Reductions in sickness with repeated exposure to HMD-based virtual reality appear to be game-specific

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Abstract

While head-mounted display (HMD) based gaming is often limited by cybersickness, research suggests that repeated exposure to virtual reality (VR) can reduce the severity of these symptoms. This study was therefore aimed at: (1) examining the exposure conditions required to reduce cybersickness during HMD VR; and (2) learning whether such reductions generalise from one HMD VR game to another. Our participants played two commercially-available HMD VR video games over two consecutive days. Their first exposure to HMD VR on both days was always to a 15-min virtual rollercoaster ride. On Day 1, half of our participants also played a virtual climbing game for 15-min, while the rest of them finished testing early. Participants in the latter group were only exposed to the climbing game late on Day 2. We found that sickness was significantly reduced for our participants on their second exposure to the virtual rollercoaster. However, sickness to the rollercoaster on Day 2 was unaffected by whether they had played the climbing game on Day 1. Sickness during virtual climbing was also unaffected by group differences in exposure to the virtual rollercoaster. This convergent evidence suggested that the reductions in cybersickness produced by repeated exposure to HMD VR were *game-specific*. While these benefits did not generalise to the second game, two 15-min exposures to the *same* HMD VR game was sufficient to significantly reduce cybersickness in this study.

Keywords Motion sickness · Cybersickness · Vection · Virtual reality · Head-mounted display · Computer games

1 Introduction

Head-mounted display (HMD) based virtual reality (VR) clearly has enormous potential. This is demonstrated by the host of applications already developed for its use. HMD VR applications have now been created for a wide variety of vocational, educational and recreational purposes, ranging from immersive home gaming and engineering design to simulation training and virtual tourism (e.g. Beck and Egger 2018; Bernardo 2017; Bharathi and Tucker 2015; Fineschi and Pozzebon 2015; Grabowski and Jankowski 2015; Jensen and Konradsen 2018; Yildirim 2020).

Unfortunately, cybersickness continues to limit the use of HMD VR (e.g. Biocca 1992; Clifton and Palmisano 2020; Draper et al. 2001; Patterson et al. 2006; Merhi et al. 2007; Munafo et al. 2017; Sharples et al. 2008; Lawson 2014;

Palmisano et al. 2017; Rebenitsch and Owen 2016, 2021; Risi and Palmisano 2019; Stanney et al. 1998; Teixeira and Palmisano 2021; Weech et al. 2018). The symptoms of this cybersickness are often similar to sickness experienced during real-world vehicular motions (such as air sickness, sea sickness, or car sickness – Cha et al. 2021). Commonly reported symptoms of cybersickness include increased sweating, dizziness and disorientation, nausea and stomach awareness, burping, as well as headaches and eyestrain (e.g. Arcioni et al. 2019; Bonato et al. 2009; Clifton and Palmisano 2020; Palmisano et al. 2017, 2019; Risi and Palmisano 2019; Teixeira and Palmisano 2021). While most participants recover soon after exposure to HMD VR, cybersickness can persist in some cases for hours (see also Stanney and Kennedy 1998 and Rebenitsch and Owen 2016).

Of the many potential uses of HMD VR, first-person immersive gaming appears to be particularly provocative for cybersickness (especially when it involves virtual navigation through the game's environment). Research has found that sickness is more common and severe with HMDs than when playing games on a desktop monitor or TV. For

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example, Yildirim (2020) reported that significant sickness was common after only 6-min playing *Serious Sam* in HMD VR. Similarly, studies by Dennison et al. (2016) and Martirosov et al. (2021) found that more than half of their participants dropped out in under 10-min when playing first-person games in HMD VR (e.g. *Half Life 2*). By contrast, in all three of these studies, no one dropped out when playing desktop versions of these same games. Other studies by Palmisano and colleagues have found that up to 80% of participants become sick when playing HMD VR games for 10-min (during *Freedom Locomotion VR* in Risi and Palmisano 2019 and *Marvel Powers United VR* in Teixeira and Palmisano 2021), with the proportion of sick participants increasing to 96% with slightly longer (16-min) exposures to HMD VR (e.g. during *Nature Treks VR* in Clifton and Palmisano 2020). This, and other evidence, suggests that cybersickness also increases with the length of each gaming session (at least up to a point¹—Cao et al. 2019; Clifton and Palmisano 2020; Gavvani et al. 2017; Kennedy et al. 2000; Lampton et al. 1994; Nalivaiko et al. 2015; Palmisano and Riecke 2018; Regan 1995; Risi and Palmisano 2019; Stanney et al. 2002a, b; Teixeira and Palmisano 2021).

Thus, summarising the above research, it appears that: (1) dropouts can be quite common during first-person HMD VR gameplay; and (2) most users report some sickness with less than 20-min exposure to HMD VR. When taken together, these findings suggest that gamers should strictly limit their time in HMD VR in order to avoid unpleasant experiences. However, it is possible that the findings of these HMD gaming studies overestimate the problem of cybersickness, because: (1) many of their participants had not experienced HMD VR before; and (2) the tasks they performed were often intentionally designed to provoke cybersickness.² Importantly, there is also evidence that cybersickness decreases significantly when users are repeatedly exposed to the *same* HMD VR game (e.g. Cobb et al. 1999; Gavvani et al. 2017; Hill and Howarth 2000; Howarth and Hodder 2008; Regan 1995; Risi and Palmisano 2019). Such findings raise the possibility that gamers might habituate, or otherwise adapt, to cybersickness given sufficient exposure to HMD VR (and the unusual patterns of multisensory motion stimulation that this generates). The current study was therefore aimed at further investigating the effects of repeated exposure on the cybersickness induced by HMD VR games.

¹ The effects of exposure duration on cybersickness may eventually plateau, and even decrease, with very long exposures to HMD VR (see Cobb et al. 1999; Stanney and Kennedy 1998).

² e.g. According to Clifton and Palmisano (2019), the unexpectedly high rates and severity of sickness in their study (using an HMD VR game rated as “comfortable”) were caused by instructions to continually move through the virtual environment.

1.1 Why might repeated exposure to HMD VR reduce cybersickness?

There are many different theories of motion sickness (please see Lawson 2014, Keshavarz et al. 2014, as well as Palmisano et al. 2020 for recent reviews). These general theories are commonly used to explain the cybersickness experienced during HMD VR. Depending on the theory, cybersickness is either triggered by the HMD user: (1) experiencing a sensory conflict (such as a visually induced illusion of self-motion—Reason and Brand, 1975; Hettinger et al. 1990), (2) making errors in perceiving the direction of gravity (Bles et al. 1998) or which parts of the scene are stationary (Prothero and Parker 2003), (3) making excessive eye-motions (Ebenholtz et al. 1994), or (4) experiencing an increase in postural instability (Riccio and Stoffregen 1991). Of these different theories, Reason’s (1978) *sensory rearrangement theory* and Riccio and Stoffregen’s (1991) *postural instability theory* appear best suited to explaining the effects of repeated exposure on cybersickness. Thus, we will first describe these two theories, and their predictions about the effects of repeated exposure on cybersickness, before discussing alternative explanations/mechanisms proposed for these effects.

