Nature and Science of Sleep

Open Access Full Text Article

ORIGINAL RESEARCH

The Effect of Total Sleep Deprivation on the Cognitive and In-Game Performance of Rocket League Esport Players

Tim D Smithies[1,2], Adam J Toth[1–4], Mark J Campbell[1–4]

[1]Department of Physical Education & Sport Sciences, University of Limerick, Castletroy, Limerick, Ireland; [2]Lero the Science Foundation Ireland Research Centre for Software, University of Limerick, Castletroy, Limerick, Ireland; [3]Health Research Institute, University of Limerick, Castletroy, Limerick, Ireland; [4]Centre for Sport Leadership, Stellenbosch University, Stellenbosch, South Africa

Correspondence: Tim D Smithies, Lero the Science Foundation Ireland Research Centre for Software, University of Limerick, Castletroy, Limerick, Ireland, Tel +61484391133, Email tidasmi@gmail.com

Purpose: It is presumed by many that acute sleep loss results in degraded in-game esports (competitive, organized video game play) performance. However, this has not been experimentally investigated to date. The objective of the current experiment was to elucidate whether ~29hrs of total sleep deprivation impacts in-game performance for the popular esport *Rocket League.*

Patients and Methods: Twenty skill-matched pairs (N = 40 total) were recruited. Within each pair, one participant was assigned to an intervention *group* (TSD), while the other was assigned to a control *group* (CON). Two test *sessions* occurred; one while both participants were rested (baseline), and the other while the CON participant was rested but the TSD participant was sleep deprived (experimental).

Results: Following total sleep deprivation, TSD participants reported higher Karolinska Sleepiness Scale-measured subjective sleepiness and lower subjective alertness and motivation, as well as worsened PVT response speed and ~5 times greater PVT lapse incidence, and worsened response speed on a two-choice categorization task. However, overall in-game *Rocket League* performance did not worsen due to total sleep deprivation. Exploratory analyses of performance indicators suggest a potential shift toward a simpler and safer strategy following sleep deprivation.

Conclusion: Following a bout of ~29hrs total sleep deprivation, overall in-game Rocket League performance remained unaffected. This presents as a promising finding given the high potential for acute pre-competition sleep disturbance in esports, though habitual sleep remains a concern for esport athletes.

Plain Language Summary: Esports are quite comfortably the fastest growing competitive activity worldwide. We performed the first experimental study exploring how an acute bout of sleep loss impacts in-game performance in any esport. We found 29 hours without sleep to have no impact on in-game outcome. This presents as a positive finding for esport athletes and coaches alike but certainly does not absolve sleep from being an impactful human factor within esports. Future studies should explore other esports with characteristics (ie, longer bouts of sustained attention, such as Multiplayer Online Battle Arena or MOBA esports) purportedly sensitive to sleep loss to see if the impact of sleep loss on esports performance is specific or agnostic to esport genre.

Keywords: gaming, human factors, athletes, cognition, task-switching, in-game performance

Introduction

Esports are by far the fastest growing competitive and high-performance activity worldwide. Defined as the competitive play of video games through the medium of cyberspace,[1] esports are a key part of the gaming industry, which has a projected market value of €375billion in 2023.[2] The value of esports as an industry can be largely attributed to the size of its audience and public engagement. With viewership estimates exceeding one billion individuals in 2020[3] (and growing yearly), esports is, and continues to be, an enticing arena for investment. As a result, companies such as Xfinity, Kraft Group, PepsiCo, FTX, Red Bull, Coca-Cola, BMW, Nike, Asos, Ralph Lauren, and DC Comics (to name a few), over 319 traditional sporting teams,[4] as well as government organizations such as the US Army[5] and Air Force, are either heavily invested in one or more esport teams,

Received: 20 May 2024
Accepted: 5 August 2024
Published: 21 December 2024

or own an esport team themselves. In response to this prolific interest in esports, there is an ever-increasing interest in understanding the human factors which influence esport competition performance in order to maximize the success of players.

One frequently highlighted human factor is sleep, or more specifically, the disturbance/ loss of sleep experienced by players. Previously published literature has cited sleep loss in esports as a cause for concern specifically due to the potential adverse impact on in-game performance.[6–11] These concerns about sleep loss impacting in-game esport performance appear to be shared with some esport athletes themselves.[12,13] Habitually, on average, professional esport athletes obtain a similar amount of sleep to others in their demographic (mid-late teenagers/young adults, mostly male).[8,10,14,15] However, esport athletes are characterized by incredibly late sleep onset (01:30–05:00) and wake (09:00–12:00) times on average, though large cultural/regional group level differences have been noted.[10] Sleep efficiency has also been cited as a concern, with a large longitudinal study of 1243 nights of habitual esport player sleep data reporting a mean sleep efficiency of only 67.7%.[15] Additional concern regarding the habitual sleep of esport players is warranted, given that multiple studies report mean insomnia severity index values at or beyond the cut-off for insomnia[8,10] and mean Pittsburgh Sleep Quality Index (PSQI) values well beyond the cut-off for poor sleep quality in this population,[9,14] somewhat mirroring the poor PSQI assessed sleep quality prevalent within traditional sport athletes.[16]

Furthermore, while elite esport athletes share many of the well-cited risk factors of sub-optimal sleep of traditional-sport athletes (ie, pre-competition arousal/ anxiety, post-competition arousal, caffeine use, travel/jet-lag), there are further risk factors uniquely associated with esports. Firstly, as esports are (mostly) played through blue-light emitting computer monitors, there is a propensity for evening or night-time play leading to melatonin suppression, which purportedly can increase sleep latency and reduce sleep quality/quantity.[17,18] Secondly, video games played as *esports* are cognitively/ physiologically arousing by design, and as such, evening or night competition can reduce sleep quality and quantity through heightened arousal.[19,20] Such risk-factors have already been identified as potential mechanisms underlying associations between various sleep problems (poorer sleep quality, lower total sleep time [TST], increased prevalence of insomnia) and gaming frequency/duration.[11] Tying these risk factors together is a *culture* among professional esport athletes which promotes (and seemingly necessitates) training and playing late at night and into the early hours of the morning.[6,21] Overall, despite mean TSTs that are comparable to their peers, esport athletes are exposed to a cocktail of factors which together appear particularly conducive to bouts of acute sleep loss.

As mentioned, a common reason given for why sleep loss should be a major concern for esport athletes is that it can lead to in-game performance decrements. In contrast to many traditional sports, esports performance is predicated largely on cognitive abilities rather than physical abilities, leading some researchers to refer to esport athletes as *cognitive athletes*.[1] Though specific cognitive demands differ between different esports,[22,23] most esport titles (especially those considered *action video games*) require rapid perception, processing and integration of multisensory stimuli originating from various sources (taxing visuospatial working memory systems), alongside fast and accurate decision-making and responses through a peripheral device (keyboard/mouse/controller). Convincing evidence can be found for the robust cognitive demands of esports by looking at the now large body of quasi-experimental and intervention studies demonstrating how exposure to video games commonly played as esports improves aspects of cognition, even when tested outside of the specific game's context.[24–26] These improvements remain present even when disentangled from general improvements in motor execution.[25] Robust evidence is present for such video games improving attentional capacities (particularly visual attention), information processing speed and accuracy, and cognitive flexibility (in particular, task-switching), speaking to the importance of such elements for gameplay success.

Simultaneously, it is understood that acute sleep loss (ie, total sleep deprivation/ sleep restriction) degrades performance in these same aspects of cognition.[27,28] Though effects tend to be larger and more robust for simple (ie, Psychomotor Vigilance Task or PVT) rather than complex attentional tasks,[28–31] sleep loss protocols have found response times and accuracy to worsen for tasks taxing visual attention, information processing, working memory, decision-making, and executive functioning. A specific aspect of executive functioning, cognitive flexibility, has been highlighted as a domain particularly susceptible to sleep loss.[32–34] Given that task-switching ability (a primary component of cognitive flexibility[35,36]) appears to be important for esports performance, the degradation of task-switching performance through sleep loss has been previously highlighted as an avenue for sleep loss to impact esports performance.[26]

Despite this logical link between sleep, cognition, and esports performance, there has been no formal investigation into the effects of experimentally induced sleep loss on esports performance. A controlled, experimental approach appears warranted to elucidate what (if any) observable effect acute sleep loss may have on the cognitive and in-game performance of esport players. Implications of such an experiment may be large for esport athletes and organizations alike, who have great desire to optimize every human factor which may impact their in-game performance.

The purpose of the current study is to explore how a bout of acute sleep deprivation (~29 hours awake) affects the cognitive and in-game performance of esport players in the esport *Rocket League*. Rocket League is a popular *vehicular soccer video game*, which averages ~90 million active players per month,[37] and, as an esport, ranks 10th for most prize money earnt.[38] This popularity allowing for the recruitment of a sufficient number of participants, alongside competitive play as individuals (1v1) allowing for a protocol without the extreme complexity that team-based video game play would present, short and predictable game lengths (5–10 min) allowing for multiple matches to occur within a predictable timeframe, and accessible in-game data and suitable performance indicators (PIs) and outcome measures,[39] made Rocket League a desirable target video game.

The weight of evidence linking sleep loss to decreased cognitive performance, combined with the substantial cognitive demands of esports, leads us to hypothesize that sleep deprivation will worsen both cognitive (specifically, vigilance and task-switching performance) and in-game performance. We also aim to explore if (and how) certain established in-game Rocket League PIs are affected by sleep deprivation.

Materials and Methods

All procedures and data collection were approved by the Education and Health Sciences Research Ethics Committee (2021_06_13_EHS) and conducted in accordance with The Declaration of Helsinki.

Participants

Sample

An a priori power analysis was conducted, based on the predicted model structure for the primary analysis exploring the effect of total sleep deprivation on our overall in-game outcome measure, *goal difference* (GD), and following simulation processes outlined by DeBruine and Barr.[40] The details of this power analysis can be found in supplementary file 1, however in short, we used an estimated effect size equivalent to the average effect size reported by a previous meta-analysis for the effect of total sleep deprivation on cognitive performance pooled across all included cognitive domains,[28] combined with estimated variance components obtained through analysis of large databases of Rocket League matches, and a predicted level of warranted random complexity. Using an alpha of 0.05, this power analysis suggested that 19 player pairs were required to achieve a power of 0.8. Adding one pair for the sake of counterbalancing evenness, we sought to include 40 participants within the current study, allowing for 20 pairs.

Participants were recruited through flyers and emails distributed to university students, as well as through social media channels (ie, X/Discord). Forty-six young (18–35 years) adults provided written informed consent to participate in study. However, due to protocol non-adherence and participant drop-outs (13%), we obtained a final sample of 40 (19.88 ± 2.07 years, 1 female) participants (20 pairs). Participants were eligible if they (a) habitually slept for six or more hours per night (as per the *Sleep Duration* recommendation within the Revised Research Diagnostic Criteria for Defining Normal Sleeping Controls (RRDC)),[41] (b) had no history of diagnosed sleep disorders and (c) were not alcohol dependent nor were habitual users of other recreational drugs (besides tobacco). A summary of the included population can be found as supplementary table 1.

Participants were required to be players of the video game *Rocket League*. Participants were required to provide their in-game ranking using a rank tracking website.[42] This website provides a constantly updated record of a given player's in-game rank and matchmaking ranking (MMR). A player's MMR is measured on a continuous scale and is indicative of expertise within the 1v1 game mode of Rocket League.[39] Through the rank checking website, we obtained each participant's highest and lowest 1v1 mmR over the most recent three months (at the time of eligibility questionnaire completion) and calculated the mean of these two values to represent the participants current expertise level. Additionally, the rank tracking website provides the participants' current rank percentile (ie, the percentile of the current playing population in which the participant's rank resides in). Lastly, we also obtained an estimate of the total number of hours that the participant had accumulated playing Rocket League. A description of the method used to obtain this estimate is provided as supplementary file 2.

When the MMR of two participants differed by less than 150 (equivalent of 15–21 total win vs loss disparity), they were paired with one another. Paired individuals would complete aspects of the study at the same time and play against one another in Rocket League matches during the two test *sessions*. We note that individuals who habitually use tobacco (N = 4) were paired with one another. For each pair, one member was randomly selected to partake in the overnight sleep deprivation protocol (TSD; mean age = 19 ± 1, mean MMR = 862 ± 221, 19m 1f), while the other individual was assigned as control (CON; mean age = 20 ± 3, mean MMR = 874 ± 190, 20m) (described below), using an automated web-based randomization service.[43]

Materials

Eligibility Questionnaires and Participant Demographics

The eligibility questionnaire provided to each participant included the Pittsburgh Sleep Quality Index (PSQI),[44] Holland Sleep Disorders Questionnaire (HSDQ),[45] Swiss Narcolepsy Scale (SNS),[46] Horne-Östberg Morningness Eveningness Questionnaire (MEQ),[47] and the Fast Alcohol Screening Test (FAST) and Alcohol Use Disorders Identification Test (AUDIT).[48] Information regarding the suitability of each instrument used (ie, reliability, validity, sensitivity, specificity) and specific cut-off values used can be found in supplementary file 3.

