Nature and Science of Sleep

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ORIGINAL RESEARCH

Earth Vertical Motions Disrupt Sleep and Next Day Performance

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Purpose: Overcoming travel-related sleep disturbances due to motions sensed by our vestibular system could help improve cognitive performance and sleep quality in many contexts. However, there is a lack of research that administers controlled motions to understand how motion negatively impacts sleep and cognitive performance.

Patients and Methods: In this experiment, nine participants (21–39 years, M = 30.3, SD = 6.76; 3 females) completed a 7-day protocol. During nights 1–3, participants wore an Actiwatch and completed sleep diaries at home. On nights 4–7, participants slept in the lab with polysomnographic recording equipment on a bed attached to a movement platform and completed a psychomotor vigilance test at 07:00AM, 1:00PM, 3:00PM, and 5:00PM. On nights 4 and 5, the bed did not move overnight. On nights 6 and 7, the bed was moved upward and downward at 1Hz up to 120 times overnight at levels between 0–100% and 0–600% of each participant's awake perceptual vertical motion threshold, respectively.

Results: Vertical motions significantly increased arousals from sleep ($p = 0.014$) and worsened morning and midday psychomotor vigilance ($p < 0.001$). Arousals caused by vertical motions occurred less than natural arousals ($p < 0.001$) and had different spectral power ($p = 0.002$). Larger motions strongly and significantly predicted a higher chance of causing arousals ($\beta = 0.0016$, $p < 0.001$).

Conclusion: These results provide evidence that overnight vertical motions disrupt sleep, lead to arousals that are distinct from natural arousals, and result in decreased cognitive performance. Strategies to reduce motion could help mitigate travel-related sleep disturbances.

Plain Language Summary: Travel related sleep disturbances are prevalent but poorly understood. The results of this study provide evidence that vertical motions disrupt sleep, lead to arousals that are distinct from natural arousals, and result in decreased cognitive performance. Strategies to reduce the number and size of vertical motions may help overcome travel-related sleep disturbances. However, whether and how motion size, frequency, and direction impact brain processes, sleep, and cognitive performance remain critical knowledge gaps. Future studies examining stronger motions administered more frequently to a larger number of participants are needed. Further, the topographic and time-frequency EEG profiles of natural and motion related arousals need to be further examined to better understand how the brain processes motion during sleep.

Keywords: sleep, polysomnography, vertical, motions, cognition, arousals

Introduction

Millions of individuals are at increased risk for health, mood, and memory issues due to sleep disruptions experienced on watercraft, aircraft, trains, and automobiles.[1–7] Several studies demonstrate that transportation related motions disrupt sleep.[8–15] Most broadly, across modes of travel poor sleep quality significantly and negatively influences tourist experiences.[4] Likewise in seafarers who are exposed to environmental factors like noises and motions that cause sleep disruptions, a review of 279 maritime accidents showed that fatigue contributed to 16% of critical ship incidents and 33% of personnel injuries.[1,12] Sleep quantity and quality were also significantly reduced during conditions simulating air travel which diminished physical and mental performance and exacerbated markers of fatigue compared to control

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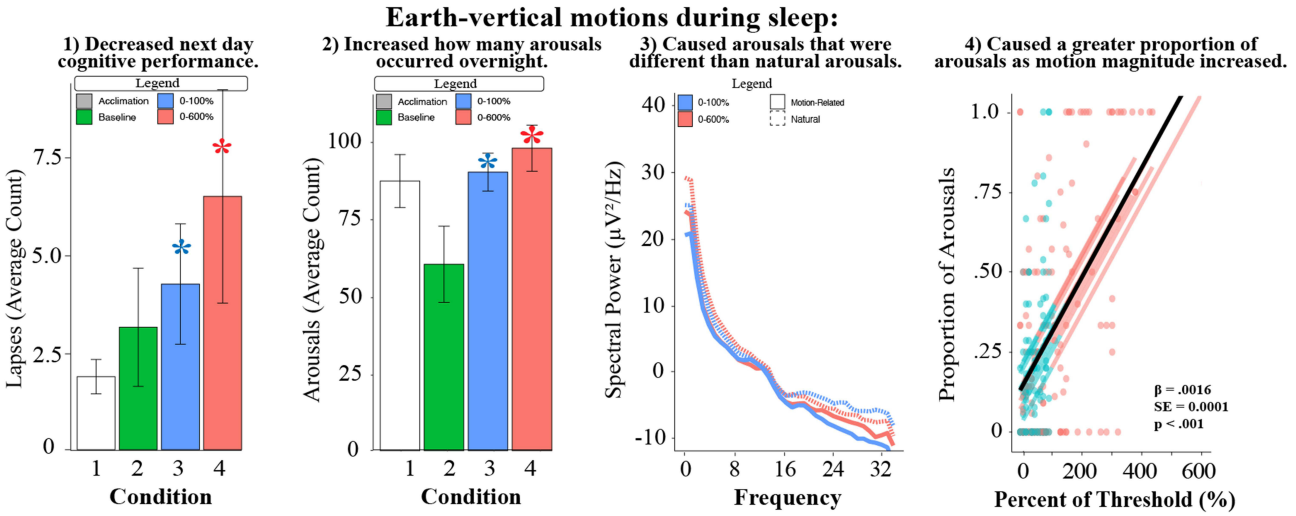
Graphical Abstract



conditions.[16,17] Simulated naval ship motions and vibrations administered during sleep significantly decreased sleep efficiency compared to a stationary condition in 100% of participants.[9] In crewmen on an offshore oil vessel, sleep problems were strongly associated with vessel motions and increased with motion magnitude.[10] Horizontal vibrations on trains negatively impacted sleep and their negative impact increased with greater vibration amplitude.[8,18,19] Body position, especially sleeping in the supine position, has also been demonstrated to significantly worsen sleep quality.[20–22]

Despite the substantial negative impacts of sleep disruption, there is a lack of well-controlled research investigating how motions negatively impact sleep and cognitive function.[11,23,24] Specifically, we found no previous study that looked at the deleterious impact of individual motions on sleep quality. Further, while it is clear that some complex motions and vibrations disrupt sleep, there is also evidence that other motions like horizontal rocking can improve sleep and next day memory performance.[25] When participants slept on a mattress that simulated wave motions, sleep efficiency, time in NREM sleep, and subjective sleep quality were significantly improved.[26] Vibrations at 1Hz have been demonstrated to promote more comfortable sleep on train cars.[11] Further, closed-loop vibrations significantly reduced waking after sleep onset, increased sleep quality, and increased delta power during N3 sleep.[27]

Although the vestibular system is neuroanatomically positioned to impact sleep, it is unclear how vestibular function changes during sleep.[23,24,28,29] There are bidirectional connections between vestibular nuclei, orexinergic neurons, and the locus coeruleus that are hypothesized to participate in transitioning an organism from awake to asleep.[24] The vestibular system also has direct connections to the supra-chiasmatic circadian clock that have been demonstrated to regulate circadian rhythms.[30] In rats with vestibular damage, NREM sleep was decreased and wake time was increased compared to controls without vestibular damage.[31] In astronauts lack of otolithic input on orexinergic neurons in space has been hypothesized to alter transitions in the sleep-wake cycle, decrease sleep time, and exacerbate sleep disruptions.[24,32] Additionally, chronic vestibular hypofunction is associated with impaired sleep.[33] While it is evident that vestibular input has substantial impacts on sleep and circadian rhythms, there is a critical lack of knowledge about how vestibular function changes during sleep. The majority of incoming visual, auditory, and somatosensory information processing is attenuated during sleep, suggesting that vestibular function may also be attenuated.[34–39] However, the sleeping brain can still detect certain stimuli suggesting that elements of vestibular function could be preserved.[34–39] Adding to the complexity, vestibular acuity differs greatly across individuals – some people can sense very small motions and others can only sense larger motions.[40,41]

Changes in sleep stages, arousals, and spectral power are sensitive indexes of brain activity that could help further elucidate the role of vestibular function and the impacts of motion during sleep. Human sleep is classified into 4 stages according to variations in muscle tone, brain wave patterns, and eye movements.[42–44] "Good" sleep typically consists of more time spent in deeper stages of sleep, and sleep becomes increasingly disrupted and gets "worse" with more time spent awake and in lighter sleep stages.[45] Disruptions due to sounds, motions, and other physiological processes have been demonstrated to result in changes in both time spent in different sleep stages and their relative proportion across the sleep period and could be an effective index of sleep disruption due to motions.[1,19,25,26,46] There is also a well-established "first-night effect", where sleeping in a new environment for the 1st time leads to more awake periods and less REM sleep because the brain is monitoring unfamiliar surroundings during sleep.[47,48]

Although changes in sleep stage are scored in 30 second epochs by convention, neural processing related to incoming visual, auditory, and somatosensory inputs occur quickly and continuously leading to awake-like brain activity called arousals.[37–39,49,50] Natural arousals are an intrinsic part of sleep but excessive arousals can cause sleep disruption, fragmentation, daytime sleepiness, and other symptoms of fatigue.[51–53] Sensory inputs like familiar versus unfamiliar sounds or vibrations have been demonstrated to exhibit distinct changes in spectral power during arousals that correlate to engagement in separate neural systems.[37,38,49,54–65] Examining how spectral power differs during motion-related compared to natural arousals could help identify neural correlates of vestibular function during sleep.

Therefore, this experiment was designed to examine the impacts of earth vertical motions (ie, upward and downward translations) on sleep stages, arousals, and next day cognitive performance. We hypothesized that, unlike the sleep-promoting effects observed with horizontal rocking, earth-vertical translations would be disruptive to sleep architecture. Specifically, we predicted a dose-dependent relationship where increasing translation magnitudes would result in greater sleep fragmentation and increased time awake. Furthermore, we hypothesized that these sleep disruptions would result in measurable impairments in next-day cognitive vigilance and attention. Finally, given that the brain processes sensory inputs differently during sleep, we predicted that arousals triggered by motion would exhibit distinct spectral power signatures compared to naturally occurring spontaneous arousals, reflecting specific vestibular processing.

Materials and Methods

Subjects

Nine participants (21–39 years, M = 30.3, SD = 6.76; 3 females) completed the 7-day protocol after providing written consent. Participants were excluded for (i) > 300mg/day caffeine, (ii) >14 drinks/week alcohol, (iii) use of medications affecting sleep or vestibular thresholds, or (iv) current tobacco use. Participants also reported no history of neurological, psychiatric, vestibular, inner-ear, or sleep-disorders. Procedures were approved by the Naval Medical Research Unit Dayton Institutional Review Board (Protocol 2021.0005) in adherence to the Declarations of Helsinki. Participants were compensated $450.