1.1.1 Explanation for reduced cybersickness based on sensory rearrangement theory

According to Reason and Brand’s (1975) *sensory conflict theory*, motion sickness occurs when signals from our different senses disagree with each other or with what is expected based on past experience. Reason (1978) subsequently modified this theory to explain why sickness might be reduced by repeated exposure to an initially provocative sensory conflict situation. In his *sensory rearrangement theory*, Reason assumed that: (1) we have internal records of all the patterns of motion stimulation we have experienced before; and (2) when we plan to move, the expected multisensory stimulation for that movement is selected from this *neural store* and compared to the actual stimulation arriving from our senses. According to Reason’s (1978) version of the theory, sickness is actually triggered by discrepancies between our currently sensed and expected patterns of motion stimulation (referred to as *neural mismatches*). The greater these *neural mismatches* are, the more likely it is that we will become sick, and the more severe our symptoms will be. However, the degree of neural mismatch produced by the same sensory conflict will also vary over time. For example, cybersickness should be more likely when HMD users first enter VR, because their expected multisensory stimulation at this time would be what they would normally experience moving in the real world (i.e. when making the same physical

head or body movements). This expectation should result in a neural mismatch, as the visual stimulation they actually receive from their HMD would be delayed relative to their non-visual information (see Palmisano et al. 2020 for an in-depth discussion of the perceptual effects of this display lag). However, with repeated exposure to HMD VR, their neural stores should gradually become recalibrated to these display lag effects.³ Subsequent head/body movements in the presence of a similar amount of display lag should result in a little less neural mismatch, and thus less cybersickness, on each subsequent exposure.

In this *sensory rearrangement theory*, sensory conflicts are regarded as a necessary prerequisite for all types of motion sickness (with the degree of the neural mismatch and motion sickness produced by the same sensory conflict expected to decrease with repeated exposure). However, it has been noted that non-redundant sensory stimulations often occur in everyday life without any sickness (Riccio and Stoffregen 1991; Stoffregen and Riccio 1991; Palmisano et al. 2011). Thus, Hettinger et al. (1990) instead proposed that sensory conflicts involving vection (i.e. visually induced illusions of self-motion⁴) might be essential for experiencing certain types of motion sickness (e.g. simulator sickness). Research has shown that when people are presented with visual self-motion stimulation only some of them become sick (Keshavarz et al. 2015). According to Hettinger et al. (1990), what differentiates sick people (from those who remain well) is the experience of vection (i.e. whether they experience illusory self-motion or not). Extrapolating from this earlier proposal (which was focussed on simulator sickness), cybersickness might only occur during HMD VR when the user actually experiences vection.⁵ If vection is taken as evidence of a potentially provocative sensory conflict, then *sensory rearrangement theory* would predict that cybersickness severity should scale (at least initially) with the strength of this vection experience.⁶ If so, we might see

a change in both vection strength and cybersickness severity with repeated exposure to simulated self-motion in HMD VR. However, also according to *sensory rearrangement theory*, repeated exposure to HMD VR might only reduce cybersickness if users continue to make similar physical movements to those that they made earlier (based on Oman's 1990 mathematical model of *sensory rearrangement theory*).

1.1.2 Explanation for reduced cybersickness based on postural instability theory

Not all researchers accept the concept of sensory conflict (e.g. Stoffregen and Riccio 1991; Riccio and Stoffregen 1991). According to Stoffregen and his colleagues, motion sickness instead occurs when our mechanisms for maintaining postural stability are undermined. Their *postural instability theory* predicts that: (1) motion sickness will always be preceded by periods of increased postural instability; and (2) this sickness will be more likely and more severe the longer that we remain unstable (e.g. Riccio and Stoffregen 1991; Stoffregen and Smart 1998; Munafo et al. 2017). According to this theory, novice HMD users would not initially have appropriate strategies for controlling their head and body posture during VR (an unfamiliar and challenging situation), which should increase the likelihood of cybersickness. However, during repeated exposure to HMD VR, they should develop more effective ways of stabilizing their posture in this situation. Indirect support for this explanation comes from recent research on seasickness. In this study, Stoffregen and colleagues (2013) examined novice maritime passengers before and during a 2-day ocean voyage. As expected, seasickness faded over the course of the voyage, despite the (initially provocative) movements of the ship continuing to occur. Importantly, these reductions were accompanied by significant improvements in passenger postural stability. As ship motions would have changed significantly during this 2-day voyage, passengers must have developed general strategies to improve their standing postural stability while at sea (such as, increasing their stance width and using the distant horizon as a visual aid). In a similar fashion, repeated exposure to HMD VR games may also allow novice users to “get their VR legs”. If the processes involved are similar to “getting one’s sea legs”, then general reductions in cybersickness may be found for multiple HMD VR games (at least those with similar postural demands to the original repeated game). While the benefits of repeated exposure may also be greater for standing HMD users, they should still be seen in seated users (who may develop more appropriate strategies for

³ A number of authors have noted that *sensory rearrangement theory*'s reliance on internal models makes it very difficult to test (Ebenholtz et al. 1994). Several recent attempts have provided only mixed/partial support for its predictions (e.g. Stoffregen et al. 2017).

⁴ Please see Palmisano et al. (2015) for alternative definitions of vection.

⁵ Bles et al. (1998) proposed that only sensory conflicts which affect the subjective vertical provoke motion sickness. We did not test this version of sensory conflict theory since we could not obtain head orientation data from the HMD (as our users always played locked commercial games).

⁶ While Hettinger et al. (1990) did not explicitly propose a scaling relationship between vection strength and sickness severity, many simulator sickness (and several cybersickness) studies have examined this possibility. To date the evidence for such a relationship is mixed (see Keshavarz et al. 2014 and Palmisano et al. 2020 for reviews). While Risi and Palmisano (2019) recently reported that stronger vec-

Footnote 6 (Continued)

tion was associated with increased cybersickness, this scaling relationship was not supported by other HMD VR studies (e.g. Palmisano et al. 2017 and Teixeira and Palmisano, 2021).

head stabilisation/control while playing HMD VR games – see also Sects. 1.1.3 a and b below).

1.1.3 Other explanations for reduced sickness with repeated exposure to HMD VR

Howarth and colleagues (Hill and Howarth 2000; Howarth and Hodder 2008) also identified several other possible explanations for the effects of repeated exposure on cybersickness. These include:

(a) *Behavioural adaptation* During repeated exposure to VR, HMD users may learn to minimise provocative head movements (Howarth and Costello 1997; Hill and Howarth 2000). For example, slower (or smaller amplitude) head movements may make it harder for them to detect visual-vestibular conflicts due to display lag (see Palmisano et al. 2020). Consistent with this explanation, cybersickness has been shown to decrease with head-velocity during active HMD VR (Kim et al. 2020; Palmisano et al. 2020).

(b) *Improvements in task performance with practice* The HMD user's sensory stimulation may also change over time as their gameplay improves with practice. Hill and Howarth (2000) argued that such improvements should also reduce user perceptions of scene instability. Consistent with this explanation, Palmisano and colleagues (2019) found evidence that cybersickness increased with perceived scene instability during HMD VR.

