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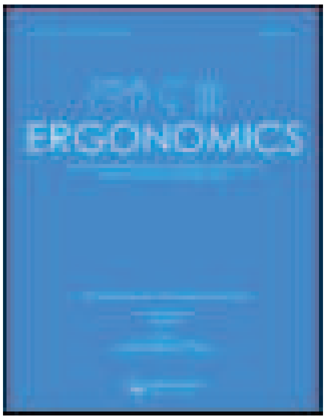

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A comparison of techniques to mitigate Simulator Adaptation Syndrome

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A comparison of techniques to mitigate Simulator Adaptation Syndrome

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We investigated the effectiveness of galvanic cutaneous stimulation (GCS) and auditory stimulation in mitigating simulator adaptation syndrome (SAS). Fifteen drivers (9 men; *M* age = 23.2 years) participated in a driving simulation experiment comparing three different stimulation conditions (GCS, auditory stimulation and no stimulation as a base line condition) in curves on a virtual urban circuit. GCS and auditory stimulation decreased SAS by reducing head sway. Both sources of stimulation can be recommended as countermeasures against SAS. We encourage the use of stimuli which influence the balancing ability to the design of future simulator protocols and devices to mitigate SAS.

Practitioner Summary: We have provided evidence on the effectiveness of two different stimuli as countermeasures against simulator adaptation syndrome (SAS). We concluded that the positive impact of body sway might play a role in SAS and therefore encourage the use of stimuli which influence the balancing ability to mitigate the symptoms of SAS.

Keywords: simulator adaption syndrome; driving task; simulator sickness questionnaire; galvanic cutaneous stimulation; auditory stimulation

1. Introduction

Simulator adaptation syndrome (SAS) is a condition which can produce dry mouth, drowsiness, disorientation, vertigo, nausea, dizziness and vomiting (Ebenholtz 1992; Cobb et al. 1999). The aetiology of SAS is not completely understood (for an extensive review of SAS see Mollenhauer 2004; J. G. Reed-Jones 2011). Several explanations for the syndrome have been proposed, such as the suggestion that SAS is caused by a mismatch between actual and expected visual, vestibular or proprioceptive inputs in the context of driving (sensory conflict theory; Reason and Brand 1975) or an inability to learn how to maintain postural stability in the simulator (postural instability theory; Riccio and Stoffregen 1991).

SAS leads to population biases and data loss (Stanney, Mourant, and Kennedy 1998), so there has been interest in techniques for mitigating SAS; galvanic cutaneous stimulation (GCS) has shown promise as a mitigation technique. GCS involves the stimulation of superficial large-diameter cutaneous nerve fibres (Levin and Hui-Chan 1993) using an electric current with a relatively short pulse duration at an intensity below the motor threshold. GCS is usually applied to the neck muscles (usually the sternocleidomastoids) approximately 3–4 cm below the mastoid process (R. Reed-Jones et al. 2008; Gálvez-García, Hay, and Gabaude forthcoming). This area is known to contain a high subcutaneous density of sensitive fibres (Lazorthes 1981). It has been postulated (Pérennou et al. 2001) that GCS stimulates the parietal–insular vestibular area. This area has neurons that respond to vestibular and visual stimulation and somaesthetic stimulation of the neck, providing central nervous system data on the position of trunk and head in space (Grüsser, Puase, and Schreiter 1990a, 1990b). GCS appears to affect these neurons, improving the balancing ability or restoring the normal balance in the context of vestibular sensory deprivation, including for patients with vestibular deficits (Vitte, Semont, and Berthoz 1994), neglect patients (Guariglia, Coriale, and Cosentino 2000; Pérennou et al. 2001) and in fixed simulators, where there is a lack of vestibular information. R. Reed-Jones et al. (2008) found that application of GCS improved balance in subjects performing a simulator task, and the improvement in balancing ability was correlated with mitigation of SAS – more specifically, the authors reported that balancing ability was negatively correlated with reported symptoms of SAS; however, they did not provide an explicit analysis of the relationship between SAS and GCS. Only two studies have replicated the positive impact of GCS on SAS without measuring the balancing ability, Chu et al. (2013) showed that GCS mitigated SAS in a flight simulator and Gálvez-García, Hay, and Gabaude (forthcoming) provided evidence that GCS mitigated SAS if applied when the driver was on the curves or at random points on a circuit in a driving simulator, whilst J. G. Reed-Jones et al. (2009) found no effect of GCS in a driving simulator. In summary, although the relationship between GCS and the balancing ability

