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Effects of within-day intervals on adaptation to visually induced motion sickness in a virtual-reality motorcycling simulator

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This study investigated the effects of the time interval between virtual reality (VR) sessions on visually induced motion sickness (VIMS) reduction to better understand adaptation to and recovery from a nauseating VR experience. The participants experienced two 6-min VR sessions of a first-person motorcycle ride through a head-mounted display with (1) a 6-min interval, (2) an interval until the VIMS score reached zero, and (3) a 60-min interval. The results showed that for each condition, VIMS in the second session was aggravated, unchanged, or attenuated, respectively, indicating that additional resting time was necessary for VIMS adaptation. This study suggests that a certain type of multisensory learning attenuates VIMS symptoms within a relatively short time, requiring at least 20 min of additional resting time after subjective recovery from VIMS symptoms. This finding has important implications for reducing the time interval between repeated challenges when adapting to nauseating stimuli during VR experiences.

Keywords Virtual reality, Simulator sickness, Motion sickness, Adaptation, Multisensory learning

Visually induced motion sickness (VIMS), which includes cyber, virtual reality (VR), and simulator sickness, impedes the VR experience and has attracted growing attention with the recent development and spread of VR technologies. VIMS is characterised by various symptoms, such as drowsiness, dizziness, fatigue, cold sweats, headaches, nausea, stomach discomfort, pallor, and vomiting[1–3]. VIMS research has identified several factors that exacerbate the condition[4–6], as well as effective means to eradicate it without compromising the realism and immersion of the VR experience[7–12]. In addition, adaptation, which refers to a long-lasting decrease in participants' susceptibility[13], induced by repeated exposure to nauseating stimuli, has been shown to effectively reduce the severity of motion sickness symptoms[13–16].

While previous studies have shown that adaptation effects increase with the number of exposures[14–16], the interval duration is also important for adaptation. Domeyer et al.[17] investigated the effect of multiple sessions of driving simulation on reducing VIMS. They showed that a two-day interval between sessions decreased VIMS in the second trial, compared with VIMS without an interval before the second trial. Reinhard et al[13] conducted a similar experiment, in which participants experienced a driving simulator twice in the first session and four times in the second session of the experiment, with a one-week interval between the sessions. The results showed that participants experienced less severe VIMS symptoms in the second session than in the first session, whereas the symptoms increased between simulations experienced within a session. Howarth and Hodder[14] investigated the effect of interval duration on adaptation, using one- to seven-day intervals, and showed significant adaptation effects in all intervals over ten sessions. These studies indicated that an interval of at least one day after the first exposure would induce adaptation to the nauseating stimuli, which would suppress the aggravation of VIMS in the following sessions.

According to sensory conflict theory[1,10,18], the reduction in VIMS through repetition can be interpreted as sensorimotor/multisensory learning[19]. Consistent with the results of the VIMS studies described above, other

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studies have shown the crucial effects of interval duration between trials on sensorimotor learning[20–22]. Sensorimotor learning is a process in which coordinated body movements are acquired and developed by updating an internal model that integrates various types of information, such as motor commands, sensory feedback, and sensory predictions. This process requires time for memory consolidation[23–28]. The reduction of VIMS, with an interval longer than one day, can be achieved by a process similar to sensorimotor learning, in which actual sensory feedback and sensory memory (or prediction) are reconciled, as sensory conflict theory assumes[1,10,18,19].

However, the duration of multisensory learning, in response to nauseating stimuli, remains unclear. While the positive effects of time intervals longer than one day on adaptation to the stimuli have been established, the effects of time intervals of less than one day have not been extensively investigated. This is likely due to the problem specific to VIMS—unlike other sensorimotor learning situations, carry-over symptoms from the first session could hinder adaptation to VIMS in subsequent sessions and even interfere with multisensory learning. Thus, this study aimed to determine the minimum time interval required to induce adaptation to a VR stimulus by focusing on short time intervals within a day. To consider the effect of carry-over symptoms or the recovery process on VIMS in the second VR exposure, we continuously evaluated participants' VIMS during the interval after the first VR exposure. This evaluation delineates the time course of recovery from VIMS, which studies have rarely investigated[29]. Golding and Stott[29] suggested that recovery in cases of subjective sickness is faster than in scenarios that involve body rotation, but the process of recovery from VIMS is still unclear. Understanding this process is particularly relevant in practice, as it effectively determines the minimum time interval required between VR sessions to avoid aggravating VIMS symptoms in the rechallenge.

The experiment comprised two 6-min VR sessions with three types of intervals: (1) 6-min interval, (2) the time required for the VIMS score to reach zero (hereinafter known as 'personalised interval'), and (3) 60-min interval. The first condition was implemented to equalise the duration of the VR experience and the interval between sessions. The second condition was introduced to examine the possibility of carry-over VIMS symptoms from the first session aggravating the VIMS in the second session, and whether adaptation occurred over a relatively short time period. The third condition tested whether extra time was required for adaptation after VIMS symptoms subsided. Based on a study that reported a discrepancy between subjective sickness rating and motion tolerance performance[29], we hypothesised that participants in the second condition (personalised interval), in which the second session started immediately after participants completed the subjective recovery from VIMS, would not show adaptation, whereas those in the third condition (with extra resting time) would show adaptation. We predicted that VIMS would worsen in the first condition (6-min interval), as Reinhard et al.[13] reported increased levels of VIMS symptoms among participants in the 5-min interval group. In addition, we hypothesised that the recovery time, which is related to the time spent on memory consolidation in the third condition, would be negatively correlated with the reduction in VIMS.