(c) *Sensory adaptation* Prolonged exposure to HMD VR may also trigger short-term changes in sensory sensitivity.⁷ Neurons (such as those involved in visual perception) are known to alter their responsiveness to sensory stimulation over time (see Solomon and Kohn 2014; Seno et al. 2011). For example, prolonged exposure to an HMD VR racing game could reduce the user's visual motion perception as they gradually adapt to the continuously presented optical flow.⁸ As this sensory adaptation should generalise to other visual motion stimuli, it could reduce sickness for a variety of HMD VR games, by decreasing the user's experience of vection/intersensory conflict (since they would be standing/seated in place while viewing simulated self-motion). However, it should be noted that, contrary to this explanation, cybersickness typically

increases (rather than decreases) over time during an individual HMD VR exposure session (e.g. Clifton and Palmisano 2020; Risi and Palmisano 2019).

(d) *Habituation* During repeated exposure to HMD VR users may habituate to their visual motion stimulation (Hill and Howarth 2000; Howarth and Hodder 2008). Habituation is often referred to as “the simplest form of learning” (Rankin et al. 2009, p. 136). Thus, its effects should last longer (i.e. days or weeks),⁹ and display greater stimulus specificity, than those due to sensory adaptation or fatigue (Rankin et al. 2009; Thompson 2009). However, habituation to cybersickness might only occur during repeated exposure to the *same* visual motion stimulation or virtual environment (see Hill and Howarth 2000; Howarth and Hodder 2008). Assuming habituation was the sole cause of such effects, repeated exposure to the *same* HMD VR game should have little effect on the sickness induced by a *different* HMD VR game. However, playing this new game might result in *dishabituation* (i.e. the recovery of the user's habituated sickness response to the original, repeatedly played game – see Rankin et al. 2009; Thompson 2009).

1.2 Research on the effects of repeated exposure to HMD VR

As noted above, a number of studies have shown that cybersickness can be reduced by repeated exposure to HMD VR (see Cobb et al. 1999; Gavvani et al. 2017; Hill and Howarth 2000; Howarth and Hodder 2008; Regan 1995; Risi and Palmisano 2019 – but see also Clifton and Palmisano 2020). Participants in these studies either actively-played, or passively-viewed playbacks of, the *same* game multiple times. Similar benefits were found for repeated active, and repeated passive, HMD VR exposures. Hill and Howarth (2000) also examined the effects of combining active and passive exposures to the *same* HMD VR racing game (*Wipeout*). Participants in this study drove a virtual vehicle for 20-min a day for 5 consecutive days. Half of them were also given an additional 15-min passive exposure each day as a virtual passenger. Interestingly, while repeated active exposures were able to reduce cybersickness on their own, the extra passive exposures further reduced its severity. Thus, Hill and Howarth concluded that these reductions were caused by *habituation to the visual motion stimulation*, rather than *improvements in task performance* or *behavioural adaptation* (as

⁷ According to Reason (1978), this sensory adaptation is different to protective sensory recalibration of the neural store (i.e. to reduce neural mismatch). While sensory adaptation effects should generalise across a broad range of stimuli within a sensory modality (e.g. vision), sensory recalibration effects involve multiple senses and may not generalise to different physical user movements.

⁸ These effects on visual perception in HMD VR could be similar to speed adaptation during real-world driving (see Denton 1980; Salvatore 1968; Schmidt and Tiffin 1969).

⁹ Thompson (2009) distinguishes short-term (or within-session) habituation from long-term (or between-session) habituation. We were primarily interested in long-term habituation effects in this study, which Rankin et al. (2009) conclude must involve qualitatively different cellular mechanisms (e.g. compared to short-term habituation). Several models of long-term habituation have been developed (e.g. Sokolov 1960; Wagner 1979).

benefits were still seen when participants were not in active control of the vehicle).

It also appears that repeated exposure can provide long-lasting benefits for HMD users (Howarth and Hodder 2008; Regan 1995). Howarth and Hodder (2008) found that reductions in cybersickness were similar with day-long and week-long delays between repeated gameplay sessions. Another study by Regan (1995) found that such benefits could last as long as four months. These findings appear difficult to explain based on *short-term sensory adaptation* (as after such long delays, the user should be completely recovered from any earlier sensory/physiological adaptation).

In most past studies, participants were repeatedly exposed to HMD VR for only 15 or 20 minutes per day. For example, Howarth and Hodder (2008) had participants play an active HMD VR racing game (*Killer Loop*) 10-times for 20-min each day. They found that cybersickness decreased across all 10 testing sessions – with half their participants no longer suffering symptoms on the tenth exposure. However, in this, and most other studies, sickness appears to have been markedly reduced by as little as 2, or perhaps 3, exposures to the *same* HMD VR game (see Cobb et al. 1999; Gavvani et al. 2017; Hill and Howarth 2000; Howarth and Hodder 2008; Regan 1995; Risi and Palmisano 2019; note: Heutink et al. 2019 also found similar effects for non-HMD based VR).

To our knowledge only two studies have examined the effects of repeated exposure on both vection and cybersickness (Clifton and Palmisano 2020; Risi and Palmisano 2019). Both studies had participants actively play an HMD VR game four times over two consecutive days. Contrary to the studies described above, Clifton and Palmisano (2020) failed to find any significant effects of repeated exposure on cybersickness. However, *sensory rearrangement theory* could potentially explain their null finding for cybersickness – because: (1) no effect of repeated exposure was found for vection; and (2) very different virtual navigation methods and physical user movements were employed on the two testing days.¹⁰ By contrast, participants in the Risi and Palmisano study always used the same virtual navigation method (and made the same control movements) during each gameplay session. As expected, they found a significant reduction in cybersickness from Day 1 to Day 2. However, this reduction in sickness severity was not accompanied by a significant change in vection strength.

¹⁰ Navigation via teleportation and steering locomotion were likely to have resulted in very different user control movements. This in turn may have prevented the recalibration of the user's neural store despite repeated exposure to the same virtual environment.

1.3 The current study

Our study asked the following questions: (1) can one or two brief exposures to the *same* HMD VR game reduce cybersickness during ecological gameplay? (2) does prior HMD VR exposure also alter the sickness induced by a *different* HMD VR game? and (3) does exposure to the new game result in dishabituation to the original game? Previously, Risi and Palmisano (2019) reported that cybersickness could be reduced by 20-min exposure to the *same* HMD VR game per day over two consecutive days. However, using slightly shorter 15-min exposures to a virtual rollercoaster, Gavvani et al. (2017) found that cybersickness was only significantly reduced in their 14 participants on Day 3. As HMD novices may not persist with cybersickness for more than one or two gameplay sessions (before completely giving up on the game or the technology), it is important to: (1) re-examine these minimum conditions for cybersickness; and (2) see if the benefits of repeated exposure can be enhanced in some way.

Thus, in the current study, we gave our participants (all HMD VR novices) three 15-min gameplay sessions over two consecutive days. Unlike the previous studies, this 45-min of gameplay consisted of exposures to two different HMD VR games (a virtual rollercoaster game and a virtual climbing game). The first 15-min exposure to HMD VR on both testing days was always to the virtual rollercoaster (with tracked head-movements allowed). However, based on Gavvani et al. (2017), it was unclear whether there would be a significant reduction in sickness to the virtual rollercoaster on Day 2. Thus, we were also interested in the possible costs or benefits of exposing our participants to an extra 15-min of virtual climbing.

