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ORIGINAL ARTICLE

Mechanism of cybersickness abatement from repeated exposure transfer between single-axis and complex motion scenarios

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Abstract
With the widespread adoption of virtual reality (VR) technology across various fields, motion sickness has become a growing concern. Prior studies suggested Cybersickness Abatement from Repeated Exposure (CARE) as a promising solution, yet CARE training typically targets only specific stimuli, its transferability and mechanisms remain unclear. This study seeks to determine whether CARE training on a single axis (pitch axis) using a TV screen can reduce visually induced motion sickness and, if so, whether this effect can be transferred to other axis movements or a rollercoaster game. Participants underwent 16-min daily pitch oscillation sessions via a 55-inch TV screen over five days. Oscillations on the yaw, roll, and pitch axes were measured pre- and post-training, alongside participants' susceptibility to a multi-axis VR roller coaster simulation via a head-mounted display. Pitch axis CARE training effectively reduced cybersickness, with significant transfer to the yaw axis but limited effects on the roll axis. The CARE effect extended from single-axis TV training to complex VR scenarios. Furthermore, the severity of motion sickness in single-axis conditions predicted cybersickness in complex VR settings. This study confirms that pitch axis training can reduce cybersickness in varied environments. The results provide valuable insight for enhancing CARE protocols for using VR technologies.

Keywords CARE training · Head-mounted display · motion sickness · Transferability · Virtual reality

1 Introduction

Prolonged exposure to large-field motion visual stimuli frequently induces motion sickness in stationary observers, a phenomenon also referred to as cybersickness or visually induced motion sickness (VIMS) Common symptoms of cybersickness include nausea, visual discomfort, and dizziness (Hettinger and Riccio 1992; Kennedy et al. 2010; Wei et al. 2024). While virtual reality (VR) technology holds significant potential for various applications (Chang et al. 2020; Tian et al. 2022), the widespread adoption of VR is substantially limited by the high prevalence of cybersickness. As a result, increasing attention has been directed towards identifying effective strategies to mitigate motion sickness (Rahimzadeh et al. 2023; Wei et al. 2018).

Numerous approaches have been developed to mitigate motion sickness, including reducing the central field of view (Adhanom et al. 2022; Al Zayer et al. 2019; Keshavarz 2016; Teixeira and Palmisano 2021; Wu & Suma Rosenberg 2022), enhancing visuospatial skills (Smyth et al. 2021), adding static visual reference frames (Hemmerich et al. 2020), and various other methods (Budhiraja et al. 2017; Clifton and Palmisano 2020; Hussain et al. 2021). However, many of these approaches have limitations, such as reduced sense of presence in virtual environments or requirements for additional setup and equipment. In contrast, repeated exposure to identical visual stimuli has been demonstrated to reduce motion sickness symptoms without those limitations, a phenomenon referred to as Cybersickness Abatement from Repeated Exposure (CARE) (I. Adhanom et al. 2022; Doty et al. 2024; Howarth and Hodder 2008; Hussain et al. 2021;

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Kelly et al. 2025; Pöhlmann et al. 2024). Although some studies describe this effect as habituation or adaptation, we adopt the term CARE to maintain theoretical neutrality and avoid implying a specific mechanism.

1.1 Why might repeated exposure reduce cybersickness?

Sensory conflict theory (Reason 1978; Reason and Brand 1975) suggests that motion sickness occurs when external sensory inputs (e.g., vision, vestibular, proprioception) conflict with the brain's internal model. When such conflict is primarily induced by visual motion, the condition is often referred to as visually induced motion sickness (VIMS) or, in virtual environments without real physical movement, as cybersickness. The present study adopts the term cybersickness, as it employs purely screen-based visual motion stimuli in the absence of vestibular input. With repeated exposure to the same visual stimuli, the internal model can gradually adapt, reducing the sensory conflict and potentially alleviating cybersickness (Koch et al. 2018; Rahimzadeh et al. 2023).

Another potential explanation pertains to behavioral adaptation (Palmisano and ConsTable 2022; Reason 1978). Prolonged exposure to visual motion stimulation may lead to short-term adaptation in visual perception. This adaptation could reduce the user's perceived visual motion intensity, thereby alleviating cybersickness (Palmisano and ConsTable 2022; Solomon and Kohn 2014).

1.2 Transfer of CARE

CARE typically requires considerable time and effort (Hill and Howarth 2000; Takata et al. 2021), and its effectiveness may be restricted to specific stimuli. The principles and mechanisms behind the transfer of CARE to different situations remain unclear, and this lack of understanding limits the broader application of CARE interventions.

Previous research investigating CARE transfer has yielded mixed results. For example, Palmisano et al. found that CARE effects from head-mounted displays (HMDs) in VR might be stimulus-specific, with limited transferability to other environments (Palmisano and ConsTable 2022). Some research has found that individuals who frequently play video games experience less motion sickness when exposed to provocative stimuli, suggesting that their adaptation may transfer from gaming environments to experimental settings. The study also found that gamers exhibited less cybersickness in VR environments and proposed that 2D gaming may help establish a protective habituation effect on 3D environment (Pöhlmann et al. 2022, 2024). Similarly, Adhanom et al. demonstrated that CARE to abstract optic flow could transfer from a virtual environment to the real world (I. Adhanom et al. 2022). Also, Kelly et al. found that CARE could generalize across experiences (Kelly et al. 2025). However, these studies have not explored how transferability is influenced by variations in stimuli. Moreover, in existing studies, various motion types (yaw, roll, pitch axes, and translational movements), complexities of motion (single-axis vs. multi-axis motion), and display devices (traditional screens vs. HMDs) have been employed (Bonato et al. 2009; Chen et al. 2016). However, the individual impacts of these variables on the transfer effects have not been separately analyzed (I. Adhanom et al. 2022; Palmisano and ConsTable 2022).

According to sensory conflict theory (Reason 1978; Reason and Brand 1975), it is believed that the human nervous system can learn patterns of visual information. When new visual stimuli resemble previously learned patterns, the internal model can be updated accordingly. (Koch et al. 2018; Rahimzadeh et al. 2023; Reason 1978; Reason and Brand 1975). Therefore, the effectiveness of the transfer effect is anticipated to depend on the level of similarity between the training and test environments. However, empirical research has not provided a clear exploration of how to precisely define similarity and which variables might significantly impact similarity.

