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Twenty-Hour Sleep Deprivation Does Not Affect Perceived Vection Strength

Masaki Ogawa[1], Takeharu Seno[1,2,3*], Kouhei Matsumori[1], Shigekazu Higuchi[1]

[1]Faculty of Design, Kyushu University, Fukuoka, Japan
[2]Institute for Advanced Study, Kyushu University, Fukuoka, Japan
[3]Research Center for Applied Perceptual Science, Kyushu University, Fukuoka, Japan
Email: *seno@design.kyushu-u.ac.jp

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Abstract

We examined the effect of sleep deprivation on self-motion perception (vection). We measured the strength of vection, its latency, and its duration in two conditions: Sleep-Deprivation and Normal-Sleep (by using the between-subject design). For the Sleep-Deprivation condition, participants did not sleep for about 20 hours. We also recorded subjective sleepiness with a subjective rating scale that was filled out by the participants. Results showed that vection strength did not differ between the two conditions. Sleep deprivation did not have any clear effect on vection. As expected, subjective sleepiness significantly increased following sleep deprivation. Further, subjective sleepiness significantly correlated with vection latency and duration only in the Normal-Sleep condition. Vection was immune to sleep deprivation. We conclude that when people are not deprived of sleep, sleepiness can enhance the perceived strength of vection.

Keywords

Sleep Deprivation, Vection, Sleepiness, Facilitation Effect

1. Introduction

Sleep deprivation can modify human performance and perception [1]. For example, sleep deprivation has been shown to enhance binocular depth inversion [2]. Paavonen *et al.* (2010) [3] examined the relationship between sleep duration and multiple cognitive tasks in 8-year-old children. They showed that shorter sleep durations were associated with lower visuospatial abilities and with worse performance on visual-motor integration tasks.

*Corresponding author.

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Araujo *et al.* (2013) [4] examined the relationship between performance of visual perception and sleep time in public school students. They revealed that going to sleep early and having a regular sleep schedule contributed to better performance on visuospatial tasks. Finally, visual short-term memory has been shown to decline after sleep deprivation [5]. Therefore, we can conclude that sleep deprivation strongly modifies our visual perceptions[1]. Indeed, such a phenomenon is intuitive; perhaps all adults have experienced this kind of visual impairment in their daily lives.

Sleep deprivation has also been shown to affect control of our posture and bodily movements. First, it has been observed to greatly affect the vestibular system. For example, Drummond and Brown (2001) [6] reported that sleep deprivation induces an alteration in the posterior parietal cortex that is absolutely linked to the processing of vestibular information. Related to this, impairments in postural control because of sleep deprivation have been repeatedly reported [7]-[11]. For example, Fabbri *et al.* (2006) [12] explored the effects of 12-hour sleep deprivation using Romberg's test under eyes-open and eyes-closed conditions and found evidence that sleep deprivation increased postural sway. Additionally, Gribble and Hertel (2004) [13] explored the effects of 48-hour sleep deprivation, finding that postural control worsened during the first 24-hour period.

Lack of sleep has also been shown to modify and influence eye movements. For example, Fransson *et al.* (2009) [14] measured smooth pursuit and saccadic eye movements following 24 and 36 hours of sleep deprivation and showed that accuracies for both types of eye movements decreased with sleep deprivation. Quarck *et al.* (2006) [15] found a post sleep-deprivation elevation in the angular vestibulo-ocular reflex[2].

When exposed to a visual motion field that simulates the retinal optical flow generated by movement (for example, through walking or driving), we perceive the subjective movement of our own body. This phenomenon is known as vection [16]. For example, in the "train illusion" [17], when stationery passengers observe a train beginning to move, they are likely to illusorily perceive that they are moving in the opposite direction to the motion of the train. One of the first experimental examinations of vection was conducted by [18]. Subsequently, various aspects of vection have been extensively examined [19]-[22].

