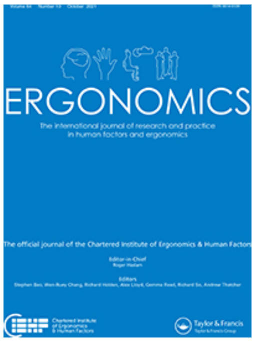

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ARTICLE

Evaluating the effect of multi-sensory stimulations on simulator sickness and sense of presence during HMD-mediated VR experience

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ABSTRACT

Some lines of evidence have shown that sensory input, especially related to vestibular and somatosensory stimulation, may reduce the symptoms related to simulator sickness and increase the sense of presence in VR. The present study aims at understanding how mechanical vibration and auditory stimulation can be used to improve user experience in the context of VR mediated by head-mounted displays. Four different groups comprising a total of 80 participants were tested under different conditions of sensory input (visual and vibration, visual-auditory, combined visual-auditory and vibratory, and visual only), during a VR roller-coaster experience. No significant differences in simulator sickness were found between the groups exposed to seat vibration and/or audio. However, sense of presence showed to be increased when vibratory stimuli were included. Post-hoc analyses showed that female users but not male ones, experienced an increase of sense of presence when vibratory stimulation was used.

Practitioner summary: The study showed that including sound or vibration stimulation during VR experience does not reduce simulator sickness. However, sense of presence is promoted by vibratory stimulation. Post-hoc analyses showed that female users experienced an increase of sense of presence by vibratory stimulation, but not male ones.

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Virtual reality; simulator sickness; presence; HMDs; vibration

1. Introduction

The idea behind virtual reality (VR) is to induce the human brain to believe that the virtual environment is the real world. Thus, VR is designed based on experienced real environments and attempts to fulfil one's expectations of the same, for example, showcasing interactions between objects and following the laws of natural motion in physics.

These tools are increasingly used for entertainment purposes. In the last decade, the use of VR has been growingly employed in the fields of medicine (Jerdan et al. 2018), education (Grassini, Laumann, and Rasmussen Skogstad 2020; Martín-Gutiérrez et al. 2017), and safety training (Deb et al. 2017; Grassini and Laumann 2020b).

Today, the term VR is often used to refer to modern head-mounted displays (HMDs). HMDs can deliver an immersive experience to the user, increasing the induced sense of presence compared to other means of visualisation (Shu et al. 2019). However, some issues are yet to be addressed to effectively implement VR and increase its acceptability, and one of the most prominent limitations of VR is simulator sickness (SS).

1.1. Simulator sickness

When discussing SS, it should be noted that not all the scholars have been using this terminology to describe the phenomenon (Stanney, Kennedy, and Drexler 1997) and the term 'cyber-sickness' (or CS) has been more widely used in the field. Another term often used in the context of HMDs is 'visually induced motion sickness' (see e.g. Sawada et al. 2020). However, in an attempt to reduce ambiguity, we decided to use only the terminology 'simulator sickness' throughout the manuscript, in line with a number of recent articles on SS in HMDs (Benz et al. 2019; Grassini and Laumann 2020b; Saredakis et al. 2020).

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SS is a phenomenon considered to be closely linked to motion sickness (MS, see Kennedy, Drexler, and Kennedy 2010). Research in visually induced motion sickness. Applied ergonomics, 41(4), 494–503.). SS was found to be often induced by the exposure to VR technology or simulators. The symptomatology of SS includes nausea, dizziness, vertigo, cold sweat, headache, sleepiness, increased salivation and general discomfort (Dużmańska, Strojny, and Strojny 2018). The adverse effect of SS poses considerable risk on the health and safety of users. Consequently, a significant research effort has aimed to determine the causes of SS in order to be able to reduce its symptoms and improve the user experience (e.g. Weech et al. 2018). A scientific explanation for SS has not yet been completely described. Several theories have been developed, as the postural instability theory (Riccio and Stoffregen 1991), and the poison theory (Treisman 1977).