1.3 Objective and hypothesis

A deeper comprehension of CARE transfer mechanisms is motivated by both theoretical and practical perspectives. Theoretically, the three axes are the foundation for decomposing complex motion stimuli and analyzing differences between various types of motion. Therefore, testing whether CARE effects can transfer across axes provides a benchmark for evaluating the potential transferability across different scenarios. From a practical perspective, if CARE achieved through traditional screens can effectively transfer to VR in HMD, which typically induces stronger symptoms (Naqvi et al. 2013; Solimini 2013), this would offer users a more comfortable pathway to develop motion tolerance before experiencing more intense VR content.

Prior research has demonstrated that motion sickness severity exhibits a hierarchical pattern across rotational axes, with pitch-axis motion eliciting the most pronounced symptoms, followed by roll and yaw axes in descending order of symptom intensity (Yang and Pei 1991). To optimize potential transfer effects and establish an effective CARE protocol, we selected pitch-axis motion as the primary training stimulus in order to examine whether pitch motion pattern could produce broad transfer effects and facilitate generalization to virtual environments in HMD. This study examines the impact of different axes (pitch,

yaw, roll) and different display types (traditional screens vs. HMDs) on CARE transfer effects. Specifically, we investigate: (1) whether CARE to pitch-axis oscillation motion can transfer to yaw and roll axes, and (2) whether CARE to a single axis on a traditional display can transfer to complex, multi-degree-of-freedom motion in immersive VR environments using HMDs. We hypothesize the following:

H1 The transfer effects of CARE to pitch motion vary across motion axes.

H2 CARE to single-axis motion on a TV screen can successfully transfer to an HMD.

H3 Susceptibility to single-axis motion indicates susceptibility to complex motion in an HMD.

2 Method

2.1 Participants

Before the experiment, participants were screened using the Motion Sickness Susceptibility Questionnaire (MSSQ-short, Golding, 1998) to evaluate their susceptibility to motion sickness. A total of 27 participants were enrolled following the provision of informed consent. These participants were randomly allocated to either the Control group (n = 12) or the Training group (n = 15) (see Table 1 for demographic specifics). One participant in the Control group withdrew from the study for personal reasons. Twenty-six participants (age: 22.58 ± 3.32 years; male/female: 14/12) completed this study.

All participants were right-handed and had normal vision of 20/20 or wore corrective lenses. All participants reported maintaining good sleep quality without the use of medication throughout the study. They were instructed to abstain from alcohol and caffeine-containing beverages for 10 h before experiments. None of the participants had a history of cardiovascular disease, neurological disorders, or vestibular impairments. Participants were compensated with 50 Chinese Yuan per hour for their involvement in the study. The study adhered to the ethical requirements of the Shenzhen University Research Ethics Committee and was in accordance with the Helsinki Declaration. Approval for the study was obtained from the Shenzhen University Human Participants Research Group.

Table 1 Demographics of participants

	Training Group (M, SE)	Control Group (M, SE)	P
N	15	11	
Gender (% male)	46.7%	63.6%	
Age (years)	23.07 (0.85)	21.91 (1.03)	0.2556
MSSQ score	22.91 (2.58)	23.31 (2.71)	0.9898
MSSQ total score	76.91 (5.67)	79.03 (5.92)	0.9898

MSSQ Motion Sickness Susceptibility Questionnaire. Data were analyzed using the Mann–Whitney U non-parametric test, with Exact Sig. $P < 0.05$ is considered statistically significant. This analysis was conducted due to the small sample size, ensuring a more accurate assessment of significance

2.2 Materials and equipment

2.2.1 Single-axis oscillation stimuli

A 55-inch TV screen (122.6 × 71.3 cm; FOV: 98.8° × 61.44°) was utilized to present the single-axis visual stimuli under three conditions. Participants sat at a viewing distance of 60 cm. The white dots of random size (pixel: 5–20) were displayed at random positions over the entire screen (Wei et al. 2024) and oscillated with an amplitude of 300 pixels at a frequency of 0.2 Hz following a sinusoidal function (Diels and Howarth 2013). Yaw stimulus consisted of horizontally oscillating dots rotating around yaw axis, simulating lateral movement (see Fig. 1b). Roll stimulus involved dots rotating around a central axis, creating a rotational motion effect (see Fig. 1c). Pitch stimulus featured dots oscillating vertically, simulating an up-and-down movement (see Fig. 1d). The duration was 8 min (Keshavarz et al. 2019). The participants were instructed to rest their heads on a chin support and fix their gaze on a red cross in the center of the screen (FOV: 1.42° × 1.42°). To reduce visual distractions, we turned off all the lights and draped a large black curtain over the TV and the participants. The screen's brightness varied from 0.015 lm/m^2 at the center to 0.070 lm/m^2 at the edges, with a brightness of 13.805 lm/m^2 at the moving dots and 2.740 lm/m^2 at the fixation point. All stimuli were programmed in MATLAB using Psychtoolbox-3 extensions (Brainard 1997; Pelli 1997).

2.2.2 Complex motion stimuli

A head-mounted display (Oculus Quest 2) was utilized to present the complex visual stimulus. The Oculus Quest 2 HMD, equipped with an LCD screen (FOV: 89° × 93), provided a resolution of 1832 × 1920 pixels per eye, and a refresh rate of 90 Hz. The participants were instructed to rest their heads on a chin support and watch the stimulus "Epic Roller Coaster", which is commonly used in research (Benelli et al. 2023; Laessoe et al. 2023; Palmisano and ConsTable 2022). The game includes various types of maps; the classic "Rock Fall" mode was selected as the stimulus (see Fig. 1a). The stimulus included 4 yaw rotations with a mean angle of 107.3°, 4 roll rotations with a mean angle of 210.0°, and 6 pitch rotations with a mean angle of 133.1°.

