Full length article

Poor sleep quality affects spatial orientation in virtual environments ☆

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ABSTRACT

Sleep is well known to have a significant impact on learning and memory. Specifically, studies adopting an experimentally induced sleep loss protocol in healthy individuals have provided evidence that the consolidation of spatial memories, as acquired through navigating and orienteering in spatial surroundings, is negatively affected by total sleep loss. Here, we used both objective and subjective measures to characterize individuals' quality of sleep, and grouped participants into either a poor (insomnia-like) or normal (control) sleep quality group. We asked participants to solve a wayfinding task in a virtual environment, and scored their performance by measuring the time spent to reach a target location and the number of wayfinding errors made while navigating. We found that participants with poor sleep quality were slower and more error-prone than controls in solving the task. These findings provide novel evidence that pre-existing sleep deficiencies in otherwise healthy individuals affects negatively the ability to learn novel routes, and suggest that sleep quality should be accounted for among healthy individuals performing experimental spatial orientation tasks in virtual environments.

1. Introduction

Obtaining sufficient sleep is crucial for optimal cognitive performance. Sleep quantity and quality are, in fact, well-known to have a significant impact on alertness, vigilance, and attention, as well as high order cognitive functions such as mental flexibility, planning, and decision making [1]. In the context of learning and memory, sleep-dependent improvements have also been well-documented in both declarative (episodic and semantic) [2] and procedural [3] memory. While investigating the specific effects of sleep on spatial memory, a component of the declarative memory system [4], some studies have reported that hippocampus-dependent spatial memories respond favourably to sleep [2], with post-training sleep enhancing spatial knowledge and allowing for individuals to navigate and orient more efficiently through an environment [5]. Hippocampal activity during slow wave sleep (SWS) has been also associated with overnight improvements in route retrieval [6], and the performance of individuals with prior navigational experience has been shown to be improved following only a brief NREM nap (as measured by polysomnography) [7]. Finally, support for the importance of sleep on

spatial memory has also been provided by behavioural sleep deprivation studies [8,9] showing that navigational accuracy in both real life and virtual environments is affected by sleep loss. In sum, although the research in the specific area of sleep and spatial memory is limited, the existing evidence suggests that spatial orientation skills are significantly related to sleep.

The majority of studies conducted on sleep and cognitive functioning have employed a total sleep deprivation protocol in which participants are typically deprived of one or more nights of sleep. An experimentally induced total sleep deprivation, however, may not accurately resemble the kind of sleep loss experienced by individuals in their daily life. To address this issue, some studies have examined the effects of chronic partial sleep deprivation [10], and showed a sleep dose-response effect on cognitive performance (e.g. behavioural alertness, working memory, and cognitive throughput). Other studies, adopting a similar chronic partial sleep deprivation protocol, revealed that restricting sleep to six hours or less per night, over a period of two weeks, results in cognitive performance deficits that are comparable to deficits experienced after two days of total sleep deprivation [11]. Altogether, these findings confirmed that sleep loss resulting from

either total or chronic partial sleep deprivation has similar detrimental effects on cognitive performance [10].

Although partial sleep restriction and sleep deprivation studies have provided insights into the relationship between sleep and cognition, it remains difficult to generalize findings to individuals with chronic sleep disorders since experimental manipulations cannot fully replicate the long-term changes in sleep patterns that characterize those individuals [12]. This is the case for insomnia, a heterogeneous sleep disorder characterized by subjective poor sleep quality [13], difficulties in initiating and maintaining sleep, and impaired daytime functioning [14]. To date, findings from studies examining the relationship between cognitive functioning and insomnia have been inconsistent [15,16]. One study reported that people with insomnia rate their subjective performance on semantic memory tasks lower than controls despite the fact that their performance does not differ from control [17]; whereas, in another study, it has been shown that people with insomnia experience deficits when trying to retrieve semantic memories relative to healthy controls [18]. Despite the equivocal findings, it is suggested that mild to moderate cognitive deficits occur in the presence of insomnia [12,16,19].

Here, we used both objective and subjective measures to characterize individuals' sleep, and, based on these measures, we grouped participants into either a poor (insomnia-like) or normal (control) sleep quality group. We aimed to (1) investigate the effects of naturally occurring poor quality of sleep (as opposed to experimentally induced sleep deprivation) on wayfinding, and (2) contribute to clarify the effects of insomnia-like symptoms on spatial orientation and navigation. Based on prior literature, we hypothesized that individuals with relatively poorer sleep quality would not only take longer, but also make more errors while performing a wayfinding task in a virtual environment.