Sleep Measurement

The Consensus Sleep Diary (Core) was used to obtain subjective sleep measures throughout the protocol.[49] Additionally, sleep variables were objectively measured using the Readiband^{TM} (v5) wrist-worn activity monitor (Fatigue Science, Canada). This device uses tri-axial accelerometry (sampling frequency = 16Hz) to record wrist acceleration data, which are used to calculate sleep and wake events through a proprietary algorithm. The Readiband has demonstrated superior performance (most notably, less bias in sleep summary measures and greater sleep/ wake specificity) than the research standard Actiwatch 2, when compared to the *gold-standard* polysomnography (PSG) or at-home electroencephalography (EEG).[50,51] It has also been independently found to be suitable when recording measures of total sleep time (TST), time at sleep onset (TASO) and time at wake (TAW),[52] demonstrates a high (ICC ≥ 0.8) inter-device reliability (including ICC = 0.99 for total sleep time),[53] and has been previously used in sleep research for a variety of populations, including traditional and esport athletes,[8,10,54–56] medical personnel,[57,58] pilots,[59] and military personnel.[60] A single trained researcher downloaded and processed the Readiband data. Outcome measures considered were TST, TASO, and TAW. Daytime naps were included in TST, with naps occurring before 12:00 added to TST for the previous night, and naps occurring after 12:00 added to the TST for the upcoming night, as per Smithies et al.[54]

Subjective Sleepiness, Alertness and Motivation

To capture subjective sleepiness, alertness, and motivation of participants throughout the experimental protocol, participants completed the Karolinska Sleepiness Scale (KSS)[61] as well as Alertness & Motivation Visual Analog Scales (VAS). For the VAS, levels of subjective alertness and motivation were assessed using slider scales, with values (between 0 and 100) hidden. The alertness VAS ranged from *sleepy* (0) to *alert* (100), and the motivation VAS ranges from *motivated* (0) to *unmotivated* (100), as per Mathew et al.[62] Motivation VAS scores were subsequently reverse scored for analysis, such that higher scores resembled greater motivation.

Cognitive Performance

Cognitive performance during the experimental protocol was assessed using the 10-minute psychomotor vigilance task (PVT) and Category Switch Task (CST). The 10-minute PVT is the gold-standard performance test for vigilance, and exhibits stable performance over repeated measures testing.[63–65] A one-minute practice block was undertaken prior to the ten-minute testing block. The test block was executed straight after the practice block with no break or indication it has changed, as per Thomann et al.[66] Throughout the task, participants were required to respond *as fast as possible* to the appearance of a red stopwatch in the center of their screen by pressing the *space bar* on their keyboard. The inter-stimulus interval was set at random between 2000 and 10,000ms for each trial.

False starts were removed from the data, as were trials responded to in ≤100ms.[63] Dependent variables considered were response speed (equivalent to 1000/reaction $time_{(msec)}$, and hereafter denoted as *RS*) and lapses, defined as trials where reaction time ≥500ms (alternatively, $RS \leq 2$), as these two measures have shown to display the best conceptual and statistical properties (including robustness to extreme values) and sensitivity to sleep loss for the PVT.[63]

The CST was adapted from that originally described by Mayr and Kliegl,[67] and is a test which assesses task-switching ability, a component of executive functioning requiring cognitive flexibility. A detailed description of the CST used in this study can be found as supplementary file 4. Participants were required to categorize words that appeared on a screen according to a categorization rule denoted by a cue. In some test blocks (*single task*), the cue was constant, while in others (*mixed task*), the cue (and categorization rule) switched between one of two cues at random, and participants had to adapt to the corresponding change in categorization rule. Stimulus-response mapping (SRM) changed from the first to second test *sessions* in a consistent manner between all participants (for the *living cue* but not *size cue*). We did not consider Switch Cost (SC) or Mixing Cost (MC) error rate, due to poor test–retest reliability of these outcome measures during an independent pilot test undertaken specifically for the CST.

In-Game Rocket League Performance

The primary aim of the current study was to assess if an acute sleep deprivation intervention influenced in-game performance on the esport *Rocket League*. In Rocket League, players use a rocket-powered vehicle to hit a large ball into an opposing goal while simultaneously defending one's own goal (as per soccer or hockey). Rocket League is played competitively in teams of 1, 2, or 3 players; in this study, we solely investigated 1v1 matches of Rocket League.

Paired participants played against one another on a local area network (LAN) connection. Participants were able to use their own input device for gameplay, however a DualShock 4 and Xbox Elite Controller (series 2), as well as a gaming mouse, keyboard, and headphones were provided if necessary. All input devices were used with a wired connection.

Participants were asked to log into their own Rocket League account on Steam or Epic, however were provided an account if they were unable. Participants were free to use headphones for game sound and/ or play music through the duration of the Rocket League matches. Participants were free to use in-game settings of their choosing (ie, controller settings, camera settings, vehicle selection etc.). Once both participants within the pair were ready, they were afforded five minutes for a warm-up. Participants were free to warm up however they chose (ie, free-play training, training packs, workshop maps), with the exception of playing an online match. Once the five minutes elapsed, participants joined a LAN (local area network) match, which was created by the researcher. Prior to the gameplay commencing, participants were asked to perform to the best of their ability for the entirety of each match, aiming to score as many goals as possible while simultaneously preventing their opponent from scoring, regardless of the match score. All participants played seven consecutive matches against their paired opponent, except for one pair in one week, where only six matches were played due to a participant needing to leave early. Short breaks (<5 minutes) in between matches were afforded *ad libitum*.

Outcome measures were obtained via. use of the ballchasing.com application programming interface (API) on saved match replays and processed as outlined by Smithies et al.[39]

Procedure

Figure 1 provides a visual outline of the study protocol. The study protocol lasted a minimum of 15-days per participant pair. On the first day (D1), participants were briefed on the study protocol, and provided their actigraphy device and sleep diary. Participants determined a *target bed* (between 22:00 and 01:00+1) and *wake time* (between 06:00 and 09:00). Participants were asked to adhere to their set *target bed* and *wake times* (± 1hr), particularly within the three days prior to each test *session*. Participants also agreed upon a *target gameplay amount* (hours) within the following week, of which they were asked to remain within ±20% of (ie, 80–120% of target hrs). *Target bed* and *wake times* and *target gameplay amount* remained consistent for individuals but did not need to be consistent between participants within a given pair.

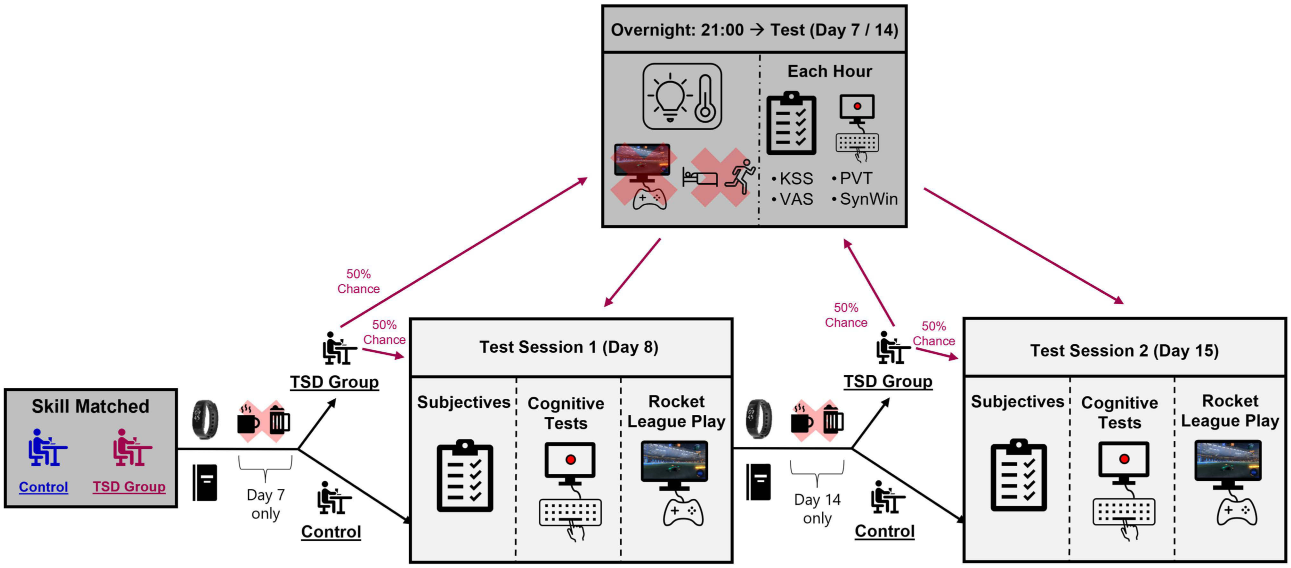

Figure 1 A timeline of the 15-day protocol for all participants within the protocol. The icons within this figure depict the following. Wristband = wrist-worn activity monitor; book = Consensus Sleep Diary; coffee mug and beer = caffeine and alcohol; clipboard = subjective measures. Computer with keyboard = computerized cognitive tests. Computer with controller = Rocket League gameplay; bed = sleeping; man running = strenuous activity; light and thermometer = light and temperature-controlled environment. TSD = participants within the sleep deprivation *group*; CON = participants within the control *group*.

Test Session Protocol

Following 12:00 on day seven (D7) and up until the upcoming test *session* (D8), participants were asked to refrain from napping, consuming caffeine, alcohol, non-essential medication or any other drugs. Participants were also asked to obtain at least six hours of sleep in the upcoming night. On the eighth day of the protocol and between the hours of 11:30 to 15:00, both participants within a given pair attended the laboratory for test *session 1*. Sleep diary information was collected from each participant, and a new sleep diary was provided. Participants self-reported the amount of Rocket League gameplay undertaken in the previous seven days and indicated their adherence to the abovementioned procedures.

Following this, the participants completed (in order) the PVT, CST, KSS, alertness and motivation VAS and played their set of Rocket League matches against one another. Following completion of the Rocket League matches, participants again completed the KSS and alertness and motivation VAS. All procedures described were collected using gaming computers, comprising of a 27-inch monitor with a 144Hz refresh rate. All measures except for those in the Rocket League performance section were taken using identical input devices (Logitech Pro mouse, keyboard, and headphones). Following the set of Rocket League matches, both participants were asked "on a scale from 0 [not at all] to 10 [extremely], how much do you feel like fatigue affected your in-game performance?", and "do you think the other participant had completed the overnight sleep deprivation protocol?".

Following test *session 1*, the protocol was repeated, such that participants wore their wrist-worn activity monitor and completed the sleep diary daily, played the agreed upon amount of Rocket League, adhered to the target bed and wake times within three days of the upcoming test *session*, and avoided consuming caffeine or alcohol, taking medication or drugs, or napping, within 24hrs of the upcoming test *session 2*. For 80% of pairs, the second test *session* was exactly seven days following the test *session*. However, due to participant availability, the timespan between tests was 14 days for three pairs and 37 days for one pair.

Total Sleep Deprivation Protocol

Within each pair, the protocol for the participant assigned to the control *group* (CON) was exactly as described above. For the participant assigned to the TSD *group*, one of the two test *sessions* (and the week prior) was exactly as described; however, for the other test *session*, the participant completed the total sleep deprivation protocol prior. The test *session* in which the prior sleep deprivation was administered was counterbalanced (ie, ten participants were sleep deprived prior to first and second *test sessions,* respectively). Participants were (a) aware that they may be asked to complete the total sleep deprivation protocol prior to either of the test *sessions*, (b) not told if they or their paired opponent were in the CON or TSD *group*, and (c) told at least three days in advance whether they were required to complete the total sleep deprivation protocol prior to the upcoming test *session*.

For the total sleep deprivation protocol, the participant arrived to the laboratory at ~21:00 the night before the *test session*. The following day, the participant would remain in the laboratory until 30 minutes before the start of the test *session*. Participants were free to engage in activities of their choosing, except for strenuous exercise or playing video games using the same input modality (ie, keyboard or controller) they used to play Rocket League with. From 22:00 onwards, participants completed a KSS, alertness and motivation VAS, 5-minute PVT, and the SynWin multitask[68] on the hour each hour. The results of these tests are not within the scope of this article.

The light and temperature in the laboratory environment remained consistent throughout this time and during all test *sessions*. Each participant was supervised throughout the duration of the sleep deprivation protocol to ensure wakefulness. Water, fruit, low-sugar snacks, and caffeine-free hot beverages (ie, peppermint tea) were available to participants *ad libitum* throughout the sleep deprivation protocol. Another standardized meal (toast with peanut butter and honey, fruit, and fruit juice) was provided at 08:00 the following morning. In the 30 minutes prior to the test *session*, participants left the laboratory and were supervised on a walk; this was to simulate a walk to the laboratory, as would occur if they were the CON participant. This protocol resulted in an average of 28.78 ± 1.22 hours between last wake time and the start of Rocket League gameplay.

Statistical Analysis

Statistical analyses were performed using R: A language and Environment for Statistical Computing (Vienna, Austria) and/or IBM SPSS Statistics v26 (Armonk, N.Y.) software. Alpha was set to $p < 0.05$ (two-tailed) for all analyses. Variance measures (±) are presented as standard error unless explicitly specified.

Participant Pairs and Rank

Means and standard deviations are provided for participant MMR. The relationship between time spent playing Rocket League (hours) and in-game expertise (MMR) was assessed through a simple linear regression, which was subsequently used to impute missing *hours played* for individuals from whom we could not obtain a confident estimate.