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has been well documented, there is a much less evidence that GCS has a positive impact on SAS (Chu et al. 2013; Gálvez-García, Hay, and Gabaude forthcoming) or for a correlation between the balancing ability and SAS (the only study to demonstrate this correlation was that of R. Reed-Jones et al. 2008). Our first objectives were therefore to contribute to the body of evidence on the effectiveness of GCS as means of mitigating SAS and the correlation between the balancing ability and SAS.

The third aim of the research was to investigate whether auditory stimulation mitigated SAS. Auditory stimulation was of interest as a potential mitigation technique because it can influence the vestibular system, improving the sense of balance and thus reducing simulation symptoms. Previous studies have shown that auditory stimulation activates vestibular receptors and vestibular areas such as the parietal–insular vestibular area (Janzen et al. 2008; Lopez, Blanke, and Mast 2012; Miyamoto et al. 2007; Schlindwein et al. 2008); however, it is still unclear how the auditory system contributes to the balancing ability. The auditory signal used in the aforementioned studies has also been shown to have a negative impact on the balancing ability (e.g. Plutchik 1959; Guest et al. 2011), perhaps because of the high intensity of the auditory signal used (around 100 dB; similar to that of a car horn). Other studies using less-intense stimuli have shown that auditory stimulation has a beneficial effect on body stability; for example, Mangiore (2012) reported that auditory white noise improved body stability in patients with vestibular problems (as in fixed simulators). The beneficial effect of auditory stimulation is probably due to activation of the vestibular system. Liégeois-Chauvel et al. (2003) found that white noise evoked EEG responses in the insula (part of vestibular cortex) and it has been shown that stimulation of the insula can evoke vestibular sensation (Blanke et al. 2002; Kahane et al. 2003; Penfield 1957). In this study, we investigated the impact of white noise (75 db) on postural control, following up earlier research by Mangiore (2012), and on SAS. White noise at this intensity is reported to be detectable but not annoying (e.g. Söderlund, Marklund, and Lacerda 2009).

We carried out an experiment comparing the effects of GCS, auditory stimulation (white noise) and no stimulation (baseline condition) on SAS and body balance. Head postural stability (head sway) as used as a measure of balance as previous research has shown that head sway can be used to index the balancing ability (Easton et al. 1998; J. G. Reed-Jones 2011).

We also investigated how GCS and auditory stimulation affected the driving performance to contribute to the small body of literature on this issue. Previous research (Gálvez-García, Hay, and Gabaude forthcoming; J. G. Reed-Jones et al. 2009) failed to find an effect of GCS on the driving performance.

We hypothesised that GCS would have a positive impact on balancing ability (less head sway), a relationship demonstrated previously by R. Reed-Jones et al. (2008). We also hypothesised that balancing ability would be negatively correlated with SAS (head sway would increase in proportion to SSQ scores) and that auditory stimulation would improve balancing ability and thus mitigate SAS.

2. Methods

2.1 Participants

Fifteen participants (9 men) took part in this study. The mean age of participants was 23.2 years, ranging from 19 to 26 years. All participants had normal or corrected-to-normal vision, were without hearing or vestibular impairment and were not fitted with a pacemaker, or taking medication which might have an impact on driving. All participants had driven at least 3000 km the previous year. They were naive to the purpose of the experiment and all received a 6 Euro gift voucher in return for their participation. Prior to the experiment, potential participants were screened for predisposition to motion sickness using the Motion Sickness Susceptibility Questionnaire (MSSQ; Golding 1998); for ethical reasons, we did not include individuals with an MSSQ scores higher than 65 (75th percentile) in the experiment, because of their susceptibility to sickness; this resulted in exclusion of one potential participant. The mean MSSQ score in our sample was 33.79 ± 17.31. This study was performed in accordance with the ethical advisory internal committee of the Granada University (Spain) and all participants gave informed consent.