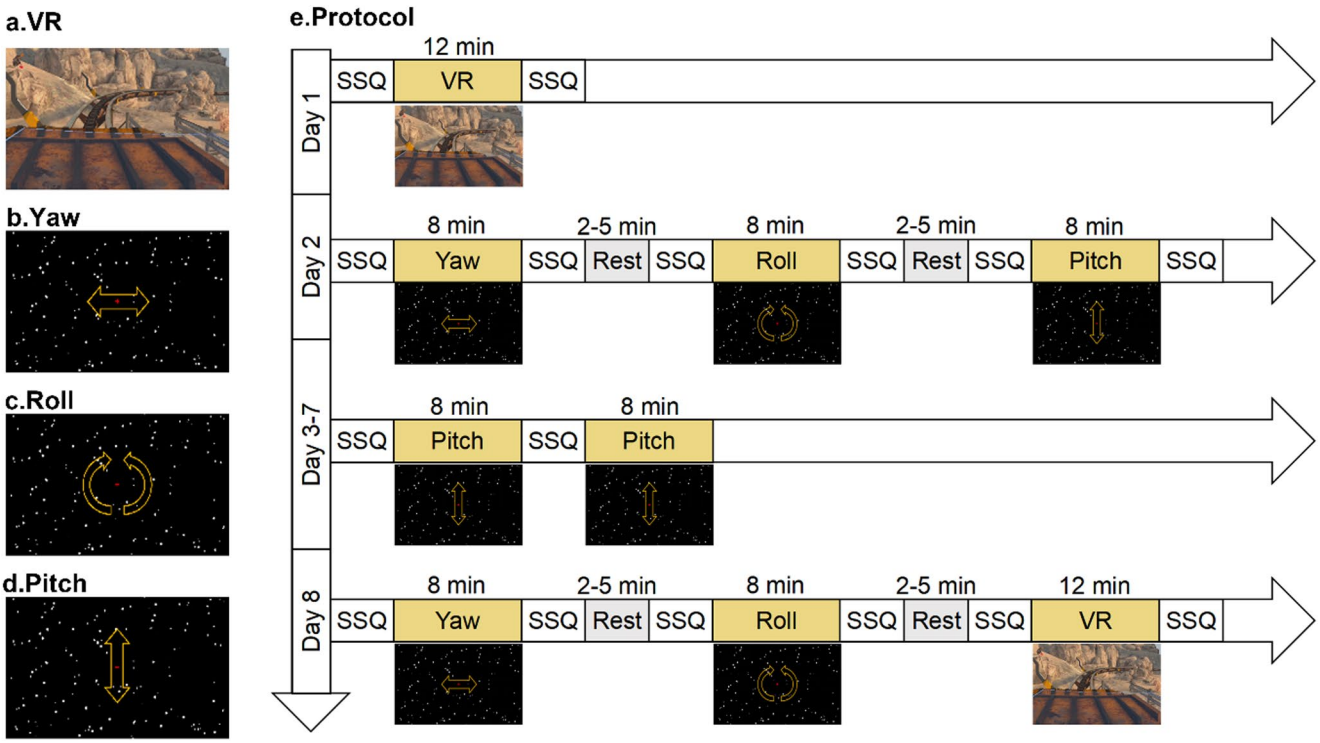

Fig. 1 Experimental procedure for the Training group. SSQ: Simulator Sickness Questionnaire. The rest section usually lasted 2–5 min **a** VR roller coaster stimulus. **b** Yaw stimulus **c** Roll stimulus **d** Pitch stimulus **e** Protocol of Training group

The duration was 3 min and 50 s. To ensure participants experienced motion sickness, it was repeated three times in succession. The total duration was 11 min and 30 s, which is sufficient to induce cybersickness based on previous work (Cobb et al. 1999; Kim et al. 2005).

2.2.3 Cybersickness measures

Cybersickness levels were measured using the Simulator Sickness Questionnaire (SSQ), which evaluates 16 symptoms across three dimensions: nausea, oculomotor disturbances, and disorientation (Carnegie and Rhee 2015; Davis et al. 2014; Kennedy et al. 1993; Lim et al. 2021). Prior studies have shown that SSQ scores tend to increase following exposure to cybersickness-inducing stimuli (Golding et al. 2021; Jasper et al. 2020; Lim et al. 2021).

The Fast Motion Sickness Scale (FMS) was used to assess real-time symptom severity, with scores ranging from 0 ("no discomfort") to 20 ("severe discomfort"). The FMS is another reliable measure for motion sickness and is faster because participants verbally report scores rather than writing them down (Keshavarz et al. 2011). It allows for a continuous measure of cybersickness throughout the experience. During the experiment, participants verbally reported their FMS scores at one-minute intervals. To ensure that participants were exposed to approximately the same duration of stimulation while preventing symptom severity from leading to dropout, if their FMS score exceeded 15, participants were instructed to close their eyes and rest until the FMS score dropped below 15. In the Training Group, three participants closed their eyes on Day 1, whereas in the Control Group one participant did so on Day 1 and again on Day 8. This protocol was specifically applied to the screen-based stimulus sessions only. To avoid cumulative effects, we inquired about their FMS score at one-minute intervals before starting the next set of experimental stimuli. The next trial would only proceed when the participant reported scores below 2 on two consecutive reports.

Multiple regression analyses were conducted. We use FMS scores and SSQ scores Before-training session in three axes to investigate the predictors of SSQ scores in VR. And we use SSQ changes between After- and Before-training sessions of Training group to investigate the predictors of SSQ score change in VR using SPSS version 27.0.

2.3 Design and procedure

2.3.1 Experiment design

A two-factor mixed design was employed. The between-subject independent variable was CARE training (Training group vs. Control group), and the within-subject variable was time (Before-training vs. After-training). Two dependent variables were: (1) scores from the Simulator Sickness

Questionnaire (SSQ) collected post-motion exposure, and (2) average of Fast Motion Sickness Scale (FMS) scores collected throughout the stimulus presentation period.