Protocol Adherence

Means and standard deviations are provided for each individual's TASO and TAW within the three days preceding either test *session*.

Additionally, means and standard deviations are provided for TST, both for the night before each test *session* (TST [1]) and the two nights (combined) prior to TST[1] (TST[2–3]), within each *group x session* combination. Independent-sample t-tests and paired-sample t-tests were used to assess by-*group* and by-*session* differences in TST[1] and TST [2–3], respectively. Nonparametric equivalents (Mann–Whitney U and Wilcoxon Signed-Rank Test) were used when mean values were significantly non-normal (Shapiro–Wilk test, $p < 0.05$).

Rate of adherence to target Rocket League gameplay was expressed as a percentage. By-*group* and by-*session* differences in target RL gameplay achieved were assessed identically to those described for TST above.

Cognitive Performance

Cognitive Performance Measures (PVT & CST) were assessed using Mixed Effect Models (MEMs; linear mixed-effects models and generalized linear mixed effects models). All MEMs were created using the *lme4* package in R (1.1–31).[69] Random effect structures were determined using a backward-selection approach as outlined by Matuschek et al,[70] deviating only to avoid selection of singular models or models which did not converge. If a selected model was singular, then the next most complex model which was not singular was selected, and if all models prior were singular, random effect simplification continued until the next most complex model that was not singular was identified, and this model was subsequently selected. Within the selection process, random slopes were considered for each fixed effect (and their interaction) that vary within a given random effect.[71] Once the most appropriate random effects structure was identified, mixed-model assumptions were visually examined using the *performance* package (0.10.4),[72] and *DHARMa* package

(0.4.6).[73] For fixed effects, degrees of freedom were estimated using the Satterthwaite method to allow for significance testing of fixed effects for any MEMs created with continuous outcomes (linear mixed-effects models; ie, for PVT RS), while the Wald method was used for confidence interval estimation. Additionally, Wald tests were used to determine fixed effect significance for any MEMs created with categorical outcomes (binomial generalized linear mixed-effects models; ie, for PVT lapses). We used *treatment coding* for all categorical *fixed effects*. Treatment coding refers to the coding of the two-levels of a dichotomous variable as 0 and 1, respectively.[74] Treatment coding was considered the intuitive option as there are sensible *baseline* levels (always coded as *0*) within each fixed effect considered. Details regarding both model selection (including specific model selection decisions made) and the details of the final model selected are provided within table layouts based on a best practice guideline[75] and are provided as supplementary file 5.

For PVT measures, MEMs were created for *RS* and lapses, respectively. We noted a deviation from normality observed at low *RS* values, however given that (a) this is representative of an expected phenomenon (lapses), (b) *RS* is an already transformed outcome measure which satisfies MEM assumptions substantially better than raw RT, and (c) *RS* is considered alongside lapses to be the best outcome variable to use for the PVT,[63] *RS* was retained as the outcome measure within the model created. The models created for *RS* and lapses included the between-participant fixed effect *group* (CON vs TSD) and the within-participant fixed effect *session* (baseline vs experimental), as well as their interaction, with participant considered as a random effect.

For CST, we planned on using $RT_{(msec)}$ as an outcome measure for Single Task, SC and MC, however MEM assumptions were not met using this outcome measure. When RTs were converted to *RS* using the same transformation used for PVT *(RS* = 1000/reaction $time_{(msec)}$), MEM assumptions were satisfied. Hence, MEMs were created for Single Task *RS* and error rate, Switch Cost RS, and Mixing Cost RS. For Single Task models, they included the between-participant fixed effect *group* (CON vs TSD) and the within-participant fixed effect *session* (baseline vs experimental), as well as their interaction, while for the SC and MC models, *group, session*, and *trial type* (for SC, this was switch vs repeat; for MC, this was repeat vs single task), as well as their interactions (ie, full factorial) were included as fixed effects. For all of these models, *participants, word* (ie, the specific word displayed), *cue* (living or size), and a *cue* by *word* interaction, were considered as random effects.

Subjective Measures

By-*group* and by-session differences in KSS, Alertness VAS and Motivation VAS were analyzed using independent/paired sample t-tests or nonparametric equivalents, as per protocol adherence measures. We note that data from one pair are missing due to a technical error (N pairs = 19). Participant's self-report of how much fatigue affected their in-game performance was also analyzed in an identical manner.

Rocket League Performance

The primary aim of the study was to test the null hypothesis that TSD would not affect our in-game outcome variable, GD. To test this, we created a MEM using the steps outlined above for cognitive performance measures, with *session* (baseline vs experimental) as a fixed effect and *pair* as a random effect.

Irrespective of the result of the above analysis, we sought to conduct analysis on whether TSD impacted any performance indicators (PIs) in Rocket League. We built five separate MEMs with identical fixed and random effects to that above, to predict the following outcome measures: *Shots Taken Difference, Time Spent Goalside of the Ball Difference, Saves Made Difference, Time Spent High in the Air Difference*, and *Demos Inflicted Difference*. These five PIs were chosen as they were the five PIs shown to predict match performance in 1v1 Rocket League when all in-game ranks are considered.[39] All metrics were calculated as the value of the TSD participant minus the value of the CON participant within each pair. As this analysis is exploratory, we did not conduct any familywise error rate adjustment; however, we do not make claims based on the results of these analyses, instead using them as ways to highlight potential effects of TSD on in-game strategy to be explored in future research.

Results

Participant Pairs and Rank

The mean MMR for participants in the study was 868.34 (SD = 203.59), corresponding to the top ~20% of the overall player base. A simple linear regression was conducted to examine the relationship between *hours played* (from participants where a reliable value estimate could be obtained, N = 37) and MMR. This model was significant, $F(1,35) = 93.48$, $p < 0.001$, $R^2 = 0.73$, with *hours played* explaining 73% of the variance of participant 1v1 Rocket League expertise. The equation for the regression model can be found below

$$MMR = 0.08853 \times Hours\ Played + 696.8$$

This equation was used to predict missing values for *hours played*, however for two of the three participants it predicted a negative value. Hence, for these participants, *hours played* was conservatively estimated as zero. After including these participants, mean *hours played* among the sample was 2014.15hrs (SD = 1881.30hrs), or ~85 days. Figure 2A shows the rank distribution of the participants and their paired opponent, and Figure 2B shows the abovementioned relationship between *Hours Played* and *MMR*.

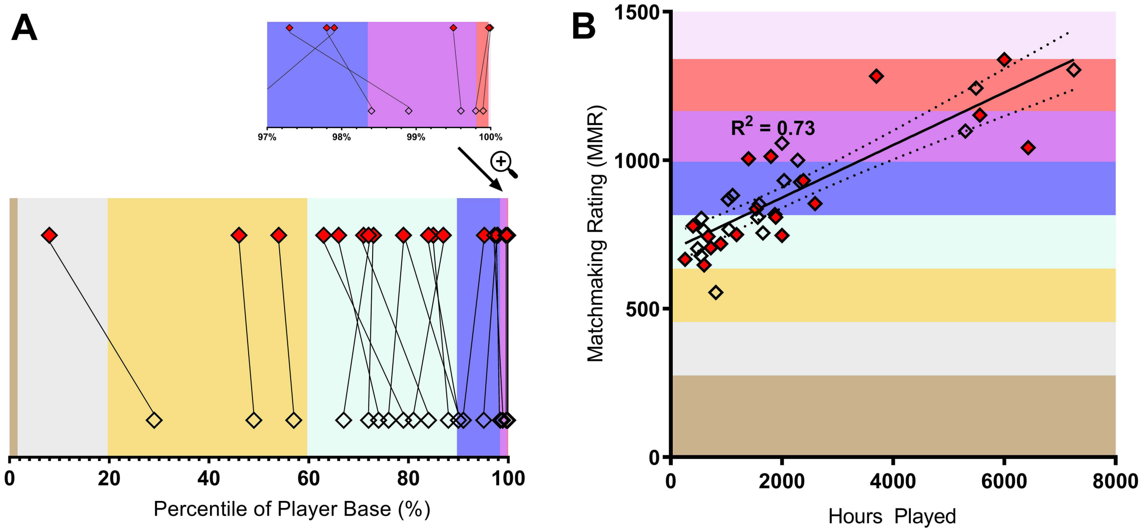

Figure 2 Graphs showcasing the Rocket League experience and expertise of the included participants. (**A**) Rank distribution and pairing of included players. Clear diamonds resemble control *group* (CON) participants, and red diamonds resemble sleep deprivation *group* (TSD) participants. Pairs are denoted by lines joining participants. The x-axis denotes the participants in-game matchmaking rating (MMR; a proxy for expertise) relative to the esports overall player base at the time of recruitment, such that lower values resemble a lower-ranked player and vice versa (ie, 99% denotes a player in the top 1% of players). To better visualize pairs in the top 3% of ranked 1v1 Rocket League players, a magnified display is depicted above the main graph, denoted by a magnifying glass icon. (**B**) Relationship between estimated total hours of Rocket League played (x-axis) and player expertise (y-axis). Dashed lines represent 95% CI for line fitted using the linear regression equation. For both A and B, colours represent the in-game rank of the participants (in order from bottom to top; bronze, silver, gold, platinum, diamond, champion, grand champion, supersonic legend).

Protocol Adherence

Subjective and Objective Sleep Data

For sleep data within 3 nights of each test *session*, 3.64% of days of actigraphy-derived sleep data were missing or unusable, while 4.55% of days of Consensus Sleep Diary (CSD) data were missing or unusable. A missing value analysis using Little's MCAR test[76] was not significant ($\chi^2 = 7.32$, p = 0.50), suggesting the data can be treated as MCAR and as such, missing actigraphy-derived sleep data were imputed using a simple imputation method described in supplementary file 6.

Actigraphy-derived TASO and TAW, in comparison to participant-defined target bed and wake times, are shown for each participant (and pair) in Figure 3. 48.2% of nights within three days of a test *session* had a TASO within one hour of the individuals target bedtime (mean difference = 1.09hrs later (SD = 1.39)), while 54.84% of TAW values were within one hour of the individuals target wake time (mean difference = 0.55hrs later (SD = 1.62).

Mean TST (including naps) the night before each test *session* (TST[1], A) as well as the mean TST for two nights prior (TST[2–3], B) are shown for each *group* in Figure 4. All between- and within-participant comparisons for TST[1] and TST[2,3] were not significant with the exception of those involving TST[1] values for TSD on the experimental *session*. In other words, for the three nights preceding test *sessions*, the only observable difference in TST was as a direct result of the sleep deprivation protocol.

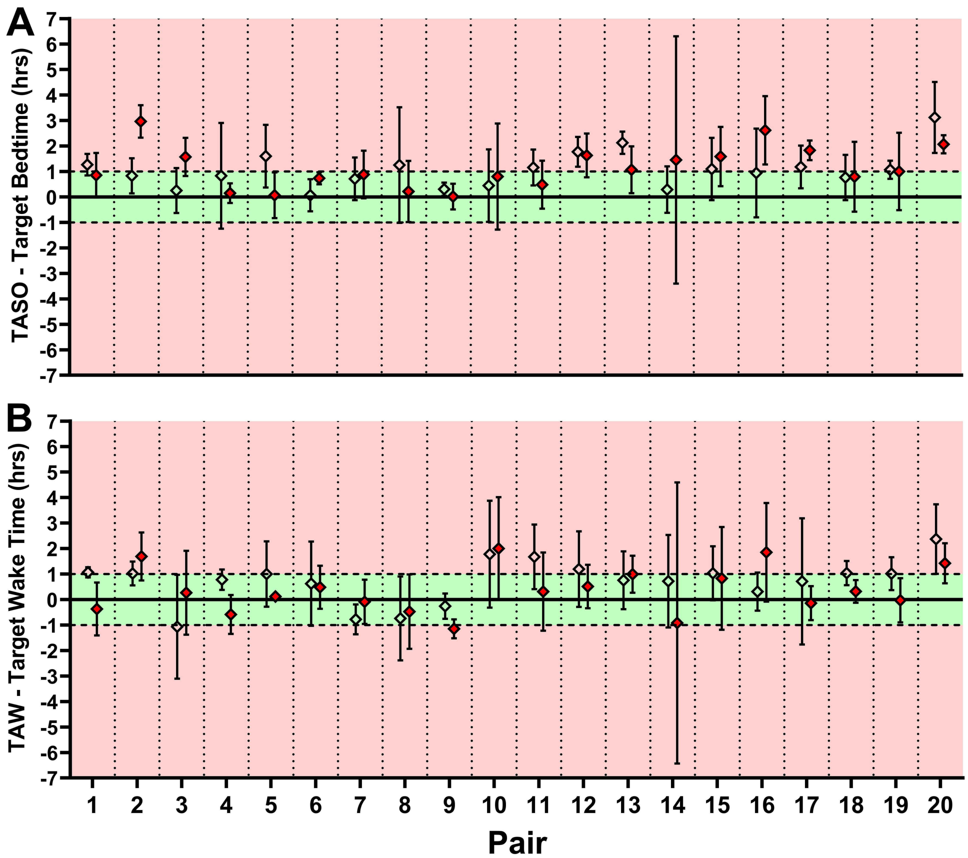

Figure 3 Mean (±SD) discrepancy between (**A**) target bedtime and time at sleep onset (TASO) and (**B**) target wake-time and time at wake (TAW), for each participant within each pair. Participants in CON are denoted by clear diamonds, while TSD participants are denoted by the red diamonds. The green band denotes TASO or TAW within 1 hour of the target bed/ wake time, while the red area denotes TASO or TAW outside of that range.