Materials and methods

Participants

In total, 60 healthy university students participated in this study. Participants were randomly divided across three equal condition groups: (1) 20 in the 6-min interval condition (7 females and 13 males; Mean age = 21.5), (2) 20 in the personalised interval condition (5 females and 15 males; Mean age = 20.4), and (3) 20 in the 60-min group (4 females and 16 males; Mean age = 21.3). All participants were recruited via a university mailing list. They had no signs of sickness, sleep problems, or sensory motor problems, and provided written informed consent before the study. Before the main experiment, participants were asked to complete the Motion Sickness Susceptibility Questionnaire (MSSQ)[30] and Simulator Sickness Questionnaire (SSQ)[31], the results of which, along with other demographic factors that could influence the severity of VIMS, are shown in S1, S2, and S3, respectively. However, only the MSSQ data were used as a covariate in the analysis. Individuals with SSQ scores of more than 20, who were not in a suitable condition for the experiment, did not participate in the experiment. Individuals who did not experience any VIMS in the first VR session were excluded from the analyses. The numbers of analysed participants were 17, 15, and 17 for the 6-min, personalised, and 60-min interval groups, respectively. The study was approved by the Ethics Committee of Shizuoka University (No. 18–14) and was conducted in accordance with the approved guidelines and regulations.

VR presentation device and stimuli

The experimental setup and VR stimulus used in this study were almost identical to those used in the no-AV (audiovisual) condition by Sawada et al.[10] Participants viewed a visual stimulus, without any sound or vibrations, through an Oculus Rift S HMD (Facebook Technologies, LLC., USA) while seated on a scooter chassis and holding on to the handgrips (Fig. 1a). The HMD projected a motorcycle driving scene, controlled by Unity software (5.4.0b19, Unity Technologies, https://unity.com/), with a visual resolution of 2560 × 1440 and a field of view of 115°. The refresh rate of the display was 80 Hz. The visual stimulus simulated a driving scene, along a winding road, from a first-person perspective (Fig. 1b), and was repeated seamlessly during the VR session (see an example of the stimulus in the Supplementary Material). Participants did not control the motorcycle in the VR scene; however, the head-tracking system was turned on, allowing participants' view to change according to their head movements. Further details regarding the experimental setup and stimulus can be found in Sawada et al.[10] As the study was conducted during the COVID-19 pandemic, participants wore masks, and the room was ventilated using a fan, while avoiding direct airflow to the participants.

Motion sickness measure

The participants verbally reported a self-rating VIMS score in the Fast Motion Sickness (FMS) scale[32], which they accessed through the word 'Answer' in the centre of the display. On the FMS scale, 0 indicates no sickness, and

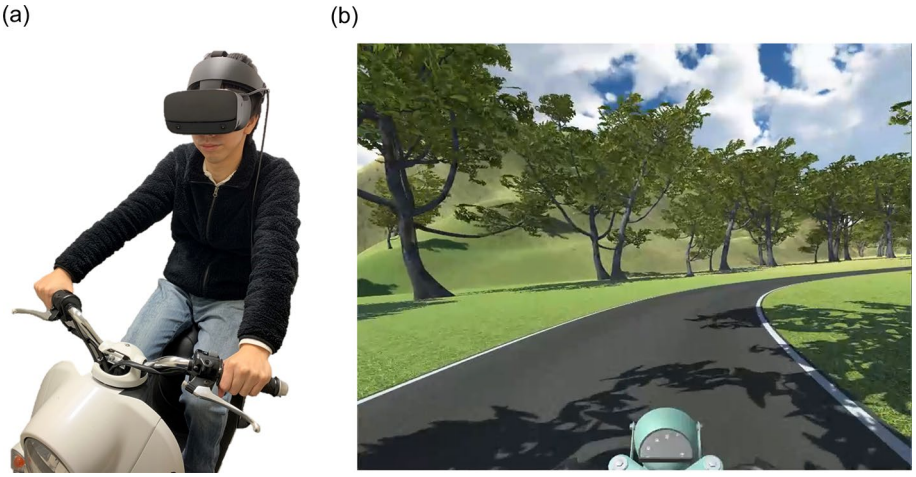

Fig. 1. (**a**) Experimental setup; (**b**) the virtual reality stimulus (motorcycle driving scene) that participants viewed though a head-mounted display. The individual in the 1a is one of the co-authors who provided informed consent to publish the image.

20 indicates frank sickness. Sawada et al.[10] showed that a 5-min presentation of a VR stimulus, without engine sounds or vibrations, induced moderate VIMS, as reflected by an average FMS score of 8.1 ($SD = 6.4$). During the intervals between VR sessions and the phase after the second VR session, sound cues were provided to alert participants to rate their VIMS on the FMS scale. All participants appropriately reported on FMS during the VR sessions and intervals.

Study design

All interval groups experienced a six-minute VR session twice with variable intervals. During the intervals, participants were asked to remain calm, relax, and engage in gentle activities, such as reading books; participants were not permitted to use electronic devices, as this might influence VIMS[33]. In the 6-min and 60-min interval groups, the interval length was fixed across participants, whereas in the personalised interval group, the second VR session started immediately after the participants' FMS scores returned to zero. In all conditions, the participants reported their FMS scores every 30 s during the VR sessions and for 6 min following each VR session. In addition to the first 6-min FMS reports, FMS scores were reported at 8, 10, 15, 20, 30, 40, 50, and 60 min for the 60-min interval group and every 2 min for the personalised interval group.