2.3.2 Experimental procedure

On Days 1 and 2, both the Training Group and the Control Group followed the same protocol. On Day 1, participants signed consent forms and familiarized themselves with the head-mounted display (HMD, Oculus Quest 2). Afterward, they wore the HMD and watched an 11-min and 30-s roller coaster simulation ("Epic Roller Coaster"). SSQ scores were recorded Before- and After-training exposure to assess their susceptibility to cybersickness. To alleviate any discomfort from the VR experience, participants were given time to rest before leaving the lab.

On Day 2, participants returned to the lab and reviewed the FMS scoring system. They were then exposed to three single-axis oscillation motion stimuli (fixed as yaw, roll, and pitch) on a TV screen. We scheduled the more provocative stimuli later to reduce the risk of participants experiencing severe discomfort early on and dropping out before completing all testing sessions (Feng et al. 2025). Each stimulus block lasted 8 min, and participants verbally reported their FMS scores at one-minute intervals. Rest periods of 2 to 5 min were provided between each block, and SSQ scores were recorded before and after each block to assess the cybersickness induced by each stimulus.

From Day 3 to Day 7, the Training Group underwent five consecutive days of pitch-axis CARE training. Each day, participants viewed two consecutive pitch-axis motion blocks, each lasting 8 min, while reporting their FMS scores at one-minute intervals. SSQ scores were recorded before and after the first block, and participants proceeded to the second block without a rest period. On Day 8, the Training Group viewed three motion stimuli: yaw, roll (each 8 min), and the roller coaster simulation (11 min and 30 s). Rest intervals of 2 to 5 min were provided between stimuli, tailored to individual needs. Both SSQ and FMS scores were recorded throughout the session to assess the transfer effects of CARE training (see Fig. 1e). While previous work has shown no significant difference in cybersickness levels between the sixth and seventh exposures (Howarth and Hodder 2008), the pitch simulation in Day 8 was omitted for the Training Group due to economic considerations.

The Control Group followed a protocol similar to the Training Group on Days 1 and 2, but did not undergo the CARE training. On Day 8, the Control Group participants viewed four stimuli: yaw, roll, pitch (each 8 min), and the roller coaster simulation (11 min and 30 s). Rest intervals of 2 to 5 min were provided between each stimulus, as needed, and SSQ and FMS scores were recorded before and after each block. This allowed for the comparison of the transfer effects of CARE training between the two groups.

3 Results

3.1 Pitch axis training effects

To examine the effectiveness of CARE training on the pitch axis, we conducted within-group comparisons for both the Training and Control groups. For the Training group, a one-way repeated measures ANOVA revealed a significant effect of training days [$F(5, 70) = 14.44$, $p < 0.001$]. FMS scores decreased progressively from Day 2 ($M = 6.92$, $SD = 4.48$) through Day 7 ($M = 3.02$, $SD = 2.32$). Bonferroni post-hoc comparisons showed significant reductions from Day 2 to Day 7 [$t = 7.351$, $p < 0.001$], from Day 3 ($M = 5.21$, $SD = 3.42$) to Day 7 [$t = 4.138$, $p < 0.001$], and from Day 4 ($M = 4.59$, $SD = 3.37$) to Day 7 [$t = 2.957$, $p < 0.05$], indicating progressive CARE throughout the training period. No significant were found form Day 5($M = 4.02$, $SD = 2.99$) to Day 7 [$t = 1.876$, $p = 0.3244$] and Day 6($M = 3.33$, $SD = 2.64$) to Day 7 [$t = 0.5934$, $p > 0.9999$].

A paired t-test between Control group and Training group in Day 2 revealed no significant difference [$p = 0.4351$]. For the Control group, a paired t-test between Day 2 ($M = 7.21$, $SD = 20.06$) and Day 8 ($M = 5.96$, $SD = 1.89$) revealed no significant reduction [$p = 0.1283$]. These results demonstrate that repeated exposure training effectively reduced motion sickness susceptibility on the pitch axis (see Fig. 2a for the progression of CARE training across days and Fig. 2b for the final training effects).

As for SSQ, the results exhibited a consistent trend with FMS results; however, the interaction effect did not reach statistical significance (see Appendix I0.1).

3.2 Transfer effects of single-axis motion

The two-factor ANOVA analysis was performed for the yaw and roll axes. The results showed a significant interaction effect between group and time on the yaw axis [$F(1, 24) = 10.53$, $p = 0.0034$]. Moreover, the follow-up comparisons with Bonferroni correction showed a significant difference in FMS scores Before- ($M = 6.38$, $SD = 3.56$) and After-training ($M = 4.32$, $SD = 2.78$) for the Training group [$p < 0.001$], while the Control group showed no significant difference between the tests on Day 2 ($M = 5.47$, $SD = 2.15$) and Day 8 ($M = 5.29$, $SD = 1.74$) [$p > 0.9999$]. The analysis showed a significant main effect of time, reflecting the effect of repeated exposure to the stimulus [$F(1, 24) = 15.97$, $p = 0.0007$]. The main effect of group was not significant [$F(1, 24) = 0.001$, $p = 0.9696$]. And simple effect analysis