In the present study, half of our 34 participants were scheduled for virtual climbing on Day 1 (GROUP 1), while the rest were scheduled to play this game on Day 2 (GROUP 2) (see Fig. 1). We were interested in whether GROUP 1's extra exposure to virtual climbing on Day 1 would alter their sickness to the rollercoaster on Day 2. If repeated exposure to HMD VR produces *general* benefits, then GROUP 1 might experience even *less* sickness than GROUP 2 during their second rollercoaster session. However, if the effects of repeated exposure are stimulus/activity *specific* (e.g. if they are due to *sensory rearrangement*, *practice effects*, or *habituation*), then GROUP 1 might display the same, or possibly even *more*,¹¹ sickness than GROUP 2 during this session.

We were also interested in whether cybersickness might be reduced for GROUP 2 during their virtual climbing session. By the time these participants started climbing on Day 2, they had already received 30-min exposure to the virtual rollercoaster. By contrast, GROUP 1 participants had only experienced a single 15-min rollercoaster session on Day

¹¹ E.g. if dishabituation was triggered to virtual rollercoaster.

Fig. 1 Study Design. Group 1 played both the rollercoaster and climbing games on Day 1, and only played the rollercoaster game on Day 2. By contrast, Group 2 only played the rollercoaster game on Day 1, and played both the rollercoaster and climbing games on Day 2

1. So, it was possible that GROUP 2 might experience less sickness than GROUP 1 during this climbing game—if the benefits of their past exposures to the rollercoaster generalised to this new game (e.g. if the effects were due to *sensory adaptation* or improvements in *postural stabilisation* while in HMD VR).

In addition to measuring cybersickness in this study, we also measured the user's vection strength and feelings of spatial presence (or “being there” in the virtual environment) during their gameplay. The purpose of including these additional measures was to see whether the effects of repeated exposure (and exposure duration): (1) might be similar for vection and cybersickness; and (2) also altered our participants' feelings of presence (often argued to be crucial for a complete VR experience—see Minsky 1980; Slater and Wilbur 1997).

In order to maximise participant safety, and minimise the postural challenges posed by HMD VR, participants played both of the HMD VR games in this study while they were seated.

2 Method

2.1 Participants

Thirty-four participants were recruited from the University of Wollongong and the general population. Of these participants, 2 reported that they remained well throughout the entire experiment. Four additional participants, who experienced severe sickness during their first exposure to HMD VR, were unable to complete the experiment. The remaining 28 ‘sick’ participants were split into two groups of 14 (each consisting of 9 females and 5 males). Participants ranged in age from 18 to 30 years ($M=21.8$ years, $SD=3.6$ years). None of them had experienced HMD VR before this experiment. All were healthy (i.e. no visual, neurological or vestibular impairments) and had either normal, or

corrected-to-normal, vision. The experiment was approved by the University of Wollongong Human Research Ethics Committee prior to testing. All of our participants provided written informed consent before participating.

2.2 Materials

The HMD VR rollercoaster and climbing games used in this study (*Rollercoaster Fun* and *Lighthouse Climbing Challenge*) were both part of the same *Summer Funland* application (https://www.oculus.com/experiences/rift/1041660492551211/?locale=en_US). This HMD VR application is a large virtual amusement park containing a variety of rides, mazes and other attractions. According to Oculus it has a “moderate” comfort rating (i.e. “appropriate for many but certainly not everyone”). The virtual rollercoaster and climbing games were both viewed using an Oculus Rift CV1 HMD with stereo headphones attached (the HMD had a resolution of 1080×1200 pixels for each eye and a refresh rate of 90 Hz using organic light-emitted diode (OLED) technology). The climbing game also required the participant to use the Oculus touch hand controls. Desk-mounted infrared cameras tracked the positions and orientations of both the participant's head (inside the HMD) and their hands (holding the touch remotes). Both PC VR games were run using a high-performance Microsoft Windows 10 Dell Precision 5820 computer, with an NVidia GeForce GTX1080 graphics card and an Intel 7th generation CPU.

In the *Rollercoaster Fun* game, participants rode around the virtual amusement park, with their simulated self-motion frequently alternating between acceleration and deceleration. While this HMD VR game is classified as passive, participants could still interact with its environment via tracked head-movements. The track, which included two full 360 degree loops, took participants close to buildings, through tunnels (filled with bats and a fire-breathing dragon) and mountain passes with falling rocks, by waterfalls, and near hot-air balloons in the sky (which sometimes released

falling objects). A number of other game events occurred during the ride, such as dolphins jumping out of the water and over the track, and fireworks being set off close to the car. These events were all clearly aimed at attracting the HMD user's attention and maintaining their interest throughout the ride.

In the “*Lighthouse Climbing Challenge*” game, participants scaled a lighthouse tower by making physical hand and arm movements, which were tracked via their Oculus touch remotes. They actively climbed the outside of this tower from its base to its top – only entering the tower when they reached its lantern room. Seated participants climbed by gripping, and then pulling, on the rungs of ladders, on a variety of ropes and chains, on wooden frames, as well as on plants and a variety of other protrusions attached to the exterior of the building.

In order to assess the incidence of cybersickness, participants were asked to answer this (yes/no) question directly after each gaming session: “did you feel sick during the game”? Their sickness symptoms were also assessed (before, as well as just after, each day's testing session) using the *Simulator Sickness Questionnaire* (SSQ) (Kennedy et al. 1993). When scored according to published guidelines (Kennedy et al. 1993), the SSQ yields three sub-scores: (1) disorientation (SSQ-D), (2) nausea (SSQ-N), and (3) oculomotor discomfort (SSQ-O). The following 16 questionnaire items contribute to these three sub-scores: general discomfort, fatigue, headache, eye strain, difficulty focusing, increased salivation, sweating, nausea, difficulty concentrating, fullness of the head, blurred vision, dizziness with eyes open, dizziness with eyes closed, vertigo, stomach awareness, and burping. In this study, our primary focus was on the changes in cybersickness severity over time. Thus, we also measured participant experiences every 3 min during each of the 15-min gaming sessions. Specifically, we obtained verbal ratings of their: (1) cybersickness severity using the *Fast Motion Sickness scale* (FMS) (from 0 = “no sickness at all” to 20 = “frank sickness”; see Keshavarz and Hecht 2011); (2) spatial presence (from 0 = “I do not feel that I am in the virtual environment” to 20 = “I feel completely present within the virtual environment”; and (3) vection strength from 0 = “no vection” to 10 = “strong vection”).

2.3 Design

Each participant was given 45-min exposure to HMD VR, which included two 15-min virtual rollercoaster sessions, as well as a 15-min session of virtual climbing. This study had the following split-plot design. There were three within-subject factors: (1) GAME TYPE: Participants played both rollercoaster and climbing games; (2) TEST DAY: Gameplay occurred over two days (with at least 20-h between the last exposure on Day 1 and the first exposure on Day 2); and

3) TIME IN TRIAL: Participant experiences were assessed five times during each gameplay session (to see changes in sickness/presence/vection over time). The study design also included GROUP (a between-subjects factor) (see Fig. 1). The first HMD VR exposure on each of the two test days was always to the virtual rollercoaster. While GROUP 1 played the climbing game on Day 1, GROUP 2 only played this game (for the first time) on Day 2 (see Fig. 1). This design should allow us to determine whether extra exposure to virtual climbing alters sickness to the virtual rollercoaster and vice versa. The dependent variables recorded for/during each gameplay session were: (1) the severity of the participant's cybersickness (based on their ratings using the FMS); (2) their experience of spatial presence (based on verbal ratings from 0 to 20); and (3) the strength of their vection (based on verbal ratings from 0 to 10). In addition, the overall change in sickness symptoms across each day was also assessed using the SSQ (this questionnaire was completed just before their first, and again just after their last, exposure to HMD VR for the day).