Sleep Questionnaires

The Morning-Eveningness Questionnaire (MEQ, Range (16–86), 70 ≥ = "definitely morning types") assessed participants' chronotype.[66] Daytime activities affecting sleep (eg, caffeine intake, exercise), information about participants' sleep the night prior (eg, onset, duration, awakenings), and information about any perceived motions or motion sicknesses overnight were collected using an in-house sleep survey (SS).

Actigraphy

To assess sleep and wake patterns and ensure protocol compliance, participants wore a Phillips Respironics Actiwatch 2 (Phillips, USA) on their non-dominant hand for 3 days prior to the in-lab portion of the study. Data were collected in 1-minute epochs, and sleep and wake patterns were scored using standard criteria using Phillips Actiware software (Phillips, USA).

Polysomnography (PSG)

To assess changes in overnight sleep physiology across conditions, each sleep period was recorded using a Grass Technologies AS40-Plus amplifier system and TWin (Natus Technologies, USA) acquisition software. Nine electroencephalography (F4, F4, C3, C4, Cz, O1, O2, M1, M2), 2 electrooculography (right and left ocular canthi), and 2 electromyography (Chin1, Chin2, ChinZ) electrodes were placed according to standard American Association of Sleep Medicine (AASM) guidelines.[44,67] PSG data were collected at a sampling rate of 200Hz with a bandpass of 0.1 to 100 Hz.

The Psychomotor Vigilance Test (PVT)

Alertness was assessed post-sleep at four time points (7:00 AM, 1:00 PM, 3:00 PM, 5:00 PM) using a 10-minute PC-PVT (Version 2.0) on a Microsoft Surface Tablet. Participants pressed a screen to stop a reaction time counter; stimuli were presented at random intervals (2–12 s).

The Motion Bed

Motion was controlled by a 6 degree of freedom motion platform (MOOG Inc, USA) supporting a king-size mattress (Hickory Springs Manufacturing Inc, USA). Single cycles of 1 Hz sinusoidal acceleration were applied along an earth-vertical superior-inferior axis by moving the entire bed and were designed to mimic the time course of natural volitional head movements.[68,69] Earth-vertical motions were chosen because total bilateral loss of the vestibular system increases vertical thresholds by over 5000%, indicating that the vestibular system predominantly determines Z-Translation thresholds—with other cues (eg, tactile, somatosensory) only contributing for motions that are a much greater magnitude than those that are typically sensed reliably by humans with a healthy vestibular system.[70] During sleep, 70 dB white noise from a fan was provided and motion-related sounds were always maintained below 80 dB.

Awake Vertical Translation Thresholds

To assess what motion magnitude each participant could reliably detect while awake in bed, a psychometric function was fit to binary responses from an adaptive two-alternative forced-choice procedure.[40,71–74] On day 1 of the study, participants laid in bed while awake and were asked to indicate the direction of 100 upward or downward motions using buttons placed in their left and right hands. Motions were administered in random directions using a 3-down 1-up staircase procedure that followed parameter estimation by sequential testing rules.[75] Briefly, each test began with an easily detectable motion, and subsequent motions became smaller when participants correctly detected the direction 3 consecutive times or larger when participants incorrectly detected the direction once. To control for potential differences in perceptual threshold based on body position, each participant repeated the test lying with their left ear down, right ear down, on their back, and on their stomach. There were not any significant differences between these 4 different orientations, and therefore the median of all 4 tests for each participant was calculated as their awake vertical translation threshold (see Table S1 for details).

Procedure

On night 1 of the study, participants completed the consent process and were oriented to the experimental procedures. Afterward, participants were asked to complete the Morningness Eveningness Questionnaire.[66] During nights 1–3, participants were asked to refrain from napping, to go to sleep at 11:00PM, and to wake up at 7:00AM while wearing an Actiwatch and completing sleep surveys (Figure 1A). On nights 4–7 of the study, participants came to the NAMRU-D Fatigue Assessment and Countermeasures lab to sleep overnight while completing 4 different conditions, 1 condition on each night. On each night, participants arrived at the lab around 9:30PM, had polysomnography (PSG) sensors applied to them, and were given an opportunity to sleep from 11:00PM to 7:00AM in the motion bed. In the morning after each night, participants went home, were asked to complete a sleep survey, and were given a Microsoft surface tablet to complete a Psychomotor Vigilance Test (PVT) at 7:00AM, 1:00PM, 3:00PM, and 5:00PM (Figure 1B).

On night 4, participants completed the acclimation condition (*white)* to reduce the impacts of the "first night effect" and were asked to adapt to sleeping in the lab and motion bed while wearing PSG sensors. On night 5, participants completed the baseline

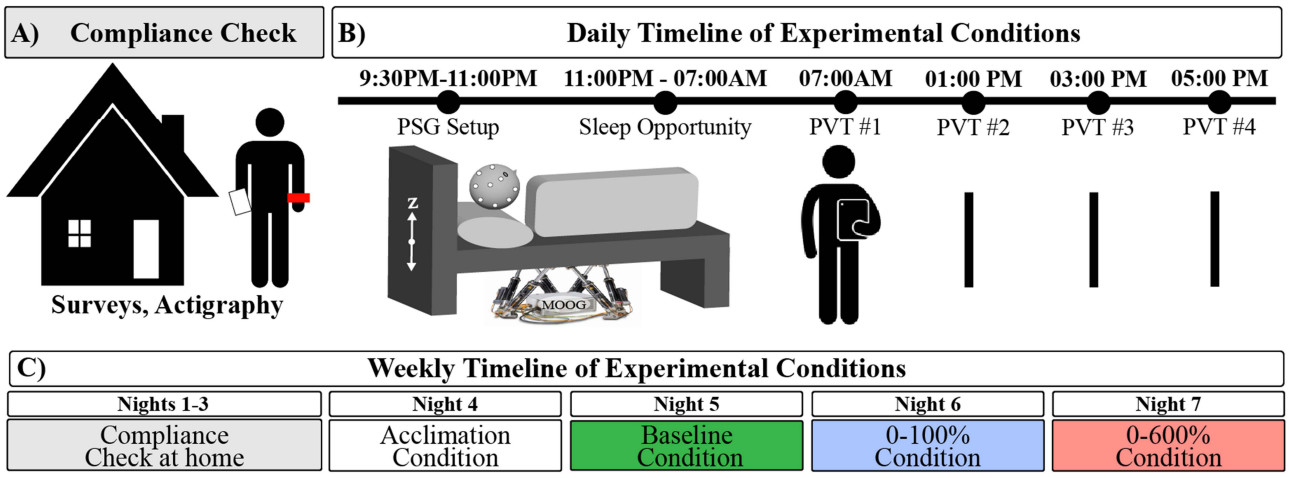


Figure 1 Experimental Timeline. Schematic of the experimental procedure. (**A**) On nights 1–3, participants slept at home, wore an Actiwatch, and completed sleep surveys. (**B**) Each night participants slept in the lab on a bed attached to a MOOG motion platform, wore polysomnography overnight (PSG), and completed 4 Psychomotor Vigilance Tests (PVTs) throughout the following day at 7AM, 1PM, 3PM, and 5PM. (**C**) On nights 4 and 5, the bed did not move overnight. On night 6, the bed moved between 0–100% of each participant's vertical motion threshold while they slept. On night 7, the bed moved between 0–600% of each participant's threshold. White = acclimation condition, green = baseline condition, blue = 0–100% of threshold condition, red = 0–600% of threshold condition.
Abbreviations: PSG, polysomnography; PVT, Psychomotor Vigilance Test; MOOG, 6 degree of freedom motion platform.

condition (*green*) and were asked to sleep normally. No movements were applied on the acclimation nor baseline nights. On night 6, in the 0–100% threshold condition (*blue*), the entire bed was moved up and down earth-vertically at levels between 0–100% of each participant's individual vertical translation threshold. On night 7, in the 0–600% threshold condition (*red*), the same procedure was applied with movements between 0–600% of each participant's individual vertical translation threshold (Figure 1C). To minimize the impact of any external noises, including those due to bed motion, a fan was run throughout each night at a volume of ~ 70 dB.

On nights 6 and 7, trained researchers monitored sleep in real time and administered motions every 3 minutes after the participant reached stage 1 sleep. When an arousal or awakening occurred, motion was delayed until the participant fell asleep again for at least 5 minutes. Motion size and direction were determined using a 3-down 1-up staircase procedure that followed parameter estimation by sequential testing rules.[75] Each test began with an undetectable motion, and subsequent motions became larger if participants stayed asleep during the motion 3 consecutive times, and motion size was reset to the starting level at any sign of awakening due to the motion. The size of motions iteratively increased between 0–100% of each participant's vertical translation threshold on night 6, and between 0–600% of each participant's vertical threshold on night 7.

Analysis

Statistics were calculated using R and R Studio (Version 4.4.1).[76,77] The lme4 and emmeans packages were utilized for linear mixed effects models, ANOVAs, and post-hoc pairwise comparisons.[78,79] To reduce Type I error and potential bias in parameter estimates due to hand selecting models,[80–82] candidate models were first compared using likelihood ratio testing, Akaike information criteria, Bayesian information criteria and deviance with the "anova" function in R. *P*-values were calculated using Type II ANOVA with Satterthwaite's approximation method and the lmerTest package.[78,83] 95% confidence intervals were calculated using the Wald method.

All comparisons were performed using the emmeans package. Effect sizes were calculated as Cohen's d using the "eff_size" function, which divides the contrast estimates by the model's residual standard deviation to provide a standardized measure of the magnitude of the predictor relative to the unexplained within-subject variance. Effect sizes were then interpreted as small ($d = 0.2$), medium ($d = 0.5$), large ($d = 0.8$), very large ($d = 1.2$), and huge ($d = 2.0$) following standard benchmarks.[84,85]

The Psychomotor Vigilance Test (PVT)

One outlier was excluded (performance > 2 SD below the mean). Lapses (> 500 ms) and reciprocal response time were compared using separate linear mixed-effect models with fixed effects for condition (acclimation, baseline, 0–100%,

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0–600%) and time (7:00AM, 1:00PM, 3:00PM, 5:00PM) plus a random effect for participants. Significant main effects were explored with pairwise *t*-tests.

Sleep Stages and Arousals

PSG data from the baseline night of one participant was missing due to technical errors. Sleep stages and arousals were scored in 30 second epochs by trained technicians using standard American Academy of Sleep Medicine criteria.[44,86] The number and duration of arousals and proportion of sleep spent in each stage were calculated and compared using separate linear mixed effect models with fixed effects for sleep stage (time asleep, time awake, NREM 1%, NREM 2%, NREM 3%, REM%), condition (acclimation, baseline, 0–100%, 0–600%), the interaction of sleep stage and condition, and random effects for participants. To further examine significant main effects, follow up pairwise t-tests compared each condition to the others.