2. Material and methods

2.1. Participants

We recruited 24 healthy undergraduate students (8 females, *M*=21.2 years old, *SD*=2.89) who received course credits for participation in the study. Participants did not report a history of medical, neurological or psychiatric disorders, and did not report the use of any psychoactive medications. The study was reviewed and approved by the local research ethics board at the University of Calgary (CHREB-22847), and all participants provided written informed consent.

2.2. Sessions

We required participants to attend two sessions in the laboratory. Session one took place at 2 p.m. and session two occurred seven days later at 10 a.m. Both sessions lasted approximately one hour. During session one, participants were asked to complete a series of questionnaires (see below); afterwards, they were given an actigraph watch (Ambulatory Monitoring Inc.) measuring rest and activity during the night, and the Consensus Sleep Diary (CSD-E) [20], which they were required to fill out every night and return to the experimenter on session two. We asked participants to wear the actigraph on their non-dominant wrist at all times for seven days and nights (except while taking a shower or swimming). The actigraph contained a piezoelectric accelerometer that measures gross motor activity, which was used to indicate not only sleep-wake schedule, but also sleep quantity. When participants came back to the laboratory the following week for session two, they returned the actigraph and the sleep diary, and completed the virtual wayfinding task.

2.2.1. Questionnaires (session one)

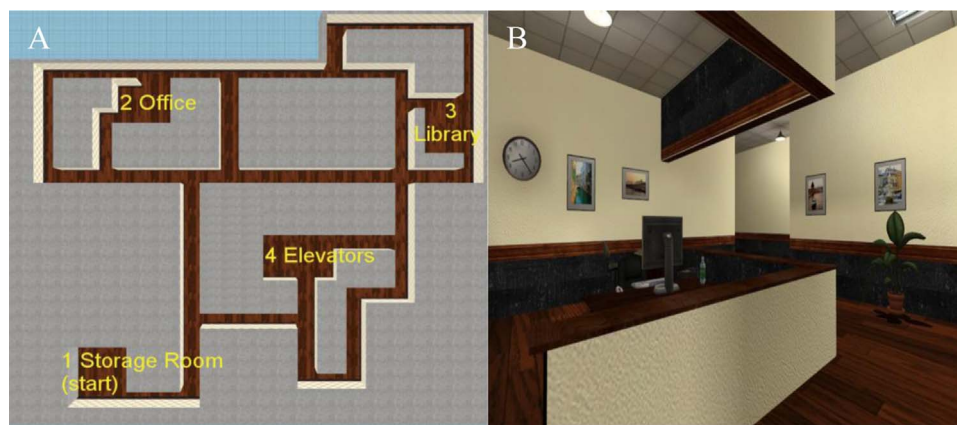Participants were brought to a quiet testing room for their first session. During this session, participants completed a battery of questionnaires. In addition to a brief demographic questionnaire, we obtained subjective sleep measures by asking participants to complete the Pittsburgh Sleep Quality Index (PSQI), which measured subjective sleep quality, sleep latency, duration, efficiency, sleep disturbance, use of sleep medications, and daytime dysfunction [21], and the Insomnia Severity Index (ISI) [22], which measured perceived day- and night-time symptoms related to insomnia for the two weeks preceding the study (scores less than eight indicated the absence of clinically significant symptoms). Participants who scored eight and higher were administered the Insomnia Interview Schedule (IIS) [23] in order to confirm and characterize sleep disturbances and obtain a better description of them. To assess participants' overall anxiety and depressive traits, we administered the State-Trait Anxiety Inventory (STAI) [24] in both state and trait forms, and the Beck Depression Inventory (BDI) [25], respectively. Participants were provided with the CSD-E after completing their questionnaires. The CSD-E provided with both objective and subjective measures of sleep quality. CSD-E objective measure consisted of the following items: (a) What time did you try to go to sleep? (b) How long did it take you to fall asleep? (c) How many times did you wake up? CSD-E subjective measures consisted of the following items: (a) How would you rate your quality of sleep? (b) How rested or refreshed did you feel when you woke up for the day? We instructed participants to log their entries before going to bed every night and upon waking up each morning. This entry logging started on the night of day one (session 1) and ended on the morning of day eight (session two) when they returned to the laboratory to perform the virtual wayfinding task.