2.4 Procedure

On their arrival in the laboratory, participants were first provided with an information sheet (which described what they would do in the experiment) and a consent form, which they signed after reading. They next received a demographics, VR and Gaming History sheet to complete. On this sheet they indicated their age, whether they had a fear of heights, the number of hours they spent playing video games per week, and their experience with HMDs. From that point on the procedure was similar on both testing days. On each day, just before they were first exposed to HMD VR, participants completed the pre-exposure SSQ (which included items that assessed their sickness background and their physiological status, as well as a checklist of their current symptoms). They were then seated on a swivel chair, given some instructions on the use of this HMD technology, and finally were assisted with donning their headset.

On each day, participants in both groups played the virtual rollercoaster game. This game was always played first (even on days where participants also played the virtual climbing game). The rollercoaster ride in *Summer Funland* lasts 3 min and 36 s. So, over each 15-min gameplay session, participants experienced four complete loops of the same track. During these rides, they were free to look around at the scenery and their virtual companions (seated in the same car). Every 3-min they were prompted to provide ratings of their cybersickness severity, feelings of presence and experience of vection. At the end of the session, the experimenter also asked them: “Did you feel sick during the game”? After answering “yes” or “no”, they then either completed the post-exposure SSQ (if gameplay was finished for the day)

or were given a 10-min rest¹² before their next gaming session (if they were scheduled for virtual climbing).

Before the climbing session, participants were given instructions on using the Oculus hand remotes and a very brief exposure to familiarise themselves with virtual climbing. After an additional break of 5-min, and another check for cybersickness, they officially started their 15-min virtual climbing session. Participants repeatedly climbed the lighthouse by gripping and pulling on ropes, chains and protrusions attached to the tower's exterior. Unlike the virtual rollercoaster, this game required vigorous physical activity. Climbing from the base to the top of the tower generally took between 5 and 10 minutes. However, if participants "fell" during the game, they respawned either at the base of the tower, or at another point higher up. Once they reached the top, the experimenter immediately returned them to the base of the tower. They then continued to play the game until their 15-min had elapsed. During the session, they were again prompted to rate of their sickness, presence and vection every 3-min. At the end of the session, participants were also asked "Did you feel sick during the trial?", and then after answering, they completed the post-exposure SSQ.

At the conclusion of testing on Day 2, all participants were fully debriefed. They remained in the laboratory until they felt well enough to leave.

3 Results

3.1 Cybersickness incidence and symptoms

The data below come from the 28 'sick' participants who completed all three HMD VR exposure sessions. As expected, exposure to HMD VR was found to produce the largest change in disorientation sub-scores¹³ ($M = 40$; $SD = 49$), followed next by nausea ($M = 16$, $SD = 28$) and then by oculomotor discomfort ($M = 13$; $SD = 23$) sub-scores. Figure 2 shows the average (post-pre) changes in symptoms on both Day 1 and Day 2 for participants in both groups. As can be seen in this figure, there was a significant reduction in disorientation symptoms from Day 1 ($M = 52$; $SD = 46$) to Day 2 ($M = 28$; $SD = 51$), $t(27) = 2.7996$, $p < 0.009$ (2-tailed), $d = 0.53$. However, the reduction in nausea from Day 1 to Day 2 (also seen in Fig. 2) did not reach statistical significance, $t(27) = 1.246$, $p = 0.22$ (2-tailed), $d = 0.24$. Figure 3 shows significant reductions in disorientation on Day 2 (relative to Day 1) for both Group 1 and Group

Fig. 2 Changes in disorientation (SSQ-D), oculomotor (SSQ-O), and nausea (SSQ-N) produced by HMD VR gaming sessions on Day 1 and Day 2. This figure shows the mean change in these SSQ sub-scores for all participants at the end of each day's testing session (relative to their baseline symptoms before exposure to HMD VR). Error bars represent standard errors of the mean

2 (see Fig. 3) – even though these groups had different numbers of exposures to HMD VR on each of these testing days.

3.2 Cybersickness severity rating data

3.2.1 Effects of TEST DAY and TIME IN SESSION on sickness to the virtual rollercoaster

From Fig. 4, it can be seen that sickness generated by the virtual rollercoaster: (1) increased with the time spent in the game (from the first rating made 3-min after the ride had begun to the last rating made after a full 15-min exposure); and (2) decreased from Day 1 to Day 2. A 2 (TEST DAY) $\times$ 5 (TIME IN SESSION) repeated measures ANOVA on sickness severity scores, confirmed that these main effects of TEST DAY ($F(1,27) = 8.265$, $p = 0.008$, $\eta^2 = 0.234$) and TIME IN SESSION ($F(1.749, 47.220) = 42.058$, $p = 0.0001$, $\eta^2 = 0.609$) were both significant. The TEST DAY by TIME IN SESSION interaction was also found to be significant, $F(2.272, 61.353) = 7.075$, $p = 0.001$, $\eta^2 = 0.208$. Figure 4 (Right) shows that although sickness increased with TIME IN SESSION on both days, the increase occurred at a faster rate on Day 1 than Day 2. It should also be noted that increases in sickness on both days appeared to plateau after 12-min exposure to the virtual rollercoaster.

3.2.2 Effects of prior exposure to virtual climbing on sickness to the virtual rollercoaster

Overall cybersickness was found to be less severe during the second exposure to the virtual rollercoaster on Day 2. However, it was possible that there might be GROUP differences in the sickness experienced during this second

¹² If participants did not reach baseline levels of sickness by the end of this rest period, the experiment was terminated.

¹³ Note SSQ-D is based on summed responses to the 'difficulty focussing', 'nausea', 'fullness of head', 'blurred vision', 'dizzy eyes open/closed', and 'vertigo' items of the SSQ.

Fig. 3 Changes in disorientation (SSQ-D), oculomotor (SSQ-O), and nausea (SSQ-N) over the two testing days for Group 1 (Left) and Group 2 (Right). Each figure shows the mean change in SSQ sub-scores for participants in each Group at the end of each day's testing session (relative to their baseline symptoms before exposure to HMD VR). Error bars represent standard errors of the mean

rollercoaster session. For example, GROUP 1 might experience *less* severe sickness than GROUP 2 on Day 2, because of their extra 15-min exposure to HMD VR on the previous day. Alternatively, GROUP 1 might experience *more* severe sickness than GROUP 2 on Day 2, if their exposure to climbing in between the two rollercoaster sessions caused dishabituation. Figure 5 shows the effects of TEST DAY (and TIME IN SESSION) on the mean sickness severity ratings for the two groups when playing the virtual rollercoaster. Contrary to both of the possibilities outlined above, an independent samples *t*-test revealed that the mean sickness ratings for this second rollercoaster session were not significantly different for GROUP 1 ($M = 3.45$, $SD = 4.02$) and GROUP 2 ($M = 3.15$, $SD = 4.11$), $t(26) = 0.195$, $p = 0.85$, two-tailed, $d = 0.05$. As an additional check, we also examined the peak sickness severity data for the rollercoaster on Day 2. Peak sickness severity ratings were not significantly different for GROUP 1 ($M = 4.93$, $SD = 4.97$) and GROUP 2 ($M = 4.71$, $SD = 4.81$), $t(26) = 0.116$, $p = 0.91$, two-tailed, $d = 0.03$. Thus, GROUP 1's extra exposure to virtual climbing did not appear to alter their sickness to the virtual rollercoaster on Day 2.