Natural versus Motion-Related Arousals

Arousals were classified as motion-related (motion occurred ≤ 30 sec prior) or spontaneous (all others). Motion-related arousals were only scored in the 0–100% and 0–600% conditions. Differences in the number and duration of natural arousals were compared using a linear mixed effect model with fixed effects for condition (0–100%, 0–600%). Differences in the number and duration of natural and motion related arousals were compared using a model with fixed effects for arousal type (natural, motion-related), condition (0–100%, 0–600%), and random effect for participants.

All spectral analyses were based on Fast-Fourier Transform of channels F3, F4, C3, C4, O1, and O2 in 10s epochs, accurately aligned with the onset of either spontaneous or motion-related arousals.[54,87,88] Prior to Fourier transformations, the data were band-passed filtered from 0.3 to 35Hz. Filtered data were then Fourier transformed in 10s epochs beginning 10 seconds before and 3 seconds after each arousal onset, using standard tapering approaches.[89] Spectral power was then calculated in the delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), sigma (12–15 Hz), and beta (15–30 Hz) frequency ranges. Differences in the spectral power of spontaneous arousals were compared across each frequency range using separate linear mixed effect models with fixed effects for condition (acclimation, baseline, 0–100%, 0–600%) and a random effect of participant. By definition, motion related arousals only occurred during 0–100% and 0–600% nights. Therefore, differences in spectral power for natural and motion-related arousals were compared using a linear mixed effect model with fixed effects for condition (0–100%, 0–600%) and arousal type (natural, motion-related) plus a random effect of participant.

Arousals and Vertical Translation Thresholds

Since motions were administered using a 3-down 1-up staircase procedure, there were always more small motions than large motions in both conditions. Therefore, to examine how translation threshold impacted the likelihood of an arousal, a proportion was calculated by dividing the number of arousals by the total number of motions at each 10% increment of a participant's vertical motion threshold. For example, if 20 motions at 10% of threshold caused 0 arousals, the proportion would be 0 whereas if 20 arousals were caused, the proportion would be 1. Upward and downward motion effects were compared using a linear mixed effect model with fixed effects for condition (0–100%, 0–600%) plus a random effect for participant. A separate linear mixed effect model compared the proportion of arousals caused by motions ≤ 100% of threshold in both conditions to motions > 100 of threshold in the 0–600% condition. Finally, a linear mixed effect model with fixed effects for motion size and a random effect for participant was used to examine the relationship between percent of threshold and arousal proportion.

Results

Participants (30.3 ± 6.76 years) were generally morning and intermediate types (59.1 ± 11.54) and were able to reliably detect 4.19 (3.33–5.26) cm/s motions while lying down awake in bed on average.

Sound Levels Across Motion Sizes

Sound levels were consistent for the 0 to 24 cm/s velocity magnitudes used in this study ranging from 69 dB unweighted sound pressure level (SPL) without motions to 79 dB SPL for the largest motions. For the majority of motions (ie, >10 cm/s), the sound level was relatively constant - varying between 73- and 79-dB SPL (Figure 2).

The Psychomotor Vigilance Test (PVT)

Including time and condition as main effects significantly improved model fit over the null model (χ^2 (3) = 15.03, p =0.002) and the condition only model (χ^2 (3) = 17.14, p <0.001), but the inclusion of a time and condition interaction did not significantly improve the model fit (χ^2 (9) = 9.15, p =0.423). Therefore, the more parsimonious time and condition model was used to analyze lapses and reciprocal reaction times.

For lapses, there was a significant main effect of both time (F(3114) = 5.73, p =0.001) and condition (F(3114) = 5.83, p <0.001). Follow up comparisons across time indicated that there were more lapses at 7:00AM compared to 1:00PM and 3:00PM (Figure 3A and Table 1). Follow up comparisons across condition indicated that there were more lapses following the 0–600% condition compared to the acclimation and baseline conditions (Figure 3A and Table 1).

For reciprocal reaction times, there was also a significant effect of both time (F(3114) = 6.56, p <0.001) and condition (F(3114) = 3.04, p =0.031). Follow up comparisons across time indicated that reciprocal reaction times were higher at 7:00AM compared to 1:00PM and 3:00PM. There was marginal evidence that reciprocal reaction times were also greater at 7:00AM than 5:00PM (Figure 3B and Table 2). Post-hoc pairwise comparisons across condition revealed that while differences between Baseline and 0–100% conditions did not reach statistical significance, they represented a medium effect size. A similar trend was observed for the Baseline and 0–600% conditions (Figure 3B and Table 2).

Sleep and Arousals

Including condition alone did not significantly improve model fit (χ^2 (3) =0.003, p =0.99) but the inclusion of sleep stage resulted in a highly significant improvement over the null model (χ^2 (2) = 962.46, p <0.001). Including a condition and sleep stage interaction significantly improve the model (χ^2 (15) = 41.10, p <0.001), suggesting that the impact of

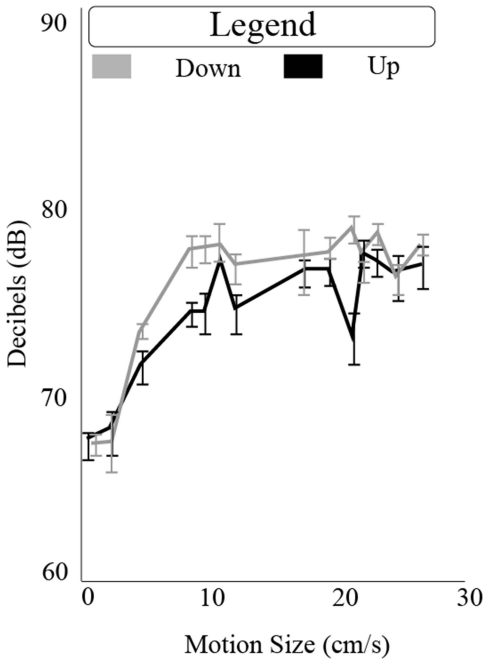

Figure 2 Sound Levels Across Motion Sizes. Mean and standard deviation of sound levels collected using an in-ear microphone at motion sizes ranging from 0, 30 centimeters per second.

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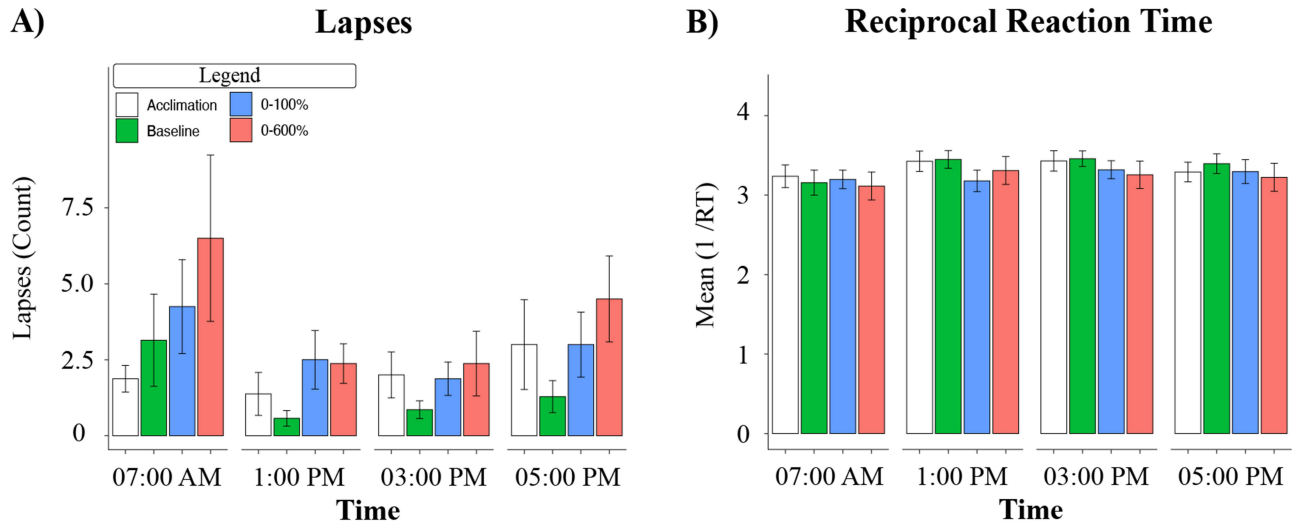

Figure 3 The Psychomotor Vigilance Test (PVT). Bar charts comparing means and standard errors of reciprocal reaction times and lapses across time and condition. (**A**) Lapses. (**B**) Reciprocal Reaction Time. White = acclimation, green = baseline, blue = 0–100% of threshold, red = 0–600% of threshold.
Abbreviations: PVT, Psychomotor vigilance test; Mean (1/RT), reciprocal reaction time.

conditions varied depending on the sleep stage being analyzed. Therefore, the interaction model was used to analyze condition related changes in sleep stages.

The proportion of time spent in different sleep stages significantly differed ($F(5, 186) = 4375.0$, $p < 0.001$), reflecting the inherent differences in the time spent in various sleep stages. There was not any main effect of condition ($F(3186) = 0.109$), suggesting that the total amount of sleep stages combined did not differ significantly between conditions. However, the impact of condition was dependent on the sleep stage being analyzed ($F(15,186) = 2.68$, $p = 0.001$).

Table 1 Lapse Results

Comparison	Estimate (SE)	t-Ratio (df)	P value	Cohen's d
7:00AM, 1:00PM	**2.24 (0.63)**	**3.56 (114)**	**0.003**	**0.89 (L)**
7:00AM, 3:00PM	**2.17 (0.63)**	**3.44 (114)**	**0.004**	**0.86 (L)**
7:00AM, 5:00PM	1.00 (0.63)	1.58 (114)	0.392	0.40 (M)
1:00PM, 3:00PM	−0.07 (0.63)	−0.14 (114)	0.999	−0.03 (S)
1:00PM, 5:00PM	−1.24 (0.63)	−1.97 (114)	0.204	−0.49 (M)
3:00PM, 5:00PM	−1.17 (0.63)	−1.86 (114)	0.251	−0.47 (M)
Acclim., Baseline	0.60 (0.63)	0.95 (114)	0.777	0.23 (S)
Acclim., 0–100%	−0.84 (0.63)	−1.34 (114)	0.539	−0.34 (S)
Acclim., 0–600%	**−1.88 (0.63)**	**−2.98 (114)**	**0.018**	**−0.75 (M)**
Baseline, 0–100%	*−1.44 (0.63)*	*−2.29 (114)*	*0.106*	*−0.57 (M)*
Baseline, 0–600%	**−2.47 (0.63)**	**−3.93 (114)**	**<0.001**	**−0.98 (L)**
0–100%, 0–600%	−1.03 (0.63)	−1.64 (114)	0.361	−0.41 (S)

Notes: Estimates, standard error, test statistics, p values, and effect sizes for follow up comparisons across time and condition. Bold = significant, Italics = trending.
Abbreviations: Acclim., Acclimation; SE, standard error; df, degrees of freedom. S, small effect; M, medium effect; L, large Effect.