2.2.2. Virtual wayfinding task (session two)

We constructed two virtual environments [26] using the Hammer map editor and Source Engine (Valve Software; www.valvesoftware.com). One environment was used as a practice environment in which participants were asked to first navigate through it in order to familiarize themselves with the movement controls. The other environment was used as the experimental environment. The experimental environment was composed of four defined areas. These areas (i.e. rooms) were connected to one another with a hallway network in such a manner that no area was visible from another. The hallways and rooms of the environment were all consistently illuminated through the use of overhead lights that were evenly spaced along the ceiling. The four rooms had unique names and contents, allowing them to be used as reference points for the task (i.e., the Storage Room, the Office, the Library, and the Elevators). Overhead and ground-level views of the experimental environment can be seen in Fig. 1.

The task was presented using a modified version of the game Half-Life 2 (Valve Software) on a PC with four 3.5 GHz processors, 8 GB of memory and a 24-in. LED monitor while running Windows 8. This program had a custom menu that offered the practice and experimental environment as the only selectable options. The participants' avatar moved at a maximum velocity of 150 map units per second, corresponding to 2.86 m/s. This velocity was accelerated to within 500 ms of initiating movement. Additionally, the avatar rotated at a rate of 60 degrees per second (therefore a full rotation required six seconds). The avatar had a horizontal field of view of 75 degrees and its viewpoint was situated at 64 map units from the ground, corresponding to a height of 1.2 m.

Before beginning the experimental task, participants completed the practice task in order to familiarize themselves with the controls for navigation. Participants used the left, right, and up arrow keys on a standard keyboard to make the avatar either turn left, turn right, and move forward, respectively. The practice task used a short maze environment with arrows directing participants down a single path. On-screen instructions prompted the participants to follow the arrows through the maze as quickly as possible while trying to avoid stopping or making contact with the walls. The practice trial ended when participants entered the elevator situated at the end of the maze. A

Fig. 1. The figure displays (A) the overhead schematic view of the environment, and (B) a ground-level perspective taken from the office.

researcher observed and provided any verbal assistance if the participant appeared to have difficulties with the controls; participants were required to repeat the practice task as much as needed until they were able to perform the entire pathway without stopping or making contact with the walls.

After having mastered the controls, participants performed the experimental task. Participants were instructed to notify the researcher if at any point during the task they began feeling nauseous or uncomfortable, in which case the task would have been terminated (this was necessary for three participants). The experimental task began with a learning phase in which the participant was first placed in the Storage room (see Fig. 1). Written instructions appeared on the screen to inform participants that they were to travel on a tour of the environment, and that they were required to pay attention to the location of the rooms relative to one another. During this learning phase, a series of arrows appeared on the walls, guiding participants through a predetermined route through the environment (see Fig. 1). To prevent deviations from this path, invisible barriers blocked the entrances to non-predefined hallways. Participants walked sequentially to the different rooms in the environment. Once they had arrived in a room, text appeared on the screen informing them of the room's name. The learning phase ended after all rooms had been toured, at which point the retrieval phase began.

The retrieval phase of the experimental task began with text informing participants that no arrows were present in the environment indicating a path to be followed, and that they were now able to access any area in the environment. They were then instructed that their task was to deliver a series of letters to the different rooms in the environment by using the fastest and most direct route possible. Since the environment was comprised of four different rooms, there were six possible room pairs and 12 possible origin-to-destination routes that could be taken. There were therefore 12 unique trials in the retrieval phase. The same room pairs (e.g., Office to Library and Library to Office) were never used in back-to-back trials, and all participants followed the same randomized room sequence (i.e., 1-3-2-1-4-2–3-4-1-2-4-3-1). At the start of each trial, participants were given the name of their destination room and asked to reach that room as quickly as possible by following the most direct route. Upon arriving at their destination, participants were informed that they had successfully delivered the letter. Following a four second delay, participants were given instructions to travel to their next destination. The retrieval phase ended once participants had successfully completed all 12 trials.

