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Brightness and contrast do not affect visually induced motion sickness in a passively-flown fixed-base flight simulator ☆

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ABSTRACT

Background: Visually Induced Motion Sickness (VIMS) or simulator sickness is often elicited by a visual stimulus that lacks the appropriate vestibular or proprioceptive feedback. In this study, we chose to investigate the effects of brightness and contrast of the visual scene on VIMS.
Hypothesis: We hypothesized that visual environments differing in brightness or contrast would differentially induce VIMS. The symptoms of VIMS should be most severe for the combination of high brightness and high contrast and conversely lowest for the low brightness and low contrast condition.
Methods: 33 healthy subjects were tested in a fixed-base flight simulator. Each subject flew in four consecutive but counterbalanced conditions during one large experimental session. The four conditions consisted of identical recorded flight paths, differing only in brightness and contrast in a fully crossed design. VIMS was assessed with the Simulator Sickness Questionnaire and the Fast Motion Sickness scale administered during and after each condition. Postural Sway (PS) was measured after each condition.
Results: All four brightness and contrast conditions were found to be effective in that they increased PS and elicited moderate VIMS. However, there were no main or interaction effects for brightness or contrast.
Conclusions: Our findings suggest that brightness and contrast do not modulate the induction of VIMS. This conclusion may be limited to moderately provocative stimuli.

1. Introduction

Ever-evolving virtual environments are part of modern life, from entertainment to professional purposes. One example of such a virtual environment is a flight simulator. Used today both for entertainment and training purposes, flight simulators offer realistic environments to the extent that flight training hours can be replaced by corresponding simulator hours [12]. In a significant number of subjects, the use of virtual environments is hampered by the occurrence of Visually Induced Motion Sickness (VIMS), a phenomenon commonly experienced in highly immersive environments. Various definitions of VIMS have been proposed. We adopt the position that any deviation from normal well-being induced by a mismatch between physical movement and perceived motion is an expression of VIMS.

1.1. Motion sickness theories

Although many different theories have been advanced to explain and predict VIMS, no unified theory exists that accounts for the elicitation and all aspects of this disorder. For a comprehensive overview, please refer to Keshavarz et al. [21].

Arguably the most cited theory of Motion Sickness (MS) is the sensory conflict theory by Reason and Brand [29]. It states that "motion sickness is a self-inflicted maladaptation phenomenon [...], which occurs at the onset and cessation of conditions of sensory rearrangement when the pattern of inputs from the vestibular system, other proprioceptors and vision is at variance with the stored patterns derived from recent transactions with the spatial environment". Thus, according to the sensory conflict theory, the interactions of the visual, vestibular and proprioceptive systems are the basis of the genesis of MS.

VIMS may be construed as an instance of a sensory conflict in which the visual system perceives self-movement while the vestibular and proprioceptive systems perceive a stationary environment. VIMS is also known as "cyber-sickness", "virtual

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reality sickness", "gaming sickness", "cinerama sickness", or "simulator sickness". The illusory impression of ego-movement in the absence of physical motion is called vection. The perceived visual movement accompanied by a lack of a correspondent physical acceleration causes a discrepancy of visual-vestibular information (i.e. a sensory conflict) which in turn results in VIMS [3,14]. It is nevertheless important to note that the exact correlation between vection and VIMS is the issue of extensive debate [23].

Reason [28] introduced the neural store into his view of sensory conflict theory, accommodating the role of past motion experience. When a movement is planned or registered by the sensory organs, it is compared to similar stored movements from the past. In the case that the newly sensed pattern of movement fails to fit a previously stored movement, it may provoke MS. Following Reason [28], Keshavarz et al. [21] have argued that MS cannot solely be explained by a concurrent sensory mismatch. Afferent sensory information can be stored, altered, even anticipated—and thus influence the evaluation of the current afferent information.