Table 2 Reciprocal Reaction Time Results

Comparison	Estimate (SE)	t-Ratio (df)	P value	Cohen's d
7:00AM, 1:00PM	**−0.17 (0.05)**	**−3.55 (114)**	**0.003**	**−0.88 (L)**
7:00AM, 3:00PM	**−0.20 (0.05)**	**−4.08 (114)**	**<0.001**	**−1.02 (L)**
7:00AM, 5:00PM	*−0.12 (0.05)*	*−2.51 (114)*	*0.063*	*−0.62 (M)*
1:00PM, 3:00PM	−0.02 (0.05)	−0.52 (114)	0.953	−0.13 (S)
1:00PM, 5:00PM	−0.05 (0.05)	−1.04 (114)	0.727	−0.26 (S)
3:00PM, 5:00PM	−0.08 (0.05)	−1.56 (114)	0.404	−0.39 (S)
Acclim., Baseline	−0.02 (0.05)	−0.49 (114)	0.961	−0.12 (S)
Acclim., 0–100%	−0.09 (0.05)	1.90 (114)	0.231	0.48 (S)
Acclim., 0–600%	−0.09 (0.05)	1.82 (114)	0.269	0.45 (S)
Baseline, 0–100%	*−0.12 (0.05)*	*2.40 (114)*	*0.084*	*0.60 (M)*
Baseline, 0–600%	*−0.11 (0.05)*	*2.31 (114)*	*0.102*	*0.58 (M)*
0–100%, 0–600%	−0.01 (0.05)	−0.09 (114)	0.999	−0.02 (S)

Notes: Estimates, standard error, test statistics, p values, and effect sizes for follow up comparisons across time and condition. Bold = significant, Italics = trending.
Abbreviations: Acclim., Acclimation; SE, standard error; df, degrees of freedom. S, small effect; M, medium effect; L, large Effect.

Follow up comparisons for each sleep stage across conditions indicated that time asleep was decreased following the 0–100% condition and 0–600% condition compared to the acclimation condition (Figure 4A and Table 3). There was also marginal evidence that time asleep was lower following the baseline condition compared to the acclimation condition, and lower following the 0–100% condition compared to the baseline condition (Figure 4A and Table 3). Notably, while the comparisons between 0–100% and Baseline and between Baseline and Acclimation were marginally significant, they exhibited large effects, indicating reductions in time asleep.

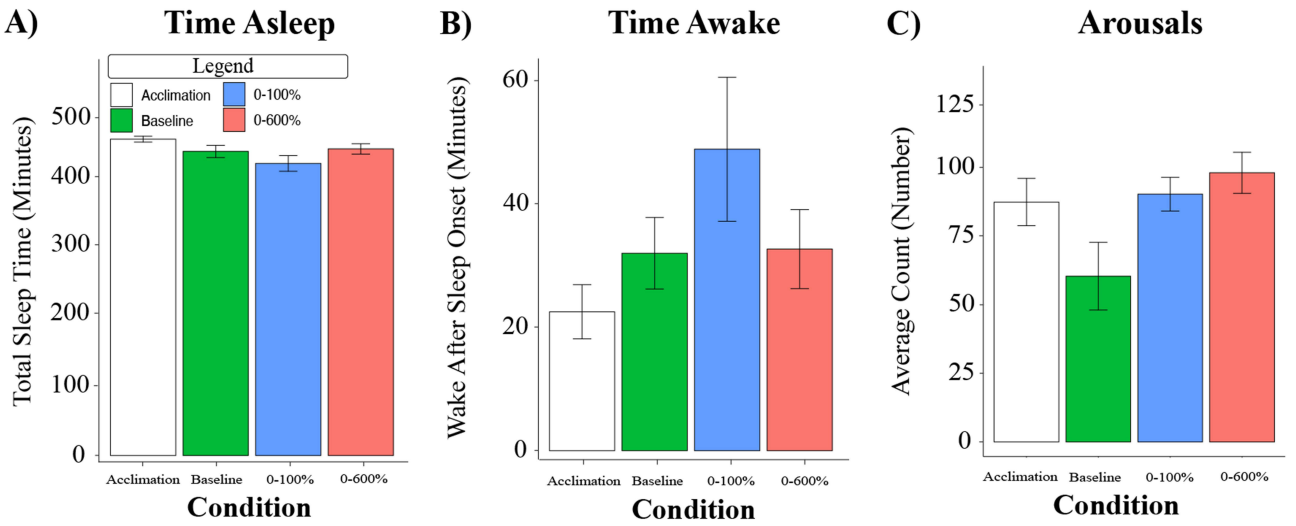

Figure 4 Sleep and Arousals. Bar charts comparing means and standard errors of time asleep, time awake, and arousals across conditions. (**A**) Time asleep. (**B**) Time awake. (**C**) Arousals. White = acclimation condition, green = baseline condition, blue = 0–100% of threshold condition, red = 0–600% of threshold condition.

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Table 3 Sleep Stage and Arousal Results

Sleep Stage	Comparison	Estimate (SE)	t-Ratio (df)	P value	Cohen's d
Time Asleep	*Acclim., Baseline*	*17.78 (7.37)*	*2.41 (179)*	*0.078*	*1.17 (L)*
Time Asleep	**Acclim., 0–100%**	**35.16 (7.37)**	**4.92 (178)**	**<0.001**	**2.32 (VL)**
Time Asleep	Acclim., 0–600%	14.12 (7.37)	1.98 (178)	0.200	0.93 (L)
Time Asleep	*Baseline, 0–100%*	*17.37 (7.37)*	*2.36 (179)*	*0.089*	*1.14 (L)*
Time Asleep	Baseline, 0–600%	−3.66 (7.37)	−0.50 (179)	0.960	−0.24 (S)
Time Asleep	**0–100%, 0–600%**	**−21.03 (7.37)**	**−2.94 (178)**	**0.019**	**−1.39 (VL)**
Time Awake	Acclim., Baseline	−9.50 (7.37)	−1.29 (179)	0.570	−0.63 (M)
Time Awake	**Acclim., 0–100%**	**−26.38 (7.37)**	**−3.69 (178)**	**0.002**	**−1.74 (VL)**
Time Awake	Acclim., 0–600%	−10.17 (7.37)	−1.42 (178)	0.486	−0.67 (M)
Time Awake	*Baseline, 0–100%*	*−16.87 (7.37)*	*−2.29 (179)*	*0.104*	*−1.11 (L)*
Time Awake	Baseline, 0–600%	−0.67 (7.37)	−0.091 (179)	0.999	−0.04 (S)
Time Awake	*0–100%, 0–600%*	*16.21 (7.37)*	*2.27 (178)*	*0.110*	*1.07 (L)*
Arousals	*Acclim., Baseline*	*27.00 (11.1)*	*2.43 (24)*	*0.099*	*1.15 (L)*
Arousals	**Acclim., 0–100%**	−2.89 (11.1)	−0.26 (24)	0.993	−0.12 (S)
Arousals	Acclim., 0–600%	−10.67 (11.1)	−0.96 (24)	0.773	−0.45 (S)
Arousals	*Baseline, 0–100%*	*−29.89 (11.1)*	*−2.69 (24)*	*0.058*	*−1.27 (VL)*
Arousals	**Baseline, 0–600%**	**−37.67 (11.1)**	**−3.39 (24)**	**0.012**	**−1.60 (VL)**
Arousals	0–100%, 0–600%	−7.78 (11.1)	−0.70 (24)	0.896	−0.33 (S)

Notes: Estimates, standard error, test statistics, p values, and effect sizes for follow up comparisons of stages across conditions. Bold = significant, italics = trending.
Abbreviations: Acclim., Acclimation; SE, standard error; df, degrees of freedom. S, small effect; M, medium effect; L, large Effect; VL, very large effect.

Time awake was also significantly greater following the 0–100% condition compared to the acclimation condition (Figure 4B and Table 3). While pairwise comparisons between the 0–100% and 0–600% conditions and between the Baseline and 0–100% condition did not reach the traditional $p<0.05$ threshold for frequentist significance, both comparisons exhibited large effect sizes indicating increases in the time awake. There were not any other significant differences between conditions for any sleep stage (p values >0.75).

For the number of arousals, including condition significantly improved model fit over the null model (χ^2 (6) = 11.71, p =0.008) and was therefore used to analyze differences in the number and duration of arousals. The number of arousals significant differed across conditions ($F(3,24) = 4.34$, p =0.014). Follow up comparisons indicated that there were more arousals following the 0–600% condition compared to the baseline condition (Figure 4C and Table 3). There was also marginal evidence, and large effect sizes, which suggested there were more arousals following the 0–100% condition than the baseline condition, and that there were more arousals following the acclimation condition compared to the baseline condition (Figure 4C and Table 3). There were not any significant differences in the duration of arousals across conditions ($F(3,23.4) =0.94$, p =0.438). Sleep stage summary statistics are included as supplemental material (Table S2).

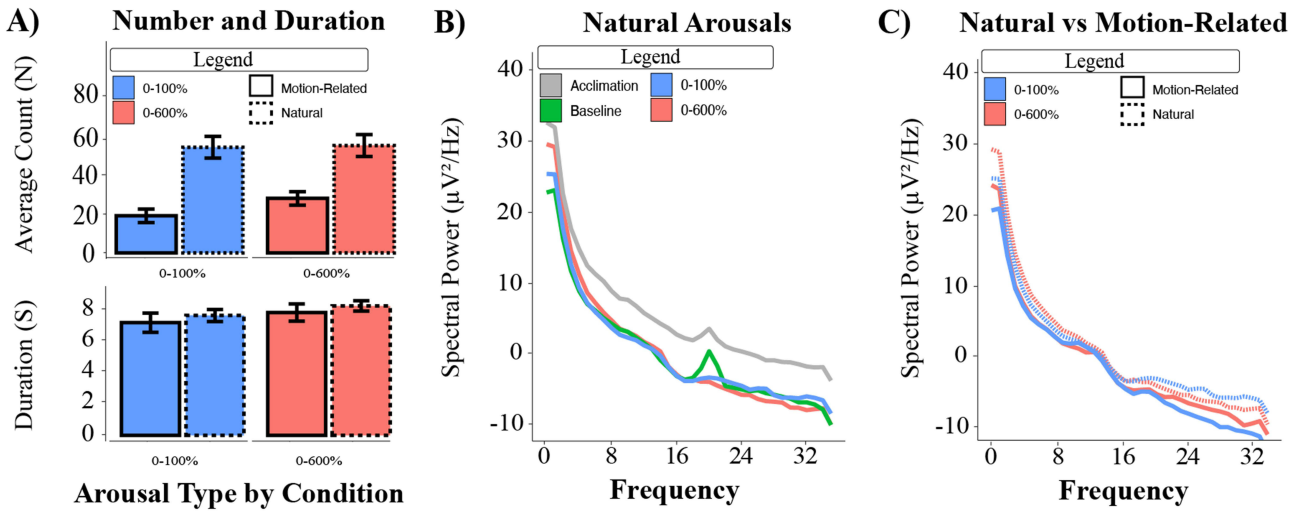

Figure 5 Natural versus motion-related arousals. Bar charts comparing means and standard errors of the number and duration of motion-related and natural arousals. (**A**) Number and duration of arousals. (**B**) Plot comparing spectral power of natural arousals across conditions. (**C**) Plot comparing spectral power of natural versus and motion-related arousals during to 0–100% and 0–600% conditions. Blue = 0–100% of threshold condition, red = 0–600% of threshold condition, solid line = motion-related, dotted line = natural, grey = acclimation condition, green = baseline condition.