2.3. Data acquisition and analyses

2.3.1. Actigraphy: objective sleep quality

The data collected from the actigraphs were analyzed using the Action W 2.7 software (Ambulatory Monitoring Inc.). For each

participant, the data were trimmed to a 6 p.m. start time and a 10 a.m. end time. The Life Measure algorithm was used to remove the intervals in which participants were not wearing the watch (i.e. when showering or involved in activities that could damage the watch), and sleep intervals were identified using the Zero Crossing Mode algorithm. All participants wore their watches throughout the sleep interval, thus we did not have to exclude any participants for non-compliance. After pre-processing the data, we computed the following five variables: Sleep Minutes (i.e. the total minutes identified as sleep), Percent Sleep (i.e. how much time was spent sleeping after first falling asleep), Sleep Efficiency (i.e. the proportion of the time in bed that was spent sleeping), Sleep Latency (i.e. the minutes elapsed from going to bed to the first continuous block of sleep of 20 min or greater), and Wake After Sleep Onset (i.e. WASO; the average amount of time spent awake after during the sleep interval).

2.3.2. ISI, PSQI and CSD-E: subjective sleep quality reports

We calculated the global score for the ISI and used it as an indicator of participants' insomnia-related symptoms (i.e. severity of difficulty falling asleep, difficulty staying asleep, and problem of waking up too early). We then used the ISI global scores to determine participants' group membership: individuals who had scores greater than eight, and had insomnia-like symptoms according to the ISI manual, were assigned to the poor sleep group (N=10, 5 females, *mean age*=20.9 years, *SD age*=3.0 years), and those with scores less than eight were assigned to the control group (N=14, 3 females, *mean age*=21.43 years, *SD age*=2.9 years). We decided to use such subjective measure for classifying participants' sleep quality based on the evidence that subjective sleep measures are more sensitive to detect and define poor sleep quality as compared to actigraphy measures, particularly in subjects that lie motionless in bed [27,28]; moreover, in a recent study we collected a variety of objective and subjective sleep measures and used a principal components analysis to provide evidence that subjective sleep measures including the ISI were the factors that best explained behavioural performance among individuals [29]. In the present study, in addition to the ISI, we calculated the global score for the PSQI by summing participants' responses from the seven subcomponents of the questionnaire; higher PSQI scores were indicative of poorer sleep quality. From the CSD-E, responses over the seven days of testing were averaged into a single score for each question.

2.3.3. Wayfinding task

Each participant's performance of the task was recorded in a single video using the software FRAPS (www.fraps.com) and ShadowPlay (www.geforce.com). Performance of the first five participants was recorded at 30 frames per second using FRAPS, and the final 19 participants' performance was recorded at 60 frames per second using ShadowPlay. The use of two different recording programs did not affect

the accuracy with which the behavioural measures were acquired. The time delay required to reach every destination over and above the optimal time (i.e. delay score) and number of errors made were the behavioural measures of interest. For each trial, the optimal time was automatically generated by timing the optimal performance while traversing the shortest pathway without stopping along the way. Errors were classified as instances in which individuals did not take the optimal route to their destination. To account for the three participants (two from the insomnia group and one control) who did not finish all the experimental trials due to motion sickness, the total number of errors were converted to a ratio of errors made according to the number of trials completed. Delay score referred to the additional time participants took to reach their destination over the minimum/optimal possible time. Additionally, for each of the 12 trials, there was a maximum time established. If a participant took more than the mean time for that trial plus one standard deviation (based on a different normative sample of 79 people), then the task automatically transported the participant to their destination to allow the task to continue. By establishing a maximum time, we were able to retain extreme values while minimizing the effects of outliers, who may have otherwise gotten lost and wandered indefinitely during the trial.

2.3.4. Statistical analyses

First, we ran a Pearson's correlation analysis to investigate the existence of potential relationships between objective actigraph measures and subjective measures of sleep. Then, we ran a second Pearson's correlation analysis to investigate the relationship between STAI-Trait and BDI scores and our behavioural variables of interest. Secondly, we assigned participants to the poor-sleep or to the control group based on their subjective experience of insomnia-like symptoms as defined by the ISI: participants in the poor-sleep group (M=14.00, SD=2.91) were characterized by higher scores than controls (M=4.36, SD=2.17), $t(22)$=9.33, $p < 0.001$. Finally, we ran a series of two-tailed independent sample t-tests to determine the existence of between groups differences in sleep variables (objective and subjective) and in the behavioural measures of interests from the wayfinding task. Specifically, we compared poor-sleep and control groups on the time delay taken to reach each destination over the optimal time (average delay score), and the number of trials for which participants did not take the most direct route to their destination (error ratio), For all analyses, we set a two-tailed level of significance at p=0.05, unless noted otherwise.