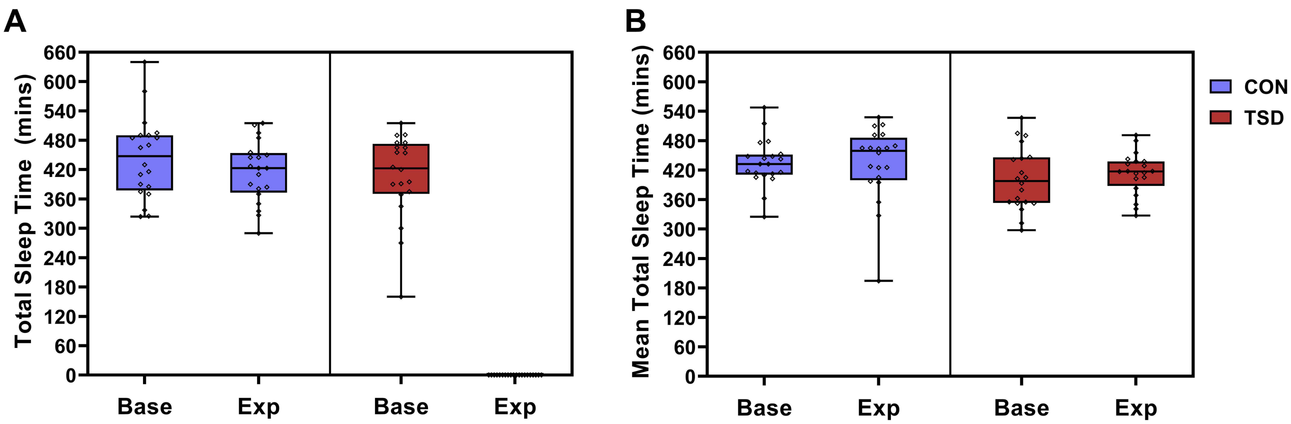

Figure 4 Box and whisker (min → max) plots showing the *group* mean total sleep times (TSTs) for CON (control *group*) and TSD (sleep deprivation *group*). (**A**) The night before test sessions and (**B**) the mean of the two nights prior to that shown in (**A**).

Caffeine, Alcohol, Napping

No participants reported caffeine or alcohol use within 24-hours of any test *session*. One participant (CON) reported medication use within 24-hours of test *sessions*; a daily asthma medication on the morning of both test *sessions*, and one dosage of cough medication the night before the experimental test *session*. Two participants (one CON, one TSD) napped (45–60mins) within 24-hours of the baseline test *session*, as both self-reported and corroborated through actigraphy.

Weekly Rocket League Play

Participants remained within ±20% of their target gameplay prior to testing for 56.25% of test *sessions* (M = 89.44% of target hours, SD = 38.02%). No significant differences were found between % target gameplay achieved prior to *baseline* and *experimental* test *sessions* for either *group*.

Cognitive Performance

Psychomotor Vigilance Task

Distributions of PVT Response time across *groups* and *sessions* are shown in Figure 5.

For PVT response time, neither *group* nor *session* alone significantly contributed to the model, however a significant *group* by *session* interaction was present ($b = -0.72 \pm 0.11$, 95% CI [−0.94, −0.51], $t(1, 37.38) = -6.58$, $p < 0.001$), such that being in the TSD *group* on the experimental day resulted in a mean reaction time worsening equivalent to 48.61msec.

For PVT lapses, neither *group* nor *session* alone significantly contributed to the model, however a significant *group* by *session* interaction was present ($b = 2.38 \pm 0.40$, 95% CI [1.56, 3.16], $z = 5.91$, $p < 0.001$), such that being in the TSD *group* on the experimental day resulted in 4.91 times more lapses occurring.

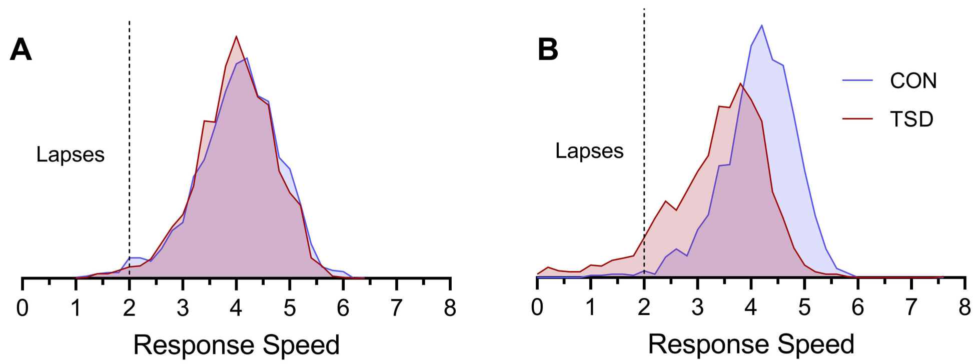

Figure 5 Frequency distribution of response speed (RS; 1000/$RT_{(msec)}$) for participants in (**A**). CON (control *group*) and (**B**). TSD (sleep deprivation *group*). We direct the reader to (**B**), and note both a leftward shift and leftward skew of the response distribution in the experimental test session for the TSD participants, consistent with previous literature (ie Figure 4 [77]) and demonstrative of both the broadband decrease in *RS* and increase in lapses observed (trials to the left of the dotted line).

Category Switch Task

For RS, neither *group* nor *session* alone significantly contributed to the model, however a significant *group* by *session* interaction was present ($b = 0.10 \pm 0.40$, 95% CI [−0.19, −0.01], $t(1, 37.90) = -2.27$, $p = 0.029$), such that being in the TSD *group* on the experimental day resulted in a mean reaction time worsening equivalent to 42.19 msec. No fixed effect nor interaction were significant within the model predicting errors in the Single Task component of the CST.

For SC RS, only *trial type* significantly contributed to the model ($b = 0.24 \pm 0.40$, 95% CI [−0.30, −0.19], $t(1, 37.83) = -8.40$, $p < 0.001$), corresponding to a switch cost of 102.19msec. No other main effects or interactions were significant. For MC RS, there was a simple main effect for *trial type* ($b = -0.27 \pm 0.05$, 95% CI [−0.36, −0.18], $t(1, 52.78) = -5.79$, $p < 0.001$), corresponding to a mixing cost equivalent to 83.45msec. There was also a significant *group* by *session* interaction present ($b = -0.10 \pm 0.04$, 95% CI [−0.19, −0.01], $t(1, 37.88) = -2.27$, $p = 0.029$), such that being in the TSD *group* on the experimental day resulted in a mean reaction time worsening equivalent to 42.21 msec. No other main effects or interactions were significant.

Subjective Sleepiness, Alertness and Motivation

KSS, alertness VAS and motivation VAS scores for CON and TSD within both the baseline and experimental test *sessions* are shown in Figure 6.

KSS scores for CON participants did not differ between baseline (3.53 ± 0.37) and experimental (3.79 ± 0.33) *sessions* ($t(18) = -0.93$, $p = 0.367$, 95% CI [−0.86, 0.33]). Additionally, KSS scores obtained in the baseline test *session* did not differ between CON and TSD participants ($Z = -1.36$, $p = 0.191$). However, significant differences were found

https://doi.org/10.2147/NSS.S470105

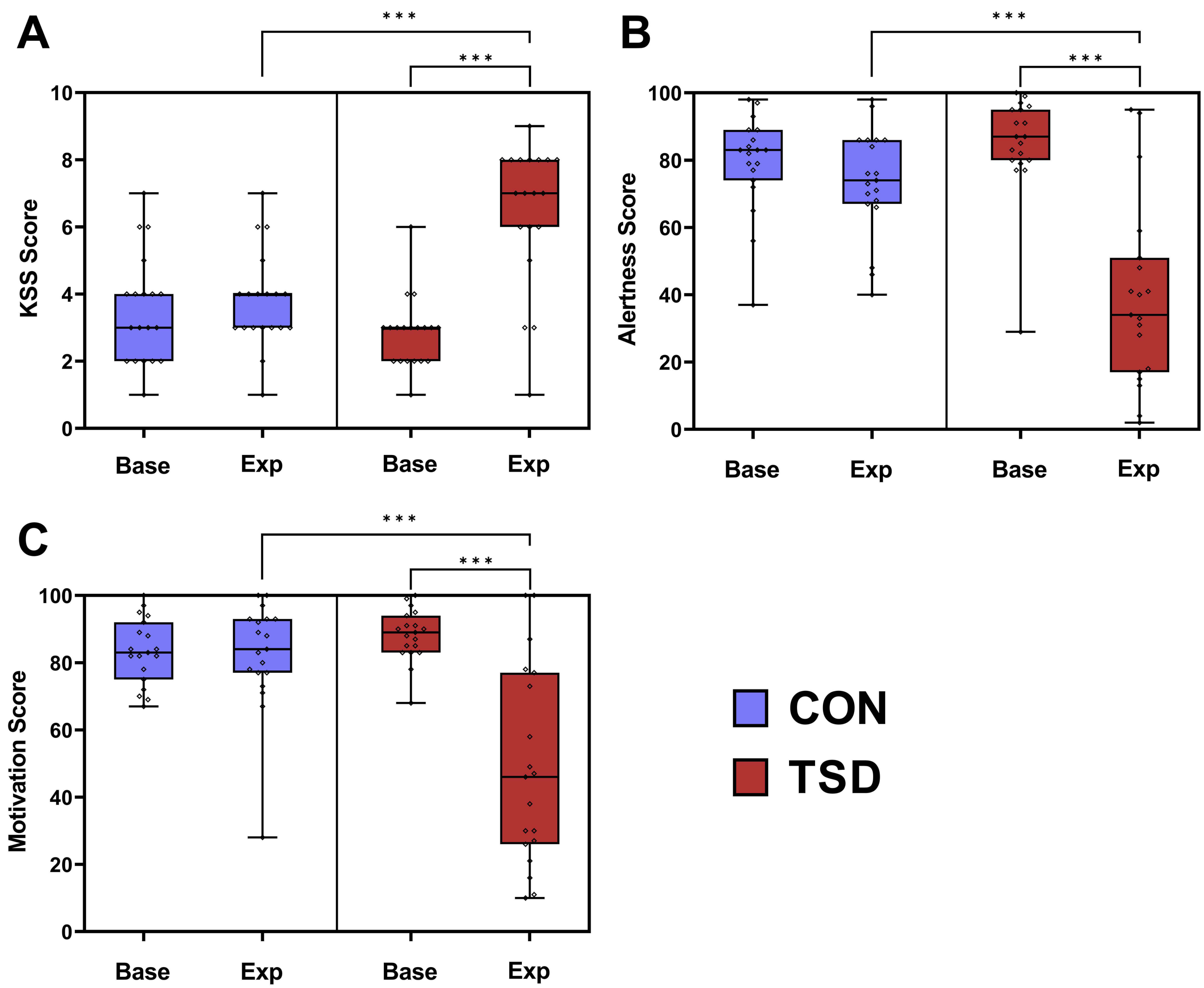

Figure 6 Box and whisker (min → max) plots showing (**A**). KSS (Karolinska Sleepiness Scale) scores, (**B**). Alertness VAS (Visual Analog Scale) scores, and (**C**). Motivation VAS scores (reverse scored) for CON (control *group*) and TSD (sleep deprivation *group*) participants in the baseline and experimental sessions. *** indicates a significant difference, $p < 0.001$.

between the KSS scores of TSD participants at baseline (2.84 ± 0.24) vs experimental (6.47 ± 0.49) *sessions* (Z = −3.74, $p < 0.001$) and between CON and TSD participants on the experimental *session* (Z = −3.66, $p < 0.001$).

Alertness VAS scores for CON participants did not change between baseline (79.26 ± 3.32) and experimental (73.53 ± 3.64) *sessions* (Z = −1.329, $p = 0.184$). Additionally, alertness VAS scores obtained in the baseline test *session* did not differ between CON and TSD participants (Z = −1.520, $p = 0.130$). However, significant differences were found between the alertness VAS scores of TSD participants at baseline (84.74 ± 3.56) vs experimental (39.21 ± 6.30) *sessions* (Z = −3.82, $p < 0.001$) and between CON and TSD participants on the experimental *session* ($t(36) = 4.72$, $p < 0.001$, 95% CI [19.56, 49.07], Hedges $g = 1.50$).

Motivation VAS scores for CON participants did not change between baseline (83.32 ± 2.25) and experimental (82.26 ± 3.76) *sessions* (Z = −0.66, $p = 0.948$). Additionally, alertness VAS scores obtained in the baseline test *session* did not differ between CON and TSD participants ($t(36) = -1.72$, $p = 0.094$, 95% CI [−10.67, 0.88]). However, significant differences were found between the alertness VAS scores of TSD participants at baseline (88.21 ± 1.75) vs experimental (48.63 ± 6.76) *sessions* ($t(18) = 6.75$, $p < 0.001$, 95% CI [27.25, 51.90], Hedges $g = 1.48$) and between CON and TSD participants on the experimental *session* (Z = −3.29, $p < 0.001$).