One of the most popular theories on the nature of SS (LaViola, 2000) is the sensory conflict theory (also known as sensory conflict theory; Reason and Brand 1975). The theory proposes that the symptoms of SS are the result of conflicting or desynchronised sensory input when the individual visually perceives motion in the virtual environment (Reason and Brand 1975). Critically, the sensory conflict theory refers to when the individual perceives visual motion while in the absence of veridical or congruent physical motion. In a model known as the 'neural mismatch model' (Reason 1978) it was proposed that SS arises from input stimuli that conflict with the user's own experience of the natural environment. In the theoretical development of the present work we have focussed on the sensory conflict theory (and its developments) of SS.

It has also being argued that the phenomenon of vection (the illusion of self-motion) could be a major cause of SS (Hettinger et al. 1990). However, whether or not vection and SS are associated is still debated, as it has been noted that an user can experience one phenomenon without the other under some circumstances (Keshavarz et al. 2015)

1.1.1. Sensory conflicts in SS

Conflicts between vestibular and visual systems have often been proposed as responsible for SS. The vestibular system senses head motion contributes to the perception of head movement, and is stimulated by accelerations of the head (Khan and Chang 2013). In addition to the vestibular system, the visual system has also been found to play a role in the generation of SS (Kennedy, Drexler, and Kennedy 2010). As the human body moves through an environment, specific patterns of light move from the centre to the outer portions of the retina, thus generating an optic flow cue that the brain uses to estimate self-motion through the environment (Bruder et al. 2012). The inputs of the somatosensory system are essential to communicate environmental information on the body position and movement to the brain (Scheidt et al. 2005). This information includes movements in space and the position of the body, referred to as proprioception. The human proprioceptive system helps to correct movements through interactions with the visual-motor feedback. Thanks to numerous nervous sensors, the human body can detect pressure and vibration, which can also help with navigation and orientation in the environment (e.g. the vibrations felt while running).

The auditory system is also widely involved in exploring and navigating through the environment; the ability to correctly localise sounds is an important tool to explore real and virtual environments. Through the basilar membrane in the cochlea, sound waves are converted into mechanical signals and then to electrical signals that various brain centres use to compare with incoming signals from both ears and localise the sounds. As an example, it has been shown that blind people can construct coherent spatial mental maps by using just virtual navigation with acoustic information (Picinali et al. 2014). Even though auditory cues are not part of the sensory conflict theory, there are evidences that auditory cues may contribute to SS (Keshavarz et al. 2014).

When the brain receives incongruent or asynchronous sensory inputs from different modalities (visual, vestibular, and auditory), SS can be generated as a maladaptive response. According to the neural mismatch model of SS (in the formulation presented in Reason 1978), when body movement occurs, a copy of the motor command and/or proprioceptive signals is compared and matched with the expectations/predictions based on the 'memories' of previous experiences of that movement. If there is a significant difference between the sensory inputs and the memorised movement patterns, a mismatch signal that further triggers the secondary mechanisms of mediating nausea and the accompanying symptoms of SS is generated (Reason 1978). It should be noted that the theory of sensory conflict is the framework within which the present research has been developed.

1.2. Sense of presence

The experience of the sense of presence is linked to the general subjective sense of feeling completely involved in the simulated environment (often referred as 'being there'; Cummings and Bailenson 2016). There have been attempts to understand and operationalise the psychological construct of 'sense of presence' (Grassini & Laumann 2020a; Slater 1999; Slater and Wilbur 1997; Steuer 1992; Witmer and Singer 1998), and several terminologies have evolved to refer to the same (or very similar) phenomenon.