3. Results

The Pearson's correlation analysis revealed the absence of correlations between objective measurements as obtained by the actigraph, and the subjective measurements of sleep (all ps > 0.068; see Table 1). No statistically significant correlations were found between STAI-Trait, the BDI scores, and our behavioural variables of interest (all ps > 0.122; see Table 2). (Table 3).

Two-tailed independent sample t-tests revealed no between groups differences in all the objective sleep measures that were obtained using the actigraph watch (all ps > 0.15). On the other hand, participants in the poor-sleep group and controls did show differences on several of the subjective sleep measures. Particularly, on the PSQI individuals in the poor-sleep group (PSQI: M=7.10, SD=2.23) reported poorer sleep quality compared to controls (PSQI: M=3.71, SD=1.59), $t(22)$=4.35, $p < 0.001$. Furthermore, on the subjective components of the CSD-E, participants in the poor-sleep group (M=2.88, SD=0.72) reported feeling less well rested as compared to controls (M=3.77, SD=0.63), $t(22)$=−3.22, p=0.004, and a general lower quality of sleep (M=3.28, SD=0.76) as compared to controls (M=4.04, SD=0.51), $t(22)$=−2.92, $p < 0.001$. In terms of objective variables measured by the CSD-E, individuals in the poor-sleep group (M=1.90, SD=1.79) solely differed from controls (M=0.64, SD=1.01) in the number of early awakenings

Table 1
Correlation coefficients between the objective actigraph (Act.) measures and subjective sleep measures (PSQI, Pittsburgh Sleep Quality Index; ISI, Insomnia Severity Index; CSD-E, Consensus Sleep Diary).

		PSQI	ISI	CSD-E Sleep Quality	CSD-E Rested
Act. Sleep minutes	r	−0.295	−0.195	0.182	0.167
	p	0.162	0.361	0.396	0.435
Act. Percent sleep	r	0.168	0.256	0.083	0.043
	p	0.432	0.227	0.700	0.841
Act. Sleep efficiency	r	0.304	0.314	0.007	0.181
	p	0.149	0.135	0.975	0.397
Act. Sleep latency	r	0.133	0.156	−0.378	−0.272
	p	0.535	0.466	0.068	0.199
Act. Wake after sleep onset	r	−0.377	−0.368	0.030	−0.076
	p	0.069	0.077	0.889	0.725

Table 2
Correlation coefficients between State-Trait Anxiety Inventory (STAI-Trait), Beck Depression Inventory (BDI), and behavioural variables (Time Delay and Error Ratio) as measured while performing the wayfinding task.

		STAI-Trait	BDI
Time delay	r	0.153	0.280
	p	0.475	0.184
Error ratio	r	0.251	0.324
	p	0.236	0.122

reported, $t(22)$=2.20, p=0.039; none of the other objective variables measured by the CSD-E were significantly different between groups. Finally, our two groups did differ on both trait anxiety ($t(22)$=2.99, p=0.002) and depression ($t(11)$=3.19, p=0.008): participants in the poor-sleep group scored higher on both of these measures (STAI-Trait: M=63.40, SD=14.39; BDI: M=15.40, SD=9.52) than controls (STAI-Trait: M=50.50, SD=6.37; BDI: M=5.14, SD=4.19).

The two-tailed t-tests on the wayfinding measurements revealed a difference in the average delay scores between the two groups ($t(22)$=2.12, p=0.046) (see Fig. 2), confirming that the poor-sleep group (M=42.16, SD=27.63) took longer than the control group (M=20.76, SD=21.90) to reach their destinations. Furthermore, when looking at the ratio of errors made by the poor-sleep (M=0.70, SD=0.22) and control (M=0.48, SD=0.26) groups, we found that individuals with insomnia-like symptoms committed more errors than controls ($t(22)$=2.20, p=0.039) while performing the wayfinding task.