Statistical analyses

To examine the effects of the interval group on the FMS in the second session by considering other variables, a linear mixed effects model was used, with fixed effects for interval group, session, and trial, and an interaction effect between the interval group and session—a covariate of the MSSQ. The model included random intercepts of the participants and random slopes of the interval group. The inclusion of the random slopes of the interval group in the model improved the overall fit of the data. The model was created separately for FMS scores in the VR sessions and the 6-min resting time after the VR session through statistical analysis in Jamovi (https://www.jamovi.org/). The model was fitted using maximum likelihood estimation, and the conditional R^2 of the model was 0.75 and 0.83 for the VR sessions and the 6-min resting periods, respectively. The p-values of the fixed effects were calculated using Satterthwaite approximation. The analysis focused on the interaction effect between the interval group and session. In other words, we expected that the FMS scores in the second session would vary among different interval groups.

To test the second hypothesis that the recovery time would negatively correlate with the reduction in VIMS, we calculated the correlation coefficients between recovery time and adaptation effect. The recovery time was defined as the duration required to reach zero FMS after the first VR session and was log-transformed to ensure linearity. The adaptation effect indicated the reduction rate of the FMS score in the second VR session and was calculated as $(B - A) / B$, where A is the maximum FMS score in the second session and B is the maximum FMS score in the first session. We predicted that a negative correlation would be found in the 60-min interval group, but not in the personalised interval group, as no additional time was spared for memory consolidation before the second VR session in the latter group. Lastly, we conducted partial correlation analyses to confirm the relationship between the adaptation effect and the MSSQ score.

Results

Figure 2a–c shows the time course of the FMS in the experiments. In the personalised interval group, the participants rested until their FMS score reached zero, after which they were immediately exposed to the second VR session. Markers depicted in blue indicate the FMS scores in the first session. Duplicates of the first session scores are shown in the background of the second session markers for direct comparison. We observed

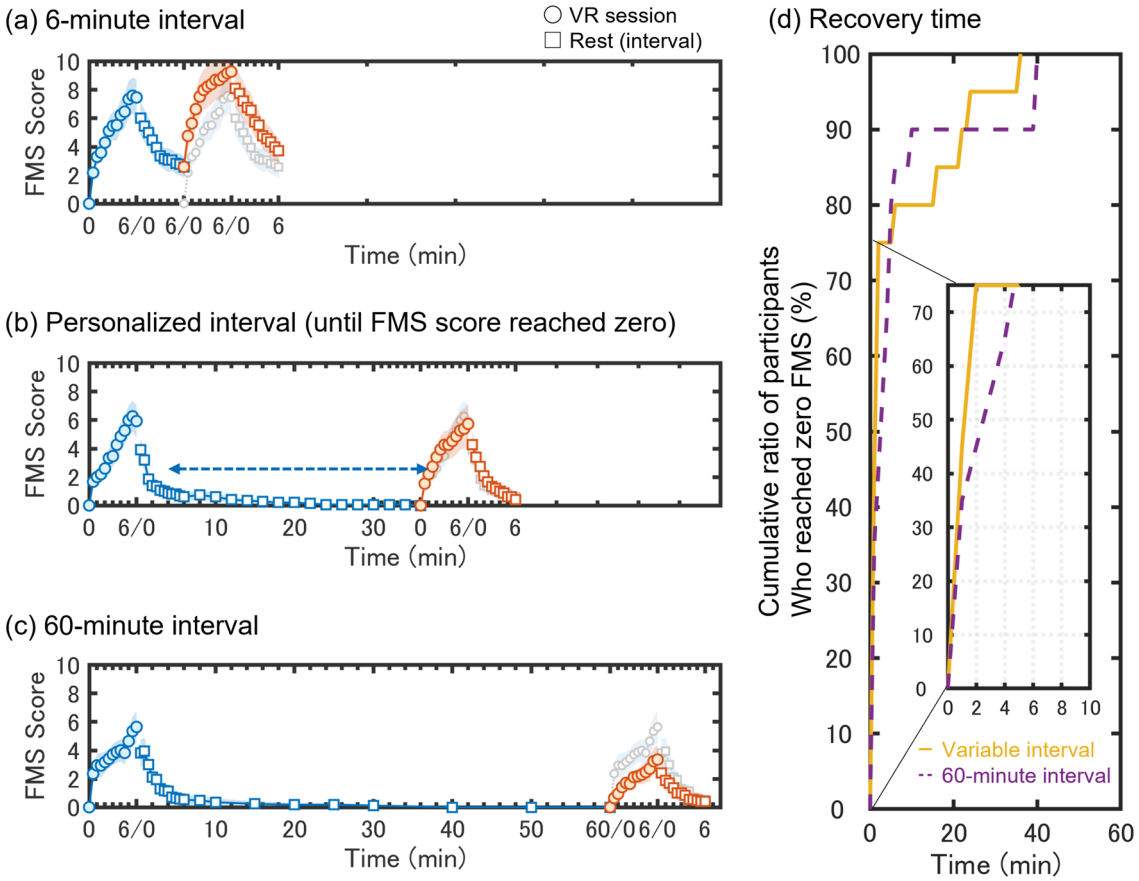

Fig. 2. (**a**–**c**) FMS scores in the three interval groups: 6-min interval (**a**), personalised interval (**b**), and 60-min interval (**c**). In the personalised interval group, participants rested until their FMS score reached zero, after which they were immediately exposed to the VR session. The depicted line is the average of participants who have an FMS score > 0 in this group. Markers depicted in blue indicate FMS scores in the first session; duplicates of the first session scores are shown in grey in the background of the second session for the sake of direct comparison. (**d**) Cumulative ratio of participants who reached zero FMS in the interval between sessions for the personalised and 60-min interval groups.