Users experiencing a high sense of presence during the VR session reported the feeling of being in a 'different place' (Slater, Usoh, and Steed 1994). Sense of presence is generally considered an important aspect of a VR experience and eliciting a high sense of presence can be considered one of the advantages of VR as compared to traditional simulations. A high sense of presence has been linked to enhanced individual performance in tasks performed in the virtual world (Nash et al. 2000) or enhancing the effectiveness of VR-mediated training (Grassini, Laumann, and Rasmussen Skogstad 2020) for real-life tasks.

The influence of multimodal stimulation has been found to enhance the sense of 'being there' of an user. Auditory inputs were found to be important for self-motion perception (Campos, Ramkhalawansingh, and Pichora-Fuller 2018; Kapralos et al. 2004; Seno et al. 2012; Valjamaae 2009), and vibratory stimulation were shown to increase realism of a virtual scene, and user's perceived sense of presence (Sakamoto et al. 2016).

1.3. Sex differences in SS and sense of presence

A wide body of literature has reported that several individual factors may affect SS, and one of the most frequently cited is user's sex. Some research have indicated that women tend to be more susceptible to SS than men (Munafo, Diedrick, and Stoffregen 2017, but see Grassini and Laumann 2020b), although the reason for such sex-related difference is not well understood. It has been speculate that it may be relate to hormonal levels during the female menstrual cycle (see Biocca 1992; Pausch et al. 1992), physical differences in field of view between males and females (Biocca 1992), and gender difference in the self-report of perceived symptoms (Biocca 1992; Kolasinski 1995).

The effect of sex on sense of presence rating has also been quite popularly widely discussed (Felnhofer et al. 2012; Slater and Usoh 1994). However, published research has reported hetereogeneous results (Felnhofer et al. 2012; Gamito et al. 2008). Taken together, the literature suggests that males and females may differ in the way they experience virtual (and real) environments, and therefore experience different levels of SS and sense of presence probably depending on a number of different factors (Grassini and Laumann 2020b). However, it has yet to be specifically studied how different stimulation modalities may differently affect male and female users.

1.4. The present study

In the present study, we attempted to assess the efficacy of a vibrating seat to reduce SS during the simulation of a rollercoaster environment, presented using modern consumer-oriented HMD technology. Indeed, removing the SS-induced side effects may prompt the implementation of VR technology in a broad range of fields such as education and training, and all the applications requiring a prolonged use of VR technologies. A general approach that might be beneficial for reducing the intensity of SS involves applying non-drug interventions that have proven effective in reducing MS. MS-mitigation techniques are believed to positively influence SS. An approach to avoid intersensory conflict in MS is to reduce certain types of conflicting vestibular stimuli, such as by avoiding movement outside the axes of the motion or avoiding low-frequency movements. Synchronisation of the visual system and body movements proved effective to reduce the symptoms of MS, e.g. by tilting the head in turns or taking over the steering/control of the motion if possible (Koch et al. 2018).

Several studies have shown that adding multimodally sensory inputs helped reduce SS (Cevette et al. 2012; Gálvez-García, Hay, and Gabaude 2015; Reed-Jones et al. 2007; Zao et al. 2016). Particularly, the study by D'Amour, Bos, and Keshavarz (2017) experimentally created an increase airflow using fans and showed that it may be a viable method to reduce overall SS symptomatology. However, they did not find any effects for seat vibration. In contrast, Sawada et al. (2020) concluded that seat vibration may be a viable way to reduce the symptoms of SS. Due to the heterogeneity of the results reported in the scientific literature, and the relative novelty of the topic, the potential for seat vibration in reducing SS symptomatology remains unclear.