Natural versus Motion-Related Arousals

Including condition alone did not significantly improve model fit (χ^2 (1) =0.51, p =0.474), and while a direct comparison was not possible as the models were not nested, the inclusion of arousal type resulted in a highly significant improvement over the null model (χ^2 (3) = 30.08, p <0.001) and a lower AIC (327.27 vs 297.19 respectively). Adding a condition and arousal type interaction did not further improve the model (χ^2 (6) =0.91, p =0.339), suggesting that the number of arousals differed by arousal type but remained stable across conditions. Therefore, the arousal type model was selected to compare the number and duration of natural and motion-related arousals. This analysis indicated that there were significantly more natural arousals than motion-related arousals (F(1,26) = 49.51, p <0.001, cohen's f = 1.38) and that the duration of natural and motion-related arousals was not significantly different (F(1,34) =0.84, p =0.364, cohen's f =0.16)(Figure 5A).

For natural arousals, spectral power significantly differed across conditions in the sigma band with a large effect size (Figure 5B and Table 4). Marginal effects of condition were observed in the alpha, theta, beta, and delta frequency bands (Figure 5B and Table 4). While pairwise comparisons in the sigma band only reached marginal significance, very large effect sizes suggested higher sigma power during the acclimation night compared to the other conditions (acclimation vs baseline: p =0.064, d = 1.23; acclimation vs 0–100%: p =0.069, d = 1.23; acclimation vs 0–600%: p =0.100, d = 1.14). There were not any significant differences between the other conditions (p values >0.989).

Table 4 Spectral Power Results for Natural Arousals

Frequency	Factor	F	df_{num}	df_{den}	P value	Cohen's f [95% CI]
Delta	*Condition*	*2.40*	*3*	*23.64*	*0.093*	*0.55 [0.00, inf]*
Theta	*Condition*	*2.68*	*3*	*23.27*	*0.071*	*0.59 [0.00, inf]*
Alpha	*Condition*	*3.01*	*3*	*23.15*	*0.051*	*0.62 [0.00, inf]*
Sigma	**Condition**	**3.35**	**3**	**23.24**	**0.036**	**0.66 [0.12, inf]**
Beta	*Condition*	*2.58*	*3*	*23.09*	*0.078*	*0.58 [0.00, inf]*

Note: ANOVA results for the spectral power of natural arousals. Bold = significant, Italics = trending.
Abbreviations: df_{num}, numerator degrees of freedom; df_{den}, denominator degrees of freedom; inf, infinity.

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Table 5 Spectral Power Results Comparing Natural and Motion-Related Arousals

Frequency	Factor	F	df_{num}	df_{den}	P value	Cohen's f [95% CI]
Delta	Condition	2.61	1	25	0.119	0.32 [0.00, inf]
Theta	Condition	1.24	1	25	0.275	0.22 [0.00, inf]
Alpha	Condition	0.15	1	25	0.699	0.08 [0.00, inf]
Sigma	Condition	0.05	1	25	0.816	0.24 [0.00, inf]
Beta	Condition	0.01	1	25	0.912	0.02 [0.00, inf]
Delta	**Type**	**12.58**	**1**	**25**	**0.002**	**0.71 [0.34, inf]**
Theta	**Type**	**10.14**	**1**	**25**	**0.004**	**0.64 [0.27, inf]**
Alpha	*Type*	*2.92*	*1*	*25*	*0.010*	*0.34 [0.00, inf]*
Sigma	Type	1.40	1	25	0.248	0.05 [0.00, inf]
Beta	*Type*	*3.14*	*1*	*25*	*0.088*	*0.35 [0.00, inf]*

Notes: ANOVA results comparing natural and motion-related arousals. Bold = significant, Italics = trending.
Abbreviations: df_{num}, numerator degrees of freedom; df_{den}, denominator degrees of freedom; inf, infinity.

When comparing natural and motion-related arousals, delta and theta power were significantly higher during natural arousals compared to motion-related arousals (Figure 5C and Table 5). There was also marginal evidence that alpha and beta power were higher during natural arousals compared to motion-related arousals (Figure 5C and Table 5).

Arousals, Motion Direction, and Motion Size

Including condition alone significantly improved fit over the null model (χ^2 (1) = 7.81, p =0.005). However, neither adding direction (χ^2 (1) =0.17, p =0.683) nor an interaction of condition and direction (χ^2 (1) = 1.97, p =0.161) as fixed effects further improved the model. These results suggest that the proportion of arousals significantly differed across conditions, but this effect was consistent regardless of the direction. Therefore, the condition model was used to analyze changes in the proportion of arousals by direction. This analysis indicated that the proportion of arousals was higher during the 0–600% condition than the 0–100% condition (F(1,26) = 8.72, p =0.007, cohen's f =0.58, Figure 6A).

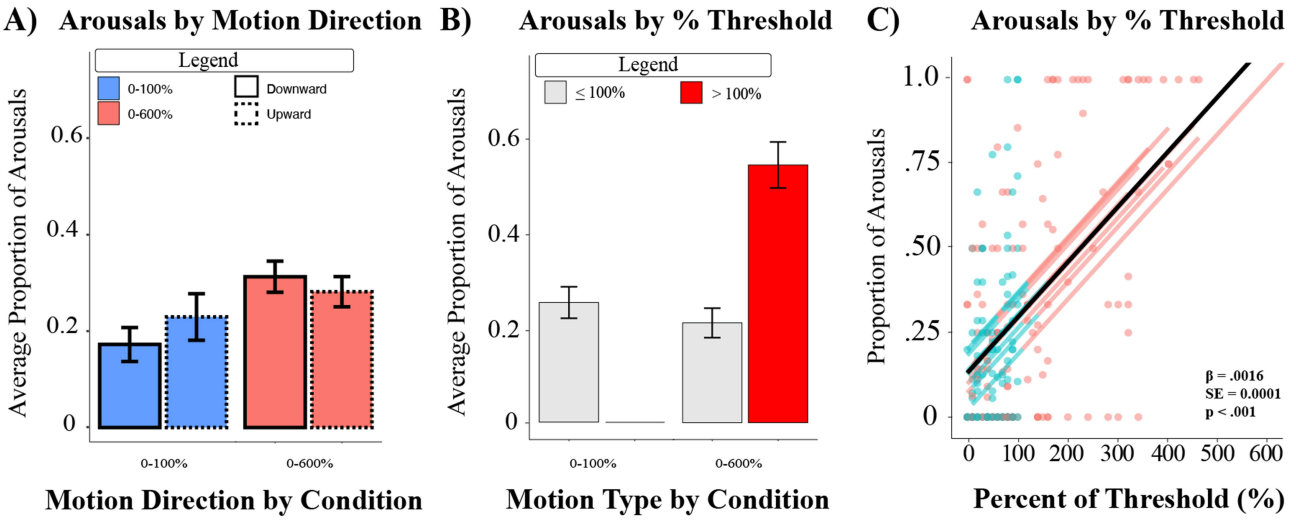

Figure 6 Arousals, Motion Directions, and Motion Size. Bar charts comparing means and standard errors in the average proportion of arousals across motion direction, type, and condition and a scatterplot depicting the relationship between percent of threshold and the proportion of arousals. (**A**) Arousals by condition and motion direction. Blue = 0–100% of threshold condition, red = 0–600% of threshold condition, solid line = downward motions, dotted line = upward motions. (**B**) Arousals by condition and percent threshold. Grey = ≤ 100% of threshold motions, red = > 100% of threshold motions. (**C**) Arousals by percent threshold.

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Including motion type significantly improved fit over the null model (χ^2 (2) = 21.36, p <0.001) and analysis with this model indicated that the proportion of arousals significantly differed across motion types (F(2,16) = 16.58, p <0.001, cohen's f = 1.44). Follow up comparisons indicated a significantly greater proportion arousals for > 100% motions compared to ≤ 100% motions during both 0–600% condition (t(16) = 5.08, p <0.001, d = 2.40) and 0–100% condition (t(16) = 4.89, p <0.001, d = 2.30). There were not any significant differences between the proportion of arousals between ≤ 100% motions during the 0–600% compared to 0–100% conditions (t(16) = −0.197, p =0.979, d = −0.09) (Figure 6B).

Including motion magnitude alone significantly improved model fit over the null model (χ^2 (1) = 74.33, p <0.001), but the addition of a random slope for motion magnitude did not further improve model fit (χ^2 (2) = 1.06, p =0.590). These results suggest that while motion magnitude significantly influenced the proportion of arousals, this effect was consistent across participants. Therefore, the random intercept model was used to analyze whether motion magnitude influenced the proportion of arousals. As predicted, larger motion magnitude significantly predicted a higher proportion of arousals (β =0.0016, SE = 0.0001, t(213.3) = 9.42, p <0.001). The 95% confidence interval for the effect of motion magnitude also did not include zero [0.0013,0.0020]. The marginal R^2 =0.276 indicated that motion magnitude alone accounted for 27.6% of the variance in arousal proportion while the conditional R^2 =0.328 showed that the total model, including the random effect of participant, explained 32.8% of the variance (Figure 6C).

Discussion

Travel-related sleep disturbances due to sounds and motions diminish sleep quality, health, and cognition. There is a critical need for experiments that use experimentally controlled motions to understand the effects of sounds and motions on sleep and cognitive performance. The results of this study demonstrate that 1 Hz earth-vertical (upward and downward) motions administered during sleep significantly disrupt next day cognitive performance, lead to arousals with brain activity that is different from natural arousals, and disrupt sleep more as the motions were larger. Implementing strategies to minimize the number and magnitude of vertical movements during sleep may mitigate the economic and health detriments caused by travel-related sleep disturbances.