In this paper, we focused on new aspect of this vection, *i.e.* the effect of sleep deprivation on perceived vection strength. Like sleep deprivation, vection is also linked to bodily control. First, it can deactivate the parieto-insular vestibular cortex, a brain area related to vestibular input processing [23]. Second, posture can influence vection strength [24]-[26]. Also vection is related to eye movements [27], and head movements [28] [29]. These findings in the previous vection studies motivated us to conduct an experiment to investigate the relationship between vection and sleep deprivation.

However, the link between vection, sleep deprivation, and bodily control remains unclear, and several different hypotheses can me made regarding the effect of sleep deprivation on vection. While some studies have reported positive correlations between postural sway and vection [30] [31], others have showed no significant correlations [32] [33]. Thus, given that sleep deprivation is known to increase body swaying [12], if vection and body sway are also positively correlated, one hypothesis (Hypothesis 1) is that vection could be enhanced by sleep deprivation.

It has been repeatedly reported that vection is very sensitive to internal bodily conditions. For example, hunger [17] and alcohol consumption [34] have been shown to enhance vection. From these facts, we could also hypothesize that sleep deprivation somehow affects vection strength, because it could modify our internal bodily conditions.

At the same time, it has been reported that vection cannot be modulated by circadian rhythms, and that vection strength remained constant from 9:00 a.m. to 9:00 p.m. [35]. From this fact, we can make a second hypothesis (Hypothesis 2) that vection strength would not be changed through sleep deprivation.

Four scenarios lead to a third hypothesis (Hypothesis 3) that sleep deprivation inhibits vection strength. First, vection can be inhibited by different kinds of stress, including hypoxia (low oxygen level and low air pressure) and social stress [39] [40]. If sleep deprivation is considered stressful, we can predict that it also inhibits vection.

Second, when we are sleepy, cognitive performance generally decreases because sleep deprivation reduces

[1]Here, we should note that there might be many possible explanations (possible mechanisms) for the effect of sleep deprivation. For example, reduced storage capacity of our memory, the worse performance in visual-motor integration and a decreased cognitive function might be the possible mechanisms.

[2]On the contrary, there are some studies repot that the sleep deprivation did not affect eye movements. Reference [36] explored the effects of sleep deprivation on the Dynamic Visual Acuity Test (DVA), which assessed gaze instability, concluding that sleep deprivation did not have a significant effect on DVA. Further, both [37] and [38] found that short-term periods of sleep deprivation failed to yield significant changes in eye-movement responses to angular stimulation.

attention [41] [42]. Some studies have reported that vection can be inhibited by the deprivation of attentional resources [43] [44]. Thus, we can predict that when sleep deprivation reduces our attention to vection, it effectively acts to inhibit the perception. Third, arousal level and vection strength appear to be linked. Ihaya *et al.* (2014) [45] reported that when participants perceived stronger vection, their pupil sizes became larger. Thus, it seems that stronger vection might induce higher arousal levels. Additionally, Seno [45] reported that when music was used to enhance the arousal level of participants, vection was also enhanced. As studies indicate that sleep deprivation can decrease human arousal level (decreased performance on a vigilance task [47]), this could also lead to weaker vection.

Fourth, sleepiness has been found to have a severe inhibitory effect on simulated driving tasks, to a degree similar to consuming alcohol [48]. Driving is deeply related to vection. When we drive a car at a constant speed in a single direction, self-motion perception is created only through vection. Therefore, Arnedt *et al.* (2001) [48] predicts that vection strength can be reduced by sleepiness if we assume that the inhibition of driving skills coincides with an inhibition in vection. Thus, the literature provides us with several conflicting hypotheses. To determine which hypothesis is correct, we designed an experiment to directly test the effect of sleep deprivation on vection.

Other recent studies have reported that vection has an effect on human cognition. For example, vection can modify our recollections, the contents of daydreams and the cognition of numbers (mental number line) [49]-[52]. Also vection strength can be modulated by the stimulus meanings [17] [53] [54]. As described above, Ihaya *et al.* (2014) [45] reported that when participants experienced stronger vection, their pupil sizes increased and they also reported that faster vection could induce faster speech [55]. We can say that, vection can alter our arousal levels and our states of cognition. Additionally, Seno [40] reported that the presence of a two-person audience could inhibit vection strength, *i.e.* the social inhibition of vection. We could say that vection could be modulated by various factors, very flexibly. Thus, we could hypothesize that sleep deprivation can modify vection strength like other factors as in the same manner described in this introduction.