We hypothesised that the inconclusive results reported in the study of D'Amour, Bos, and Keshavarz (2017) could have been driven by the non-synchronized presentation of the stimuli, or by the simultaneous use of another type of simultaneous sensory stimulation (airflow). In the present study, we attempted to assess the efficacy of different multi-

Figure 1. Example of scenes from the roller coaster simulator ("Epic Roller Coaster" by B4T Games).

sensory stimulations to reduce SS during the simulation of a rollercoaster environment, presented using modern consumer-oriented HMD technology. Our investigation implemented a four-armed study conditions similar to D'Amour, Bos, and Keshavarz (2017), using auditory input instead of the airflow; and, similarly to Sawada et al. (2020) employed synchronized vibration and auditory/visual stimuli. The presentation of synchronous sensory stimulation, from a theoretical perspective, may be an important factor for the reduction of SS or for increasing sense of presence in a virtual environment.

The main goals of this study were: (1) to investigate whether presence/absence of mechanical chair vibration and presence/absence of auditory stimulation influences SS symptomatology during HMD-mediated VR experience, (2) to establish whether multi-sensory inputs influence the experienced sense of presence, and (3) to establish if SS and presence are related in our experimental framework. In line with the theory that links SS with sensory conflict, we hypothesised that auditory and vibratory stimuli coordinated with the simulated scene may reduce SS and increase sense of presence due to the improved realisticity of the scene. The secondary aim was to identify how participants' sex may influence how multi-sensory stimulation affects SS and presence

2. Method

2.1. Participants

Eighty participants (40 females) took part in the experiment (age range 19–33 years, mean = 24.10, SD = 2.51). The participants were selected from volunteers among the student population at the Norwegian University of Science and Technology (Trondheim, Norway). The participant number was established in line with published similar research (D'Amour, Bos, and Keshavarz 2017). All participants self-reported as not being affected by psychological disorders and as being generally healthy.

All the participants were presented with a short study description and asked to read and sign the informed consent before the experimental session. The study was conducted with the permission of the Norwegian Data Protection Agency (NSD), and in accordance with the ethical guidelines of the declaration of Helsinki.

2.2. Experimental design and materials

Participants were evenly assigned (20 per group), based on the order they were invited to participate to the experiment, and on their biological sex, to one of the four experimental groups: visual and vibration (group 1), visual-auditory (group 2), visual-auditory and vibration (group 3), and visual only (group 4). The sex of the participants was balanced for all the groups to control for possible sex effects. Participants were not explicitly told of the existence of the test groups other than their assigned group; however the experimenters were aware of them all (single-blind). All participants were exposed to the same visual stimulation: an approximately three-minute long, first-person view, roller coaster simulation (examples from the VR roller coaster simulator are presented in Figure 1). All the participants attended the experiment in a seated position; they each wore an HTC Vive Pro headset and handled the two standard controls. The software used for the simulation was the game 'Epic Roller Coaster' by B4T Games. Written permission for the use of the software was obtained from the copyright holders before the commencement of the present research.