In summary, KSS, alertness VAS, or motivation VAS scores did not change except as a direct result of the sleep deprivation protocol. Within 10 minutes of the Rocket League matches commencing, participants who had undertaken the sleep deprivation protocol reported higher subjective sleepiness, and lower subjective alertness and motivation.

In-Game Performance

To assess the effect of the TSD protocol on overall in-game performance, a model was created with GD as the outcome variable, *session* (baseline vs experimental) as a fixed effect, and with a by-pair random intercept.

By-pair random intercept standard deviation was 2.61, and residual standard deviation was 2.83. The model intercept (corresponding to GD for the baseline *session*) was −1.01 ± 0.63, which was not significantly different to 0 (t(1, 22.05) = −1.61, p = 0.12), suggesting that neither *group* of participants were significantly better than the other at baseline. The effect of *session* (ie, change from baseline to experimental) was not significant (ΔGD = 0.23 ± 0.34msec, 95% CI [−0.43, 0.89], t(1, 258.02) = 0.68, $p = 0.498$), suggesting that the sleep deprivation protocol did not significantly impact GD. Figure 7A shows the distribution of GD for baseline and experimental *sessions*.

Similar models were created to assess whether the TSD protocol impacted any of the top five PIs within 1v1 Rocket League (Figure 7B–F). The only PI to significantly change from baseline to experimental test *session* was *Time Spent High in the Air Difference* ($b = -0.48 \pm 0.19$, 95% CI [−0.85, −0.10], t(1, 257.01) = −2.49, p = 0.013) (Figure 7E), such that (compared to their opponent) the TSD individual spent 0.48 ± 0.19% less time in the air in the experimental *session*, compared to the control *session*.

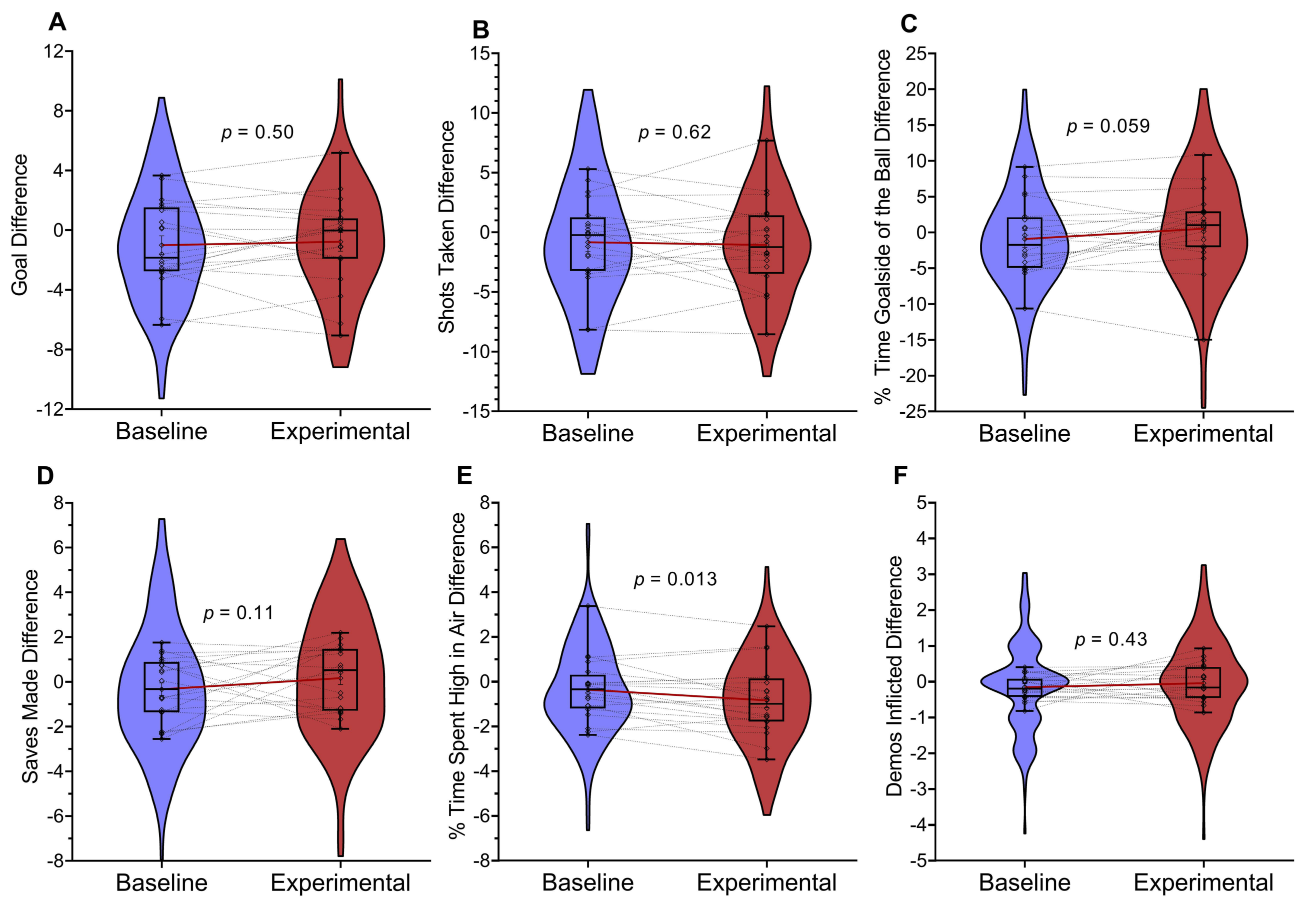

Figure 7 Violin plots displaying the distribution of (**A**) Goal Difference (GD) and (**B-F**) exploratory performance indicators (PIs; (**B**) *Shots Taken Difference*, (**C**) *Time Spent Goalside of the Ball Difference*, (**D**) *Saves Made Difference*, (**E**) *Time Spent High in the Air Difference*, (**F**) *Demos Inflicted Difference*) for *baseline* and *experimental* sessions, across all 279 matches. Box and whisker (min → max) plots inside the violin plots resemble the distribution of *mean* outcome variables across a test session for a given pair (N = 20 for each box and whisker plot). Diamonds represent pair means for each session, with pair means connected via the dotted lines. The solid red line represents the estimated mean±SE from each model used for analysis. *P-values* are provided for each graph.

Lastly, participant's self-reported ratings for how much fatigue affected their in-game performance did not change between baseline (1.85 ± 0.39) and experimental (2.40 ± 0.46) *sessions* (Z = −1.15, *p* = 0.251). Additionally, ratings obtained in the baseline test *session* did not differ between CON and TSD participants (Z = −0.30, *p* = 0.779). However, significant differences were found for TSD participants at baseline (1.70 ± 0.44) vs experimental (4.75 ± 0.50) *sessions* (Z = −3.33, *p* < 0.001) and between CON and TSD participants in the experimental *session* (Z = −2.96, *p* = 0.003). Participants in the CON *group* correctly guessed when their TSD *group* opponents were rested (*baseline*) 80% of the time and when TSD *group* opponents were sleep deprived (*experimental*) 95% of the time. Participants in the TSD *group* correctly guessed that their CON *group* opponents were rested 85% of the time.

Discussion

The current study aimed to establish whether an acute bout of total sleep deprivation (TSD) decreased in-game performance in the popular esport *Rocket League*. We included 40 Rocket League players, pairing them based on expertise level, with half of the participants completing two test *sessions* while rested (CON), and the other half (TSD) completing one test *session* while rested (baseline) and the other test *session* following ~29 hours of TSD (experimental). Following this bout of TSD, we found these individuals to respond ~50msec slower and lapse (responses >500msec after stimulus onset) almost five times more often on the Psychomotor Vigilance Task (PVT). They also responded slower on the two-choice component of the Category Switch Task (CST), however, error rate on this component of the CST as well as Switch Cost and Mixing Cost (SC and MC respectively; measures of task-switching ability) response speeds were unchanged. Additionally, immediately (~10min) before Rocket League play, participants reported higher subjective sleepiness and lower subjective alertness and motivation when sleep deprived, when compared both to their own scores when well rested and compared to their paired opponents for Rocket League gameplay. Despite these results, as well as the fact that participants felt that fatigue affected their in-game performance more following TSD, we did not find evidence that TSD impacted match outcome in Rocket League matches. The implications of our findings are discussed.

While we hypothesized that TSD would negatively impact our in-game esports outcome measure (GD), in line with the sentiment of previous articles[6–10] and some esports athletes themselves, ie,[12,13] we can identify (at least) six rational arguments for why such an effect was not found in the current study.

First, we note that not all aspects of cognitive performance are equally affected by sleep loss,[27,28,31,78] with the general trend being that as task complexity increases (for which, esports would be considered particularly complex), the magnitude of measurable adverse effect of sleep loss decreases.[32]

Second (however relatedly), motivation (both intrinsic and extrinsic) appears to play an important role in the maintenance of performance (top-down mechanisms) in spite of sleep loss.[79] As stated by Massar et al (p. 2),

> In conditions in which incentives are high to perform, e.g., in military emergency situations, people may be able to maintain performance. However, situations that do not contain significant extrinsic incentives may fail to generate sufficient motivation—and thus lead to reduced performance.

Our study involved the play of an esport highly familiar to participants in a competitive (and hence, motivating) environment. It is understood that task-specific factors can influence the degree to which performance occurs, specifically through promoting/dissuading motivation. Regarding task complexity, for example, Harrison and Horne[32] (p.g. 236) state

> the prevailing view in SD [sleep deprivation] research is that high-level complex skills are relatively unaffected by SD because of the interest they generate and the implicit encouragement for participants to apply compensatory effort to overcome their sleepiness.

Not only is Rocket League a highly complex activity, the play of Rocket League in the current study was undertaken in a set of circumstances which plausibly lends itself to compensatory mechanisms being activated.

Third, very repetitive tasks (often labelled monotonous) may experience greater performance loss due to persistent use of a very specific brain circuitry,[80] while tasks with greater stimulus/response diversity (for which Rocket League very much fits) may not experience this effect.

Fourth, we note that the *time on task* effect (or vigilance decrement), which is accelerated and exaggerated by sleep loss,[81] may not have been a factor within Rocket League gameplay. Rocket League matches are only ~6–7 minutes in length (average length in our sample = 6min 42 sec) and allow ~10 second breaks between each goal (occurring every ~40 seconds in the current study), allowing for frequent brief rest opportunities. This time span is particularly pertinent when considering TSD-induced performance impairment on the PVT. Figure 8A shows the difference in response time between individual trials (including the first minute practice block, which was excluded from statistical analysis) for one randomly selected TSD participant. This figure clearly shows that for this participant, while response time was *slightly* poorer on average in the experimental *group* compared to the baseline in the first 6 minutes, this difference only became pronounced (accompanied by an increase in lapse frequency and reaction time variation) after 6 minutes into the PVT, roughly corresponding to the average Rocket League game length. This pattern of a severe increase in reaction time, response variability and lapse likelihood