2. Methodology

2.1. Ethics Statement

Our experiments were pre-approved by the Ethics Committee of Kyushu University, and written informed consent was obtained from each participant prior to testing.

2.2. Participants

The experiment used a within-subjects design with 16 participants (all men[3], mean age: 22.3 ± 1.8 years). All participants reported normal vision and had no history of vestibular system disease. All were either graduate or undergraduate students at Kyushu University, and none knew the purpose of the experiment.

2.3. Apparatus

Stimuli were generated and controlled by a MacBookPro computer (MD101J/A; Apple) and presented on a plasma display (3D Viera, 50-inch, Panasonic, 1920 × 1080 resolution with 60 Hz refresh rate). The experiment was conducted in a dark chamber.

2.4. Stimuli

All stimuli were created using OpenGL. Optic flow displays consisted of 1240 randomly positioned dots per frame with projected global dot motion that simulated forward self-motion. The self-motion displays were created by positioning 16,000 dots at random inside a simulated cube (length 20 m) (**Figure 1**), and moving the observer's viewpoint to simulate forward self-motion at a rate of 20 m/s. Stimulus duration was 40 s. The stimuli subtended 72˚ (horizontal) × 57˚ (vertical) at a viewing distance of 57 cm. As dots disappeared at the edge of the screen, they were replaced at the far depth plane (thereby creating an endless visual motion display). The dots did not form a density gradient. Therefore, there were no static depth cues, and the only moving depth cue was motion parallax. The stimuli were nearly identical to those used in our previous studies [56].

[3]We did not recruit women participants because of possible issues related to sleeping in the same room with many men participants. This limitation is discussed in the Results and Discussion sections.

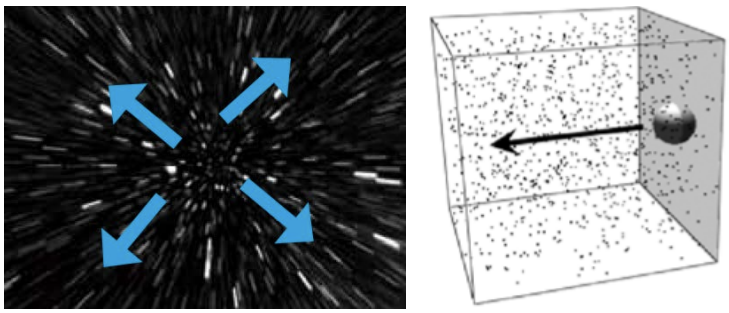

Figure 1. A schematic illustration of the vection stimuli.

2.5. Design

We compared vection under two conditions: Sleep-Deprivation and Normal-Sleep. All participants experienced both conditions. Condition order was counter-balanced across the 16 participants.

2.6. Procedure

Beginning one week before the experiment, participants were instructed to wake up between 08:00 and 09:00 and to go to bed between 0:00 and 01:00 to maintain regular sleep/wake cycles. Sleep/wake patterns were recorded using an activity monitor (Lifecorder PLUS; Suzuken Co. Ltd., Japan) that was attached to each participant's waist [57]. The experiment was conducted in an environmentally controlled chamber at 25˚C and 50% relative humidity. The participants were told not to ingest alcohol or caffeine or to exercise during the course of the experiment. All participants experienced a practice vection experiment to become familiar with the simulated vection experience. In the Normal-Sleep condition, the participants slept in the laboratory from 01:00 to 09:00. After breakfast, the vection experiment was conducted from 10:00. In the Sleep-Deprivation condition, after normal sleep in the laboratory from 01:00 to 09:00, participants stayed awake for 20 hours in the laboratory. The vection experiment was conducted at 05:00. Multiple participants slept in a single chamber during the experiment; therefore we decided not to recruit women participants because of possible issues related to sleeping in the same room. Subjective sleepiness was measured using the Stanford Sleepiness Scale (SSS) following the vection experiments. In the control condition, vection measurement was carried out at 10:00 a.m., approximately one hour after waking up.