exponential decreases in FMS scores after the VR sessions in all interval groups. Figure 2d shows the cumulative ratio of participants in the personalised and 60-min interval groups, whose FMS scores reached zero (subjective full recovery) in the interval between sessions. The FMS scores of all participants in the personalised interval group reached zero at 36 min after the first VR session and at 40 min in the 60-min interval group. The average recovery time was 7.8 min ($SD = 10.8$) and 7.6 min ($SD = 12.0$) in the personalised and 60-min interval groups, respectively, and the median was 1.5 and 3.5 min, respectively. The average MSSQ scores were 46.9 ($SD = 41.7$), 47.7 ($SD = 29.9$), and 36.6 ($SD = 27.4$) in the 6-min interval, personalised interval, and 60-min interval groups, respectively. Participants' MSSQ scores were comparable to the 50th percentile of Golding's[30] younger population scores.

Using the linear mixed effects model for FMS scores in the VR sessions, the analysis showed significant fixed effects of the Interval group ($F(2,15.6) = 8.29$, $p = 0.004$), Trial ($F(11,1113.0) = 30.79$, $p < 0.001$), MSSQ ($F(1,25.8) = 44.52$, $p < 0.001$), and the interaction between the Interval group and Session ($F(2,1113.0) = 84.94$, $p < 0.001$), but not Session ($F(1,1113.0) = 3.08$, $p = 0.08$). The post-hoc comparisons using Holm's method are presented in Table 1. The most important results were as follows: (1) the FMS scores of the second session in the 6-min group were higher than those of the first session; (2) the FMS scores of the second session in the 6-min interval group were higher than those in the personalised interval and 60-min interval groups, whereas there were no significant differences in the FMS scores of the first sessions between the three groups; and (3) the FMS scores of the second session were lower than those of the first session in the 60-min interval group but not in the personalised interval group. Notably, there were no significant differences in FMS in the first VR session across groups after controlling for random effects.

Using the linear mixed effects model for FMS scores in the resting periods, the analysis showed significant fixed effects of the Interval group ($F(2,11.5) = 5.76$, $p = 0.002$), Session ($F(1,1113.0) = 30.35$, $p < 0.001$), Trial ($F(11,1113.0) = 52.72$, $p < 0.001$), MSSQ ($F(1,16.0) = 29.15$, $p < 0.001$), and the interaction between the Interval group and Session ($F(2,1113.0) = 78.97$, $p < 0.001$). The post-hoc comparisons using Holm's method are presented in Table 2. The pattern of statistical differences in the VR sessions was replicated without the FMS score of the first session in the 6-min interval group being higher than that of the second session in the 60-min interval group.

		6-min		Personalised		60-min	
		1st	2nd	1st	2nd	1st	2nd
6-min	1st	–	***	*n.s*	*n.s*	*n.s*	*
	2nd		–	*	*	**	***
Personalised	1st			–	*n.s*	*n.s*	*n.s*
	2nd				–	*n.s*	*n.s*
60-min	1st					–	***
	2nd						–

Table 1. Post-hoc comparisons of FMS scores in the VR sessions. Note that these comparisons controlled the random effects using a linear mixed effects model. ***Indicates $p < 0.001$; **indicates $p < 0.01$; * indicates $p < 0.05$; and *n.s.* indicates no significant difference between pairs.

		6-min		Personalised		60-min	
		1st	2nd	1st	2nd	1st	2nd
6-min	1st	–	***	*n.s*	*n.s*	*n.s*	*n.s*
	2nd		–	*	*	*	**
Personalised	1st			–	*n.s*	*n.s*	*n.s*
	2nd				–	*n.s*	*n.s*
60-min	1st					–	***
	2nd						–

Table 2. Post-hoc comparisons of FMS scores in the resting periods. Note that these comparisons controlled the random effects, using a linear mixed effects model. ***Indicates $p < 0.001$; **indicates $p < 0.01$; * indicates $p < 0.05$; and *n.s.* indicates no significant difference between pairs.

As in the results for the VR session, there were no significant differences in FMS in the first resting period across groups, controlling for random effects. All statistical results regarding multiple comparisons for VR sessions and resting periods are shown in the Supplementary Material (Tables S4 and S5).

Next, we examined the relationship between the log-transformed recovery time (duration required to reach zero FMS) and adaptation effect (% decrease) in the personalised interval and 60-min interval groups (Fig. 3a). While the correlation coefficient was significant in the 60-min interval group ($r = -0.68$, $t\,(15) = 3.61$, $p = 0.003$), it was not significant in the personalised interval group ($r = 0.03$, $t\,(13) = 0.10$, $p = 0.923$). To further understand the relationship between the factors, the partial correlation coefficients, using the MSSQ scores as the third variable, are presented in Table 3. The results showed that the recovery time and MSSQ scores were positively correlated in both interval groups ($pr = 0.27$ for the personalised interval group and 0.24 for the 60-min interval