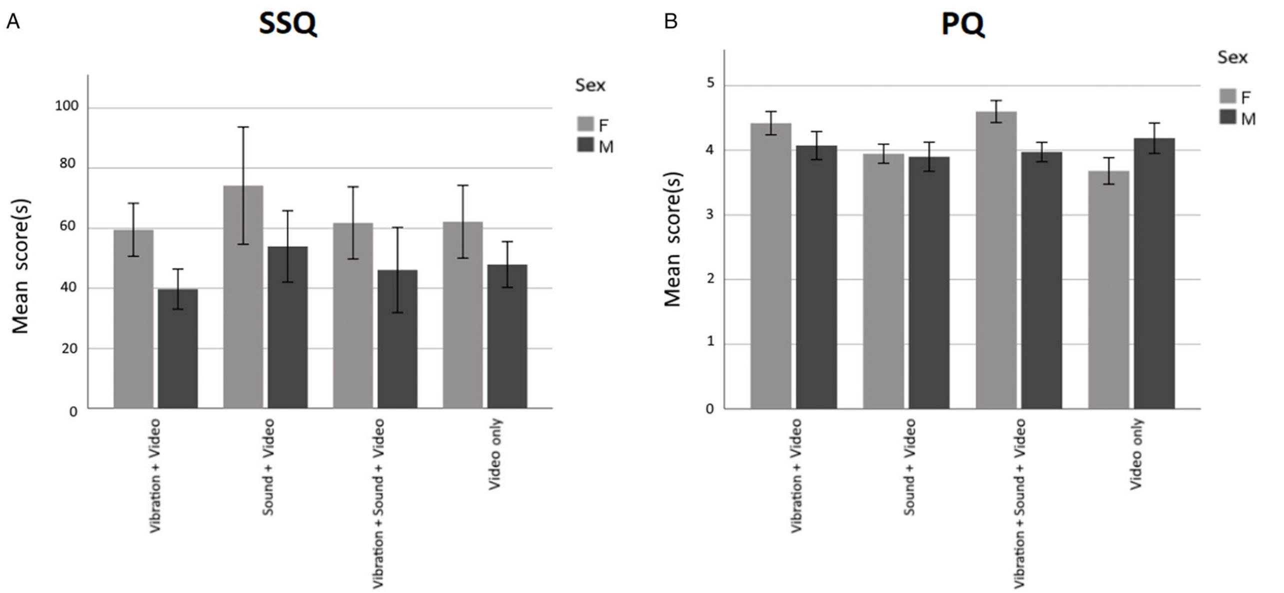

Figure 2. Panel A: SSQ Mean Scores (total SSQ) for the four different experimental conditions, for females (light columns)), and males (dark columns). Panel B: PQ Mean Scores. Error bars show standard error of the mean (SEM).

Even though three minutes might be consider a too short period to optimally promote SS an sense of presence, the high-arousing VR scenario promoted a good level of SS compared to the level reported in the literature (Saredakis et al. 2020). Furthermore, a short experiment had the advantage to not promoting boredom and tiredness in the participants, improving the quality of the questionnaire data collected after the experiment.

Mechanical vibrations were achieved using an Aurasound Bass Shaker Tactile Transducer (Frequency Range: 20–80 Hz, Resonance Frequency: 40 Hz, Force: 66.8 N, Peak Force: 132 N), attached underneath the participants' chair during the experiment. The vibration device did not provide low-frequencies oscillatory stimulations which have been shown to promote motion sickness (Diels and Howarth 2013). Vibration intensity of the equipment was modulated by the bass sounds of the VR environment. The bass sounds in the environment were connected to the actions taking place in the simulation (e.g. acceleration of the roller coaster cart, turns and movements, etc.). The VR environment was thought to be well-suited for such types of sound-induced vibration, as reported by the software developers of the VR scene (private correspondence). Auditory stimulation was provided using the headphones integrated in the HMD. The auditory stimuli were aligned spatially and temporally with the visual. Auditory cues were environmental sounds (e.g. waterfalls, birds sound, sound of the cart on the rails). The volume was adjusted by every participant to reach a comfortable level. The HMD used was an HTC-vive PRO (Resolution: 1440×1600 pixels per eye, screen: Dual AMOLED 3.5″ diagonal, screen refresh rate 90 Hz). The computer used was equipped with an intel core i7-8086K (4 GHz), 32 GB ram memory, and windows 10.

To investigate the degree of SS experienced by the participants, the simulator sickness questionnaire (SSQ, Kennedy et al. 1993) was used. Each item of the questionnaire was rated from 0 (no SS) to 3 (severe level of SS). The total score of the questionnaire was obtained using a weighted calculation among the items, as described in the literature (e.g. Walter et al. 2019).

To investigate the degree of presence experienced by the participants, a modified version of the Presence Questionnaire (PQ) by Witmer and Singer (1998) was used. The modified PQ (final number of items = 15) was obtained by removing the questions that referred to sound (as sound was not proposed in every experimental conditions) and controllers (as controllers were not needed for the roller-coaster scenario) from the original PQ (Witmer and Singer 1998). The items of the questionnaire had a scale from 1 to 7, with 1 referring to the lowest level of presence and 7 to the highest. The total score of the questionnaire for each subject was obtained averaging the score of the individual items (max score = 7). Both questionnaires were administered immediately after the VR experience.