2.2 Apparatus and stimuli

The experiment was carried out in an instrumented fixed-base simulator with sensors on the pedals, wheels and gearbox. The simulator was also equipped with virtual reality-based visual system. A high-speed digital camera (S-MOTION) was used to record the head movements. The virtual environment simulated a 7.5 km flat route through an urban environment. Participants negotiated 18 curves (9 lefts and 9 rights) gradual or sharp 90° turns. The gradual turns (GTs) consisted of a 70 m lead-in, a 140 m curve, and a 70 m lead-out (240 m in total). The sharp turns (STs) were modelled on a T-junction and consisted of a 40 m lead-in, 40 m curve transitioning immediately to the next road (80 m in total). The straight sections (SCs) of the circuit were between 200 and 300 m in length. The topography of the circuit was as follows: 300 m SC; right

ST; 250 m SC; left GT; 240 m SC; left ST; 210 m SC; right GT; 300 m SC; right ST; 225 m SC; left GT; 260 m SC; left ST; 215 m SC; right GT; 300 m SC; right ST; 250 m SC; left GT; 280 m SC; left ST; 220 m SC; right GT; 300 m SC; right ST; 250 m SC; left GT; 200 m SC; left ST; 220 m SC; right GT; 280 m SC; right ST; 200 m SC.

We measured SAS using the Simulator Sickness Questionnaire (SSQ; Kennedy et al. 1993). The questionnaire is composed of 16 symptoms that the participant has to rate on a scale from none (0) to severe (3). We analysed the SSQ total scores (SSQ TS) provided by the questionnaire in the three different stimulation conditions.

Auditory stimulation (white noise at 75 dB) was delivered bilaterally through headphones. GCS was delivered using the same procedure as previous studies (Gálvez-García, Hay, and Gabaude forthcoming, R. Reed-Jones et al. 2008), and GCS supplied by a linear stimulus isolator device (STMISOLA, Biopac) was applied through electrodes (2.5 cm^2) placed bilaterally on the neck, on the top of the sternocleidomastoid muscles. GCS output was adjusted individually to the participants' thresholds and delivered at an intensity ranging from 0.6 to 1.25 mA. Threshold was assessed before the driving trials, and testing started at 0.05 mA and was increased in increments of 0.05 mA until the threshold was reached. Threshold was determined from verbal reports of sense of movement and the investigator's visual observation of very small movements of the head. If a particular stimulus intensity elicited a borderline or ambiguous response, the experimenter increased the intensity by 0.05 mA and then reduced it again to confirm the presence and severity of the disturbance. For all participants, the stimulation applied was adjusted to twice the determined threshold. As a safety precaution, the software delivering GCS was programmed to deliver a maximum of 200 mJ (according the device instruction manual more than 300 mJ is dangerous).

2.3 *Procedure*

Participants completed a familiarisation driving session lasting about five minutes in a virtual urban scenario before the experiment. After the familiarisation, participants drove the experimental circuit. They were instructed to drive in the right lane, not to exceed 90 km/h and to adjust their speed on the curves in order to perform this manoeuvre efficiently. Participants drove the simulation circuit three times, once under each of the three experimental conditions: (1) no stimulation condition; (2) GCS condition, GCS was delivered from 40 m before a curve until the end of the curve and (3) auditory stimulation condition, auditory stimulation was delivered from 40 m before a curve until the end of the curve. The order of the conditions was counterbalanced across participants to control for practice effects. Participants completed the SSQ after each circuit.

2.4 *Design*

SAS indexed by SSQ TS in the three experimental conditions (no stimulation, GCS and auditory stimulation). The exclusion criterion was a total SSQ TS more than 2.5 standard deviations (SDs) from the mean. No data were excluded from the analysis.

Head sway was measured as the SD of head movements (measured in pixels) along the X and Y axes during the curves in the three experimental conditions.

Four driving variables were measured to assess the differences in driving behaviour between the three experimental conditions: average speed (km/h); accelerator percentage (percentage of depression of accelerator pedal); brake percentage (percentage of depression of brake pedal) and SD of the steering variability angle during the curves.