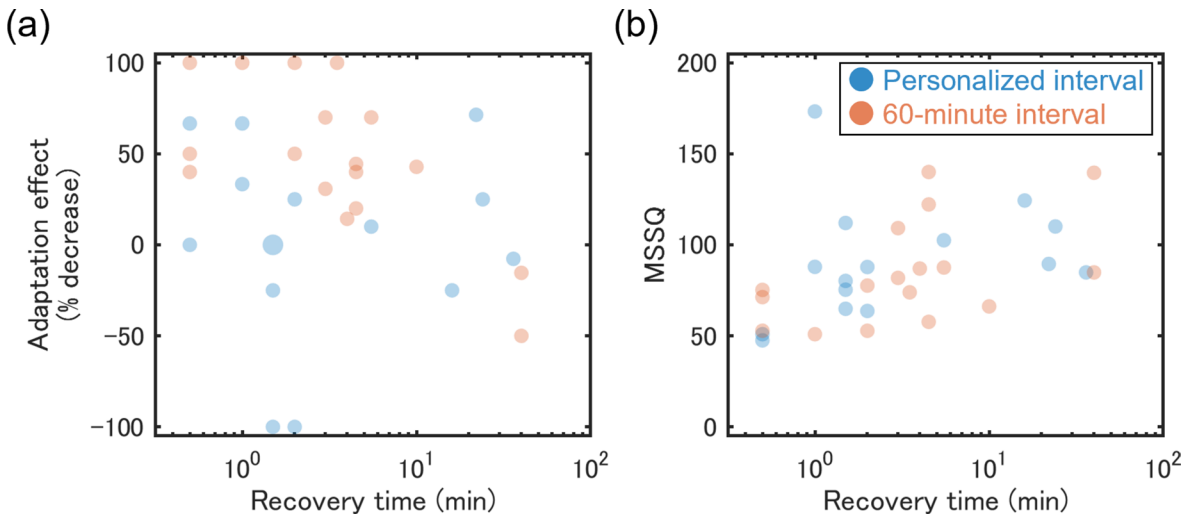

Fig. 3. The relationships between the log-transformed recovery time (minutes) and adaptation effect (% decrease) (**a**) and MSSQ (**b**). The number of plotted points is less than the number of participants because some points overlap. Marker size reflects the amount of overlapping data. Notably, in the personalised interval group, there was no extra resting time after the VIMS score reached zero.

Interval		Recovery time	Adaptation effect	MSSQ
Personalised	Recovery time	–	0.02	0.27
	Adaptation effect	–	–	0.04
	MSSQ	–		–
60-min	Recovery time	–	−0.56	0.24
	Adaptation effect	–	–	−0.30
	MSSQ	–		–

Table 3. Partial correlation coefficients between the log-transformed recovery time, the adaptation effect (% decrease), and the MSSQ score in the personalised interval and 60-min interval groups.

group). Statistical tests were not conducted in these partial correlation analyses as they were explorative. The raw relationship between the recovery time and MSSQ is shown in Fig. 3b.

Discussion

This study clearly showed that a period of additional rest is necessary after the subjective rating of VIMS has reached zero to attenuate VIMS symptoms during subsequent VR exposure. A 6-min interval between sessions aggravated the severity of VIMS symptoms in the second session; subjective recovery without extra rest neither aggravated nor attenuated them; and an additional rest period after subjective recovery successfully attenuated the symptoms. Furthermore, the time required to reach zero FMS was negatively correlated with the degree of VIMS adaptation (rate of FMS reduction) in the 60-min interval group. These results suggest that the state of sickness disrupts the multisensory learning required for VIMS adaptation, and that a healthy state is crucial for effective learning. Furthermore, our findings provide a practical standard for the resting interval required before re-exposure to nauseating VR stimuli. Specifically, a 20-min rest period, in addition to the subjective recovery time, may facilitate adaptation to such stimuli and prevent the exacerbation of VIMS symptoms.

The effect of interval length on VIMS severity in multiple experiences with the VR stimulus, observed in this study, is consistent with indications from previous research: a short interval between sessions aggravates VIMS symptoms in subsequent sessions, whereas a long interval attenuates them. Domeyer et al.[17] showed that a driving simulator with a two-day interval after the first exposure reduced VIMS symptoms more than a trial without an interval (immediate condition), although it was not reported whether participants' immediate condition induced an adaptation effect. Reinhard et al.[13] also reported an increase in VIMS symptoms when participants experienced a driving simulator twice with a 5-min interval or after the FMS score had fallen below six, whereas an interval of one to two weeks reduced VIMS severity. These reports suggest that a minute-level interval or experiencing VIMS symptoms, even if not severe, aggravates VIMS severity, whereas an interval of a day or longer induces adaptation to nauseating stimuli and reduces symptom severity. Our results are consistent with these indications but provide additional insight by confirming that the minimum time interval necessary for adaptation may be less than an hour.

The estimated minimum extra resting time required for adaptation was relatively short given the one-day interval. In the 60-min interval group, only two participants showed negative adaptation effects (FMS scores increased in the second VR session) after taking 40 min to recover from VIMS symptoms and spending an additional 20 min of rest without experiencing symptoms. The remaining participants showed positive adaptation effects. These results suggest that a resting time of over 20 min after subjective sickness recovery may be a suitable interval standard before a second VR exposure. It should be noted that an individual's susceptibility to motion sickness, conventionally measured using the MSSQ, can influence the required resting time, and a longer resting time ensures positive adaptation effects, as shown by the correlation analyses. A significant difference between this study and previous studies that used within-day intervals[13,17] is that we compared the effects of fixed and personalised duration intervals on VIMS severity and showed that a relatively short resting time adequately attenuated sickness symptoms during subsequent sessions. Future studies could further investigate the effects of multiple intervals (more than two) on adaptation and determine the number of times individuals must be exposed to nauseating stimuli to achieve perfect adaptation.