We intentionally chose a between-subjects design over a within-subjects design. Following the arguments already reported in D'Amour, Bos, and Keshavarz (2017), the published literature has shown evidences for adaptation to SS and carry-over effects after repetition of the same nauseating stimulus (e.g. Hill and Howarth 2000; Keshavarz et al. 2018).

2.3. Data analysis and statistics

The data analysis software SPSS was used for the statistical analyses (IBM SPSS Statistics 26). The average scores for the total SSQ scores, as well as the PQ scores are reported in Figure 2. The relationship between sense of presence and SS was studied using a two-tailed Pearson's correlation.

Two separate three-way analysis of variance (ANOVA) were performed using the SSQ and PQ scores as dependent variables. Separate ANOVAs analyses were preferred over a multivariate analysis of variance (MANOVA) – proposed in D'Amour, Bos, and Keshavarz (2017) – as earlier correlation analyses revealed that our two dependent variables (SSQ and PQ scores) were largely uncorrelated, an such may negatively affect the power of the statistical test (Huang 2020; Tabachnick and Fidell 2019, French et al. 2008).

The between-subject independent variables included in the ANOVAs were: sound (present/absent), vibration (present/absent), and participant' sex (male/female). Finally *post-hoc* *t*-tests were performed to further explore interaction effects revealed by the ANOVAs. Males and females participant scores were analysed separately using PQ scores as dependent variable, and the condition vibration (present/absent) as the independent grouping variable. All statistical analyses were considered significant for $p<.05$.

3. Results

3.1. Main analysis

Pearson's correlation did not reveal a significant association between sense of presence and SS ($r = 0.075$, *p*hx2009;= .507). Three-way ANOVAs showed that auditory stimulation did not significantly affect SSQ scores nor PQ scores (*p*hx2009;= .442 and *p*hx2009;= .913). A significant main effect of vibration on PQ was found, F(1,72)hx2009;= 6.09, *p*hx2009;= .016, η^2phx2009;= .078, indicating that the experimental conditions where the vibration was included promoted an overall higher level of presence (M = 4.27, SD = 0.61), compared to those conditions were vibration was not included (M = 3.93, SD = 0.65). Vibration was found not to affect SSQ scores (*p*hx2009;= .371). A significant main effect of sex was found for SS total score, F(1, 72)hx2009;= 4.09, $p = .047$, $\eta^2 p = 0.054$, indicating that women (M = 64.41, SD = 42) reported a stronger SS than men (M = 46.93, SD = 32.47). No effect was found for sex on PQ scores (*p*hx2009;= .352). A significant interaction effect of Sex * Vibration was revealed for sense of presence F(1,72)hx2009;= 6.83, *p*hx2009;= .011, $\eta^2 p = 0.087$. No other interaction effects were revealed by the analyses ($p > .133$).

3.2. Post-hoc analyses

To understand the effect of vibration for males and female participants, we analysed participant of different sex separately, performing *t*-tests using vibration (present/absent) as a grouping variable. For female participants, vibration increased the perceived sense of presence, $t(38)=3.96$, $p<.001$, whereas, for male participants, experienced sense of presence was not affected by vibration (*p*hx2009;= .924). Figure 2 reports the overview of the mean scores divided by participants' sex.