Increased lapses and reciprocal reaction times following overnight sleep with motions demonstrate that earth vertical motions disrupt next day cognitive performance. Disrupted sleep has been demonstrated to impair human performance.[90–92] Following sleep deprivation and circadian disturbance, studies reliably show alterations in attention, vigilance, executive function, emotional reactivity, memory formation, decision making, and judgement.[93] However, it is not clear whether all tasks and cognitive functions are affected by sleep disruption equally.[90] For example, sleep disruption degrades performance on complex cognitive tasks less than simple tasks.[90,93] In this study, sleep disruptions due to motion decreased attention and vigilance, but potential effects on memory remain untested.

Further, it is unclear whether different types of sleep disruptions affect performance equally. Health and memory detriments related to sleep disruptions are thought to be related to increased activation of the sympathetic nervous system and hypothalamic-pituitary-adrenal axis, and motion-related arousals could increase sympathetic activation more compared to natural arousals.[94–97] Changes in sleep composition, circadian changes, and increases in the number of arousals have all been demonstrated to impair performance.[90–93] During arousals, metabolism and oxygen consumption coincidently increase the production of carbon dioxide and cortisol.[94] Further, brain activity during arousals has been demonstrated to change across sensory modalities of sounds, smells, and nociceptive inputs.[49,50,54–58,61,63,98–100] Therefore, while additional neuroscientific studies will be required, there is strong evidence to suggest that arousals related to different sensory modalities like motions or sounds during sleep could negatively affect next day brain function in different ways. The results of this study demonstrate that sleep disruptions related to motion decrease levels of attention and vigilance the day following the sleep disruptions.

Less time asleep, more time awake, and more arousals during nights with motion demonstrate that earth vertical motions disrupt sleep. Converging neuroanatomical and behavioral evidence strongly suggest that vestibular function significantly impacts sleep and circadian rhythms.[23,24,28–31] The results of this study provide novel evidence that 1Hz earth vertical motions disrupt sleep. Further, a strong and significant positive relationship between the probability of an arousal and motion magnitude demonstrate that larger motions disrupt sleep more than weaker motions.

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The vestibular system is thought to impact sleep through neural connections to brain areas vital to sleep and alertness like the suprachiasmatic nucleus, locus coeruleus, and orexinergic neurons.[23] The activity of vestibular neurons varies in response to motion stimuli across direction, size, and speed.[23,28,41,101,102] For example, upright horizontal and rocking motions predominantly involve the utricular otolith organs whereas up and down vertical motions predominantly involve the saccular otolith organs.[23,28,103,104] Differences in the neuroanatomical and functional correlates that underly processing horizontal and vertical motions could be a potential mechanism underlying whether motions during sleep are beneficial or detrimental. Further understanding how vestibular function impacts sleep disruption could be valuable for identifying strategies to maximize beneficial motions and minimize detrimental motions during sleep.

Although this article only tests 1 Hz motions, easy and cost-effective strategies such as changing the orientation of a naval ship during rough seas could help transform disruptive vertical motions caused by waves to beneficial horizontal rocking motions from the same waves. Since sleep disruption increased with increasing motion magnitude, other strategies to reduce motion magnitude, such as motion dampening beds or navigating vehicles to environments that cause less motion, may be helpful to mitigate sleep disruptions. Additional studies will be required to determine whether and how motion magnitude, frequency, and direction impact brain processes, sleep, and cognitive performance. Further, additional studies will be required to determine appropriate countermeasures like pharmacotherapies or motion-reducing beds that can reduce the impacts of motion related sleep disruptions and resultant cognitive disruptions.

Differences in number and spectral power demonstrate that natural and motion-related arousals are distinct from each other. The neural correlates of vestibular perception during sleep remain unclear.[23,24] During sleep the flow of most sensory neural activity related to sounds, smells, and visual inputs is inhibited through activity in the thalamus.[39] However, sensory inputs like sounds and smells have been demonstrated to elicit different cognitive responses and impact long-term memory retention – in some cases participants can even learn new words while asleep.[34,39,105,106] Spectral power has been demonstrated to change in response to different sounds and smells, and can be a reliable index of underlying neural processes like alertness and cognitive processing.[36–38,51,54,58,87,99] Here, decreased delta and theta activity during motion-related compared to natural arousals could indicate greater vigilance and brain processing during motion-related arousals. While there is strong evidence that vestibular inputs would be salient inputs for processing during sleep, additional neuroimaging studies are needed to examine the impacts of different motions of sleep disturbances and changes in brain activity. Quantifying sleep disturbances and spectral changes related to vestibular processing during sleep could index underlying neural processes and future topographic and time-frequency studies will be needed.

Limitations

The results of this study should be considered in light of three main limitations. First, the sample size of 9 participants was relatively small. However, despite the limited number of participants, the effect sizes observed were large and statistically significant, suggesting that the impact of vertical motion on sleep disruption is robust. As well, an a priori power analysis for a within-subject ANOVA with alpha set to.05, desired power set to.95, and a medium effect size of.45 determined that 8 participants would be required (G*Power 3.1).

Second, the order of motion conditions (0–100% followed by 0–600%) was not counterbalanced across participants to ensure that participants could tolerate moderate stimuli before being exposed to the higher motion magnitudes. Consequently, it is possible that participants habituated to the motions over time, potentially dampening the observed effects on the 0–600% nights. Additionally, sleep disruption on the 0–100% nights could have led to recovery sleep on the 0–600% nights. Furthermore, sleep quality decreased from acclimation to baseline, diverging from the traditional "First Night" effect. Speculatively, elevated sleep pressure upon study entry may have facilitated a sleep rebound during the acclimation night, masking initial environmental novelty. Conversely, the baseline night may have been impacted by anticipatory vigilance or sensitization to the discomfort of the equipment, a phenomenon consistent with the "night watch" hemispheric asymmetry observed in novel sleep environments.[48] Future studies should utilize a randomized and counterbalanced design to disentangle the effects of motion magnitude from potential habituation or sensitization.

Third, although the motion device and fan providing white noise created a loud sleeping environment, sound levels only varied by ~10 dB between the smallest and largest motions. Notably, the proportion of arousals increased

significantly with motion magnitude even when sound levels were near-constant. This indicates that the physical size of the earth-vertical translation, not the noise produced by the motion device during the applied translation, was the primary cause of the arousals.

Conclusion

In conclusion, this study demonstrates that 1 Hz earth-vertical (ie, upward and downward) motions disrupt sleep and next-day attention and vigilance. These motions induce arousals characterized by unique spectral power signatures distinct from natural arousals, suggesting a specific neural response to vestibular input during sleep. Furthermore, the disruption is dose-dependent, with larger motions causing greater sleep fragmentation. These findings highlight the critical need for strategies to mitigate vertical motion in travel environments — such as motion-dampening technologies or altering vehicle orientation — to preserve human health and cognitive function.

Abbreviations

PSG, Polysomnography; REM, Rapid Eye Movement; NREM, Non-Rapid Eye Movement; MEQ, Morning Eveningness Questionnaire; PVT, Psychomotor Vigilance Test.

Data Sharing Statement

The data underlying this article will be shared on reasonable request to the corresponding author.

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Author Contribution

Kyle Kainec: conceptualization, software, validation, formal analysis, data curation, writing, original draft, writing, review and editing, visualization. Allison Ludwig: methodology, validation, investigation, data curation, project administration. Megan Boltz: methodology, validation, investigation, data curation, project administration. John Oas: methodology, validation, investigation, data curation, project administration. J. Lynn Caldwell: conceptualization, resources, supervision, project administration, funding acquisition. Daniel Merfeld: conceptualization, resources, supervision, writing, review and editing, project administration, funding acquisition. All authors took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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References