When viewing the computer-generated radially expanding pattern, participants were asked to press a designated button with their dominant hand as soon as they perceived forward self-motion. After each trial, they rated the subjective vection strength using a 101-point rating scale ranging from 0 (no vection) to 100 (very strong vection) (we named this "magnitude of vection"). Very strong vection meant that participants perceived self-motion very naturally, as if they were moving throughout the stimulus presentation. This methodology has been used in several of our studies [26] [56] and has been confirmed as a valid means to evaluate vection strength.

The dependent variables in this study were the required period for the first vection appearance (the latency of vection), the total accumulation of the vection-periods (the duration of vection), and the subjective strength of vection (magnitude). Each participant performed four trials for each condition (deprivation or no deprivation). We assumed button-pressing data (latency and duration) reflected the perceptual aspect of vection and that the magnitude reflected both perceptual and cognitive aspects of vection. Previous studies [58] reported that these three indices of vection strength could be inconsistent sometimes. If the effect of vection modulation was so strong, the three indices were consistent, but if it was weak, there were inconsistencies. Thus the degree of the consistency over the three indices can imply the strength of the effect of the independent variables. Because previous studies have found that vection can be modulated by instructions that induce cognitive biases, we took care to avoid any suggestion of our hypotheses [59].

3. Results and Discussion

As expected, subjective sleepiness significantly increased following sleep deprivation ($t(15) = 7.33$, $p < 0.01$) in **Figure 2(a)**. All participants reported substantially strong vection. For 12 participants, vection was stronger in the Sleep-Deprivation condition than in the Normal-Sleep condition. For the other four participants, vection was

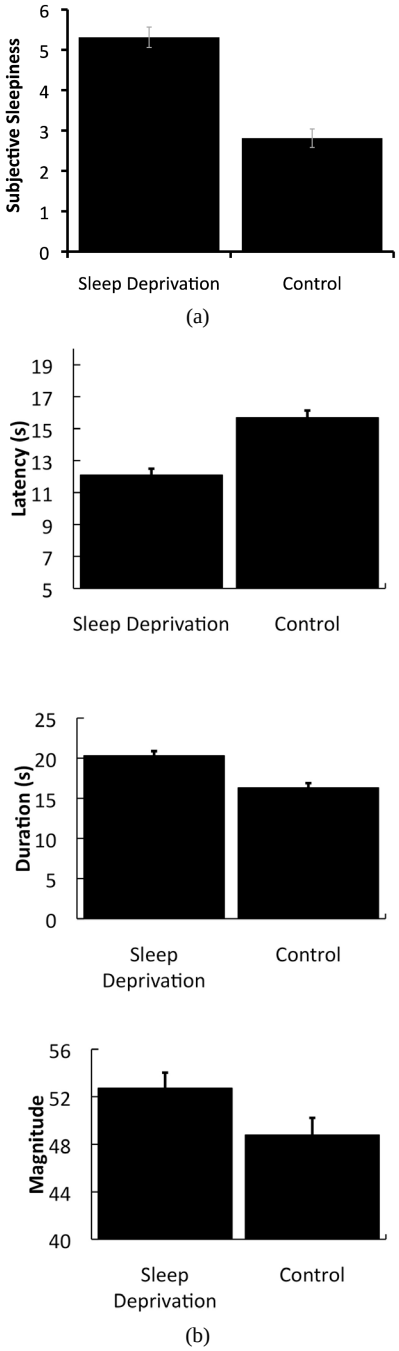

Figure 2. (a) Average subjective sleepiness for each condition (n = 16). Error bars indicate SEs; (b) The results of vection, latency, duration and magnitude of vection. Error bars indicate SEs.

stronger in the Normal-Sleep condition. T-tests revealed no significant differences at the 5%-level in latency, duration, or magnitude (latency, $t(15) = 1.73$, $p = 0.10$; duration, $t(15) = 1.65$, $p = 0.12$; magnitude, $t(15) = 0.77$, $p = 0.45$) (for individual data, please see supplemental **Figure 1**). Thus, we conclude that 20-hour sleep deprivation does not have any significant effect on vection strength.