4. Discussion

The purpose of the present investigation was to study the effect of multi-sensory stimulation – specifically vibration and sounds – on SS and sense of presence. SS theories on how direct stimulation of systems affected by sensory conflict can reduce SS (see e.g. Reason and Brand 1975) suggested the possibility that multi-sensory stimulation might be beneficial for reducing SS. Furthermore, increased presence (obtained increasing the level of immersion using multi-sensory stimuli) may be negatively associated with Weech, Kenny, and Barnett-Cowan 2019). An increase of realisticity of the simulation, due to diverse multi-sensory stimulation, could as well increase the experienced sense of presence (Welch et al. 1996). The main findings of the present study are that seat vibration did not reduce the level of SS. Nevertheless, it did increase the experienced sense of presence. Auditory stimulation did not show any effect either on SS or sense of presence. In the present study, female participants reported a higher degree of discomfort related to SS. This result is in line with some previous researches on SS and virtual reality (Munafo, Diedrick, and Stoffregen 2017). However, recent research showed that it is not generalisable, as it does not apply to all experimental settings (Grassini and Laumann 2020c). *Post-hoc* analyses revealed that the increase sense of presence associated with chair vibration was observed only for female participants. No statistically significant association between sense of presence and SS was found.

Our results for SS are partially coherent with those reported by D'Amour, Bos, and Keshavarz (2017). In their experiment (simulated bicycle ride), the addition of vibration to the seat did not reduce the symptoms of SS. However, their results were challenged by recent published studies (Lucas et al. 2020; Sawada et al. 2020), which found instead that adding vibration to a driving simulator can reduce the level of SS in the users. The methods used by Sawada et al. (2020) and D'amour et al. (2019) for delivering the vibration were similar to the one used in our study (vibration device under the chair), while Lucas et al. (2020) used a vibrating platform. Different methodologies for delivery vibratory stimuli may differently affect the user.

While in the present study we found that vibration increased sense of presence, the previous studies of D'Amour, Bos, and Keshavarz (2017) and Sawada et al. (2020) did not report the same finding. However, Sawada et al. (2020) reported an increased sense of realism for the condition were vibration was used, and realism has been shown to be one of the factors associated with sense of presence (e.g. Vinayagamoorthy et al. 2004; Welch et al. 1996). Importantly, D'Amour, Bos, and Keshavarz (2017) provided vibratory stimulation that were not coherent with the simulated environment, and this aspect of their experiment may have affected the realisticity of the virtual environment and therefore impaired the possibility of the seat vibration to increase the experienced sense of presence. The addition of vibration synchronized with the simulated environment in the present study might have elicited the sense of presence, thus proving as an advantageous feature to implement in the VR experience.

In the present study, the effect of vibration on sense of presence was highly significant in female users, but not significant in males. Assuming that such effect is produced only for women, as our *post-hoc* analyses suggests, the small sample of female users in the study of Sawada et al. (2020) may be the reason why the researchers did not find an effect of vibration on sense of presence at the group level. To the best of our knowledge, the present study is the first that showed that female participants may experience an increased sense of presence in VR when vibration stimuli are included in the simulation.

Providing vestibular cues that align with the visual scene may be able to reduce sensory conflict, thus potentially decreasing SS. However, high frequent vibration (D'Amour, Bos, and Keshavarz 2017) may not necessarily reduce a sensory conflict as the vibration was not coherent to the visual scene. Instead, the high frequent vibration may deliver 'noise' to the vestibular system which may mask a potential sensory conflict. Differently to the study of D'Amour, Bos, and Keshavarz (2017), in our experiment, the vibration stimuli were aligned with the experienced environment, and this may have driven the vibratory stimulation to increase the sense of presence.

A possible explanation for the vibration stimulation failing to reduce SS in the present investigation might be related to the methods used for delivering the vibration. Indeed, an intense stimuli might be required to reduce SS, and the vibratory stimuli in the seat of the participants only introduced a weak additional somatosensory stimulation. Weech et al. (2018) found that situating the source of vibration against the mastoid bone behind the ear significantly reduced SS. The type of vibratory stimulation used in Weech et al. (2018) might represent a more intense type of stimulation and have a greater effect than using a vibration chair. On the other hand, both the recent studies of Sawada et al. (2020) and Lucas et al. (2020) found that vibration reduced SS when a vibration chair or platform was used.