3.2.3 Effects of prior exposure to the virtual rollercoaster on sickness during virtual climbing

Before they played the virtual climbing game, GROUP 2 received twice as much exposure to the virtual rollercoaster as GROUP 1. To examine whether this extra exposure to the virtual rollercoaster altered their experience of virtual climbing, we conducted an independent samples *t*-test on the sickness severity ratings for the two groups. Mean sickness severity ratings were not found to differ significantly for GROUP 1 ($M = 3.54$, $SD = 4.26$) and GROUP 2 ($M = 3.81$; $SD = 5.15$), $t(26) = 0.15$, $p = 0.88$, two-tailed, $d = 0.04$. As an additional check, we also examined whether there were any GROUP differences in terms of peak sickness during virtual

climbing. Peak sickness severity ratings were not found to be significantly different for GROUP 1 ($M = 5.43$, $SD = 5.56$) and GROUP 2 ($M = 5.28$; $SD = 6.41$), $t(25) = 0.06$, $p = 0.48$, two-tailed, $d = 0.06$. Thus, our participants' experiences of cybersickness during this virtual climbing game were not significantly altered by doubling their prior exposure to the rollercoaster.

3.3 Vection and presence data

3.3.1 Vection and presence during the virtual rollercoaster

Since no GROUP effects were found for cybersickness, we pooled the data for our analyses of vection strength and spatial presence below.

From Fig. 6 (Left), it can be seen that the second exposure to the virtual rollercoaster on Day 2 generated less vection than the first exposure on Day 1. A 2 (TEST DAY) $\times$ 5 (TIME IN SESSION) repeated measures ANOVA¹⁴ conducted on vection strength ratings during this game, confirmed that the main effect of TEST DAY was significant, $F(1,27) = 6.785$, $p = 0.015$, $\eta^2 = 0.201$). However, neither the main effect of TIME IN SESSION ($F(1.961, 52.939) = 2.377$, $p = 0.104$, $\eta^2 = 0.081$), nor the TEST DAY by TIME IN SESSION interaction, were found to reach significance ($F(2.670, 79.090) = 1.403$, $p = 0.238$, $\eta^2 = 0.049$).

A 2 (TEST DAY) $\times$ 5 (TIME IN SESSION) repeated measures ANOVA was also conducted on the spatial presence ratings made during the virtual rollercoaster—see Fig. 6 (Right). However, the main effects and the interaction all failed to reach significance (TEST DAY: $F(1,27) = 3.979$, $p = 0.056$, $\eta^2 = 0.128$; TIME IN SESSION: $F(1.661, 44.855) = 1.773$, $p = 0.186$, $\eta^2 = 0.062$; TEST DAY by

¹⁴ Note: during such analyses, whenever there was a violation of sphericity, Greenhouse–Geisser corrections were applied.

Fig. 4 Effects of TEST DAY and TIME IN SESSION on mean sickness severity ratings for the virtual rollercoaster (data averaged across all participants). (Left) This shows that the second exposure to the virtual rollercoaster produced less severe sickness (i.e. the mean sickness experienced during the rollercoaster was less on Day 2 com-

pared to Day 1). (Right) This shows that mean sickness severity also increased with the TIME IN SESSION. The rate of this increase was greater on Day 1 than Day 2. Error bars in both plots represent standard errors of the mean

Fig. 5 (Left) Effects of TEST DAY and TIME IN SESSION on the mean sickness severity ratings for GROUP 1 when playing the virtual rollercoaster. (Right) Effects of TEST DAY and TIME IN SESSION on the mean sickness severity ratings for GROUP 2 when playing the same game. Error bars represent standard errors of the mean

Fig. 6 Effects of TEST DAY and TIME IN SESSION on mean vection strength ratings (Left) and mean spatial presence ratings (Right) for the virtual rollercoaster (data averaged across all participants). Error bars represent standard errors of the mean

Fig. 7 Effects of TEST DAY and TIME IN SESSION on mean vection strength ratings (Left) and mean presence ratings (Right) during virtual climbing. Error bars represent standard errors of the mean

TIME IN SESSION interaction: $F(2.677, 72.289) = 1.065$, $p = 0.365$, $\eta p^2 = 0.038$).

3.3.2 Vection and presence during virtual climbing

A 2 (TEST DAY) $\times$ 5 (TIME IN SESSION) split-plot ANOVA was performed on the vection strength ratings obtained during virtual climbing – with TEST DAY serving as a between-subjects factor (since participants in the two groups played this game on different days) and TIME IN SESSION serving as a within-subjects factor (see Fig. 7 Left). We found that there was a significant main effect of TIME IN SESSION on vection strength ratings, $F(1.686, 43.832) = 3.745$, $p = 0.038$, $\eta p^2 = 0.126$ (there was a slight increase in vection with longer TIME IN SESSION). However, neither the main effect of TEST DAY ($F(1, 26) = 1.858$, $p = 0.185$, $\eta p^2 = 0.067$), nor the interaction between TEST DAY and TIME IN SESSION ($F(1.686, 43.832) = 0.702$, $p = 0.478$, $\eta p^2 = 0.026$), were found to reach significance.

A 2 (TEST DAY) $\times$ 5 (TIME IN SESSION) split-plot ANOVA was also performed on the spatial presence ratings obtained during virtual climbing – with TEST DAY again serving as a between-subjects factor and TIME IN SESSION serving as a within-subjects factor. However, the main effects and the interaction all failed to reach significance (TEST DAY: $F(1, 26) = 0.431$, $p = 0.517$, $\eta p^2 = 0.016$; TIME IN SESSION: $F(1.691, 43.965) = 2.953$, $p = 0.102$, $\eta p^2 = 0.062$; TEST DAY by TIME IN SESSION interaction: $F(1.691, 43.965) = 2.451$, $p = 0.100$, $\eta p^2 = 0.086$).

3.4 Relationships between vection, sickness and presence

Regression and correlation models both assume that each data point is derived from a different participant (Lorch and Myers 1990). However, as this experiment had a split-plot design, its data did not represent independent samples.

Each participant rated their cybersickness severity 15 times (5 times per session for 3 gameplay sessions). They also rated their vection strength and feelings of presence 15 times as well. Thus, in order to investigate the possible relationship between vection and cybersickness in this study, we did the following: (1) each participant's 15 vection strength ratings were correlated with their corresponding cybersickness severity ratings; (2) individual linear regression coefficients were computed for each participant; and (3) a one sample t -test was conducted on these regression coefficient data to see if they differed significantly from zero. The same method was also used to test for possible relationships between vection and presence, and between presence and cybersickness. We found significant positive relationships between vection strength and cybersickness severity ($t(27) = 4.012$, $p < 0.0001$, $d = 0.76$) and between vection strength and spatial presence ($t(27) = 9.124$, $p < 0.0001$, $d = 1.72$). However, the relationship between spatial presence and cybersickness severity did not reach significance, $t(27) = 1.949$, $p = 0.06$, $d = 0.42$.