Shapiro–Wilk tests confirmed that all variables were normally distributed. SSQ TS; $W = 0.93, p = 0.25$, head sway along the X-axis; $W = 0.92$, $p = 0.21$, head sway along the Y-axis; $W = 0.92$, $p = 0.19$, average speed; $W = 0.96$, $p = 0.77$, accelerator percentage; $W = 0.90$, $p = 0.12$, brake percentage; $W = 0.95$, $p = 0.53$, SD of the steering variability angle; $W = 0.91, p = 0.16$. Repeated measures (within factor) ANOVA and planned comparisons were used to compare SSQ scores and driving performance variables in the three stimulation conditions. Eta-square (η^2) was also calculated to provide a measure of effect size. Pearson's correlation coefficients were used to evaluate the relationship between head sway (along the X and Y axes) and SSQ TS (we had hypothesised that head sway would increase in proportion to SSQ TS). The Bonferroni correction procedure was applied to significance levels for planned comparisons to reduce the overall probability of type I errors. Results were therefore considered significant at $p < 0.05/4$, i.e. $p < 0.0125$ (driving performance variables; four ANOVAs were carried out for these variables) or $p < 0.05/2$, i.e. $p < 0.025$ (head sway; two ANOVAs).

3. Results

3.1 *SSQ scores*

Data of SSQ TS are presented in Figure 1. There was an effect of condition on SSQ TS ($F(2,28) = 18.42, p < 0.001, \eta^2 = 0.66$), with significantly higher scores in the no stimulation condition (49) than the GCS condition (23; $p < 0.001$) and auditory stimulation condition (23; $p < 0.001$). There was no difference between the GCS and auditory stimulation conditions ($p = 0.89$).

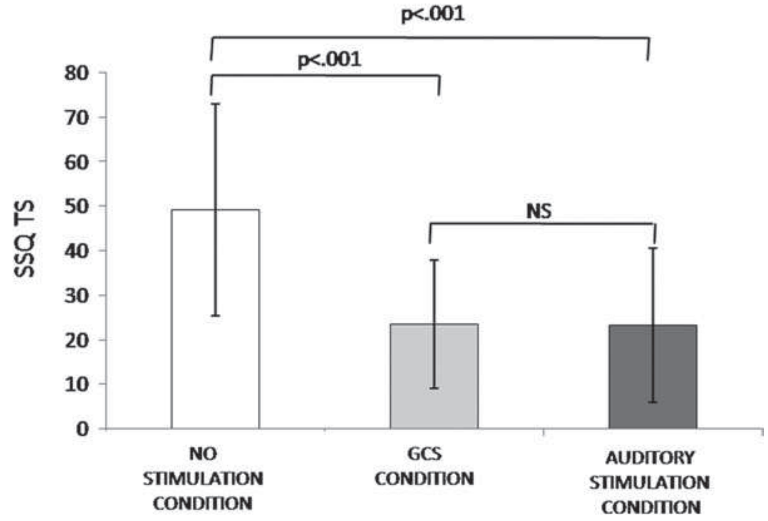

Figure 1. Mean and standard error for post-drive SSQ TS and comparison between experimental conditions.

3.2 Head sway

Data on head sway along the *X* and *Y* axes are presented in Figure 2. There was a condition effect on head sway along the *X*-axis ($F(2,28) = 62.01$, $p < 0.001$, $\eta^2 = 0.67$), with more head sway in the no stimulation condition (9.31) than the GCS condition (5.14; $p < 0.001$) and auditory stimulation condition (6.08; $p < 0.001$); there was also more head sway in the GCS condition than the auditory stimulation condition ($p < 0.001$). There was no difference between the conditions in head sway along the *Y*-axis ($F(2,28) = 0.38$, $p = 0.69$, $\eta^2 = 0.01$).

3.3 Correlation between SSQ scores and head sway

Correlations between SSQ TS and head sway are presented in Table 1. SSQ TS was positively correlated with head sway along the *X*-axis, i.e. variability in head position increased with severity of SAS symptoms for all the conditions of stimulation. There was no correlation between SSQ TS and head sway along the *Y*-axis.

3.4 Driving performance variables

Data on driving performance are presented in Table 2. We did not find any difference between conditions.