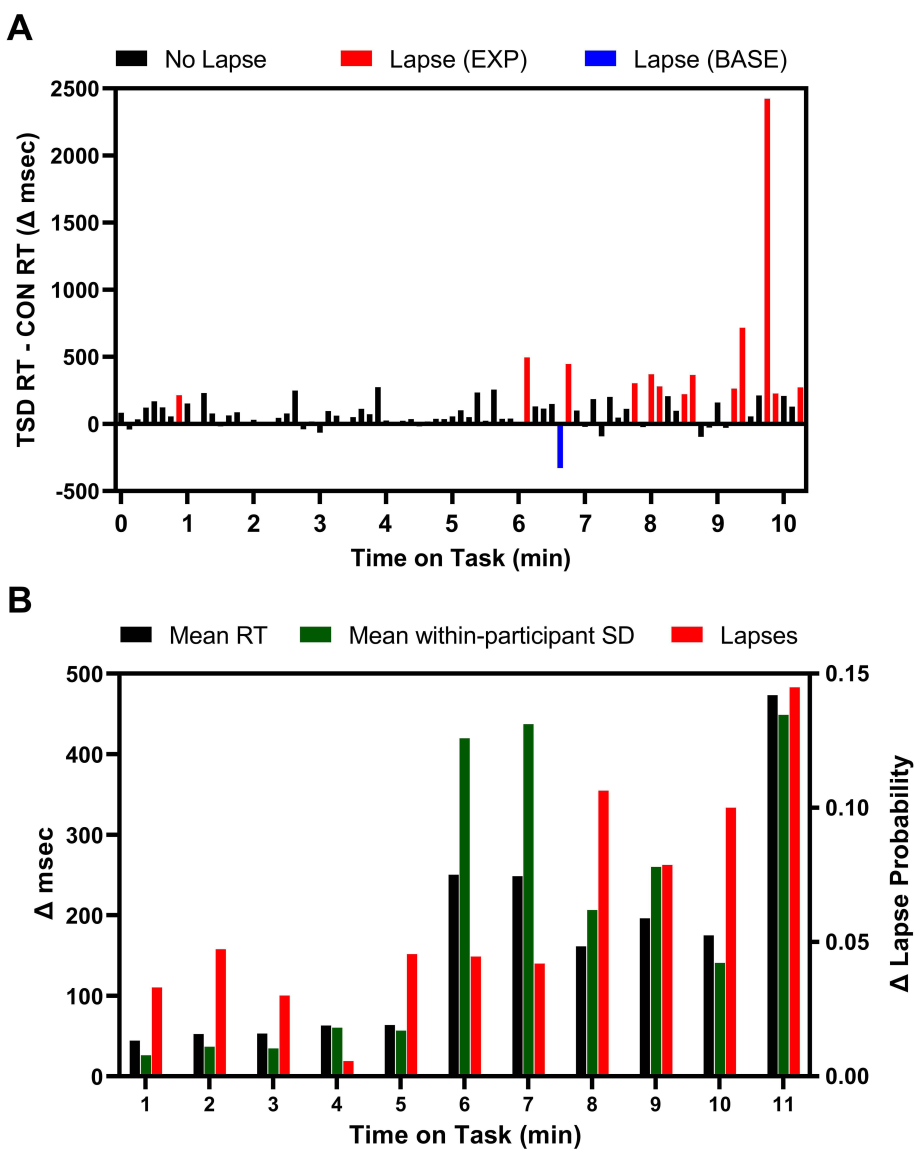

Figure 8 (**A**) Bar chart showing the difference in mean reaction time for each trial of the psychomotor vigilance task (PVT; including the first minute practice block) for a randomly selected TSD (sleep deprivation *group*) participant. Values above zero resemble a trial in which the reaction time was poorer following sleep deprivation, compared to when well rested. Red bars resemble trials which were a lapse within the session while sleep deprived, and blue bars resemble trials which were a lapse within the session when rested. (**B**) Bar chart showing the difference in mean reaction time (black), mean within-participant standard deviation or reaction time (ie, green), and lapse probability (red), for TSD participants following sleep deprivation protocol and when well rested, within each one-minute epoch of the 10-min PVT (inclusive of the first minute of the PVT). Values above 0 resemble greater mean values following sleep deprivation, compared to when rested. Black and green bars are measured on the left y-axis, and red bars are measured on the right y-axis.

following ~5–6 minutes on the PVT in the experimental *group* vs baseline across all TSD participants is shown in Figure 8B. Thus, it is possible that this pronounced negative impact on sleep loss on performance was not experienced in-game due to the short game length of Rocket League. We note that the short game length of Rocket League is somewhat uncommon in popular esports. For example, major multiplayer online battle arena (MOBA) esports such as DOTA2 and LoL (the first and fourth largest esports by prize money earned[38]), have average match lengths of ~20–30 minutes (but can extend to >90 minutes) with very limited and unpredictable rest break opportunities.

Fifth, it is important to consider that in-game performance may not be affected by attentional lapses or sleep loss induced temporary lapses in performance unless such lapses occur at a critical point within the context of the game. In other words, a lapse may not affect game outcome if it occurs while the player and ball are far away from the opponent; conversely, if a certain set of aligning in-game circumstances are present (ie player and ball are near the opponent and one's own-goal, and the opponent is facing the player), a lapse may result in a negative game outcome (in a similar vein to Reason's Swiss Cheese model of accident causation[82]). Other esports may present with a greater or lesser frequency of in-game circumstances in which a lapse may result in a negative game outcome. For example, first person shooter esports (ie, Counter Strike Global Offensive or *CS:GO*) frequently involve scenarios in which success is determined by accurately responding faster than your opponent, and so performance in such esports may be more sensitive to sleep loss as a result.

Lastly, while esports performance appears to be largely predicated on cognitive performance, there are a myriad of other factors involved, such as mood, biomechanics related factors, *playstyle* (individual differences in in-game abilities and strategy preferences) and interactions between competitor's playstyles. Such factors could increase performance variation, confounding any expected effects of sleep loss.

With regard to the last argument, the authors argue that even if there are many extraneous factors in play, it is very unlikely that these factors would have completely nullified the effects of TSD on GD in the current study. A power analysis conducted a priori provided an estimated power of 0.829 for our analysis on GD, using estimated effect size and variance measures, and an estimated MEM design. We observed variance that was larger than predicted (random intercept SD = 2.61 [predicted = 1.94], residual SD = 2.83 [predicted = 1.83]); however, we also found that our data did not (according to the procedure outlined by Matuschek et al[70]) warrant a model including a by-*session* random slope. Retaining the estimated mean effect of TSD as a GD change of 1.218 from the a priori power analysis and including the variance measures and model structure from the results, an updated power analysis suggested that if the predicted mean effect magnitude was accurate, the power to detect it would have been 0.958. Hence, we argue that our underestimation of variance is highly unlikely to be the root cause of the inability to reject the null hypothesis that TSD has no impact on in-game Rocket League performance and that if an effect of ~29hrs of TSD on GD exists, the magnitude of this effect is most likely substantially smaller than anticipated.

In addition to the in-game outcome measure (GD), we gathered in-game data pertaining to a myriad of game-specific factors (ie, offense/defense, boost, movement and positioning) and explored whether established performance indicators (PIs) in 1v1 Rocket League[39] varied as a function of sleep deprivation. Through this exploratory analysis, we identified the PI *time spent high in the air difference* (TSD minus CON) to lower quite substantially (0.48%; average time spent high in the air across all matches in our sample = 3.13%) between *baseline* and *experimental sessions*. We also noted numerical increases in the *time spent goalside of the ball difference*, though with greater overall uncertainty as indicated by $p = 0.059$. These two PI's were specifically discussed by Smithies et al[39] as potentially indicating *safer* or *riskier* playstyles, with greater time *goalside of the ball* and less time *high in the air* resembling a *safer* overall playstyle. However, changes in these specific PIs could alternatively be argued to resemble an individual adopting an *easier* in-game strategy, as voyages *high in the air* typically involve much more difficult and precise movements, while staying grounded and *goalside of the ball* and relying primarily on counterattacking may present as a strategy requiring comparatively less effort than complicated attacking approaches. Sleep deprivation resulting in either (or both) *safer* or *simpler* decision-making has theoretical support. While sleep loss is generally considered to result in *riskier* decision-making,[83,84] decision-making tasks (ie, the Balloon Analog Risk Task or BART) typically show safer strategy employment following sleep deprivation (when 48hrs or less),[85,86] a trend mimicked by subjective risk-taking propensity following sleep deprivation of 48hrs or less.[87–89] Interestingly, when discussing why sleep deprivation leads to a safer strategy on the BART but not other decision-making tasks (ie, Iowa Gambling Task), Satterfield and Killgore[83] note that riskier decisions on the BART are also more effortful and that "sleep deprived individuals appear to be less willing to expend effort to engage in risky activities." (p. 353). Work by Engle-Friedman et al[88,89] can be looked to for additional support for the notion that TSD evoked a *simpler* strategy among our participants. Despite these hypotheses regarding our observed PI differences, we emphasize the exploratory nature of this analysis and emphasize the need for more formal testing before claims can be substantiated. Nonetheless, we note this as an interesting line of future enquiry, especially given participants tended to *feel* (self-report) that fatigue affected their in-game performance following TSD.

Along with in-game performance, we also examined how sleep loss impacted the cognitive performance of esport players using the PVT and CST. As expected, overall response speeds worsened, and the likelihood of lapses increased substantially (~5 times) following TSD, indicating that players' vigilance was impaired. In the single task component of the CST, response speed slowing was similar in magnitude to that observed in the PVT, which was somewhat surprising given previous research[31] suggested the level of impairment decreases as task complexity increases so long as cognitive flexibility is not introduced as a task requirement. Even more surprisingly, we found no evidence for decreases in task-switching ability (measured both by SC and MC response time), contrasting findings by Couyoumdjian et al.[90] However, these findings were consistent with Nakashima et al,[91] who noted no change in SC reaction time following TSD, and somewhat in agreement with Slama et al[92] who noted a change in SC accuracy but not SC reaction time following TSD. Overall, these contrasting findings may be a result of specific task-characteristics (ie, types of stimuli, the changing of stimulus-response mappings, interstimulus intervals, frequency of task switches) which warrant further investigation. The ability to rapidly switch ones' attention between multiple information sources appears integral to esports performance (in the context of Rocket League, this could be the switching of visual attention between the ball, the opponent, the players vehicle and the players boost meter), as demonstrated by improvements in task-switching ability coinciding with the play of action video games.[26] Although the results of our study suggest that this ability may be unaffected by acute sleep loss for esport athletes, we interpret with caution given mixed findings in the literature.

Limitations

We outline several limitations regarding the presented experimental study.

Despite our best efforts, we had only one female participant in our final sample of 40, resulting in a clear sex imbalance. Similar difficulties recruiting female esport players have been previously noted.[93] We also note that this large gender imbalance is (regrettably) reflective of *elite* esport demographics (with estimates of only 5% of professional esport athletes being female; Hilbert[94]), a disparity actively highlighted in many articles.[95,96]

We note a lesser degree of control over factors such as participant demographics, sleep, and weekly gameplay than desirable. We note the extreme difficulty in recruiting participants sufficiently experienced with Rocket League while also fulfilling criteria for healthy sleeping participants such as that outlined in the RRDC.[41] We found that many participants reported great difficulty maintaining a regular sleep and wake time in particular, as resulting in some participants experiencing less than desired TST (ie, ~3hrs) in the 1–3 nights prior to testing, even when meant to be well rested (see Figure 4). Due to this, affordances were made to the inclusion criteria and as such, our participant pool included some individuals screening at risk for sleep disorders, and one participant with habitual caffeine use > 400mg. We note this difficulty in sleep and wake time regularity and encourage future research to explore sleep/wake variability within habitual esport playing populations, potentially through the use of the sleep regularity index (SRI[97]), as done recently in elite team sport athletes by Halson et al.[98] Continuing the topic of sleep and wake times, implementing somewhat standardized target bed (22:00–01:00) and wake times (06:00–09:00) that were outside of those habitually experienced by some participants may have affected the sleep experienced by some participants within the three nights prior to test *sessions*, potentially leading to the higher-than-desired variability in TST on these days. However, we note that this research design decision was made to better comply with the RRDC criteria and for logistical reasons (ie, some participants' habitual wake times could interfere with test *session* availability).

The bout of TSD is another factor worth discussing. A bout of ~29hrs TSD (alongside the TSD protocol and test *session* timings used) was used primarily for logistical reasons, including participant availability, travel times to test *sessions*, and overall time burden. It is possible (and probable, if taken to extremes) that an increase in TSD length may have increased the decreases in cognitive performance experienced and potentially led to an impact on in-game Rocket League performance, through homeostatic processes.[80] However, in order to achieve this TSD length increase, test sessions would have occurred later, and likely closer to the individual's circadian acrophase,[80] where performance is somewhat protected within sleep deprivation protocols. Hence, it is also possible that the bout of sleep deprivation used may have led to a decreased impact on cognitive performance. We also note that the acute sleep loss bout used is on the extremity of ecological relevance within an esports context to begin with. More broadly, TST may not be the only sleep measure that is important for performance within esports (other measures such as sleep quality and sleep efficiency were mentioned in this regard in the introduction). TST was the primary sleep outcome within the current study due to (a) being the standard primary outcome when exploring sleep and performance (either cognitive or else, including athletic performance), (b) being far easier to experimentally manipulate compared to other sleep outcomes (ie, sleep onset latency or wake after sleep onset), and (c) our sleep measurement devices (actigraphy, and more specifically, Readiband), providing far more reliable estimates of TST (and TASO & TAW) than other objectively measured sleep outcomes.[52]

We caution that the results of the current study may have limited applicability to other esports besides Rocket League. Although most major esports share a lot of similarities (fast and accurate responses to rapidly changing stimuli executed through fast and precise fine motor movements, complex interactions with other individuals, use of computer peripheries, seated environment etc.), their diversity has resulted in some observed differences in the relevant importance of specific cognitive abilities,[22,23] and hence potentially, diversity in the impact of acute sleep loss. Also as previously mentioned, Rocket League has short match lengths with frequent break opportunities when compared to other esports, which may lend to a lesser ability of the *time on task* effect (which sleep loss accelerates and exaggerates) to negatively impact performance. We note, however, that the short and predictable match lengths within Rocket League are also one of the key characteristics which make it a feasible esport to conduct experimental research on (as it allows for multiple and consistent amounts of trials per test *session*[39]). Nonetheless, generalizing the results of the current study to other esports should be done with caution.

Lastly, we note that our subjective measure of motivation (motivation VAS[68]) was not suitably timed or worded to appropriately capture participants' motivation to perform within the Rocket League gameplay. Had this item been implemented immediately following either the warm-up provided or in between the matches played, it may have been able to shed light on whether this mechanism may have played a role in performance preservation despite sleep loss.