The ecological theory of motion sickness and postural instability [32] is another attempt at providing an etiologic explanation for the genesis of MS. This theory builds on the ecological theory of orientation perception, which postulates that the perception of upright stance is not determined by the acting gravitational forces [40]. The authors argue that concordance of sensory information is not required or expected. Instead, MS should occur when an individual is unable to use or has not yet learned the appropriate strategies necessary to maintain a stable posture. On several occasions, Stoffregen and others found that no MS was elicited even though a sensory conflict was present (e.g. [8,31,41]). Postural instability is hypothesized to precede the onset of MS symptoms and to be a prerequisite for all other symptoms. According to Riccio and Stoffregen [32], motion sickness is preceded by significant increases in several indices of Postural Sway (PS). Stoffregen and Smart [41] also showed that PS preceded the subjective symptoms of MS. They went on to show that a correlation exists between the pre-exposure postural sway of a subject and his or her vulnerability to MS. Subjects with high pre-exposure PS showed significantly higher MS values than those with lower pre-exposure PS.

While some studies support this theory, numerous findings cannot be reconciled with this hypothesis [5,21,26]. According to Bos [5] the unresolved issues include, but are not limited to, the fact that people without functioning organs of balance do not get sick from motion; negative correlations that have been found between VIMS symptoms over time and postural instability; and medical conditions, such as Ménière's disease, where patients experience symptoms of MS while lying in bed. Bos [5] concluded that while MS and PS may be linked by a shared mechanism, the co-occurrence of these two phenomena does not establish causality.

1.2. Visual perception of light

A visual stimulus can be described using various parameters (e.g. sharpness, saturation, hue, etc.), which affect the way we perceive the stimulus [46]. As much as we know about these parameters, their effect on the elicitation of VIMS has not yet been investigated. Thus, we have focused on two of the most prominent features of the visual stimulus, its brightness and contrast.

It is beyond the scope of this article to give an in-depth account of theories on brightness and contrast and their role in human visual perception. Basically, **brightness** is the amount of light originating from a specific target or a scene [2]. It is also referred to as luminance. **Contrast** is the difference between maximum and minimum intensities of a pattern or a scene, relative to the overall intensity [6].

Whereas brightness is the physical dimension of the amount of light emitted or reflected from the scene, **lightness** refers to the subjective light intensity perceived by the viewer [1]. Although not the subject of this study, it is nevertheless of importance to differentiate between brightness and lightness in the following discussions.

1.3. Vision at high and low intensities

Following the separate definitions of brightness and contrast, a closer account of their possible interaction is given in the following. Visual acuity and visual sensitivity vary with luminance [46]. While the cones in the human eye allow for high acuity in well-lit environments, the rods optimize sensitivity in low brightness, at the account of acuity [6]. As both contrast and luminance may weaken the stimulus with respect to its ability to induce VIMS, it is of interest to explore the role of brightness *and* contrast as well as their possible interaction.

1.4. Brightness & contrast in flight

Both brightness and contrast vary extensively within different flight conditions, such as night flight or flight in different weather conditions.

1.4.1. Brightness in flight

Changes in ambient lightness have crucial effects on man's perception of his environment. One does not have to be a pilot to be able to appreciate the fundamental differences between day and nighttime flight. Night vision sensors have been developed in order to overcome the limitations on performance posed by darkness. These technologies employ various methods (e.g. infrared imaging and residual light amplification) in order to enable the human eye to perceive the environment beyond its normal brightness envelope. In terms of ambient brightness, we therefore suggest that flight can nowadays be divided into three types of brightness levels: daytime flight, nighttime flight, and aided nighttime flight.

1.4.2. Contrast in flight

Wright [46] has referred to changes in contrast as crucial when describing the effects of fog. Visual stimuli during flight in clear weather are experientially different from those in flight in fog or haze. Although the term "contrast" is not used in the aviation jargon, it is our contention that, following Wright's observation, contrast is the salient variable associated with changes caused by fog.

