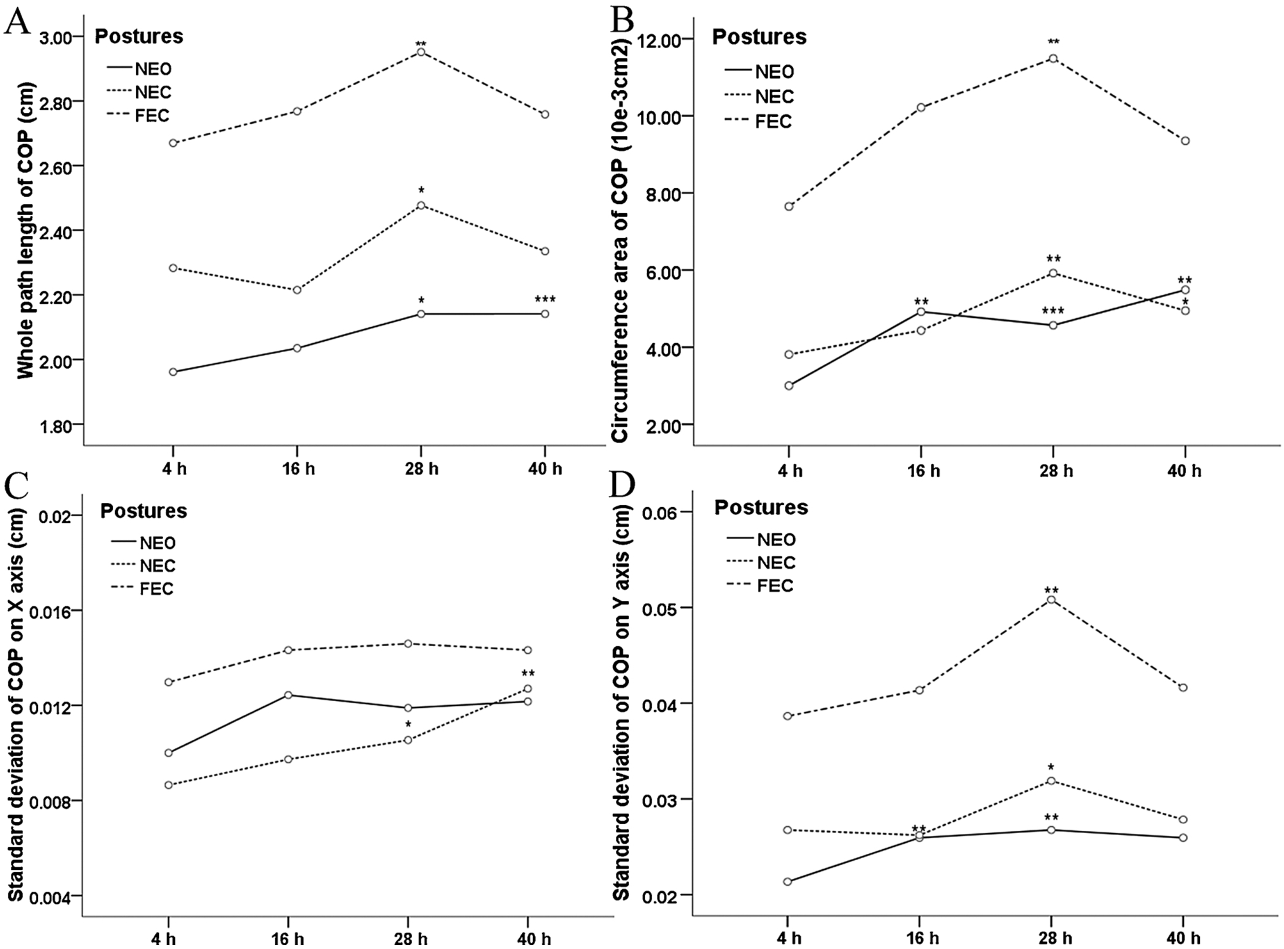

Fig. 1. Force platform analysis of static upright postural stability at the 4, 16, 28, and 40 h time points of the sleep deprivation period for Cohort 1. The subjects were awakened at 06:00 on day 1, and the mean values of the **(A)** whole path length; **(B)** circumference area; **(C)** mean displacement along the x-axis; and **(D)** mean displacement along the y-axis were recorded with subjects standing normally on a solid platform with eyes open (NEO), solid platform with eyes closed (NEC), and foam-padded platform with eyes closed (FEC). Statistical differences between the parameters recorded at baseline (4 h) and those recorded at the 16, 28, and 40 h time points are indicated by *p < 0.05, **p < 0.01, and ***p < 0.001 based on Roy's largest root for repeated measures, with inter-subject and intra-subject dof of 1 and 3, respectively.

Cohort 2 (age: 22.3 ± 1.11 y; BMI of 22.4 ± 1.79 kg/m^2). Cadets who had suffered bone fractures, muscle injuries, vestibular dysfunction, or other diseases affecting upright posture or balance equilibrium in the 3 months preceding our study were excluded from enrollment. Our protocols were approved by the Research Ethics Committee of Beijing Military Region General Hospital. Written, informed consent was obtained from all of the participants prior to participation.

2.2. Study design

The 2-week enrollment period culminated in 2 days of testing. Participants were blinded regarding the actual test date. During the enrollment period, the participants agreed to the following: (a) Sleep at least 6 h per night, (b) refrain from consuming medications or beverages that might act as stimulants, and (c) arise from sleep at 06:00 everyday. Participants were summoned to the laboratory at 08:00 on day 1 of testing. Two different cohorts were deprived of sleep for 40 continuous hours (06:00 on day 1 to 22:00 on day 2). Participants in both cohorts were subjected to posturographic testing at 4, 16, 28, and 40 h of sleep deprivation. Data for Cohort 1 were used to construct a static upright balance index (SUBI). Using the SUBI, data for Cohort 2 were compared to the results of the Stanford Sleepiness Scale (SSS) and Pittsburgh Sleep Quality Index (PSQI) [5–8].

2.3. Posturographic balance testing

Static postural stability was assessed for both cohorts using the Active Balancer EAB-100 (Sakai Medical, Tokyo, Japan) or Tetrax (Sunlight Medical, TelAviv, Israel) force-platform systems, as described previously [9–11]. The following testing conditions were implemented in randomized order: standing on a solid platform with eyes open (NEO), standing on a solid platform with eyes closed (NEC), and standing on a foam-padded platform with eyes closed (FEC). Postural control was assessed based on changes in parameters derived from center of pressure (COP), including whole path length (WPL), circumference area (CA), mean and standard deviation of lateral displacement of COP (MDx ± SDx), mean and standard deviation of anterior-posterior displacement of COP (MDy ± SDy), and the ratio of weight distribution, as described previously [11]. The intensity of body sway at very low (0.01–0.099 Hz), medium-low (0.1–0.499 Hz), medium-high (0.5–0.99 Hz), and high (1.0–3.0 Hz) frequency were recorded to determine whether changes in variation at different frequency bands were associated with the effects of sleep deprivation, as described previously [9]. For additional details see the Supplementary material.