4. Discussion

We collected multiple sleep measures in order to better characterize the quality of sleep of the individuals and to define our poor-sleep group. First, to place individuals in the poor-sleep group, we administered the Insomnia Severity Index (ISI), a measure that is designed to evaluate perceived day-time and night-time symptoms of insomnia [22]. We also asked participants to complete the PSQI. Although not specifically designed to diagnose insomnia, the PSQI is a widely accepted instrument that assesses sleep quality and disturbance over the course of the past month [21]. We found that participants experiencing insomnia-like symptoms also reported poorer sleep quality, as measured by the PSQI, compared to controls. Participants in the poor-sleep group also differed significantly from controls in subjective sleep quality as assessed by the CSD-E, a standardized tool assessing qualitative (e.g. sleep quality) and quantitative (e.g. sleep duration) aspects of sleep [20], which is consistent with previous

Table 3
Participants' demographics and questionnaires data, and *t*-test comparisons between groups (*refers to significant differences between groups). BDI, Beck Depression Inventory; PSQI, Pittsburgh Sleep Quality Index; ISI, Insomnia Severity Index; CSD-E, Consensus Sleep Diary; Act., Actigraph.
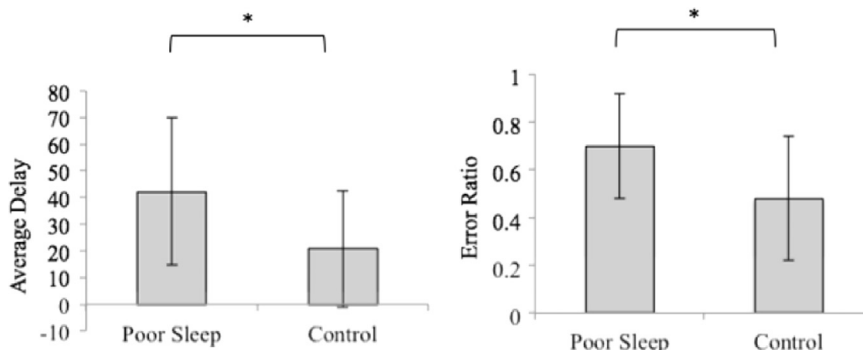
	Poor-sleep group		Control group		df	t	p
	Mean	SD	Mean	SD			
Age	20.90	3.00	21.43	2.90	22	−0.43	0.668
Anxiety state	56.10	13.01	52.21	11.58	22	0.77	0.449
Anxiety trait*	63.40	14.39	50.50	6.37	22	2.99	0.002*
BDI*	15.40	9.52	5.14	4.19	11.50	3.19	0.008*
PSQI*	7.10	2.23	3.71	1.59	22	4.35	< 0.001*
ISI*	14.00	2.91	4.36	2.17	22	9.32	< 0.001*
Act. Sleep minutes	449.27	55.78	450.17	54.33	22	−0.04	0.969
Act. Percent sleep	97.13	1.23	95.76	2.88	22	1.40	0.175
Act. Sleep efficiency	97.97	1.14	96.52	2.96	22	1.46	0.160
Act. Sleep latency	5.59	5.39	3.93	2.72	12.28	0.89	0.389
Act. Wake after sleep onset	7.87	3.39	14.10	13.13	22	−1.46	0.159
CSD-E Time to bed	0.49	0.04	0.48	0.03	22	0.75	0.461
CSD-E Time to sleep	0.54	0.05	0.51	0.04	22	1.76	0.093
CSD-E Time to fall asleep	22.88	16.11	12.30	5.86	10.71	1.99	0.073
CSD-E Time to bed	0.49	0.04	0.48	0.03	22	0.75	0.461
CSD-E Time to sleep	0.54	0.05	0.51	0.04	22	1.76	0.093
CSD-E Time asleep	22.88	16.11	12.30	5.86	10.71	1.99	0.073
CSD-E n wakeups	1.73	1.76	1.13	0.92	12.52	0.98	0.344
CSD-E Wake after sleep onset	8.72	12.22	7.40	6.89	22	0.34	0.740
CSD-E Time of final awakening	0.33	0.05	0.33	0.06	22	0.08	0.938
CSD-E Time in bed after wake	20.47	17.56	10.24	12.68	22	1.66	0.111
CSD-E n Final awakening early*	1.90	1.79	0.64	1.01	22	2.20	0.039*
CSD-E Time out of bed	0.37	0.05	0.34	0.03	22	1.43	0.166
CSD-E Sleep duration	0.32	0.05	0.32	0.03	22	−0.29	0.774
CSD-E Sleep quality*	3.28	0.76	4.04	0.51	22	−2.92	0.008*
CSD-E Rested*	2.88	0.72	3.77	0.63	22	−3.22	0.004*

studies suggesting that complaints of poor sleep quality are a defining feature of insomnia [13]. Overall, sleep quality (as measured by PSQI, ISI and items of the CSD-E) was consistently measured to be poorer in the poor-sleep group than in the control group, and it was the distinguishing feature between our two sleep groups.