1.5. Brightness, contrast and VIMS

As previously discussed, both brightness and contrast play a significant role in providing visual information of the perceived environment. Based on the theories of sensory conflict [29] and neural storage [28], changes in the visual stimulus could induce different degrees of sensory conflict between modalities, which could, in turn, evoke different levels of VIMS.

Changes in brightness and contrast are inherent in everyday flight conditions. Based on previous MS research and on the changing characteristics of flight environments, both real and simulated, we set out to explore the effects of visual aspects of the simulated outside world on the viewer's well-being in terms of VIMS. While this connection between the environment's visual characteristics and the corresponding VIMS is plausible, it has yet to be investigated.

1.6. Hypothesis

This study aims to explore the role of brightness and contrast in the elicitation of VIMS. We hypothesize that visual environments differing in brightness or contrast could significantly and differentially alter a person's well-being and induce subjective VIMS. An increase in brightness should lead to an increase in visual information by increasing visibility and in turn increase the effects of VIMS. Conversely, low contrast should increase visual uncertainty, which may subdue the visual stimulus and consequently reduce the sensory conflict.

2. Method

We designed an environment consisting of a flight simulator able to display identical flight paths in four distinctive flight conditions, varying only in brightness and contrast. A pressure-sensitive surface was used to measure subjects' PS after each visual stimulation. Subjective VIMS was measured using standardized questionnaires. A fully-crossed, counterbalanced, 2×2 (brightness and contrast, low and high) within-subjects factorial design with repeated measures was used.

2.1. Subjects

Thirty-three volunteers participated in this study. Subjects ranged in age from 18 to 51 years ($M = 22.58$, $SD = 5.97$, 27 female). Most subjects were psychology students, recruited at the Johannes Gutenberg University of Mainz, Germany. Subjects received partial course credit for their participation.

2.2. Apparatus and stimuli

The experiment was run using a Dell Precision T3500 personal computer with 6 GB RAM, (Intel Xeon W3520@2.67 GHz) with an nVidia GeForce GTX 650 graphics card and the operating system Windows 7 Enterprise. Three full-HD (1080p) 24-inch flat screens were placed adjacent to each other at an angle of 120° in a cave-like setup.

The experiment was conducted in a small room that could be completely darkened and which accommodated the three hi-resolution screens (see Fig. 1):

2.2.1. Subject position

Subjects were asked to sit in front of a computer with three adjacent 24-inch screens encompassing 172° of the visual field. We used a chin rest to minimize head movement during the exposure to each stimulus and allow for comparable viewing conditions (see Fig. 2).

Fig. 1. A picture of the three computer screens in the Cave setup, together with the chin rest, which was used to position the subject at the exact eye position.

2.2.2. Balance Board Recording Position

In order to induce sufficient variability in posture, subjects were asked to stand on one leg, with the other leg resting on the first, hands to their thighs and eyes continuously directed to a fixation point at 1.5 m from them on the opposite wall. The measurement itself was conducted for 45 s.

2.3. Stimulus

The stimulus consisted of a 10-min flight across a realistic virtual mountainous terrain (see images in Table 2). To create and present the stimulus we used Unity3D, a cross-platform game creation system with emphasis on rendering speed and realism. We created a seemingly infinite 30 by 30-km virtual terrain using the plugin TerrainComposer [10]. Using realistic flight dynamics, an air force pilot (AS) recorded the flight sequence, aiming for the creation of a low altitude, aggressively maneuvered flight using the model of a Beechcraft King Air B200 [7]. Average indicated airspeed was 240 Knots. This recording was then visually altered to create four conditions, differing in brightness and contrast. This was done by applying post-render shaders to the active camera objects in Unity3D as well as space-aware volumetric effects (such as fog). High and low brightness created day and night scenes respectively. Similarly, low and high contrast created foggy and clear skies, respectively.

The variation of both brightness and contrast resulted in a total of four conditions: DAY, FOG, NIGHT and NVG, as described in Table 2.