We conducted correlation analyses between all combinations of the indices and estimated sleepiness both in the Sleep-Deprivation and Normal-Sleep conditions. **Table 1** shows all the resulting r-values. We found no significant correlations between subjective sleepiness and the vection indices in the Sleep-Deprivation condition

Table 1. R-values for the correlations between the three vection indices and sleepiness.

Sleep Deprivation				
	Latency	Duration	Magnitude	Sleepiness
Latency	1			
Duration	−0.50720146*	1		
Magnitude	−0.465429114**	0.559030502*	1	
Sleepiness	−0.222236603 ns	0.055204164 ns	−0.171743897 ns	1
Control				
	Latency	Duration	Magnitude	Sleepiness
Latency	1			
Duration	−0.780338044**	1		
Magnitude	−0.60993589*	0.813463902**	1	
Sleepiness	−0.579339748*	0.518186291*	0.308305333 ns	1

*5% significance, **10% level tendency, ns, Not significant.

(latency, r = 0.22, p = 0.40; duration, r = 0.05, p = 0.83; magnitude, r = −0.17, p = 0.52). In contrast, we found that sleepiness significantly correlated with latency (r = −0.57, p = 0.01) and duration (r = 0.51, p = 0.03) in the Normal-Sleep condition, but not with magnitude (r = 0.30, p = 0.24). **Figure 3** shows the results of these correlations. Sleepiness and vection strength were correlated only in the normal sleep condition. We obtained significant correlations only for latency and duration but not for magnitude. This discrepancy across these three vection indices has been repeatedly reported in other studies [58], and suggests that the effect of sleepiness on vection was not as strong as stimulus properties such as depth and size of vection stimuli.

In the Sleep-Deprivation condition, sleepiness was not found to be significantly correlated with any of the three vection indices. We thought this might be related to a ceiling effect because the average sleepiness value was 5.31 ± 1.046, out of a maximum value of 7. Thus, in this condition there might not have been a sufficiently wide range of sleepiness. To account for this artifact, we should set several degrees of sleep deprivation (e.g., 5-, 10-, 15-, 20-, 25-, and 30-hour deprivation) in the next set of experiments. This approach will allow us to obtain gradual changes in sleepiness and the respective effects on vection modulation. Additionally, other indices such as the degree of fatigue and physiological measurements such as heart rate, body temperature, and the degree of body sway would have been useful and should be included in future studies.

Here we present two findings. First, vection was not affected by 20-hour sleep deprivation. This corresponds to Hypothesis 2 and with the fact that vection has been shown not to change according to our circadian rhythms. Second, when we are sleepy, some vection parameters can be enhanced if sleepiness is within a normal range and not a result of extensive deprivation. These two findings are quite new and important for vection research.

Because the literature suggested several ways that sleep deprivation would inhibit vection, we favored Hypothesis 3 and thought that vection would be weaker in the Sleep-Deprivation condition. We predicted that sleep deprivation would decrease attention and function as a kind of stress for the participants. If these were the case, vection would be inhibited because it requires attentional resources [43] [44] and because stress can inhibit vection [39] [40]. Additionally, Hypothesis 1 predicted that vection would increase when sleep deprivation decreased postural control [30] [31]. However, there was no effect of sleep deprivation on vection strength. This result coincides with Hypothesis 2, which incorporated the idea that vection is not affected by circadian rhythms [35].