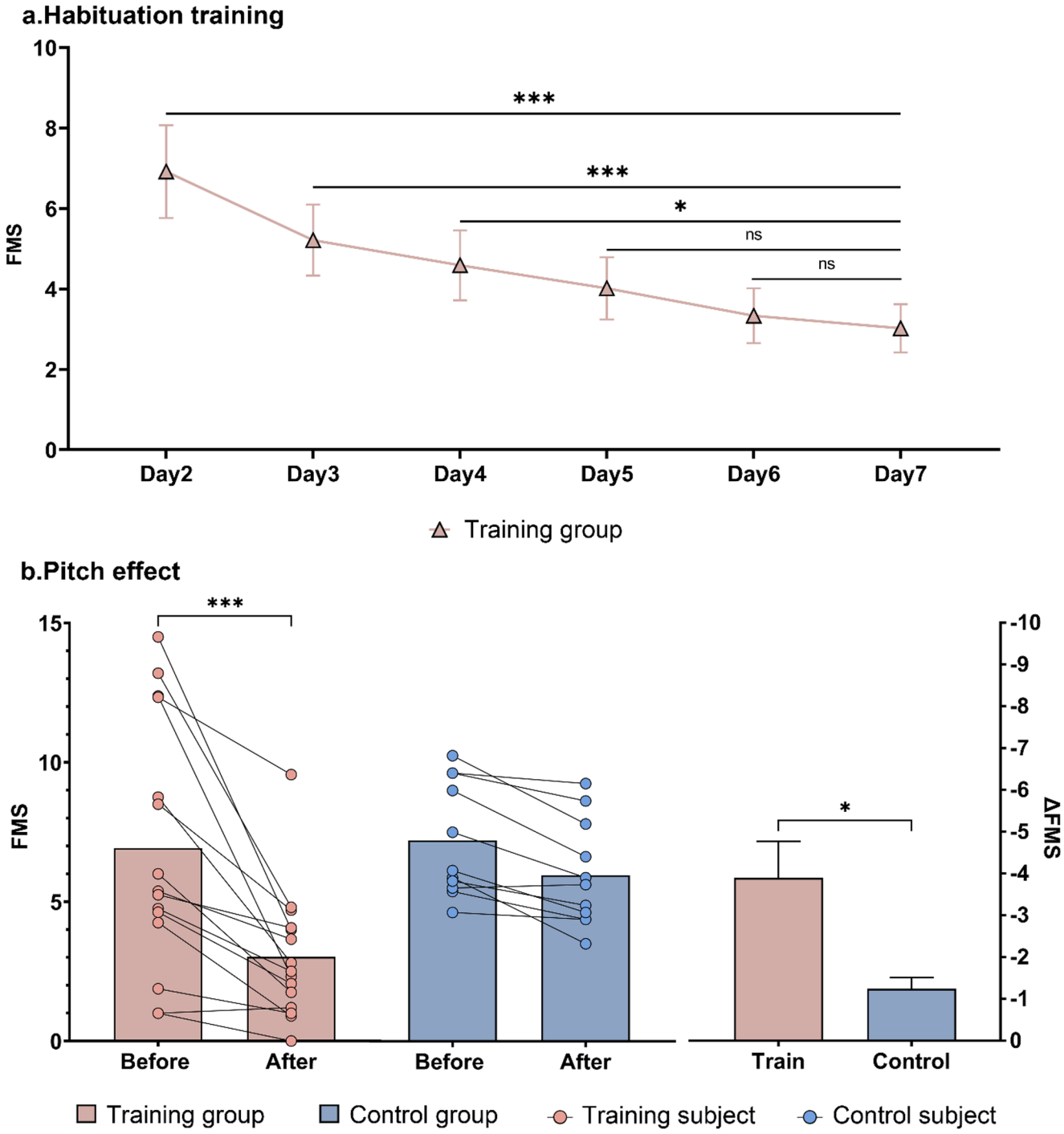

Fig. 2 Experimental procedure for the Training group. *$p<0.05$, ***$p<0.001$. FMS: Fast Motion Sickness score. ΔFMS: difference of FMS score between After and Before-training session (after minus before). Before represents the score Before-training, while After represents the score After-training. **a** FMS scores trend on the pitch axis; **b** Single-axis training effects. The red bars represent Training group results, blue bars represent Control group results. Red dots refer to subjects in the Training group, blue dots refer to subjects in the Control group

validated that there were no significant differences between groups in the tests conducted before training ($p=0.4820$). In summary, this finding suggested that CARE training on the pitch axis successfully transferred to the yaw axis, with the transfer effect being significantly greater than the effect of a single repeated exposure to the stimulus alone (refer to Fig. 3a).

For the roll axis, the interaction effect between group and time was not significant [$F(1, 24)=1.666$, $p=0.2091$]. However, the results of comparisons with Bonferroni correction showed a significant difference in FMS scores Before- ($M=5.74$, $SD=4.01$) and After-training ($M=3.95$, $SD=3.19$) for the Training group [$p=0.0006$], while the Control group showed no significant difference between the tests on Day 2 ($M=6.56$, $SD=2.31$) and Day 8 ($M=5.61$,