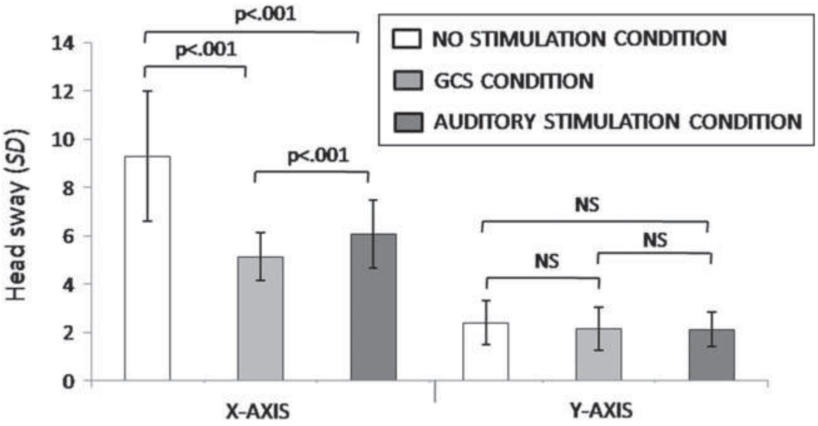

Figure 2. Mean and standard error for head sway and comparison between experimental conditions.

Table 1. Correlation coefficients between SSQ TS and head sway along the *X*- and *Y*-axes and comparison between the experimental conditions.

	X-axis	*Y*-axis
No stimulation condition	0.57 ($p = 0.02$)	0.09 ($p = 0.75$)
GCS condition	0.83 ($p < 0.001$)	−0.11 ($p = 0.70$)
Auditory stimulation condition	0.60 ($p = 0.02$)	−0.14 ($p = 0.60$)

4. Discussion

This research has several aims. First, we will replicate previous results which suggested that GCS mitigates SAS (Chu et al. 2013; Gálvez-García, Hay, and Gabaude forthcoming) and extend the limited body of evidence on effects of GCS. Second, we will add to the evidence on a putative correlation between the balancing ability and SAS (R. Reed-Jones et al. 2008). Third, we will test whether auditory stimulation improved balancing ability, as one previous study had suggested (Mangiore 2012) and whether balance was negatively correlated with SAS. Fourth, we will investigate how GCS and auditory stimulation influenced various driving performance variables.

Our data corroborated earlier studies showing that GCS mitigates SAS: Chu et al. (2013) found that GCS reduced SSQ TS in a flight simulator and Gálvez-García, Hay, and Gabaude (forthcoming) reported that GCS reduced SSQ TS when applied on curves or intermittently at random intervals in a driving simulator. We therefore recommend that GCS be used in future driving simulation experiments.

Analysis of head movements showed that GCS affected balancing ability. There was less head sway (4.16 SD) along the *X*-axis (medial–lateral movements) in the GCS condition than the no stimulation condition. As stated in the Introduction section, improvement in balance is a well-established effect of GCS, having been demonstrated on a simulator task (R. Reed-Jones et al. 2008), in patients with vestibular deficits (Vitte, Semont, and Berthoz 1994) and in neglect patients (Guariglia, Coriale, and Cosentino 2000; Pérennou et al. 2001); however, only R. Reed-Jones et al. (2008) reported a correlation between the balancing ability and SAS; these authors observed that the balancing ability was negatively correlated with the reported symptoms. Our results confirmed their finding; we found that the head sway increased with the severity of sickness symptoms in all the experimental conditions (no stimulation, GCS and auditory).

White noise also had an impact on balancing ability; there was less head sway in the auditory stimulation condition that in the no stimulation condition (3.23 SD). This result corroborates Mangiore's (2012) earlier demonstration that auditory white noise improved balance and equilibrium in patients with vestibular problem. A similar effect was reported by Easton et al. (1998) who showed that bilateral auditory stimulation with human voice sounds improved the balancing ability in both sighted and visually impaired subjects. We found that auditory stimulation reduced SAS symptoms, presumably as a consequence of the improvement in body stability. SSQ TS was lower in the auditory stimulation condition than in the no stimulation condition. There were no differences between SSQ scores in the auditory stimulation and GCS conditions, so both techniques can be recommended equally for decreasing SAS.

The driving performance variables showed no difference between the no stimulation condition, GCS condition and auditory stimulation condition. This finding is in line with previous literature that did not find any significant driving performance variable differences when GCS was applied (Gálvez-García, Hay, and Gabaude forthcoming; J. G. Reed-Jones et al. 2009). Although the interpretation of null effect could be controversial, it is important to note that at least GCS and auditory stimulation did not adversely affect any driving variable, which is fundamental for the recommendation of both sources of stimulation for future interventions reducing SAS.