Practical Implications

It should be explicitly stated that our results do not suggest that sleep is a human factor to be disregarded within the world of esports. Sufficient sleep health is imperative for physical and mental wellbeing,[99] and plays an instrumental role in memory consolidation;[100,101] these are all critical factors when considering the everyday life of esport athletes and the downstream effects of sleep on competition performance. Furthermore, we certainly do not suggest that an acute bout of sleep deprivation does not impact alertness or cognitive performance, as our measures for such (as well as many decades of research; see Lim and Dinges[28] for meta-analyses) are mostly in direct conflict with such a notion. What our results do suggest, however, is that an acute bout of ~29 hours of sleep deprivation may not impact in-game esports performance to any measurable degree. This perhaps provides a positive message to esports players and coaches that a night of poor sleep immediately prior competition is perhaps unlikely to adversely impact in-game performance. This message has high importance given that some traditional athletes often experience sleep disturbances the night prior to competition,[102] with some scholars suggesting that these disturbances are equally likely for esport athletes.[7]

Conclusion

Overall, the results of our study suggest that an acute bout of sleep loss (~29hrs TSD) does not adversely impact in-game Rocket League performance, despite degrading vigilance and attentional capabilities as measured by both subjective and objective instruments. Our findings suggest that efforts may be better placed optimizing day-to-day sleep health, as opposed to austere avoidance of sleep loss immediately prior to competition.

Data Sharing Statement

The data underlying this article, and code for MEM creation and analysis, are available at osf.io, and can be found at https://osf.io/daf4w/ (DOI will be created upon article acceptance). Any other data regarding this article will be shared on a reasonable request to the corresponding author.

Acknowledgments

The authors would like to thank Dr Ian C. Dunican and Prof John A. Caldwell for initial discussions on study protocol. The authors would also like to thank Dr. Fazilat Hojaji, Sophie Cunneen and Eoin Conroy for their assistance with overnight supervision of participants and with data collection. The authors would also like to thank Fatigue Science for supplying the Readibands used in the current study. Results within the study provided within this paper (preliminary or full) have been presented as:

a) Doctoral Thesis (Chapters 7 and 9) – available at https://researchrepository.ul.ie/articles/thesis/An_empirical_investigation_into_the_effects_of_sleep_loss_on_esports_performance/25102469/1.
b) Conference Abstract: P376 Don't lose sleep over esports: exploring how total sleep deprivation affects cognitive and in-game performance of rocket league players (Poster Abstract, Sleep Europe 2022; *Journal of Sleep Research*). Available at https://doi.org/10.1111/jsr.13740.
c) Conference Abstract: P104 The Impact of Total Sleep Deprivation on Performance in the Esport 'Rocket League' (Poster Abstract, Sleep DownUnder 2023; *Sleep Advances*). Available at https://doi.org/10.1093/sleepadvances/zpad035.189.

Disclosure

This work was supported with the financial support of the Science Foundation Ireland grant 13/RC/2094_P2 and co-funded under the European Regional Development Fund through the Southern & Eastern Regional Operational Programme to Lero—the SFI Centre for Software Research (www.lero.ie). TS was receiving funding from the Irish Research Council Employment-Based Postgraduate Program Scholarship (EBPPG/2019/21), with Logitech as the Employment Partner and is employed as a Scientific Consultant by Melius Consulting Pty Ltd. The authors report no other conflicts of interest in this work.

References

1. Campbell MJ, Toth AJ, Moran AP, Kowal M, Exton C. eSports: a new window on neurocognitive expertise? *Prog Brain Res*. 2018:161–174. doi:10.1016/bs.pbr.2018.09.006
2. Statista. Video Games - Worldwide. Statista. Availabe from: https://www.statista.com/outlook/dmo/digital-media/video-games/worldwide?currency=EUR. Accessed December 11, 2024.
3. Ahn J, Collis W, Jenny S. The one billion dollar myth: methods for sizing the massively undervalued esports revenue landscape. *IJESPORTS*. 2020;1(1):1–19.
4. Code Red Esports. Data from: sports teams in Esports by Redeye. *Google Sheets*; 2017.
5. Nicholson J Dignitas takes flight with U.S. Air Force partnership. esportsinsider, 2022. Availabe from: https://esportsinsider.com/2021/07/dignitas-us-air-force-partnership/. Accessed December 11, 2024.
6. Bonnar D, Lee S, Gradisar M, Suh S. Risk Factors and Sleep Intervention Considerations in Esports: a Review and Practical Guide. *Sleep Med Res*. 2019;10(2):59–66. doi:10.17241/smr.2019.00479
7. Bonnar D, Castine B, Kakoschke N, Sharp G. Sleep and performance in Eathletes: for the win! *Sleep Health*. 2019;5(6):647–650. doi:10.1016/j.sleh.2019.06.007
8. Bonnar D, Lee S, Roane BM, et al. Evaluation of a Brief Sleep Intervention Designed to Improve the Sleep, Mood, and Cognitive Performance of Esports Athletes. *Int J Environ Res Public Health*. 2022;19(7):4146. doi:10.3390/ijerph19074146
9. Sanz-Milone V, Yoshinori P, Maculano Esteves A. Sleep quality of professional e-Sports athletes (Counter Strike: global Offensive). *IJESPORTS*. 2021;1(1):1–10.
10. Lee S, Bonnar D, Roane B, et al. Sleep Characteristics and Mood of Professional Esports Athletes: a Multi-National Study. *Int J Environ Res Public Health*. 2021;18(2):664. doi:10.3390/ijerph18020664
11. Kemp C, Pienaar PR, Rosslee DT, Lipinska G, Roden LC, Rae DE. Sleep in Habitual Adult Video Gamers: a Systematic Review. *Front Neurosci*. 2021;15:1–15. doi:10.3389/fnins.2021.781351
12. Baumann A, Mentzoni RA, Erevik EK, Pallesen S. A qualitative study on Norwegian esports students' sleep, nutritional and physical activity habits and the link to health and performance. *IJESPORTS*. 2022;1(1):1–13.

13. Rudolf K, Bickmann P, Froböse I, Tholl C, Wechsler K, Grieben C. Demographics and Health Behavior of Video Game and eSports Players in Germany: the eSports Study 2019. *Int J Environ Res Public Health*. 2020;17(6):1870. doi:10.3390/ijerph17061870
14. Gomes MA, Narciso FV, de Mello MT, Esteves AM. Identifying electronic-sport athletes' sleep-wake cycle characteristics. *Chronobiol Int*. 2021;38(7):1002–1009. doi:10.1080/07420528.2021.1903480
15. Moen F, Vatn M, Olsen M, Haugan JA, Skalicka V. Sleep Characteristics in Esport Players and Associations With Game Performance: residual Dynamic Structural Equation Modeling. *Front Sports Act Living*. 2022;3:1–13. doi:10.3389/fspor.2021.697535
16. Doherty R, Madigan SM, Nevill A, Warrington G, Ellis JG. The Sleep and Recovery Practices of Athletes. *Nutrients*. 2021;13(4):1330. doi:10.3390/nu13041330
17. Green A, Cohen-Zion M, Haim A, Dagan Y. Evening light exposure to computer screens disrupts human sleep, biological rhythms, and attention abilities. *Chronobiol Int*. 2017;34(7):855–865. doi:10.1080/07420528.2017.1324878
18. Schöllhorn I, Stefani O, Lucas RJ, Spitschan M, Slawik HC, Cajochen C. Melanopic irradiance defines the impact of evening display light on sleep latency, melatonin and alertness. *Commun Biol*. 2023;6(1):228. doi:10.1038/s42003-023-04598-4
19. Higuchi S, Motohashi Y, Liu Y, Maeda A. Effects of playing a computer game using a bright display on presleep physiological variables, sleep latency, slow wave sleep and REM sleep. *J Sleep Res*. 2005;14(3):267–273. doi:10.1111/j.1365-2869.2005.00463.x
20. Roberts SSH, Teo W-P, Warmington SA. Effects of training and competition on the sleep of elite athletes: a systematic review and meta-analysis. *BJSM*. 2019;53(8):513–522. doi:10.1136/bjsports-2018-099322
21. Lee S, Bonnar D, Kim Y, et al. Sleep Characteristics and Risk Factors of Korean Esports Athletes: an Exploratory Study. *Sleep Med Res*. 2020;11(2):77–87. doi:10.17241/smr.2020.00773
22. Toth AJ, Conroy E, Campbell MJ. Beyond action video games: differences in gameplay and ability preferences among gaming genres. *Entertain Comput*. 2021;38:100408. doi:10.1016/j.entcom.2021.100408
23. Dobrowolski P, Hanusz K, Sobczyk B, Skorko M, Wiatrow A. Cognitive enhancement in video game players: the role of video game genre. *Comput Hum Behav*. 2015;44:59–63. doi:10.1016/j.chb.2014.11.051
24. Bediou B, Adams DM, Mayer RE, Tipton E, Green CS, Bavelier D. Meta-analysis of action video game impact on perceptual, attentional, and cognitive skills. *Psychol Bull*. 2018;144:77–110. doi:10.1037/bul0000130
25. Bediou B, Rodgers MA, Tipton E, Mayer RE, Green CS, Bavelier D. Effects of action video game play on cognitive skills: a meta-analysis. *TMB*. 2023;4(1):1–21. doi:10.1037/tmb0000102
26. Toth AJ, Ramsbottom N, Kowal M, Campbell MJ. Converging Evidence Supporting the Cognitive Link between Exercise and Esport Performance: a Dual Systematic Review. *Brain Sci*. 2020;10(11):859. doi:10.3390/brainsci10110859
27. Lowe CJ, Safati A, Hall PA. The neurocognitive consequences of sleep restriction: a meta-analytic review. *Neurosci Biobehav Rev*. 2017;80:586–604. doi:10.1016/j.neubiorev.2017.07.010
28. Lim J, Dinges DF. A meta-analysis of the impact of short-term sleep deprivation on cognitive variables. *Psychol Bull*. 2010;136(3):375–389. doi:10.1037/a0018883
29. Glenville M, Broughton R, Wing AM, Wilkinson RT. Effects of Sleep Deprivation on Short Duration Performance Measures Compared to the Wilkinson Auditory Vigilance Task. *Sleep*. 1978;1(2):169–176. doi:10.1093/sleep/1.2.169
30. Pilcher JJ, Huffcutt AI. Effects of Sleep Deprivation on Performance: a Meta-Analysis. *Sleep*. 1996;19(4):318–326. doi:10.1093/sleep/19.4.318
31. Smithies TD, Toth AJ, Dunican IC, Caldwell JA, Kowal M, Campbell MJ. The effect of sleep restriction on cognitive performance in elite cognitive performers: a systematic review. *Sleep*. 2021;44(7):zsab008. doi:10.1093/sleep/zsab008
32. Harrison Y, Horne JA. The impact of sleep deprivation on decision making: a review. *J Exp Psychol Appl*. 2000;6(3):236–249. doi:10.1037//1076-898x.6.3.236
33. Honn KA, Hinson JM, Whitney P, Van Dongen HPA. Cognitive flexibility: a distinct element of performance impairment due to sleep deprivation. *Accid Anal Prev*. 2019;126:191–197. doi:10.1016/j.aap.2018.02.013
34. Whitney P, Hinson JM, Nusbaum AT. A dynamic attentional control framework for understanding sleep deprivation effects on cognition. *Progress in Brain Research*. 2019:111–126. doi:10.1016/bs.pbr.2019.03.015
35. Ionescu T. Exploring the nature of cognitive flexibility. *New Ideas Psychol*. 2012;30(2):190–200. doi:10.1016/j.newideapsych.2011.11.001
36. Uddin LQ. Cognitive and behavioural flexibility: neural mechanisms and clinical considerations. *Nat Rev Neurosci*. 2021;22(3):167–179. doi:10.1038/s41583-021-00428-w
37. Player A. Rocket League Live Player Count and Statistics. Availabe from: https://activeplayer.io/rocket-league/. Accessed December 11, 2024
38. Esports Earnings. Top Games Awarding Prize Money. Availabe from: https://www.esportsearnings.com/games. Accessed December 11, 2024.
39. Smithies TD, Campbell MJ, Ramsbottom N, Toth AJ. A Random Forest approach to identify metrics that best predict match outcome and player ranking in the esport Rocket League. *Sci Rep*. 2021;11(1):19285. doi:10.1038/s41598-021-98879-9
40. DeBruine LM, Barr DJ. Understanding Mixed-Effects Models Through Data Simulation. *Adv Methods Pract Psychol Sci*. 2021;4(1):1–15. doi:10.1177/2515245920965119
41. Beattie L, Espie CA, Kyle SD, Biello SM. How are normal sleeping controls selected? A systematic review of cross-sectional insomnia studies and a standardized method to select healthy controls for sleep research. *Sleep Med*. 2015;16(6):669–677. doi:10.1016/j.sleep.2015.01.010
42. Rocket League Stats. Rocket League Stats, Leaderboards & More! Rocket League; 2023. Availabe From: https://rocketleague.tracker.network/. Accessed December 11, 2024
43. Haahr M RANDOM.ORG: true Random Number Service. Randomness and Integrity Services Ltd; 2021. Availabe from: https://www.random.org. Accessed December 11, 2024
44. Buysse DJ, Reynolds CF, Monk TH, Berman SR, Kupfer DJ. The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research. *Psychiatry Res*. 1989;28(2):193–213. doi:10.1016/0165-1781(89)90047-4
45. Kerkhof GA, Geuke MEH, Brouwer A, Rijsman RM, Schimsheimer RJ, Van Kasteel V. Holland Sleep Disorders Questionnaire: a new sleep disorders questionnaire based on the International Classification of Sleep Disorders-2. *J Sleep Res*. 2013;22(1):104–107. doi:10.1111/j.1365-2869.2012.01041.x
46. Sturzenegger C, Bassetti CL. The clinical spectrum of narcolepsy with cataplexy: a reappraisal. *J Sleep Res*. 2004;13(4):395–406. doi:10.1111/j.1365-2869.2004.00422.x