1. Kerkamm F, Dengler D, Eichler M, et al. Measurement methods of fatigue, sleepiness, and sleep behaviour aboard ships: a systematic review. *Int J Environ Res Public Health*. 2021;19(1):120. doi:10.3390/IJERPH19010120
2. Nittari G, Gibelli F, Bailo P, Sirignano A, Ricci G. Factors affecting mental health of seafarers on board merchant ships: a systematic review. *Rev Environ Health*. 2024;39(1):151–160. doi:10.1515/REVEH-2021-0070/MACHINEREADABLECITATION/RIS
3. Leatherwood WE, Dragoo JL. Effect of airline travel on performance: a review of the literature. *Br J Sports Med*. 2013;47(9):561–567. doi:10.1136/BJSPORTS-2012-091449
4. Yang Y, Mao Z, Zhang X. Better sleep, better trip: the effect of sleep quality on tourists' experiences. *Ann Tour Res*. 2021;87:103153. doi:10.1016/J.ANNALS.2021.103153
5. Crizzle AM, Bigelow P, Adams D, Gooderham S, Myers AM, Thiffault P. Health and wellness of long-haul truck and bus drivers: a systematic literature review and directions for future research. *J Transp Health*. 2017;7:90–109. doi:10.1016/J.JTH.2017.05.359
6. Vink P, Vledder G, Smulders M, Song Y. How do we sleep? Towards physical requirements for space and environment while travelling. *Appl Ergon*. 2025;122:104386. doi:10.1016/J.APERGO.2024.104386
7. Bor R, Hubbard T. Psychological stress and air travel: an overview of psychological stress affecting airline passengers. In: *Aviation Mental Health*. Routledge; 2016:13–25. doi:10.4324/9781315568560-3
8. Smith MG, Croy I, Hammar O, Persson Waye K. Vibration from freight trains fragments sleep: a polysomnographic study. *Sci Rep*. 2016;6(1):1–10. doi:10.1038/srep24717
9. Sullivan M, Grow B. Assessing the effect of shipboard motion and sleep surface on sleep effectiveness; 2009. Available from: https://calhoun.nps.edu/bitstream/handle/10945/4507/09Dec_Grow.pdf?sequence=1. Accessed March 10, 2025.
10. Haward BM, Lewis CH, Griffin MJ. Motions and crew responses on an offshore oil production and storage vessel. *Appl Ergon*. 2009;40(5):904–914. doi:10.1016/J.APERGO.2009.01.001
11. Kimura H, Endo M, Koseki M, Inou N. Sleep-inducing factors in mechanical environment. *Nihon Kikai Gakkai Ronbunshu C Hen/Transact Jpn Soc Mech Eng Part C*. 2008;74(4):806–813. doi:10.1299/KIKAIC.74.806
12. Jepsen JR, Zhao Z, van Leeuwen WMA. Seafarer fatigue: a review of risk factors, consequences for seafarers' health and safety and options for mitigation. *Int Marit Health*. 2015;66(2):106–117. doi:10.5603/IMH.2015.0024
13. Maki KA, Fink AM, Weaver TE. Sleep, time, and space—fatigue and performance deficits in pilots, commercial truck drivers, and astronauts. *SLEEP Adv*. 2022;3(1). doi:10.1093/SLEEPADVANCES/ZPAC033
14. Filtness AJ, Naweed A. Causes, consequences and countermeasures to driver fatigue in the rail industry: the train driver perspective. *Appl Ergon*. 2017;60:12–21. doi:10.1016/J.APERGO.2016.10.009
15. Lee DW, Kim SJ, Shin NY, et al. Sleeping, sleeping environments, and human errors in South Korean male train drivers. *J Occup Health*. 2019;61(5):358–367. doi:10.1002/1348-9585.12059
16. Fowler P, Duffield R, Vaile J. Effects of simulated domestic and international air travel on sleep, performance, and recovery for team sports. *Scand J Med Sci Sports*. 2015;25(3):441–451. doi:10.1111/SMS.12227
17. Elmenhorst EM, Rooney D, Benderoth S, Wittkowski M, Wenzel J, Aeschbach D. Sleep-induced hypoxia under flight conditions: implications and countermeasures for long-haul flight crews and passengers. *Nat Sci Sleep*. 2022;14:193–205. doi:10.2147/NSS.S339196
18. Smith MG, Croy I, Ögren M, Persson Waye K. On the influence of freight trains on humans: a laboratory investigation of the impact of nocturnal low frequency vibration and noise on sleep and heart rate. *PLoS One*. 2013;8(2):e55829. doi:10.1371/JOURNAL.PONE.0055829
19. Croy I, Smith MG, Waye KP. Effects of train noise and vibration on human heart rate during sleep: an experimental study. *BMJ Open*. 2013;3(5):e002655. doi:10.1136/BMJOPEN-2013-002655
20. Alfaiate D, Pereira A, Guerra P, Pinto N. Body posture as a factor determining sleep quality in patients using non-invasive ventilation. *Sleep Breath*. 2023;27(6):2437–2442. doi:10.1007/s11325-023-02817-0
21. Cary D, Jacques A, Briffa K. Examining relationships between sleep posture, waking spinal symptoms and quality of sleep: a cross sectional study. *PLoS One*. 2021;16(11):e0260582. doi:10.1371/journal.pone.0260582
22. Zhang Y, Xiao A, Zheng T, Xiao H, Huang R. The relationship between sleeping position and sleep quality: a flexible sensor-based study. *Sensors*. 2022;22(16):6220. doi:10.3390/s22166220
23. Ebben MR. The impact of vestibular stimulation on sleep and respiration in humans. *Curr Sleep Med Rep*. 2024;10(2):226–231. doi:10.1007/S40675-024-00289-6/METRICS
24. Besnard S, Tighilet B, Chabbert C, et al. The balance of sleep: role of the vestibular sensory system. *Sleep Med Rev*. 2018;42:220–228. doi:10.1016/J.SMRV.2018.09.001
25. Subramaniam A, Eberhard-Moscicka AK, Ertl M, Mast FW. Rocking devices and the role of vestibular stimulation on sleep—a systematic review. *Clin Transl Neurosci*. 2023;7(4):40. doi:10.3390/CTN7040040
26. Muto T, Yoshizawa MI, Kim C, Kume K. Sleep-improving effects of a novel motion mattress. *Sleep Biol Rhythms*. 2021;19(3):247–253. doi:10.1007/S41105-021-00310-3/FIGURES/3
27. Kwon HB, Jeong J, Choi B, Park KS, Joo EY, Yoon H. Effect of closed-loop vibration stimulation on sleep quality for poor sleepers. *Front Neurosci*. 2024;18:1456237. doi:10.3389/FNINS.2024.1456237/BIBTEX
28. Khan S, Chang R. Anatomy of the vestibular system: a review. *NeuroRehabilitation*. 2013;32(3):437–443. doi:10.3233/NRE-130866
29. Sendesen E, Kocabay AP, Yiğit Ö. Does sleep quality affect balance? The perspective from the somatosensory, vestibular, and visual systems. *Am J Otolaryngol*. 2024;45(3):104230. doi:10.1016/J.AMJOTO.2024.104230
30. Fuller PM, Jones TA, Jones SM, Fuller CA. Neurovestibular modulation of circadian and homeostatic regulation: vestibulohypothalamic connection?. *Proc Natl Acad Sci U S A*. 2002;99(24):15723–15728. doi:10.1073/PNAS.242251499

31. Yan G, Li F, Tao Z, et al. Effects of vestibular damage on the sleep and expression level of orexin in the hypothalamus of rats and its correlation with autophagy and akt tumor signal pathway. *J Oncol*. 2022;2022(1):2514555. doi:10.1155/2022/2514555
32. Gonfalone AA. Sleep and gravity. *Med Hypotheses*. 2018;113:81–84. doi:10.1016/J.MEHY.2018.02.020
33. Katzenberger B, Brosch F, Besnard S, Grill E. Chronic vestibular hypofunction is associated with impaired sleep: results from the DizzyReg Patient Registry. *J Clin Med*. 2023;12(18):5903. doi:10.3390/JCM12185903/S1
34. Ruch S, Alain Züst M, Henke K. Sleep-learning impairs subsequent awake-learning. *Neurobiol Learn Mem*. 2022;187. doi:10.1016/J.NLM.2021.107569
35. Züst MA, Ruch S, Wiest R, Henke K. Implicit vocabulary learning during sleep is bound to slow-wave peaks. *Curr Biol*. 2019;29(4):541–553.e7. doi:10.1016/J.CUB.2018.12.038
36. Bastuji H, Perrin F, Garcia-Larrea L. Semantic analysis of auditory input during sleep: studies with event related potentials. *Int J Psychophysiol*. 2002;46(3):243–255. doi:10.1016/S0167-8760(02)00116-2
37. Colrain IM, Campbell KB. The use of evoked potentials in sleep research. *Sleep Med Rev*. 2007;11(4):277–293. doi:10.1016/J.SMRV.2007.05.001
38. Atienza M, Cantero JL, Escera C. Auditory information processing during human sleep as revealed by event-related brain potentials. *Clin Neurophysiol*. 2001;112(11):2031–2045. doi:10.1016/S1388-2457(01)00650-2
39. Coenen A. Sensory gating and gaining in sleep: the balance between the protection of sleep and the safeness of life (a review). *J Sleep Res*. 2024;33(5):e14152. doi:10.1111/JSR.14152
40. Karmali F, Rey MCB, Clark TK, Wang W, Merfeld DM. Multivariate analyses of balance test performance,vestibular thresholds, and age. *Front Neurol*. 2017;8:295341. doi:10.3389/FNEUR.2017.00578/BIBTEX
41. Clark TK, Galvan-Garza RC, Merfeld DM. Intra-individual consistency of vestibular perceptual thresholds. *Atten Percept Psychophys*. 2024;86(4):1417–1434. doi:10.3758/S13414-024-02886-7/TABLES/3
42. Patel AK, Reddy V, Shumway KR, Araujo JF. Physiology, sleep stages. *StatPearls*; 2024. Available from: https://www.ncbi.nlm.nih.gov/books/NBK526132/. Accessed March 17, 2025.
43. Born J, Wilhelm I. System consolidation of memory during sleep. *Psychol Res*. 2012;76(2):192–203. doi:10.1007/s00426-011-0335-6
44. Silber MH, Ancoli-Israel S, Bonnet MH, et al. The visual scoring of sleep in adults. *J Clin Sleep Med*. 2007;3(2):121–131. doi:10.5664/jcsm.26814
45. McCarter SJ, Hagen PT, St. Louis EK, et al. Physiological markers of sleep quality: a scoping review. *Sleep Med Rev*. 2022;64:101657. doi:10.1016/J.SMRV.2022.101657
46. Rahimimoghadam S, Khanjani N, Jalali M, Khorashadizadeh F, Shahmohammadi A. The effect of exposure to noise and vibration and ergonomic factors on sleep quality and musculoskeletal disorders in bus drivers in Iran. *Int J Environ Health Eng*. 2024;13(1). doi:10.4103/IJEHE.IJEHE_28_24
47. Agnew HW, Webb WB, Williams RL. THE FIRST NIGHT EFFECT: AN EEG STUDYOF SLEEP. *Psychophysiology*. 1966;2(3):263–266. doi:10.1111/j.1469-8986.1966.tb02650.x
48. Tamaki M, Bang JW, Watanabe T, Sasaki Y. Night watch in one brain hemisphere during sleep associated with the first-night effect in humans. *Curr Biol*. 2016;26(9):1190–1194. doi:10.1016/j.cub.2016.02.063
49. Griefahn B, Bröde P, Marks A, Basner M. Autonomic arousals related to traffic noise during sleep. *Sleep*. 2008;31(4):569–577. doi:10.1093/SLEEP/31.4.569
50. Lechat B, Hansen K, Micic G, et al. K-complexes are a sensitive marker of noise-related sensory processing during sleep: a pilot study. *Sleep*. 2021;44(9). doi:10.1093/SLEEP/ZSAB065
51. Boselli M, Parrino L, Smerieri A, Terzano MG. Effect of age on EEG arousals in normal sleep. *Sleep*. 1998;21(4):361–367. doi:10.1093/SLEEP/21.4.361
52. Force AT. A preliminary report from the sleep disorders atlas task force of the American Sleep Disorders Association. *Sleep*. 1992;15(2):174–184. doi:10.1093/SLEEP/15.2.174
53. Mathur R, Douglas NJ. Frequency of EEG arousals from nocturnal sleep in normal subjects. *Sleep*. 1995;18(5):330–333. doi:10.1093/SLEEP/18.5.330
54. Dunbar C, Catcheside P, Lechat B, et al. EEG power spectral responses to wind farm compared with road traffic noise during sleep: a laboratory study. *J Sleep Res*. 2022;31(3):e13517. doi:10.1111/JSR.13517
55. Mainieri G, Loddo G, Castelnovo A, et al. EEG activation does not differ in simple and complex episodes of disorders of arousal: a spectral analysis study. *Nat Sci Sleep*. 2022;14:1097–1111. doi:10.2147/NSS.S360120
56. Dressle RJ, Riemann D, Spiegelhalder K, Frase L, Perlis ML, Feige B. On the relationship between EEG spectral analysis and pre-sleep cognitive arousal in insomnia disorder: towards an integrated model of cognitive and cortical arousal. *J Sleep Res*. 2023;32(4):e13861. doi:10.1111/JSR.13861
57. Stuck BA, Stieber K, Frey S, et al. Arousal responses to olfactory or trigeminal stimulation during sleep. *Sleep*. 2007;30(4):506–510. doi:10.1093/SLEEP/30.4.506
58. Heiser C, Baja J, Lenz F, et al. Trigeminal induced arousals during human sleep. *Sleep Breathing*. 2015;19(2):553–560. doi:10.1007/S11325-014-1046-1/TABLES/3
59. Qian X, Qiu Y, He Q, et al. A review of methods for sleep arousal detection using polysomnographic signals. *Brain Sci*. 2021;11(10):1274. doi:10.3390/BRAINSCI11101274
60. Lendner JD, Helfrich RF, Mander BA, et al. An electrophysiological marker of arousal level in humans. *eLife*. 2020;9:1–29. doi:10.7554/ELIFE.55092
61. Lavigne G, Zucconi M, Castronovo C, Manzini C, Marchettini P, Smirne S. Sleep arousal response to experimental thermal stimulation during sleep in human subjects free of pain and sleep problems. *Pain*. 2000;84(2–3):283–290. doi:10.1016/S0304-3959(99)00213-4
62. Bonnet MH, Doghramji K, Roehrs T, et al. The scoring of arousal in sleep: reliability, validity, and alternatives. *J Clin Sleep Med*. 2007;3(2):133–145. doi:10.5664/JCSM.26815
63. Neckelmann D, Ursin R. Sleep stages and EEG power spectrum in relation to acoustical stimulus arousal threshold in the rat. *Sleep*. 1993;16(5):467–477. doi:10.1093/SLEEP/16.5.467