Table 2. Driving performance variables (average speed, accelerator percentage, brake percentage and steering variability angle) and comparison between the experimental conditions.

	Average speed (km/h) F(2,28) = 0.57, $p = 0.57$, $\eta^2 = 0.01$	*Accelerator percentage (%)* F(2,28) = 0.78. $p = 0.47$, $\eta^2 = 0.01$
No stimulation condition	65.78	17.05
GCS condition	66.22	16.38
Auditory stimulation condition	63.63	15.82
	Brake percentage (%) F(2,28) = 0.26. $p = 0.78$, $\eta^2 < 0.01$	*Steering variability angle (SD)* F(2,28) = 0.03. $p = 0.97$, $\eta^2 < 0.01$
No stimulation condition	5.57	1096.26
GCS condition	4.97	1093.17
Auditory stimulation condition	5.09	1098.86

It should be noted that although GCS and auditory stimulation mitigated symptoms of SAS, SSQ scores were approximately 47% lower in these conditions – they did not abolish SAS altogether. SSQ scores above 20 indicate significant discomfort (Webb et al. 2009), and in our experiment SSQ TS was higher than 20 in the GCS (23.44) and auditory stimulation conditions (23.18).

On the basis of these results, we conclude that both sources of stimulation had a beneficial impact on balancing ability, which is negatively correlated with SAS; however, the exact mechanism by which GCS and auditory stimulation influence balance remains unclear. Although we did not address mechanism in this research, we consider it important to provide a brief discussion of the processes by which the types of stimulation we used may affect balance. It has been argued that GCS improves postural control because the intensification of visual perturbation forces a sensory recalibration (R. Reed-Jones et al. 2008) or that GCS intensifies awareness of the spatial orientation of the body (Pérennou et al. 2001). White noise may improve postural stability by activating the vestibular system and producing a similar effect to GCS; Liégeois-Chauvel et al. (2003) found that white noise evoked EEG responses in the insula (part of vestibular cortex) and it has been shown that stimulation of the insula can evoke vestibular sensation (e.g. Blanke et al. 2002). Studies of auditory feedback have suggested another plausible explanation for the beneficial impact of auditory stimulation on body balance (see Dozza, Horak, and Chiari 2007 for an extensive review). In these studies, individually calibrated auditory feedback provided subjects with information about their body sway. This method produced a substantial reduction in body sway in subjects with bilateral vestibular loss when the environment provided limited visual and somatosensory information (Dozza, Chiari, and Horak 2005; Hegeman et al. 2005). It is suggested that auditory biofeedback works because it provides the nervous system with augmented sensory information corresponding to the information that would normally be provided by the vestibular system to compensate for lost vestibular information. In this experiment, auditory stimulation may have increased the sensory information available to the vestibular system to compensate for the absence of vestibular information and thus have influenced the balancing ability. This proposed mechanism is similar to the stochastic resonance (SR) phenomenon. SR is a statistical phenomenon resulting from an effect of noise on information transfer; SR occurs when the addition of a random interference noise (in our experiment, the auditory stimulation) to a weak signal (a sub-threshold stimulus; in our experiment, the vestibular information) enhances the sensitivity of the system used to detect it (Moss, Ward, and Sannita 2004).

This study has several limitations, but the most important are the sample size and range of stimuli. It is essential that these results are replicated in a broader sample, e.g. one including participants with greater variability in predisposition to SAS and using a wider range of stimuli, e.g. tactile stimuli, another auditory stimulus and methods such as auditory biofeedback method. Further research is also needed to determine whether our findings generalise to other cohorts, scenarios and simulators and to determine the mechanism by which the various forms of stimulation influence balance and thus SAS.

Finally, we want to conclude highlighting the applicability of our research. (a) We have confirmed that GCS and auditory stimulation are effective in reducing SAS symptoms in a fixed-base simulator. More specifically, we found that SSQ TS was approximately 47% lower under GCS and auditory stimulation. These findings should help researchers to counteract SAS in participants receiving simulator-based training. (b) We confirmed the correlation between the balancing ability and SAS, a relationship which is of fundamental importance to the design of future simulator protocols and devices to mitigate SAS.

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Disclosure statement

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