Since we found a general relationship between vection and cybersickness, we also examined whether changes in vection strength might be associated with the reductions in cybersickness found with repeated exposure. We calculated each participant's average vection-change and average sickness-change scores for the virtual rollercoaster (i.e. their average score on Day 2 minus their average score on Day 1; with a negative score indicating that a reduction had occurred on Day 2). We found a significant positive linear relationship between vection-change and sickness-change scores, $R^2 = 0.25$, $t(27) = 2.96$, $p = 0.007$. However, we do note that vection strength only decreased on Day 2 for 11 of our 28 participants – as indicated by their negative vection-change scores in Fig. 8. By contrast, cybersickness can be seen in the same figure to have decreased on Day 2 for 21 of the 28 participants.

Fig. 8 Relationship between the mean changes in vection strength (horizontal axis) and the mean changes in sickness severity (vertical axis) for each participant during the virtual rollercoaster as a function of TEST DAY. There are two possible outliers in this figure – the data point located at $(-2, -11)$ and another data point located at $(0.7, 6.8)$. However, the positive linear relationship between vection change and sickness change remains significant when both these outliers are removed, $R^2 = 0.263$, $t(25) = 2.930$, $p = 0.007$

4 Discussion

As predicted, cybersickness was generally found to: (1) increase with the time spent in each gameplay session, and (2) decrease on the second exposure to the *same* HMD VR game. Importantly, we found that significant reductions in cybersickness could be produced with as little as 15-min exposure to the virtual rollercoaster per day over *two consecutive* days. This repeated exposure resulted in significant reductions in cybersickness severity ratings (as well as reported disorientation symptoms – which are based in part on responses to the ‘nausea’ and ‘vertigo’ items of the SSQ). While cybersickness severity was still found to increase with TIME IN SESSION on both days, the rate of this increase was significantly slower for the virtual rollercoaster on Day 2 (compared to that for the rollercoaster on Day 1).

That we observed significant reductions in cybersickness with so few exposures, and under relatively normal gameplay conditions, was clearly encouraging for the future of HMD VR gaming. Both groups of participants displayed significant reductions in sickness during their second exposure to the virtual rollercoaster on Day 2.¹⁵ However, GROUP 1 (who had received 30-min exposure to HMD VR on Day 1)

showed no additional benefits during this rollercoaster session compared to GROUP 2 (who had received only 15-min exposure to HMD VR on Day 1). Sickness during virtual climbing was also not different for these two groups, even though GROUP 2 had received twice as much exposure (i.e. 30-, as opposed to 15-, minutes) to the virtual rollercoaster before climbing.

When taken together, the current findings suggest that the benefits of two or three, relatively brief HMD VR exposures may be *game specific*. However, before making such a conclusion, we first need to consider whether GROUP effects in our study could have been suppressed by extraneous factors. In the previous research, prior experience using HMDs, time spent playing video games, and biological sex have all been claimed to influence cybersickness (see Munafo et al. 2017; Pot-Kolder et al. 2018; Rebenitsch and Owen 2014; Stanney et al. 2003). Thus, we attempted to control these, and other extraneous, factors in the current study. None of the participants in either group had experienced HMD VR before. Both groups had the same 5:9 ratio of males to females. These two groups also had the same number of participants that reported playing video games regularly (5 out of the 14 participants in each group). In addition, while past research suggests that cybersickness increases with user anxiety (Pot-Kolder et al. 2018), a chi-squared analysis revealed that the percentage of participants with a fear of heights did not differ significantly between our two groups, $\chi^2(1, N=28) = 1.35$, $p = 0.246$, $\phi = -0.219$. In terms of whether it was appropriate to use these two particular HMD VR games (which were both part of the same *Summer Funland* application), follow-up statistical tests confirmed that they generated reasonably similar levels of sickness. We found that mean sickness for the virtual climbing game was not significantly different to that experienced during the first, or the second, exposure to the virtual rollercoaster ($t(27) = 2.028$, $p > 0.05$, two-tailed, $d = 0.38$; $t(27) = -.6320$, $p > 0.05$, two-tailed, $d = 0.12$, respectively).

4.1 Possible underlying mechanisms for these reductions in sickness with repeated exposure

Based on the convergent evidence outlined above (as well as associated checks ruling out the influence of extraneous factors in this study), we conclude that cybersickness was: (1) reduced by repeated exposure to the *same* HMD VR game (i.e. the virtual rollercoaster); (2) unaffected by the amount of prior exposure to a *different* HMD VR game (i.e. virtual climbing). As was noted in the introduction, the possible mechanisms underlying reductions in cybersickness with repeated exposure include *sensory rearrangement/vection*, *changes in the HMD user’s postural stability*, *behavioural adaptation*, *task improvement*, *sensory adaptation* and

¹⁵ Note: cybersickness was confirmed to be less severe on Day 2 (compared to Day 1) for both GROUP 1 ($t(13) = 2.03$, $p = 0.03$) and GROUP 2 ($t(13) = 3.04$, $p = 0.005$).

long-term habituation. Thus, we will attempt to relate the current findings to these different theories/explanations as follows:

(a) *Behavioural adaptation and task improvement* The reductions in sickness seen for the virtual rollercoaster on Day 2 were unlikely to have been due to either game-specific practice effects or behavioural adaptation. This particular game was primarily a passive viewing experience, with little opportunity for participants to improve their task performance. Furthermore, as experimenters, we did not notice any obvious differences in participant behaviour during the virtual rollercoaster between Day 1 and Day 2.

(b) *Sensory adaptation* Repeated exposures to HMD VR could have reduced our participants' visual motion perception via sensory adaptation. As such effects should generalise to other visual self-motion stimuli, sensory adaptation to the rollercoaster could also have suppressed sickness during climbing later that day. However, this short-term sensory adaptation would likely have been extinguished prior to testing on Day 2. Contrary to this explanation, the effects of prior HMD VR exposure on cybersickness were not: (1) found to generalise to other visual self-motion stimuli, and (2) extinguished by 20 plus hour delays between testing sessions.

(c) *Long-term habituation to the visual stimulation* Consistent with predictions based on habituation (e.g. Hill and Howarth 2000), reductions in cybersickness with repeated exposure appeared to be *specific* to the same HMD VR game. Long-term habituation could therefore potentially explain why sickness was reduced for GROUP 2 during their second exposure to the rollercoaster on Day 2. By contrast, GROUP 1 played a very different (climbing) game in-between their two rollercoaster sessions. Thus, if habituation had occurred during their first exposure to the rollercoaster, this group should have experienced dishabituation during their second exposure to the rollercoaster. However, as was noted above, there was no significant GROUP difference in sickness to the rollercoaster on Day 2. This suggests that the benefits of repeated exposure were not due to habituation in the current study. However, it is still possible that habituation might contribute to reducing sickness when users have more exposures to the *same* HMD VR game.