We chose to present the stimuli in a counterbalanced sequence between subjects so that the influence of the stimulus sequence on the elicitation of VIMS could be excluded as a confounding factor.

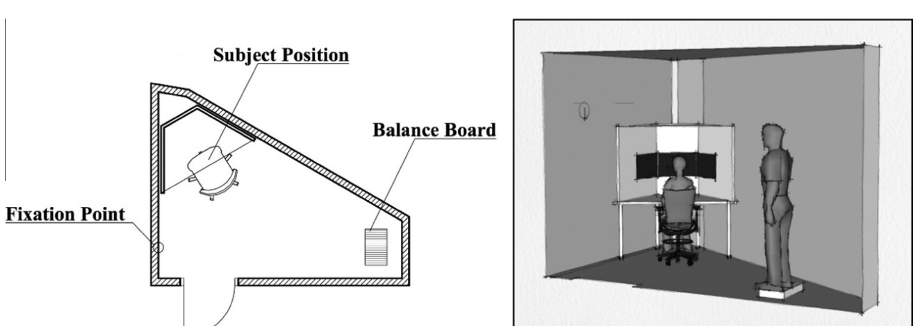


Fig. 2. Experiment setup. The left panel presents the test environment from above, whereas the right panel shows the subject in both experiment positions. Note that only one subject was tested at any given time.

2.4. Evaluation of the visual stimuli realism

Eleven air force pilots with first-hand flight experience in all four flight conditions were asked to evaluate the realism of each stimulus. Because of availability constraints (pilots could not travel to the lab), stimuli were presented to the pilots with the help of a 15-inch laptop, in a well-lit environment. Pilots were shown each stimulus and asked to evaluate its realism on a 6-point Likert scale, ranging from 0 (unrealistic) to 6 (highly realistic). The pilots' rankings are presented in Table 1:

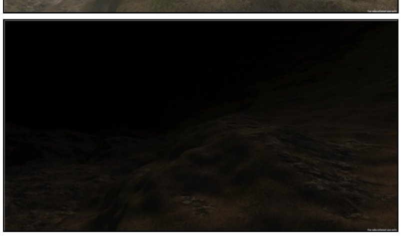
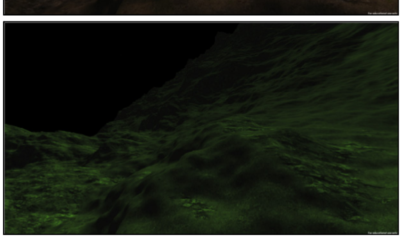
2.5. Stimulus spatial frequency

As So et al. [36] have shown that spatial frequency correlates with VIMS, we calculated spatial frequency for each condition for ten randomly selected screenshots at the same time code using the SHINE toolbox [45]. By averaging these values for each condition, we calculated four α-values ($M_{DAY} = -1.29$, $M_{FOG} = -1.31$, $M_{NIGHT} = -1.03$, $M_{NVG} = -1.15$). Since these values differed only marginally, we assume that spatial frequency did not introduce a confounding factor between conditions.

Table 1
Pilot evaluation of the realism of the different conditions.

Condition	N	Minimum	Maximum	Average	SD
DAY	11	3.0	6.0	4.773	0.7538
FOG	11	2.0	5.0	3.909	0.9439
NIGHT	11	2.0	6.0	3.727	1.4206
NVG	10	2.0	6.0	3.400	1.4298

Table 2
The same scene presented in the four possible conditions.

Condition	Stimulus	Example picture
DAY	High brightness (0.514), High contrast (2.569)	
FOG	High brightness (0.596), Low contrast (1.137)	
NIGHT	Low brightness (0.031), Low contrast (1.172)	
NVG	Low brightness (0.099), High contrast (2.093)	

Note: Numbers in parenthesis indicate the averaged calculated values for each condition and parameter. Values were computed on screenshots taken at intervals of 1 s for each stimulus. Brightness was calculated by converting images to HSV color space and averaging the values for the V component of each image and then across all images, ranging from 0 (maximum darkness) to 1 (maximum brightness). Contrast was calculated using the Global Contrast Factor [25], averaged across all images.