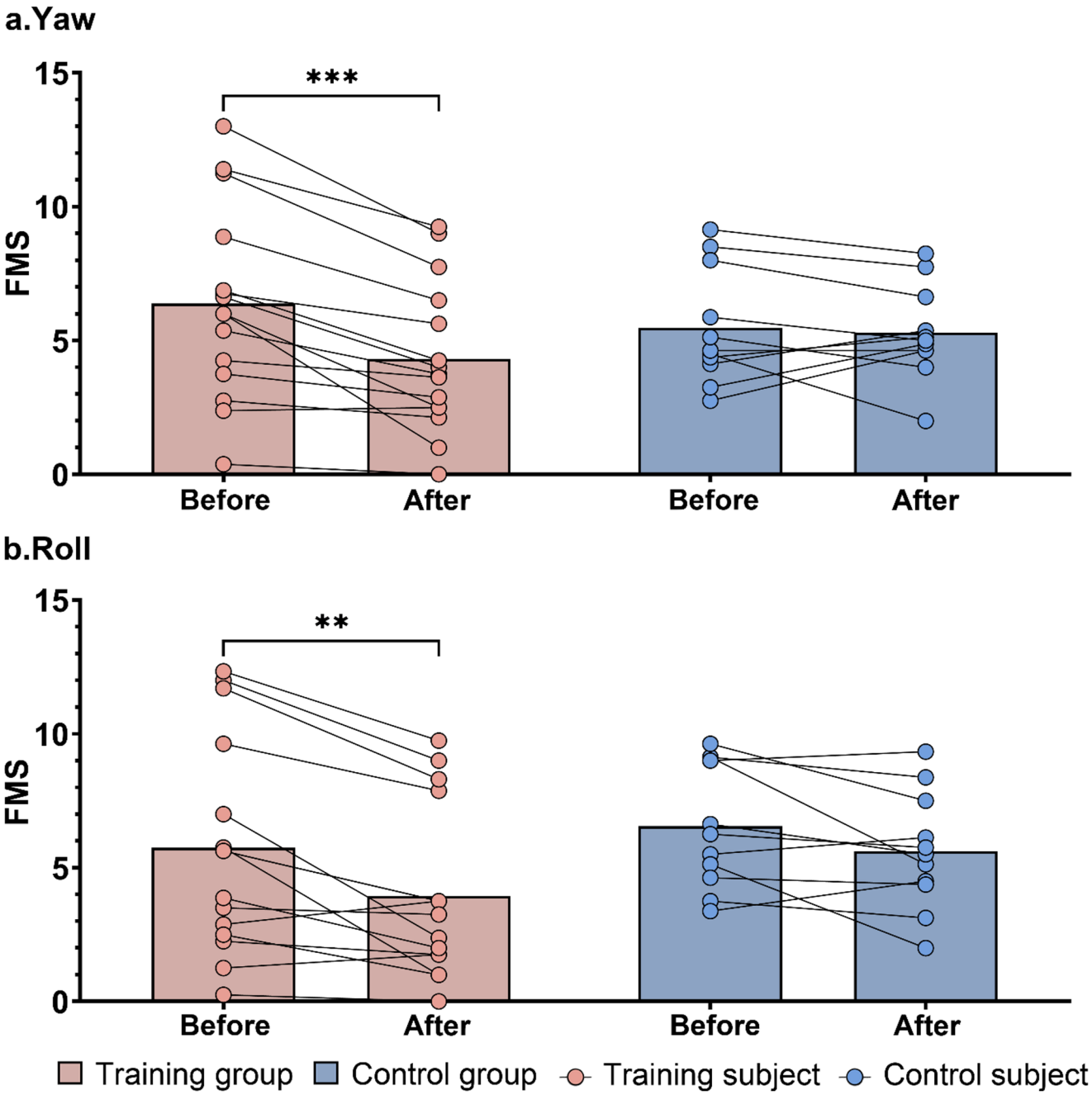

Fig. 3 Transfer effect of yaw and roll axes. $^{**}p<0.01$, $^{***}p<0.001$. FMS: Fast Motion Sickness score. Before represents the score Before-training, while After represents the score After-training. **a** Transfer effects of yaw axis motion; **b** Transfer effects of roll axis motion. The red bars represent Training group results, blue bars represent Control group results. Red dots refer to subjects in the Training group, blue dots refer to subjects in the Control group

SD = 2.18) ($p > 0.1369$). Similarly, the analysis revealed a significant main effect of time [F(1, 24) = 17.54, $p = 0.0003$]. The main effect of group was not significant [F(1, 24) = 1.065, $p = 0.3125$]. Simple effect analysis validated that there were no significant differences between groups in the tests conducted before training ($p = 0.5147$). In summary, this finding suggests that the pitch axis CARE training also has a certain transfer effect to the roll axis, but the transfer effect was not significantly greater than the effect of a single repeated exposure to the stimulus alone (see Fig. 3b).

3.3 Transfer effects between display devices

For the VR experience, the same two-factor ANOVA was used. The results showed a significant interaction effect between group and time [F(1, 24) = 5.574, $p = 0.0267$]. Further comparisons with Bonferroni correction showed a significant difference in SSQ scores Before- (M = 52.35, SD = 7.80) and After- training (M = 22.51, SD = 5.50) for the Training group [$p = 0.0009$], while the Control group showed no significant difference between the tests on Day 1 (M = 32.03, SD = 7.28) and Day 8 (M = 28.88, SD = 8.56) [$p > 0.9999$]. The result showed a significant main effect of time [F(1, 24) = 8.513, $p = 0.0075$]. The main effect of group was not significant [F(1, 24) = 0.6364, $p = 0.4328$]. This indicates that CARE training on the pitch axis on the TV screen had successfully transferred to the complex motion in the VR environment (see Fig. 4).

Similarly, the analysis showed a significant main effect of time [F(1, 24) = 8.513, $p = 0.0075$], and the simple effect analysis validated that there were no significant differences between groups in the tests conducted before training [F(1, 24) = 1.065, $p = 0.3125$]. We also conducted analyses on the subscales of SSQ, and a significant interaction effect in the Oculomotor subscale was found (see Appendix I0.2).

3.4 Predictive effects of single-axis on VR

Multiple regression analysis results show that. In the model 1, using average FMS scores during the first exposure to screen stimuli (FMS-Y, FMS-R, FMS-P) of both groups, the model was significant, F(3,22) = 4.763, $p = 0.010$, $R^2 = 0.394$. Although FMS-P approached significance ($\beta = 0.616$, $p = 0.075$), none of the predictors reached statistical significance individually, and moderate multicollinearity was detected (FMS-P VIF = 3.955) (see Table 2).

In the model 2 using SSQ Before- training session in three axes (SSQ-Y, SSQ-R, SSQ-P) of both groups, the regression was significant, F(3,22) = 9.033, $p < 0.001$, explaining 55.2% of the variance in SSQ-VR. Notably, SSQ-Y significantly predicted the outcome ($\beta = 0.754$, $p = 0.013$), while other predictors were not significant. Nonetheless, this model exhibited high multicollinearity, with VIF values for SSQ-R (VIF = 10.315) and SSQ-P (VIF = 6.045) (see Table 2).

In the model 3, three predictors, SSQ changes between After- and Before- training session (ΔSSQ-Y, ΔSSQ-R, ΔSSQ-P) of Training group were entered,