In addition to subjective measures, sleep quality can be evaluated through the use of objective methods such as actigraphy or polysomnography (PSG). In our study, we used actigraphy to collect objective data characterizing the quality of sleep of our participants. Our analyses did not reveal any group differences using this approach. Coherently, the correlation analysis between subjective and objective measures of sleep in our sample revealed no relationship between these two different types of measurements. Though this may seem surprising at first, the inconsistency between objective and subjective measures characterizing sleep quality, is an issue that has been already raised to question the ability of actigraphy to detect periods of wakefulness in specific populations or people with specific sleep disorders [30]. In fact, actigraphy utilizes a piezoelectric accelerometer that measures motor activity [27], which is used to characterize wakefulness, but the technique cannot distinguish between sleep and lack of movement [28]. This is an important issue as some insomnia sufferers will often remain in bed motionless and awake for extended periods of time [30], which results in the technique to be unable to detected their wakefulness. This issue is well-known in the field, and it is the main reason for which objective parameters acquired through the actigraphy are often not routinely used in the clinical practice for evaluation and diagnosis of insomnia while PSG remains the gold standard. In our specific study, there may be two potential explanations for why we did not find any group differences in the actigraph measures. First, the sleep quality identified in our poor-sleep group may refer to insomnia-like symptoms representative of subjective paradoxical insomnia, which refers to individuals reporting poor sleep quality despite having relatively normal PSG and actigraphy recordings [31]. On the other hand, the lack of group differences could be attributed to the actigraphy's inability to detect motionless wakefulness in our poor-sleep group. Either way, our findings are in support of revaluing the use of subjective measures in clinical setting.

The neurological mechanisms underlying our findings may be related to the key role played by the hippocampus on the human ability to orient in spatial surroundings [32]. Sleep deprivation before learning affects activity in the medial temporal lobe (MTL) reducing its ability to encode new declarative memories, with the duration of the

Fig. 2. The figure displays the differences detected between the poor-sleep and control groups in both average time delay (secs) and error ratio (*p < 0.05).

deprivation being suggested to be proportional to the extent to which the MTL is affected [33]. Therefore, it is possible that the decreased navigational performance in our participants experiencing poor sleep and insomnia-like symptoms may be a result of the hippocampus' reduced ability to encode new memories. This interpretation is consistent with recent neuroimaging studies that have begun to establish a link between poor sleep and hippocampal volume. In one exploratory study, differences in hippocampal volumes were found between patients with chronic insomnia and healthy good sleepers [34]. Although unable to replicate these exact results, more recent studies have reported other important associations between sleep and neurological measures: one study found that poor sleep efficiency and increased wake after sleep onset are associated with decreased hippocampal volume in individuals with insomnia [35]; a different study revealed further correlations between insomnia duration, arousal index, and hippocampal volume, as well as impairments in memory and frontal lobe functioning in those individuals with poor sleep quality [36]. These findings support the crucial relationship between medial temporal structures, such as the hippocampus, and quality of sleep, and may suggest a specific mechanism by which poor sleep quality may be affecting the ability to orient and navigate in novel surroundings. Importantly, however, this remains a pure speculation since we did not collect any neurological measures in our group of participants.

Our findings should be interpreted with caution. In addition to significant differences in sleep quality between the two groups, we also found differences in both STAI-Trait and the BDI measures, assessing symptoms of anxiety and depression, respectively. Although no correlation was found between these measures and our behavioural variables of interest, we can not exclude that differences in the ability of our participants to navigate through the novel environment resulted in part from their inability to deal with stressors (i.e. getting lost) and ineffective problem solving strategies found in anxious individuals [37]. Indeed, traits such as neuroticism, which is associated with the experience of anxiety, have been linked to decreased performance on spatial tasks [38]. Alternatively, differences in performance between groups could be attributed to participants' varying scores on depression since history of depression has been linked to hippocampal volume loss and poor declarative memory [39]. Furthermore, since the hippocampus is critical for spatial memory, hippocampal volume loss due to depression may be an alternate mechanism by which spatial learning was affected in our participants.

In conclusion, the present study provides the very first evidence that poor sleep quality affects learning of novel routes in virtual environments and influences subsequent performance in wayfinding. These findings are consistent with reports of detrimental effects of sleep restriction on general cognitive functioning [40], and are complementary to studies using total sleep deprivation paradigms [8,9], confirming the critical role of good quality sleep on spatial navigation and orientation.

Acknowledgement

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