According to sensory conflict theory[1,10,18], a certain type of multisensory learning may occur during the interval between sessions, when the subjective sickness score is zero or small. Sensorimotor learning requires memory consolidation[34,35], which is sometimes referred to as 'offline learning'[21,24,28,36,37], in addition to repetitive practice itself. Repetitive practice establishes or updates an internal model, which is a model of the external world and highlights the relationships among sensory signals (from reafference and exafference) and motor commands[38–40]. The model can cancel both reafference and exafference by providing inhibitory signals to a system that induces motion sickness when the prediction (or memory) from the model matches the sensory afferences[19]. Carriot et al.[41] found vestibular neurons in macaques that respond only to passive motion (exafference) but not to active motion that can be anticipated (reafference). These 'sensory conflict neurons' may receive cancelling signals from the internal model[19,42]. Regarding the physiological role of time interval after a VR experience for updating an internal model, synaptic consolidation occurs within the first minutes to hours after learning, whereas system consolidation takes days[43,44]. Synaptic consolidation, which may be relevant for multisensory learning to reduce motion sickness, involves physiological changes such as long-term synaptic potentiation[45] and protein synthesis[46]. Regarding sensorimotor learning, Shadmehr et al.[26,33] found, using a force field paradigm,

that an approximately 6-h interval allowed participants to retain the advantage gained in the first session for the second session, even if another type of learning was introduced between the two sessions. Otherwise, distractor learning interfered with the performance in the second session. These results suggest that multisensory memory undergoes a process of consolidation, whereby an acquired internal model becomes increasingly resistant as a function of time[34]. In the general framework of multisensory conflict theory, experiencing a new multisensory correspondence, in which ongoing sensory feedback disagrees with a prediction based on sensory memory, results in sickness. However, learning new multisensory correspondences can resolve this conflict, resulting in less severe VIMS symptoms in later sessions.

The application of sensorimotor learning theory to motion sickness studies helps provide not only techniques for reducing or preventing motion sickness but also a theoretical foundation for existing techniques and understanding, thus expanding the field of research. For example, a psychological theory of memory hints at the possibility that forgetting or interfering processes may occur during the course of VIMS adaptation. Although it is unclear at what point the interfering effects become dominant, the theory predicts that the advantage of the time interval between sessions will eventually deteriorate. This idea is supported by Golding and Stott[28] who used an objective measure and reported a relapse of vulnerability to motion sickness (not VIMS) two hours after the first session. Future research should integrate motion sickness theory with sensorimotor learning theory to gain a better understanding of and enhance the processes of adaptation.

It is unclear whether the difference in adaptation effect among the experimental groups persists after days. One study showed that adaptation to motion sickness induced by optokinetic rotation was almost completely maintained for a month, and partially maintained for a year, after participants experienced extended practice until they no longer felt motion sickness[47]. In normal sensorimotor learning, the amount of practice/experience contributes to learning[22], whereas in the present study, the severity of VIMS increased in participants with a shorter interval between sessions compared to longer intervals, even though participants experienced the same amount of VR sessions. We predict that the long-term effect of the within-day adaptation effect would also be limited in participants who showed a higher severity of VIMS in the second session than in the first session, because it is likely that sensorimotor learning in the interval was hindered by VIMS—however, practice is not without effect. This possibility for the long-term effect of the within-day interval on VIMS adaptation should be explored in future studies.

Limitations and future research directions

Several limitations hinder the generalisability of our findings. First, the sample size was small, and there was not much variability concerning participants' age. Susceptibility to motion sickness decreases with age, at least after adolescence[48,49], and older adults experience more severe VIMS[7] and take longer to recover from VIMS than do younger adults[50]. Perhaps the underlying mechanisms for the occurrence and exacerbation of VIMS are not the same. To apply our finding to populations other than college students, studies with more diverse populations are needed. Second, our study used a passive rather than an active VR experience. Although we do not make any specific predictions, active interaction could lead to a shorter additional time required to mitigate the severity of motion sickness in the second session, as studies have shown that yield greater sensorimotor learning compared to passive learning in general[51–53]. These limitations do not necessarily ensure that a 60-min or additional 20-min interval will always result in VIMS reduction in the second session, and the interval required for VIMS reduction would depend on the participant characteristics, the VR environment, and the nauseating stimulus. Third, we used a simple scoring system of motion sickness but did not use a measure multidimensional questionnaire, such as the SSQ, or physiological responses to assess the severity of VIMS. Studies have proposed various measures to assess the severity of motion sickness, such as electroencephalography, electrooculography, heart rate variability, galvanic skin response, and electrocardiography[54–57], which may quantify subtle differences in adaptation effect, although the techniques are not yet complete. Finally, the lack of seat motion should be mentioned as a limitation. Motion control and the resulting inertial feedback are unavoidable when riding a motorcycle in the real world. It has been suggested that the fidelity of the motion control simulation is important in mitigating motion sickness[58]. Similarly, sensory conflict theory predicts that VR simulations lacking inertial feedback may lead to sickness due to mismatched vestibular sensory expectations.

Data availability

The datasets used and/or analysed during the study are available from the corresponding authors on reasonable request.

Code availability

The underlying code for this study is not publicly available but may be made available from the corresponding authors to qualified researchers on reasonable request.