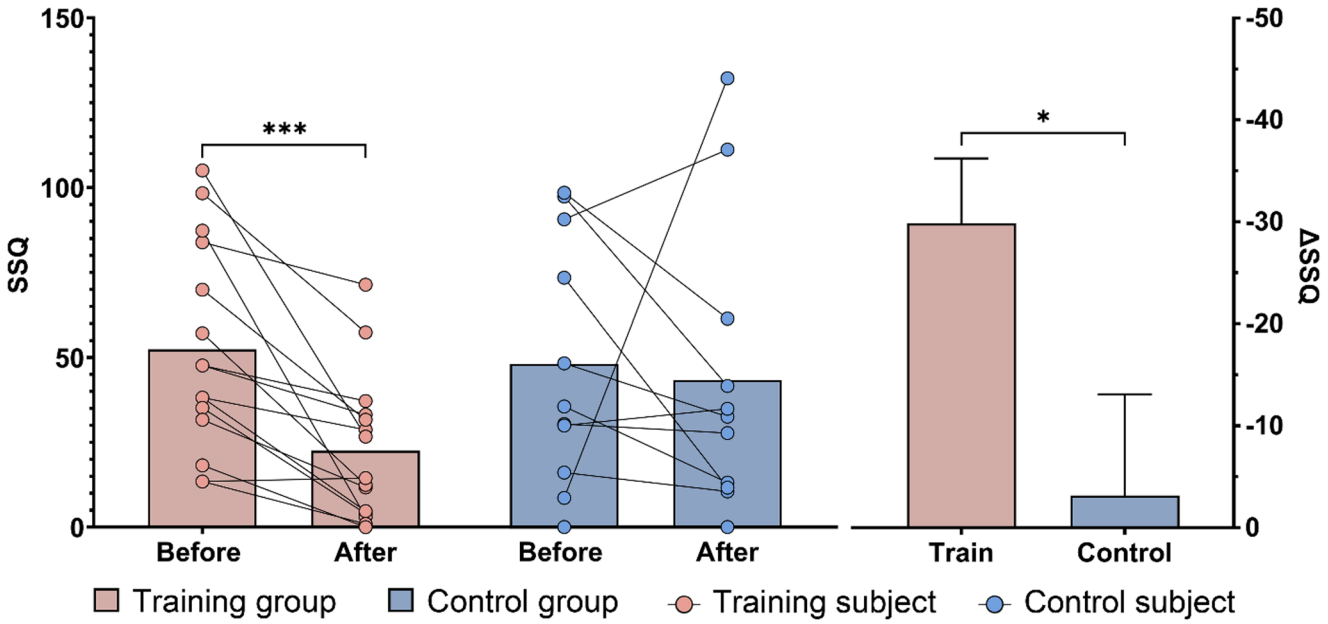

Fig. 4 SSQ scores of VR experience for participants. *$p < 0.05$, ***$p < 0.001$. SSQ: Simulator Sickness Questionnaire score. ΔSSQ: difference of SSQ score between after and before training session (after minus before). Before represents the score Before-training, while After represents the score After-training. The red bars represent Training group results, blue bars represent Control group results. Red dots refer to subjects in the Training group, blue dots refer to subjects in the Control group

Table 2 Multiple regression analysis of motion sickness score

Model	Predictors	R^2	F	p	Sig. Predictors (β, p)	Max VIF
1	FMS-Y, FMS-R, FMS-P	0.394	4.763	0.010	None (FMS-P marginal, 0.075)	4.406
2	SSQ-Y, SSQ-R, SSQ-P	0.552	9.033	< 0.001	SSQ-Y (0.754, 0.013)	10.315
3	ΔSSQ-Y, ΔSSQ-R, ΔSSQ-P	0.521	6.083	0.011	ΔSSQ-R (0.571, 0.017)	1.845

FMS-Y, FMS-R, and FMS-P stand for average FMS score while first time watching yaw, roll, and pitch stimuli, respectively. SSQ-Y, SSQ-R, SSQ-P, and SSQ-VR stand for SSQ score after watching yaw, roll, pitch, and VR stimuli for the first time, respectively. ΔSSQ-Y, ΔSSQ-R, ΔSSQ-P, and ΔSSQ-VR stand for changes in SSQ score between two times watching yaw, roll, pitch, and VR stimuli of Training group, respectively. A multiple regression model showed that ΔSSQ-R was a significant predictor of ΔSSQ-VR

yielding a significant model, $F(3,11) = 6.083$, $p = 0.011$, with $R^2 = 0.521$, indicating that 52.1% of the variance in SSQ-VR was explained. Among the predictors, ΔSSQ-R approached significance ($\beta = 0.571$, $p = 0.017$). VIF values for ΔSSQ-Y (VIF = 1.744) and ΔSSQ-P (VIF = 1.845) (see Table 2). Overall, these findings suggest that the subjective symptom score changes, particularly in the roll axis, are probably predictors of SSQ change in VR. Regression models using the ΔFMS were also tested, but their predictive power for VR SSQ scores was inferior to models using ΔSSQ (see Appendix I0.3).

4 Discussion

This study investigated the transferability of CARE training across different motion axes and display devices, yielding several key findings on the transfer mechanism of CARE training.

4.1 Cross-axis and cross-display transfer mechanisms

Our study reveals a notable decrease in cybersickness after CARE training on the pitch axis among participants. This effect was significantly transferred to the yaw axis. However, for the roll axis, the transfer effect was not as significant, showing individual differences. This aligns with previous research on CARE training by Howarth and Hodder (2008) and Hill and Howarth (2000), as well as the findings of Adhanom et al. (2022). Overall, this means that CARE effects are potentially transferable between environments under specific circumstances. Our research is the first to analyze this transferability between axes specifically, finding that the transfer from pitch to yaw proves more effective than to the roll axis. It is worth noting that the SSQ focuses on different aspects and is less sensitive compared to the FMS, which may explain the non-significant results. In future VR applications, FMS prompts could appear as brief visual cues within the headset or as mapped controller inputs to capture real-time cybersickness ratings without breaking immersion. Such integration would enable continuous monitoring of cybersickness during complex, realistic tasks and support adaptive interventions based on user feedback.

Moreover, we further clarify the transfer mechanism by showing that CARE effects can also transfer across devices, specifically from TV screens to HMDs. This is consistent with previous findings (Adhanom et al. 2022). It is noteworthy that in terms of effect size, the transfer effects for complex motion in VR are greater than independent cross-axis transfers. The likely reason is that complex motion includes components from the pitch axis, and the CARE training on the pitch axis has the most significant effect in alleviating cybersickness sensitivity. Further results also suggest that the susceptibility of the pitch axis can effectively predict the severity of motion sickness in VR (see Sect. 4.3 for details).