In our experiment, female participants experienced a higher sense of presence when vibration was used. It has been previously argued that females and males might experience moving environments (e.g. boats) and virtual environments (e.g. Biocca 1992; Kolasinski 1995; Munafo, Diedrick, and Stoffregen 2017) differently. Cognitive (Giammarco et al. 2015; Kimura 1999; Voyer, Voyer, and Bryden 1995), and physical differences between women and men (referred as sexual dimorphism, as proposed regarding SS in, e.g. Koslucher, Haaland, and Stoffregen 2016; Munafo, Diedrick, and Stoffregen 2017) may explain the different effects of multisensory stimulation (vibration in this case) on the experienced sense of presence. Furthermore, it has been reported that female users experience a higher (compared to males) feeling of vection (D'Amour, Bos, and Keshavarz 2017). The vibratory stimulation may stimulate the vestibular and somatosensory systems in a way that down-modulate a particularly high feeling of vection. Nevertheless, these explanations are only speculative, and more research is needed to better understand the phenomenon.

The present study used a between-subject design, and the four study groups were established by randomly selecting the participants for each group. Since each participant was only tested with one of the four conditions, the design avoided potential learning and adaptation effects that may have arisen due to the repeated exposure to the VR simulation. However, choosing a between-subject instead of a within-subject experimental design introduces variables that are difficult to assess and control in the study, for example individual susceptibility to SS, that may have been different between groups of participants assigned to different experimental conditions.

The vibration device (bass-shaker) was synchronized with bass auditory outputs of the VR scene. However, although a vibration was coherently provided with the scene (e.g. following jumps and acceleration movements of the roller-coaster cart), such a stimulation is just one single part of the complex vestibular and somato-sensory stimulation that is experienced when in a real roller-coaster. This may have greatly hindered the effectiveness of the method as an SS reduction technique.

Previous research has also found that SS symptoms can progressively increase over time during the VR immersion. However, in the present study, the participants were exposed to the VR environment only for around three minutes. The short duration of the exposure may have affected the results by impairing the development of SS. However, the overall high scores (in line with the scores of participants labelled as 'simulator sick' (e.g. Walter et al. 2019; Munafo, Diedrick, and Stoffregen 2017) in the SSQ seems to reject this hypothesis. It is possible that sound and vibration may have an effect on SS, but the effect is too small to be detectable with the chosen sample size.

Our results may not be generalisable to every types of VR simulation—the used VR simulation (roller-coaster) may particularly promote SS (and MS when experienced in real life), and the vibrating seat might be insufficient to reduce it in the majority of the participants. Furthermore, the use of the between-subject design, while reducing the risk of training and adaptation effects, may have introduced a number of uncontrolled variables that might have affected the results.

Future studies can attempt to use more relevant vibration stimuli (e.g. producing higher intensity vibration, or stimulating different parts of the body) as well as other types of multi-sensory stimulation, such as chair movements during the HMD-mediated simulation, to potentially provide a more relevant and realistic stimulation.

5. Conclusion

The present study tested the possibility of multi-sensory stimulation during the use of HMD-mediated VR, to reduce SS and increase the user's experienced sense of presence. The data suggest that seat vibration does not affect SS, but may be able to promote an higher level of sense of presence. *Post-hoc* analyses showed that women, but not men, experienced an increase level of presence when vibration was included in the experiment.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Author contributions

S.G. was responsible for the study idea, the experimental design, the data analysis, and for writing the present manuscript. K.L. provided fundings for the project, gave feedbacks at every stage of the study, and extensively commented on earlier drafts of the present manuscript. V.M.T. and S.T. gave early feedbacks on the study design, had the responsibility to test the participants in the laboratory, and commented earlier drafts of the manuscript. All the authors have read and approved the final version of the article.

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Data availability statement

The data used for the present article can be retrieved at the DOI: 10.5281/zenodo.4287334

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