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References

1. Oman, C. M. Motion sickness: A synthesis and evaluation of the sensory conflict theory. *Can. J. Physiol. Pharmacol.* **68**, 294–303 (1990).
2. Ebenholtz, S. M. Motion sickness and oculomotor systems in virtual environments. *Presence Teleoperators Virtual Environ.* **1**, 302–305 (1992).
3. Cobb, S. V. G. Measurement of postural stability before and after immersion in a virtual environment. *Appl. Ergon.* **30**, 47–57 (1999).

4. Munafo, J., Diedrick, M. & Stoffregen, T. A. The virtual reality head-mounted display oculus Rift induces motion sickness and is sexist in its effects. *Exp. Brain Res.* **235**, 889–901 (2017).
5. Milleville-Pennel, I. & Charron, C. Do mental workload and presence experienced when driving a real car predispose drivers to simulator sickness? An exploratory study. *Accid. Anal. Prev.* **74**, 192–202 (2015).
6. Roenker, D. L., Cissell, G. M., Ball, K. K., Wadley, V. G. & Edwards, J. D. Speed-of-processing and driving simulator training result in improved driving performance. *Hum. Factors* **45**, 218–233 (2003).
7. Brooks, J. O. *et al.* Simulator sickness during driving simulation studies. *Accid. Anal. Prev.* **42**, 788–796 (2010).
8. Grassini, S., Laumann, K., de Martin Topranin, V. & Thorp, S. Evaluating the effect of multi-sensory stimulations on simulator sickness and sense of presence during HMD-mediated VR experience. *Ergonomics* **64**, 1532–1542 (2021).
9. Keshavarz, B., Riecke, B. E., Hettinger, L. J. & Campos, J. L. Vection and visually induced motion sickness: How are they related?. *Front. Psychol.* **6**, 472 (2015).
10. Sawada, Y. *et al.* Effects of synchronised engine sound and vibration presentation on visually induced motion sickness. *Sci. Rep.* **10**, 7553 (2020).
11. Caserman, P., Garcia-Agundez, A., Gámez Zerban, A. & Göbel, S. Cybersickness in current-generation virtual reality head-mounted displays: Systematic review and outlook. *Virtual Real.* **25**, 1153–1170 (2021).
12. Keshavarz, B. & Golding, J. F. Motion sickness: Current concepts and management. *Curr. Opin. Neurol.* **35**, 107–112 (2022).
13. Reinhard, R. *et al.* The best way to assess visually induced motion sickness in a fixed-base driving simulator. *Transp. Res. F* **48**, 74–88 (2017).
14. Howarth, P. A. & Hodder, S. G. J. D. Characteristics of habituation to motion in a virtual environment. *Displays* **29**, 117–123 (2008).
15. Kennedy, R. S., Stanney, K. M. & Dunlap, W. P. Duration and exposure to virtual environments: Sickness curves during and across sessions. *Presence Teleoperators Virtual Environ.* **9**, 463–472 (2000).
16. Mackrous, I., Lavallière, M. & Teasdale, N. Adaptation to simulator sickness in older drivers following multiple sessions in a driving simulator. *Gerontechnology* **12**, 101–111 (2014).
17. Domeyer, J. E., Cassavaugh, N. D. & Backs, R. W. The use of adaptation to reduce simulator sickness in driving assessment and research. *Accid. Anal. Prev.* **53**, 127–132 (2013).
18. Reason, J. T. Motion sickness adaptation: A neural mismatch model. *J. R. Soc. Med.* **71**, 819–829 (1978).
19. Zhang, L. L. *et al.* Motion sickness: Current knowledge and recent advance. *CNS Neurosci. Ther.* **22**, 15–24 (2016).
20. Krakauer, J. W., Ghez, C. & Ghilardi, M. F. Adaptation to visuomotor transformations: Consolidation, interference, and forgetting. *J. Neurosci.* **25**, 473–478 (2005).
21. Trempe, M. & Proteau, L. Distinct consolidation outcomes in a visuomotor adaptation task: Off-line leaning and persistent after-effect. *Brain Cogn.* **73**, 135–145 (2010).
22. Yamada, C., Itaguchi, Y. & Fukuzawa, K. Effects of the amount of practice and time interval between practice sessions on the retention of internal models. *PLOS One* **14**, e0215331 (2019).
23. Criscimagna-Hemminger, S. E. & Shadmehr, R. Consolidation patterns of human motor memory. *J. Neurosci.* **28**, 9610–9618 (2008).
24. Doyon, J. *et al.* Contribution of night and day sleep versus simple passage of time to the consolidation of motor sequence and visuomotor adaptation learning. *Exp. Brain Res.* **195**, 15–26 (2009).
25. Morita, Y., Ogawa, K. & Uchida, S. The effect of a daytime 2-h nap on complex motor skill learning. *Sleep Biol. Rhythms* **10**, 302–309 (2012).
26. Pekny, S. E. & Shadmehr, R. Optimizing effort: Increased efficiency of motor memory with time away from practice. *J. Neurophysiol.* **113**, 445–454 (2015).
27. Shadmehr, R. & Brashers-Krug, T. Functional stages in the formation of human long-term motor memory. *J. Neurosci.* **17**, 409–419 (1997).
28. Walker, M. P., Brakefield, T., Morgan, A., Hobson, J. A. & Stickgold, R. Practice with sleep makes perfect: Sleep-dependent motor skill learning. *Neuron* **35**, 205–211 (2002).
29. Golding, J. F. & Stott, J. R. Objective and subjective time courses of recovery from motion sickness assessed by repeated motion challenges. *J. Vestib. Res.* **7**, 421–428 (1997).
30. Golding, J. F. Motion sickness susceptibility questionnaire revised and its relationship to other forms of sickness. *Brain Res. Bull.* **47**, 507–516 (1998).
31. Kennedy, R. S., Lane, N. E., Berbaum, K. S. & Lilienthal, M. G. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *Int. J. Aviat. Psychol.* **3**, 203–220 (1993).
32. Keshavarz, B. & Hecht, H. Validating an efficient method to quantify motion sickness. *Hum. Factors* **53**, 415–426 (2011).
33. Stoffregen, T. A., Chen, Y.-C. & Koslucher, F. C. Motion control, motion sickness, and the postural dynamics of mobile devices. *Exp. Brain Res.* **232**, 1389–1397 (2014).
34. Brashers-Krug, T., Shadmehr, R. & Bizzi, E. Consolidation in human motor memory. *Nature* **382**, 252–255 (1996).
35. Krakauer, J. W. Motor learning and consolidation: The case of visuomotor rotation. *Adv. Exp. Med. Biol.* **629**, 405–421 (2009).
36. Itaguchi, Y. & Fukuzawa, K. Influence of speed and accuracy constraints on motor learning for a trajectory-based movement. *J. Mot. Behav.* **50**, 653–663 (2018).
37. Albouy, G. *et al.* Daytime sleep enhances consolidation of the spatial but not motoric representation of motor sequence memory. *PLOS One* **8**, e52805 (2013).
38. Miall, R. C. & Wolpert, D. M. Forward models for physiological motor control. *Neural Netw.* **9**, 1265–1279 (1996).
39. Wolpert, D. M., Ghahramani, Z. & Jordan, M. I. An internal model for sensorimotor integration. *Science* **269**, 1880–1882 (1995).
40. Itaguchi, Y., Sugimori, E. & Fukuzawa, K. Schizotypal traits and forearm motor control against self-other produced action in a bimanual unloading task. *Neuropsychologia* **113**, 43–51 (2018).
41. Carriot, J., Brooks, J. X. & Cullen, K. E. Multimodal integration of self-motion cues in the vestibular system: Active versus passive translations. *J. Neurosci.* **33**, 19555–19566 (2013).
42. Cullen, K. E. Internal models of self-motion: Neural computations by the vestibular cerebellum. *Trends Neurosci.* **46**, 986–1002 (2023).
43. Dudai, Y. The neurobiology of consolidations, or, how stable is the engram?. *Annu. Rev. Psychol.* **55**, 51–86 (2004).
44. Gais, S. *et al.* Sleep transforms the cerebral trace of declarative memories. *Proc. Natl Acad. Sci. USA* **104**, 18778–18783 (2007).
45. Tetzlaff, C., Kolodziejski, C., Timme, M., Tsodyks, M. & Wörgötter, F. Synaptic scaling enables dynamically distinct short- and long-term memory formation. *PLOS Comput. Biol.* **9**, e1003307 (2013).
46. Rosenberg, T. *et al.* The roles of protein expression in synaptic plasticity and memory consolidation. *Front. Mol. Neurosci.* **7**, 86 (2014).
47. Hu, S. & Stern, R. M. The retention of adaptation to motion sickness eliciting stimulation. *Aviat. Space Environ. Med.* **70**, 766–768 (1999).
48. Paillard, A. C. *et al.* Motion sickness susceptibility in healthy subjects and vestibular patients: Effects of gender, age and trait-anxiety. *J. Vestib. Res.* **23**, 203–209 (2013).
49. Ugur, E., Konukseven, B. O., Topdag, M., Cakmakci, M. E. & Topdag, D. O. Expansion to the motion sickness susceptibility questionnaire-short form: A cross-sectional study. *J. Audiol. Otol.* **26**, 76–82 (2022).