Our results show that the effect of repeated exposure to the same visual stimulus on reducing cybersickness could transfer to other axis movements or roller coaster game. This provides new evidence for sensory conflict theory, suggesting that exposure enhances the brain's general ability to resolve sensory mismatches rather than just adapting to specific patterns. Our findings also indicate that visual adaptation alone cannot fully explain cybersickness reduction, as the transfer to untrained stimuli extends beyond stimulus-specific adaptation.

4.2 Predict VR susceptibility with single-axis data

Considering both explanatory power and collinearity model indices, Model 3 performed the best. Which used the SSQ changes between the After- and Before-training sessions of the Training group to investigate predictors of SSQ score changes. Among the three axes, the roll condition demonstrated the strongest predictive effect, suggesting that improvement in the roll condition may predict improvement in the VR segment. This is probably because roll is the most common type of sustained rotation experienced by humans (Keshavarz et al. 2019). And it has relatively larger rotation angles of Roll in the video compared to the other axes.

Compared to the duration of training in previous studies, such as 20 h (Takata et al. 2021), 135 min (Stern et al. 1989), and 100 min (Hill and Howarth 2000) the training duration in this study was significantly shorter (16 min) but still yielded significant CARE effects. This result is noteworthy

as it suggests that by designing a relatively short, single-axis CARE training program, individuals can still effectively reduce the occurrence of motion sickness under different axes and screen conditions. This provides new directions and ideas for developing more convenient and time-efficient CARE programs for practical applications. In particular, for frequent VR users, early intervention training with mild motion stimuli could effectively prevent more severe cybersickness symptoms.

4.3 Implications

Our findings demonstrate that CARE training with 2D displays can effectively transfer to HMD VR environments, significantly reducing cybersickness symptoms. This protocol has substantial practical applications across multiple domains. For the VR industry, this approach could help more people use VR by reducing cybersickness. VR developers could prepare training using 2D displays as 'onboarding experiences' before users transition to VR environments, potentially increasing user retention and satisfaction. For VR users, implementing brief CARE training sessions before engaging with gaming, educational, or medical VR applications could substantially improve comfort and extend possible usage duration, as these fields often require sustained VR engagement that may be limited by cybersickness symptoms in susceptible individuals. By enabling virtually anyone to use VR with reduced discomfort, these training protocols could expand the accessibility and effectiveness of VR technology across numerous application domains.

4.4 Limitations and future directions

Although this study yielded some important findings, several limitations remain, which provide avenues for improvement in future research. First, this study primarily focused on CARE training for the pitch axis and its transfer effects, with little exploration of CARE and transfer effects for other axes (such as the roll axis). Future studies delving into the transfer effects on other axes will contribute to a more comprehensive understanding of the transfer mechanism of CARE training. However, VR experiences include lateral forward motion that can induce cybersickness differently than rotational stimuli, so pure rotational CARE training may only partially generalize to such motion patterns. Future investigations should explore mixed-axis CARE protocols to optimize adaptation across diverse VR motion patterns.

Secondly, the experimental design of this study mainly focused on observing short-term CARE effects, without thoroughly examining the long-term stability of these effects. Although CARE was successfully achieved within a relatively short period in this study, it is unknown how long the effects last. Future research involving the extended tracking of participants over longer time scales will be beneficial in assessing the durability and stability of CARE training.

Thirdly, the stimulus presentation order was fixed as yaw–roll–pitch (increasing likelihood of cybersickness) (Feng et al. 2025), because we aimed to prevent participants from experiencing the more nauseating conditions first, which could lead to early withdrawal. We implemented several measures to minimize its impact. Participants were given sufficient time to rest until participants reported FMS scores ≤ 2 for two consecutive assessments. We also conducted validations, confirming that there were no significant differences in pre-SSQ scores (Training group: 6.51 ± 3.3; Control group: 4.92 ± 1.5; $p = 0.49$). And pre-SSQ scores were not significantly correlated with post-SSQ scores. The validation indicated that there was no evidence of accumulated fatigue or symptom-related correlations. Notably, the differences in susceptibility across axes were not significant, which is consistent with the findings of Lo and So (2001) but inconsistent with Yang and Pei (1991). However, potential order effects may still exist. The fixed order protocol used in this study may introduce undetected order effects; therefore, it should be cautious when direct comparing susceptibility and training effects values across different axes in the current work. Future studies can investigate this through other approaches.

Besides, the roller coaster exposure emphasized ecological validity. Since sound is typically present during regular gameplay, we retained the audio of the video game to closely match the real-world experience. Therefore, continuous FMS recording was not conducted during VR exposure to avoid interfering with the sense of immersion. In future studies, we may explore alternative methods to collect FMS scores while preserving the immersive experience.

Lastly, in designing the CARE training program, this study employed a uniform training intensity and duration, without fully accounting for individual differences. Participants of different sensitivity types exhibited significant variation in CARE effects, highlighting the importance of personalized training. It is worth noting that participants showed varying susceptibility across different axes, and that training and transfer effects differed by participant type on each axis (see Appendix I.4). Further research is needed to confirm this finding with a larger sample size.

Future research aimed at developing more effective, personalized CARE training programs based on participants' sensitivity types and individual characteristics will help maximize training outcomes.

5 Conclusion

Aiming at investigating CARE transfer mechanisms across axes and display devices, we controlled axis and display variables. Findings indicate that training on the pitch axis exhibits varying transfer effects on different axes, with strong transfer to the yaw axis and limited impact on the roll axis. The single-axis pitch training can transfer to multi-axis motion environments, including complex VR scenarios. Moreover, individual susceptibility differences across axes significantly impact transfer effectiveness, with sensitivity to motion on the yaw axis playing a significant role. Results support the development of personalized CARE training protocols tailored to individual sensitivities. Further research could explore transfer effects across additional axes and the long-term stability of CARE, enhancing its potential applications.

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Author contributions Chen Xinjia conducted the experiments. Both Chen Xinjia and Wei Yue contributed to the experimental design, procedures, methods, and wrote the main manuscript text and prepared Figs. 1, 2, 3, 4 and 5. Professor Richard H.Y. So provided resources and research methods, and revised the manuscript. All authors reviewed the manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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