47. Horne JA, Östberg O. A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *Int J Chronobiol*. 1976;4:97–110.
48. Hodgson R, Alwyn T, John B, Thom B, Smith A. The Fast Alcohol Screening Test. *Alcohol Alcohol*. 2002;37(1): 61–66. doi:10.1093/alcalc/37.1.61
49. Carney CE, Buysse DJ, Ancoli-Israel S, et al. The Consensus Sleep Diary: standardizing Prospective Sleep Self-Monitoring. *Sleep*. 2012;35 (2):287–302. doi:10.5665/sleep.1642
50. Chinoy ED, Cuellar JA, Huwa KE, et al. Performance of seven consumer sleep-tracking devices compared with polysomnography. *Sleep*. 2021;44(5). doi:10.1093/sleep/zsaa291
51. Chinoy ED, Cuellar JA, Jameson JT, Markwald RR. Performance of Four Commercial Wearable Sleep-Tracking Devices Tested Under Unrestricted Conditions at Home in Healthy Young Adults. *Nat Sci Sleep*. 2022;14:493–516. doi:10.2147/nss.S348795
52. Dunican IC, Murray K, Slater JA, et al. Laboratory and home comparison of wrist-activity monitors and polysomnography in middle-aged adults. *Sleep Biol Rhythms*. 2018;16(1):85–97. doi:10.1007/s41105-017-0130-x
53. Driller MW, McQuillan J, O'Donnell S. Inter-device reliability of an automatic-scoring actigraph for measuring sleep in healthy adults. *Sleep Sci*. 2016;9(3):198–201. doi:10.1016/j.slsci.2016.08.003
54. Smithies TD, Eastwood PR, Walsh J, Murray K, Markwick W, Dunican IC. Around the world in 16 days: the effect of long-distance transmeridian travel on the sleep habits and behaviours of a professional Super Rugby team. *J Sports Sci*. 2021;1–7. doi:10.1080/02640414.2021.1947617
55. Dunican IC, Perry E, Maisey G, Nesci E, Roberts S. Sleep hygiene education for improving sleep in ultra-marathon swimmers: guidance for coaches and swimmers. *Int J Sports Sci Coach*. 2023;1018–1024. doi:10.1177/17479541231152196
56. Power CJ, Fox JL, Teramoto M, Scanlan AT. Sleep Patterns Fluctuate Following Training and Games across the Season in a Semi-Professional, Female Basketball Team. *Brain Sci*. 2023;13(2):238. doi:10.3390/brainsci13020238
57. James L, Smart D, Odom-Maryon T, Honn KA, Rowan S. Sleep deprivation in Air National Guard medical personnel responding to simulated disaster-training exercises. *Mil Psychol*. 2019;31(2):138–146.10.1080/08995605.2019.1565909.
58. Min A, Hong HC, Son S, Scott LD. Overtime and alertness of rotating-shift nurses: an observational study using ecological momentary assessment. *J Clin Nurs*. 2023;32(1–2):199–207. doi:10.1111/jocn.16218
59. Rocha J, Silva J. Pilots Performance and Flight Safety: the Case of Cognitive Fatigue in Unpressurized Aircraft Cabins. In: *Presented At: International Congress of the Iberoamerican Air Transportation Research Society*. Covilhã, Portugal: University of Beira Interior; 2019.
60. Edgar DT, Beaven CM, Gill ND, Zaslona JL, Driller MW. Operation early-bird: investigating altered light exposure in military barracks on sleep and performance—a placebo-controlled study. *J Sleep Res*. 2023;32(4):e13837. doi:10.1111/jsr.13837
61. Åkerstedt T, Gillberg M. Subjective and Objective Sleepiness in the Active Individual. *Int J Neurosci*. 1990;52(1–2):28–37. doi:10.3109/00207459008994241
62. Mathew GM, Strayer SM, Bailey DS, et al. Changes in Subjective Motivation and Effort During Sleep Restriction Moderate Interindividual Differences in Attentional Performance in Healthy Young Men. *Nat Sci Sleep*. 2021;13:1117–1136. doi:10.2147/NSS.S294409
63. Basner M, Dinges DF. Maximizing Sensitivity of the Psychomotor Vigilance Test (PVT) to Sleep Loss. *Sleep*. 2011;34(5):581–591. doi:10.1093/sleep/34.5.581
64. Balkin TJ, Bliese PD, Belenky G, et al. Comparative utility of instruments for monitoring sleepiness-related performance decrements in the operational environment. *J Sleep Res*. 2004;13(3):219–227. doi:10.1111/j.1365-2869.2004.00407.x
65. Basner M, Hermosillo E, Nasrini J, et al. Repeated administration effects on Psychomotor Vigilance Test performance. *Sleep*. 2017;41(1):1–6. doi:10.1093/sleep/zsx187
66. Thomann J, Baumann CR, Landolt H-P, Werth E. Psychomotor Vigilance Task Demonstrates Impaired Vigilance in Disorders with Excessive Daytime Sleepiness. *J Clin Sleep Med*. 2014;10(09):1019–1024. doi:10.5664/jcsm.4042
67. Mayr U, Kliegl R. Task-set switching and long-term memory retrieval. *J Exp Psychol Learn Mem Cogn*. 2000;26(5):1124–1140. doi:10.1037//0278-7393.26.5.1124
68. Elsmore TF. SYNWORK1: a PC-based tool for assessment of performance in a simulated work environment. *Beh Res Meth Instr Comp*. 1994;26(4):421–426. doi:10.3758/BF03204659
69. Bates D, Mächler M, Bolker B, Walker S. Fitting Linear Mixed-Effects Models Using lme4. *J Stat Softw*. 2015;67(1):1–48. doi:10.18637/jss.v067.i01
70. Matuschek H, Kliegl R, Vasishth S, Baayen H, Bates D. Balancing Type I error and power in linear mixed models. *J Mem Lang*. 2017;94:305–315. doi:10.1016/j.jml.2017.01.001
71. Barr DJ. Random effects structure for testing interactions in linear mixed-effects models. *Front Psychol*. 2013;4:328. doi:10.3389/fpsyg.2013.00328
72. Lüdecke D, Ben-Shachar MS, Patil I, Waggoner P, Makowski D. performance: an R package for assessment, comparison and testing of statistical models. *J Open Source Softw*. 2021;6(60):3139. doi:10.21105/joss.03139
73. *DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models*; 2022. Availabe from: https://CRAN.R-project.org/package=DHARMa. Accessed December 11, 2024.
74. Brehm L, Alday PM. Contrast coding choices in a decade of mixed models. *J Mem Lang*. 2022;125:104334. doi:10.1016/j.jml.2022.104334
75. Meteyard L, Davies RAI. Best practice guidance for linear mixed-effects models in psychological science. *J Mem Lang*. 2020;112:104092. doi:10.1016/j.jml.2020.104092
76. Little RJA. A Test of Missing Completely at Random for Multivariate Data with Missing Values. *J Am Stat Assoc*. 1988;83(404):1198–1202. doi:10.1080/01621459.1988.10478722
77. Grant DA, Honn KA, Layton ME, et al. 3-minute smartphone-based and tablet-based psychomotor vigilance tests for the assessment of reduced alertness due to sleep deprivation. *Behav Res Methods*. 2017;49(3):1020–1029. doi:10.3758/s13428-016-0763-8
78. Wickens CD, Hutchins SD, Laux L, Sebok A. The Impact of Sleep Disruption on Complex Cognitive Tasks: a Meta-Analysis. *Hum Fact*. 2015;57(6):930–946. doi:10.1177/0018720815571935
79. Massar SAA, Lim J, Huettel SA. Sleep deprivation, effort allocation and performance. *Progress in Brain Research*. 2019:1–26. doi:10.1016/bs.pbr.2019.03.007

80. Hudson AN, Van Dongen HPA, Honn KA. Sleep deprivation, vigilant attention, and brain function: a review. *Neuropsychopharmacol*. 2020;45 (1):21–30. doi:10.1038/s41386-019-0432-6
81. Doran SM, Van Dongen HP, Dinges DF. Sustained attention performance during sleep deprivation: evidence of state instability. *Arch Ital Biol*. 2001;139(3):253–267. doi:10.4449/aib.v139i3.503
82. Reason J. Human error: models and management. *BMJ*. 2000;230(7237):768–770. doi:10.1136/bmj.320.7237.768
83. Satterfield BC, Killgore WDS. Sleep and Health. In: *Sleep Loss, Executive Function, and Decision-Making*. Academic Press; 2019:–339358.10.1016/ B978–0–12–815373–4.00026–5.
84. Womack SD, Hook JN, Reyna SH, Ramos M. Sleep Loss and Risk-Taking Behavior: a Review of the Literature. *Behav Sleep Med*. 2013;11 (5):343–359. doi:10.1080/15402002.2012.703628
85. Killgore WDS. Effects of sleep deprivation and morningness-eveningness traits on risk-taking. *Psychol Rep*. 2007;100(2):613–626. doi:10.2466/pr0.100.2.613-626
86. Killgore WDS, Grugle NL, Killgore DB, et al. Restoration of Risk-Propensity During Sleep Deprivation: caffeine, Dextroamphetamine, and Modafinil. *Aviat Space Environ Med*. 2008;79(9):867–874. doi:10.3357/ASEM.2259.2008
87. Chaumet G, Taillard J, Sagaspe P, et al. Confinement and Sleep Deprivation Effects on Propensity to Take Risks. *Aviat Space Environ Med*. 2009;80(2):73–80. doi:10.3357/ASEM.2366.2009
88. Engle-Friedman M, Palencar V, Riela S. Sleep and effort in adolescent athletes. *J Child Health Care*. 2010;14(2):131–141. doi:10.1177/ 1367493510362129
89. Engle-Friedman M, Riela S, Golan R, et al. The effect of sleep loss on next day effort. *J Sleep Res*. 2003;12(2):113–124. doi:10.1046/j.1365-2869.2003.00351.x
90. Couyoumdjian A, Sdoia S, Tempesta D, et al. The effects of sleep and sleep deprivation on task-switching performance. *J Sleep Res*. 2010;19(1 Pt 1):64–70. doi:10.1111/j.1365-2869.2009.00774.x
91. Nakashima A, Bouak F, Lam Q, Smith I, Vartanian O. Task switching following 24 h of total sleep deprivation: a functional MRI study. *Neuroreport*. 2018;29(2):123–127. doi:10.1097/wnr.0000000000000934
92. Slama H, Chylinski DO, Deliens G, Leproult R, Schmitz R, Peigneux P. Sleep Deprivation Triggers Cognitive Control Impairments in Task-Goal Switching. *Sleep*. 2018;41(2):zsx200. doi:10.1093/sleep/zsx200
93. Ratan RA, Taylor N, Hogan J, Kennedy T, Williams D. Stand by your man: an examination of gender disparity in League of Legends. *Games Cult*. 2015;10:438–462. doi:10.1177/1555412014567228
94. Hilbert J Gaming & gender: how inclusive are eSports? The Sports Integrity Initiative. Availabe from: https://www.sportsintegrityinitiative.com/gaming-gender-how-inclusive-are-esports/. Accessed December 11, 2024.
95. Darvin L, Holden J, Wells J, Baker T. Breaking the glass monitor: examining the underrepresentation of women in esports environments. *Sport Manag Rev*. 2021;24(3):475–499. doi:10.1080/14413523.2021.1891746
96. Taylor N, Stout B. Gender and the two-tiered system of collegiate esports. *Crit Stud Media Commun*. 2020;37(5):451–465. doi:10.1080/ 15295036.2020.1813901
97. Phillips AJK, Clerx WM, O'Brien CS, et al. Irregular sleep/wake patterns are associated with poorer academic performance and delayed circadian and sleep/wake timing. *Sci Rep*. 2017;7(1):3216. doi:10.1038/s41598-017-03171-4
98. Halson SL, Johnston RD, Piromalli L, et al. Sleep Regularity and Predictors of Sleep Efficiency and Sleep Duration in Elite Team Sport Athletes. *Sports Med - Open*. 2022;8(1):79. doi:10.1186/s40798-022-00470-7
99. Itani O, Jike M, Watanabe N, Kaneita Y. Short sleep duration and health outcomes: a systematic review, meta-analysis, and meta-regression. *Sleep Med*. 2017;32:246–256. doi:10.1016/j.sleep.2016.08.006
100. Stickgold R. Sleep-dependent memory consolidation. *Nature*. 2005;437:1272–1278. doi:10.1038/nature04286
101. Walker MP, Stickgold R. Sleep-Dependent Learning and Memory Consolidation. *Neuron*. 2004;44(1):121–133. doi:10.1016/j. neuron.2004.08.031
102. Juliff LE, Halson SL, Peiffer JJ. Understanding sleep disturbance in athletes prior to important competitions. *J Sci Med Sport*. 2015;18 (1):13–18. doi:10.1016/j.jsams.2014.02.007