50. Keshavarz, B., Ramkhalawansingh, R., Haycock, B., Shahab, S. & Campos, J. L. Comparing simulator sickness in younger and older adults during simulated driving under different multisensory conditions. *Transp. Res. F* **54**, 47–62 (2018).
51. Lo, H. S. & Xie, S. Q. Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects. *Med. Eng. Phys.* **34**, 261–268 (2012).
52. Lotze, M., Braun, C., Birbaumer, N., Anders, S. & Cohen, L. G. Motor learning elicited by voluntary drive. *Brain* **126**, 866–872 (2003).
53. Péruch, P. & Wilson, P. N. Active versus passive learning and testing in a complex outside built environment. *Cogn. Process.* **5**, 218–227 (2004).
54. Dennison, M. S., Wisti, A. Z. & D'Zmura, M. Use of physiological signals to predict cybersickness. *Displays* **44**, 42–52 (2016).
55. Naqvi, S. A. A. *et al.* EEG based time and frequency dynamics analysis of visually induced motion sickness (VIMS). *Australas. Phys. Eng. Sci. Med.* **38**, 721–729 (2015).
56. Sugita, N. *et al.* Evaluation of adaptation to visually induced motion sickness based on the maximum cross-correlation between pulse transmission time and heart rate. *J. Neuroeng. Rehabil.* **4**, 35 (2007).
57. Krokos, E. & Varshney, A. Quantifying VR cybersickness using EEG. *Virtual Real.* **26**, 77–89 (2022).
58. Venkatakrishnan, R. *et al.* Comparative evaluation of the effects of motion control on cybersickness in immersive virtual environments. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces. (VR)*. 672–681 (2020).

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Author contributions

All authors contributed to the design of the experiments and discussed the results. C.K., Y.Y., and M.H. conducted the experiments and performed basic data processing. Y.I. conducted statistical analyses and wrote the manuscript. M.M. supervised the project. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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