(d) *Sensory Conflict/Rearrangement* While the cybersickness produced by the rollercoaster was less severe on Day 2, sickness during virtual climbing was found to be similar on both testing days. Consistent with the notion that vection might have contributed to this cybersickness, we found that vection was weaker for the virtual rollercoaster on Day 2 and similar for virtual climbing on both testing days. According to *sensory rearrange-*

ment theory, repeated exposure to HMD VR should only have reduced cybersickness if participants continued to make similar physical movements to those they made in earlier exposures. Assuming this was the case, this theory would also predict the decline in cybersickness severity found for the rollercoaster on Day 2 – as changes made to the neural store during the first rollercoaster session should reduce neural mismatches/vection strength during the second exposure. This could also explain why such benefits did not generalise to the virtual climbing game. Sensory rearrangement would only change the expected pattern of multisensory stimulation for a particular type of body movement. Thus, it is possible that: (1) the physical user movements made during the climbing game were too different to those made during the rollercoaster; and (2) as a result, sensory rearrangements generated by the rollercoaster were not applied to participant movements made during virtual climbing. If this was the case, then their expected patterns of multisensory stimulation during this HMD VR game should still have been (at least initially) what they would normally experience in the real world. This would explain why no obvious reductions in cybersickness were seen when participants were exposed to virtual climbing after two virtual rollercoaster sessions.

(e) *Postural Instability* Unfortunately, our seated HMD user study was not well suited to examining the *postural instability theory* of cybersickness. As we used locked commercial games, and we were not able to obtain head and hand tracking data during gameplay, we cannot rule out the possibility that improvements in head/torso stabilisation were responsible for the reductions in sickness severity found (for the rollercoaster) on Day 2. Demonstrating that this particular mechanism was responsible would require a very different study – with active head and body tracking throughout each HMD VR exposure and ideally with standing (as opposed to seated) HMD users.

4.2 Effects of repeated exposure on presence and vection

In this study, cybersickness and vection strength were both found to decrease with repeated exposure to the *same* HMD VR game. We were thus also interested in the effects that repeated exposure might have on feelings of presence. While cybersickness is recognised to be a major problem for HMD VR, feelings of presence are often regarded to be one of the primary benefits of using this technology. So, sickness countermeasures that reduce user feelings of presence would be undesirable. However, in the current study we found no significant effects of either TEST DAY or TIME IN SESSION on our participants' experiences of spatial presence. These results suggest that repeated exposure to the *same*

HMD VR game can decrease cybersickness severity with little cost to feelings of spatial presence. However, it should be noted that we only measured the strength of our participants' "place illusion" in this study (i.e. the degree to which they perceived that they were actually there in the virtual environment – Slater 2009). We did not measure the effects of repeated exposure on the strength of their "plausibility illusion" (i.e. the degree to which they perceived that what was apparently happening was actually happening – Slater 2009). Thus, the possibility remains that repeated exposure to HMD VR might alter the user's plausibility illusion (although we would expect that if it did, this illusion would probably increase – rather than decrease – with the time spent playing the game).

As was noted in the introduction, vection is often regarded to be a problem that should be avoided in HMD VR – due to its assumed relationship with cybersickness. If there is indeed a relationship between vection and cybersickness, then it is likely to be a rather complex one (see also Ji et al. 2009; Keshavarz et al. 2015; Kuiper et al. 2019; Nooij et al. 2018; Risi and Palmisano 2019). However, it is worth noting that these illusions of self-motion can also enhance user experiences in virtual reality (Keshavarz et al. 2019; Palmisano et al. 2015; Riecke 2006, 2010; Riecke and Schulte-Pelkum 2013, 2015). Indeed, there is growing evidence that vection improves user feelings of spatial presence (see Keshavarz et al. 2019; Riecke et al. 2006; Teixeira and Palmisano 2021 – but not Clifton and Palmisano 2020). In the current study, we also found a significant positive relationship between vection strength and spatial presence. That is, stronger illusions of self-motion were found to be associated with more compelling experiences of "being there" in the virtual environment. By contrast, while a recent review concluded that there is a negative relationship between presence and cybersickness (Weech et al. 2019), we failed to find a significant relationship between spatial presence and cybersickness severity in the current study. Indeed, our findings suggest that it is possible to simultaneously experience strong feelings of spatial presence and severe sickness (this appeared to have happened for at least 4 of our participants).

4.3 Implications and future directions

This study examined the effects of repeated exposure to HMD VR on cybersickness under reasonably realistic conditions. Our participants played two different commercially available games, much as they were meant to be played recreationally. Unlike past studies, which always exposed participants to the same HMD VR game, our study had participants sometimes play two different games on the same day (approximating what might happen when one successfully completes a demo or a level, or alternatively loses interest in a game). Under the ecological conditions of our study,

the minimum requirements for a significant reduction in cybersickness appeared to be two 15-min long exposures to the *same* HMD VR game. By contrast Gavvani et al. (2017), found that three 15-min exposures were required to significantly reduce cybersickness in their study. Both of these studies repeatedly exposed participants to one virtual rollercoaster session per day, with significant effects being observed (in terms of sickness severity/tolerated ride duration) on Day 2 in our study, and Day 3 in their study. As HMD VR novices may only persist with cybersickness for a few gameplay sessions, it is clearly important to confirm our current minimum requirements for reducing cybersickness and determine under exactly what conditions they apply. Compared to the participants in the Gavvani et al. study, our participants may have been more susceptible to cybersickness, because (1) none of them had been exposed to HMD VR before; (2) very few of them played video games regularly; and (3) they were encouraged to actively explore their virtual environment during their rollercoaster rides. However, different subjective sickness measures were also used, and different numbers of participants were tested, in these two studies (34 participants in our study versus only 14 participants in theirs). Thus, our testing of more/particularly susceptible participants, our instructions to actively explore the environment, and our use of potentially more sensitive subjective measures, might all explain the significant reductions in cybersickness found in our study on Day 2 (but not in the Gavvani et al. study).

It should be noted that while the reductions in cybersickness observed in this study appeared to be *game-specific*, the possibility remains that they might still generalise to other games if more/longer exposures to HMD VR are provided. Based on past research (e.g. Howarth and Hodder 2008), we would expect to see further reductions in cybersickness severity with additional exposures to the *same* HMD VR game. Thus, future research will need to: (1) not only confirm significant *game-specific* reductions in cybersickness following two brief exposures to HMD VR; but also (2) check for *generalised* effects on cybersickness following many more repeated exposures to HMD VR.

Our study suggests that significant reductions in cybersickness can be produced by a few relatively brief exposures to the *same* HMD VR game. While the study was focussed exclusively on HMD VR gaming, its findings may also be relevant for other HMD VR applications, such as those used for VR simulation training and VR-based psychological treatments. Assuming the minimum requirements to see reductions in cybersickness are similar for these other types of HMD VR, trainees and clients might need to be given 15 to 30 min preliminary exposure to the application's virtual environment (i.e. before the VR training or psychological treatment starts), in order to maximise their learning and treatment effectiveness.

5 Conclusions

It had been hoped that most HMD users would simply get used to VR given enough prior exposure and gameplay. In partial support of this notion, our study shows that repeated exposure to the *same* HMD VR game can significantly reduce cybersickness. However, we found that: (1) extra exposure to a *different* HMD VR game did not significantly alter cybersickness to the original game; and (2) cybersickness to the new game was unaffected by the amount of prior exposure to the original game. Thus, we conclude that the benefits of repeated exposure to HMD VR may be *game-specific* (i.e. they do not appear to generalise to other HMD VR games and applications). Importantly, we have shown that these *game-specific* benefits can be produced in most users with only two, relatively brief exposures to HMD VR.

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Data availability Data will be made available upon request.

Code availability We used a commercially available video game in this study.

Declarations

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

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