2.6. Measurement tools

2.6.1. SSQ

The most common tool for measuring VIMS is the Simulator Sickness Questionnaire (SSQ) by Kennedy et al. [17]. This questionnaire is a derivative of the MSQ [19] that focuses on VIMS symptoms. The SSQ contains 16 scored items, which are rated by the subjects on 4-point Likert scales. The items are divided into three subscales with overlapping descriptors, which are in turn divided into three principal subscales: Nausea, Oculomotor, and Disorientation. Based on these three sub-scores, a total score is also calculated.

2.6.2. FMS

As it is not possible to administer the SSQ during stimulus exposure, a rapid self-report technique was employed. The Fast Motion Sickness Scale (FMS) by Keshavarz and Hecht [20] is a verbal rating scale administered during the stimulus in 60-s intervals. The scale ranges from 0 (no sickness at all) to 20 (severe sickness) and focuses on the subject's general discomfort, nausea and stomach problems. During each condition, subjects are asked for their numeric FMS score and respond verbally. The FMS has been proven to have a 0.80 correlation with the SSQ, and its rapid administration allows for the quantification of the time course of MS.

2.6.3. Postural sway measurements

PS is commonly measured using a pressure-sensitive platform (force plate), which quantifies the ground reaction forces and the kinematics of the center of pressure of a body standing on it. Recent developments in technology have given rise to consumer technologies that offer comparable validity and reliability to a laboratory grade system [9]. In this study, we used the Wii Balance Board by Nintendo®. The Nintendo Wii Balance Board (WBB) was introduced in 2007 to serve as a controller for the Nintendo Wii and Wii U game consoles. The balance board is of rectangular design, with a pressure sensor located at each of its four corners. Data is transferred wirelessly via Bluetooth. Though the internal sampling rate is roughly 100 Hz, we used a low-level high precision timer API to resample the data to 10 Hz, by buffering and averaging the raw data points.

2.7. Study protocol

Upon arrival, the subjects were informed of the study objectives and methods and told that they could abort the study at any given time without negative consequences. All subjects gave their signed consent in accordance with the Declaration of Helsinki. The experimenter described the study protocol and gave an explanation of the scales used (SSQ, FMS). Fig. 3 is a schematic example of the test sequence performed with each subject.

2.7.1. Baseline measurements

Prior to exposure to the first condition, subjects filled out the SSQ. Next, subjects were asked to stand on a balance board for 45 s, to quantify the kinematics of their center of pressure during stance. These initial measurements served as a baseline.

2.7.2. Subsequent measurements

Balance board measurements were obtained immediately after the presentation of each of the test conditions for a period of 45 s, followed by an assessment of the subjective experience of VIMS using the SSQ. Subjects were then asked to wait until their FMS scores returned to below 2. On average this took 4 min (M = 233 s., SD = 184 s.) from the end of the previous stimulus to the beginning of the next. Waiting until the FMS scores returned to baseline was crucial to allow for consecutive presentations of the four test stimuli. As FMS and SSQ have been shown to be strongly correlated [20], and because FMS is by nature quick to administer, we preferred its use over the SSQ measurement, for the purpose of determining the subject's return to baseline VIMS before proceeding to the next condition. A post SSQ measurement for the verification of the return to baseline VIMS levels was not performed. We attend to this method choice in detail in the discussion section.

3. Results

All subjects chose to complete the study protocol. Post-exposure FMS scores returned to 2 or below within a 20-min time frame after the balance board measurement in all subjects. Two subjects were excluded from analysis due to incomplete data.