64. Gosselin N, Michaud M, Carrier J, Lavigne G, Montplaisir J. Age difference in heart rate changes associated with micro-arousals in humans. *Clin Neurophysiol*. 2002;113(9):1517–1521. doi:10.1016/S1388-2457(02)00189-X
65. Halász P, Terzano M, Parrino L, Bódizs R. The nature of arousal in sleep. *J Sleep Res*. 2004;13(1):1–23. doi:10.1111/J.1365-2869.2004.00388.X
66. Horne JA, Ostberg O. A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *Int J Chronobiol*. 1976;4(2):97–110.
67. Berry RB, Brooks R, Gamaldo C, et al. AASM scoring manual updates for 2017 (version 2.4). *J Clin Sleep Med*. 2017;13(5):665–666. doi:10.5664/jcsm.6576
68. Olasagasti I, Bockisch CJ, Zee DS, Straumann D. Dynamic cyclovergence during vertical translation in humans. *J Neurosci*. 2011;31(27):9991–9997. doi:10.1523/JNEUROSCI.0064-11.2011
69. Moore ST, Hirasaki E, Raphan T, Cohen B. The human vestibulo-ocular reflex during linear locomotion. *Ann N Y Acad Sci*. 2001;942:139–147. doi:10.1111/j.1749-6632.2001.tb03741.x
70. Valko Y, Lewis RF, Priesol AJ, Merfeld DM. Vestibular labyrinth contributions to human whole-body motion discrimination. *J Neurosci*. 2012;32(39):13537–13542. doi:10.1523/JNEUROSCI.2157-12.2012
71. Chaudhuri SE, Merfeld DM. Signal detection theory and vestibular perception: III. Estimating unbiased fit parameters for psychometric functions. *Exp Brain Res*. 2013;225(1):133–146. doi:10.1007/S00221-012-3354-7/TABLES/6
72. Leek MR. Adaptive procedures in psychophysical research. *Percept Psychophys*. 2001;63(8):1279–1292. doi:10.3758/BF03194543/METRICS
73. Treutwein B. Adaptive psychophysical procedures. *Vision Res*. 1995;35(17):2503–2522. doi:10.1016/0042-6989(95)00016-X
74. Grabherr L, Nicoucar K, Mast FW, Merfeld DM. Vestibular thresholds for yaw rotation about an earth-vertical axis as a function of frequency. *Exp Brain Res*. 2008;186(4):677–681. doi:10.1007/S00221-008-1350-8/FIGURES/2
75. Taylor MM, Taylor MM. PEST: efficient estimates on probability functions. *ASAJ*. 1967;41(4A):782. doi:10.1121/1.1910407
76. Posit T. RStudio: integrated development environment for R. *Posit Software, PBC*; 2025. Available from: http://www.posit.co/. Accessed April 15, 2026.
77. R Core Team. R: a language and environment for statistical computing. *R Foundation for Statistical Computing*; 2024:4.4.1.
78. Pond RS, McCool MW, Bulla BA. Multilevel modeling of interval-contingent data in neuropsychology research using the lmerTest package in R. *J Pediatr Neuropsychol*. 2021;7(3):102–112. doi:10.1007/s40817-020-00095-2
79. Lenth RV, Banfai B, Bolker B, et al. Emmeans: estimated marginal means, aka least-squares means; 2025. Available from: https://cran.r-project.org/web/packages/emmeans/index.html. Accessed April 15, 2026.
80. Ding J, Tarokh V, Yang Y. Model selection techniques: an overview. *IEEE Signal Process Mag*. 2018;35(6):16–34. doi:10.1109/MSP.2018.2867638
81. Breuer M, Dehaan E. Using and interpreting fixed effects models. *J Account Res*. 2024;62(4):1183–1226. doi:10.1111/1475-679X.12559
82. Brown VA. An introduction to linear mixed-effects modeling in R. *Adv Methods Pract Psychol Sci*. 2021;4(1):2515245920960351. doi:10.1177/2515245920960351
83. Kuznetsova A, Brockhoff PB, Christensen RHB. lmerTest package: tests in linear mixed effects models. *J Stat Softw*. 2017;82(13). doi:10.18637/jss.v082.i13
84. Sawilowsky SS. New effect size rules of thumb. *J Mod Appl Stat Methods*. 2009;8(2):597–599. doi:10.22237/jmasm/1257035100
85. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 0 ed. Routledge; 2013. doi:10.4324/9780203771587
86. Berry RB, Budhiraja R, Gottlieb DJ, et al. Rules for scoring respiratory events in sleep: update of the 2007 AASM manual for the scoring of sleep and associated events. *J Clin Sleep Med*. 2012;8(5):597–619. doi:10.5664/JCSM.2172
87. Lustenberger C, Patel YA, Alagapan S, et al. High-density EEG characterization of brain responses to auditory rhythmic stimuli during wakefulness and NREM sleep. *Neuroimage*. 2018;169:57–68. doi:10.1016/J.NEUROIMAGE.2017.12.007
88. Kato T, Montplaisir JY, Lavigne GJ. Experimentally induced arousals during sleep: a cross-modality matching paradigm. *J Sleep Res*. 2004;13(3):229–238. doi:10.1111/J.1365-2869.2004.00409.X
89. Delorme A, Makeig S. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J Neurosci Methods*. 2004;134(1):9–21. doi:10.1016/j.jneumeth.2003.10.009
90. Wickens CD, Hutchins SD, Laux L, Sebok A. The impact of sleep disruption on complex cognitive tasks. *Hum Fact*. 2015;57(6):930–946. doi:10.1177/0018720815571935/ASSET/3E1B5572-726A-4D1A-8E5E-A2C50439EDDE/ASSETS/IMAGES/LARGE/10.1177_0018720815571935-FIG4.JPG
91. Medic G, Wille M, Hemels MEH. Short- and long-term health consequences of sleep disruption. *Nat Sci Sleep*. 2017;9:151–161. doi:10.2147/NSS.S134864
92. Potter GDM, Skene DJ, Arendt J, Cade JE, Grant PJ, Hardie LJ. Circadian rhythm and sleep disruption: causes, metabolic consequences, and countermeasures. *Endocr Rev*. 2016;37(6):584–608. doi:10.1210/ER.2016-1083
93. McCoy JG, Strecker RE. The cognitive cost of sleep lost. *Neurobiol Learn Mem*. 2011;96(4):564–582. doi:10.1016/J.NLM.2011.07.004
94. Bonnet MH, Berry RB, Arand DL. Metabolism during normal, fragmented, and recovery sleep. *J Appl Physiol*. 1991;71(3):1112–1118. doi:10.1152/JAPPL.1991.71.3.1112
95. Tiemeier H, Pelzer E, Jönck L, Möller HJ, Rao ML. Plasma catecholamines and selective slow wave sleep deprivation. *Neuropsychobiology*. 2002;45(2):81–86. doi:10.1159/000048681
96. Vgontzas AN, Tsigos C, Bixler EO, et al. Chronic insomnia and activity of the stress system: a preliminary study. *J Psychosom Res*. 1998;45(1):21–31. doi:10.1016/S0022-3999(97)00302-4
97. Vgontzas AN, Bixler EO, Lin HM, et al. Chronic insomnia is associated with nyctohemeral activation of the hypothalamic-pituitary-adrenal axis: clinical implications. *J Clin Endocrinol Metab*. 2001;86(8):3787–3794. doi:10.1210/JCEM.86.8.7778
98. Berridge CW. Noradrenergic modulation of arousal. *Brain Res Rev*. 2008;58(1):1–17. doi:10.1016/J.BRAINRESREV.2007.10.013
99. Peter-Derex L, Magnin M, Bastuji H. Heterogeneity of arousals in human sleep: a stereo-electroencephalographic study. *Neuroimage*. 2015;123:229–244. doi:10.1016/J.NEUROIMAGE.2015.07.057
100. Bhat SY, Akhtar N, Sengupta T, Netam R, Kumar VM, Mallick HN. Electroencephalographic and electromyographic events during spontaneous and final arousal from sleep: study of the sequence of appearance and significance. *Sleep Vigil*. 2022;6(1):153–163. doi:10.1007/S41782-021-00185-X/METRICS

101. Nakul E, Bartolomei F, Lopez C. Vestibular-Evoked Cerebral Potentials. *Front Neurol*. 2021;12:674100. doi:10.3389/FNEUR.2021.674100/BIBTEX
102. Kobel MJ, Wagner AR, Merfeld DM. Vestibular contributions to linear motion perception. *Exp Brain Res*. 2024;242(2):385–402. doi:10.1007/S00221-023-06754-Y/TABLES/3
103. Ertl M, Klaus M, Mast FW, Brandt T, Dieterich M. Spectral fingerprints of correct vestibular discrimination of the intensity of body accelerations. *Neuroimage*. 2020;219:117015. doi:10.1016/J.NEUROIMAGE.2020.117015
104. Ertl M, Zu Eulenburg P, Woller M, Mayadali Ü, Boegle R, Dieterich M. Vestibular mapping of the naturalistic head-centered motion spectrum. *J Vestib Res*. 2023;33(5):299–312. doi:10.3233/VES-210121
105. Schouten DI, Pereira SIR, Tops M, Louzada FM. State of the art on targeted memory reactivation: sleep your way to enhanced cognition. *Sleep Med Rev*. 2017;32:123–131. doi:10.1016/j.smrv.2016.04.002
106. Laurino J, Forcato C, Coaker N, Pedreira ME, Kaczer L. Learning new words: memory reactivation as a mechanism for strengthening and updating a novel word's meaning. *Mem Cognit*. 2022;50(4):655–671. doi:10.3758/s13421-021-01247-1