Three possible artifacts may explain why sleep deprivation had no effect on vection. First, the degree of sleep deprivation (20 hours) might not be long enough for modulating vection. Employing much longer (30- or even 40-hour) sleep deprivation might yield an effect that was not possible in this study. Second, the sample size might have been too small for detecting the effects of sleep deprivation. **Figure 2** shows some tendency of vection enhancement in the sleep deprivation condition, however for some participants the effect was the opposite. Thus, if we included 30 or more participants, the statistics might reveal a significant result, rather than a ten-

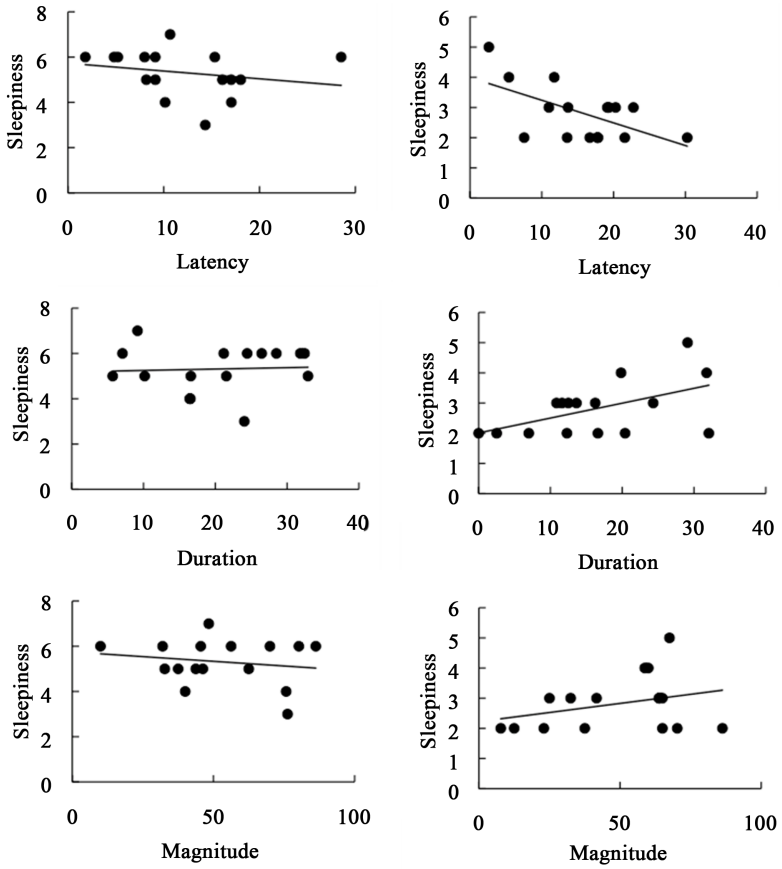

Figure 3. Scatter plots showing subjective sleepiness vs. vection latency, duration, and magnitude and the correlation r-values. (Left row) Sleep-Deprivation condition; (Right row) Normal-Sleep condition.

dency. Third, the individual differences in tolerance to sleep deprivation might be so large that the individual differences in changes in vection would also be too large for the statistics to resolve. The best solution for these possible artifacts is to set several degrees of sleep deprivation as described above and include more participants in future.

Finally, we should note here that in this experiment, measurement was carried out at 10:00 am, approximately one hour after waking up in the control condition. However, some participants felt sleepy at this time despite their sleep schedule having been controlled before the start of the experiment. This surprisingly large amount of individual difference in sleepiness in the control condition might be one of the reasons why we failed to find a significant effect of sleep deprivation. It is known that there are circadian variations in sleepiness and cognitive functions [60] and that these circadian variations can be influenced by a person's chronotype (morning type vs. evening type) [61]. Controlling for the chronotype of the participants should therefore be considered in future studies.

Another limitation in this study was that we could not recruit female participants. We have previously reported no sex-based difference in vection [62]. Thus, we thought that the results of this study could be expanded to include female participants. However, this does not solve problem created by this limitation. All aspects of the next experiment should be repeated on different days and include a complimentary number of female participants. In this way we will be able to examine whether the correlation between vection and sleepiness can be generalized to all people.

A further limitation is that we could not separate the effect of fatigue from the effect of sleepiness. Indeed, fatigue could be the largest artifact in our experiment. This possible artifact should be further examined in the next stage.

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Supplemental Materials

Supplementary **Figure 1**.
Individual Data for the three indices of vection strength.
Each color indicates a different participant.