We conducted a multivariate repeated measures Analysis of Variance (MANOVA) to compare baseline with post-test scores. Within-subject analyzes included SSQ, FMS and balance board baseline and post-test scores, setting $p < 0.05$ as the statistical significance threshold level.

Two main approaches were taken in the analysis of the data: comparison with baseline values and inter-stimulus comparison, investigating main and interaction effects of brightness and contrast. While the former enabled us to test for MS elicitation in general, the latter allowed the comparison between the four different stimuli.

3.1. SSQ

We compared baseline scores with post-exposure measurements for all SSQ-subscales (Nausea, Oculomotor, Disorientation) and the SSQ-total score. All comparisons yielded a significant increase of simulator sickness ($p < 0.001$ for all comparisons, after Bonferroni-correction). As shown in Fig. 4, results show a consistent significant difference between subjects' baseline SSQ ratings and the post-conditions SSQ ratings, suggesting that all conditions did, in fact, elicit VIMS.

In order to compare the various conditions, we conducted a repeated measures 2 × 2 MANOVA, comparing brightness (high and low) and contrast (high and low) for all four SSQ subscales. No significant main effects or interactions were found ($F[3, 28]$ = 0.349, p = 0.790, Wilk's Λ = 0.964, η_p^2 = 0.036), showing that—at least for the SSQ measurements—conditions did not significantly differ from each other in MS elicitation levels.

3.2. FMS

An advantage of the FMS scale is that it allows for the repeated direct measurement of the subject's current subjective MS severity, over the course of the stimulus presentation. With the help of this measurement, we demonstrated the MS build-up, as shown in Fig. 6.

As with the SSQ, we calculated a repeated measures ANOVA for the FMS scores in order to ascertain whether baseline FMS scores differed significantly from the mean condition FMS scores. As can be seen in Fig. 5, all peak FMS were significantly different from the baseline ($F[2.77, 88.58]$ = 27.70, $p < 0.001$, η_p^2 = 0.436).

Whereas all FMS were significantly above baseline, the conditions did not differ among each other ($F[1, 32]$ = 0.033, p = 0.858, η_p^2 = 0.001), as can be seen in Fig. 6.

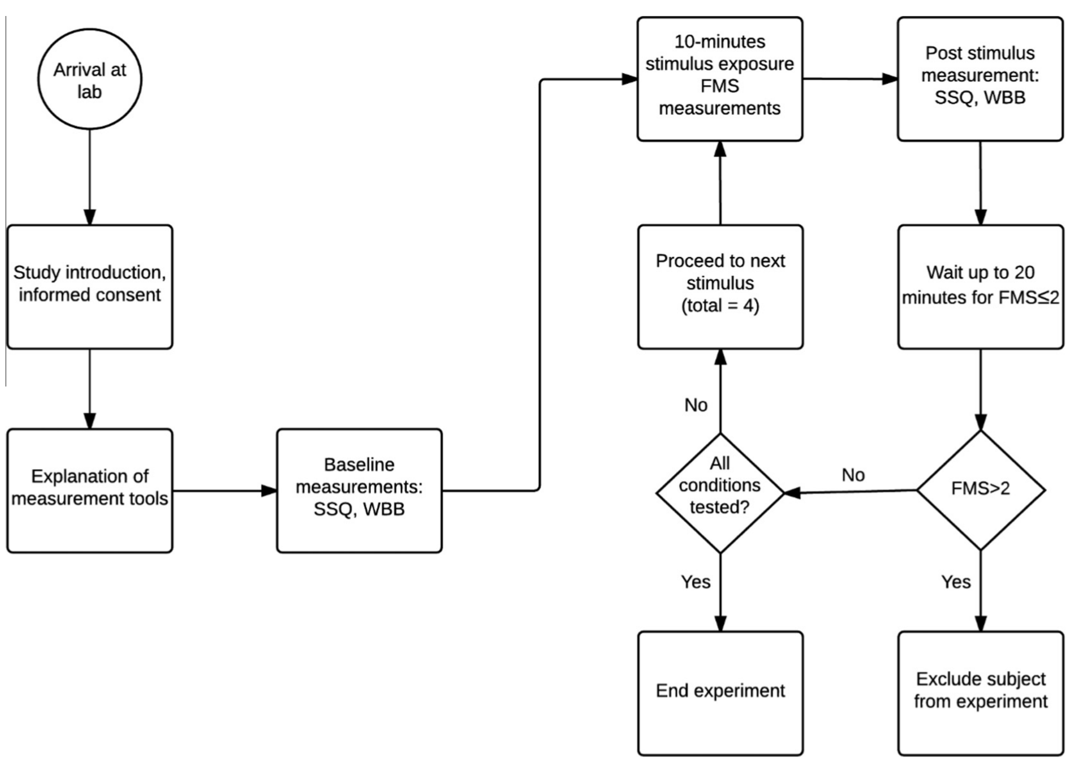


Fig. 3. Flow chart of the study protocol.

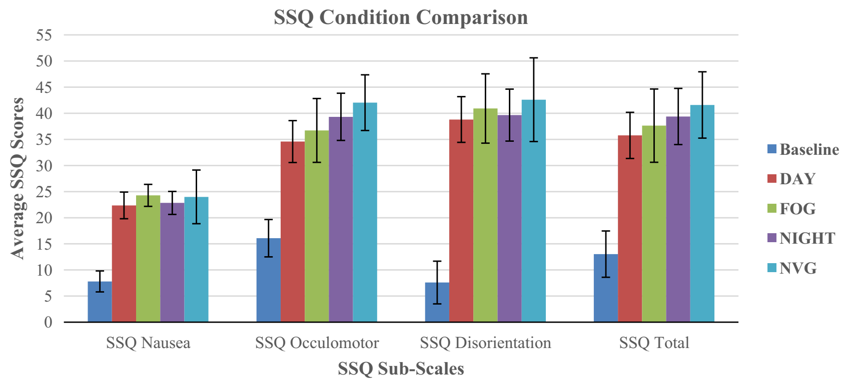


Fig. 4. Comparison of all conditions with the respective baseline scores. Mean SSQ scores are plotted for each subscale as well as the total score. Error bars represent SEM.

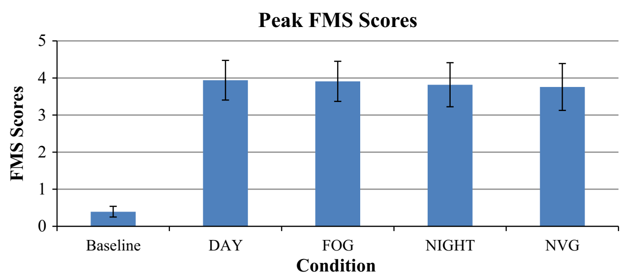


Fig. 5. Peak FMS scores (across all subjects) for each condition. Error bars represent SEM.

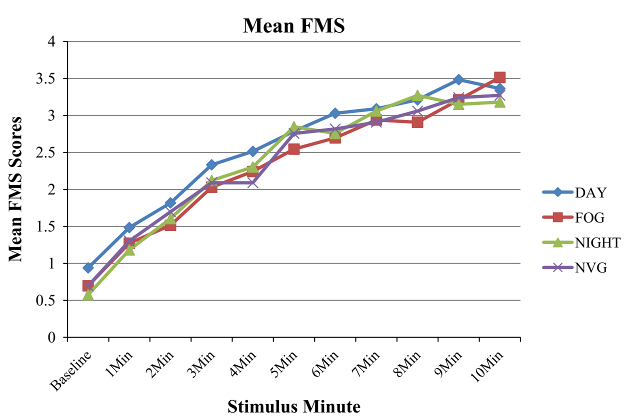


Fig. 6. Mean FMS scores for each condition and measurement interval during the 10-min exposure.

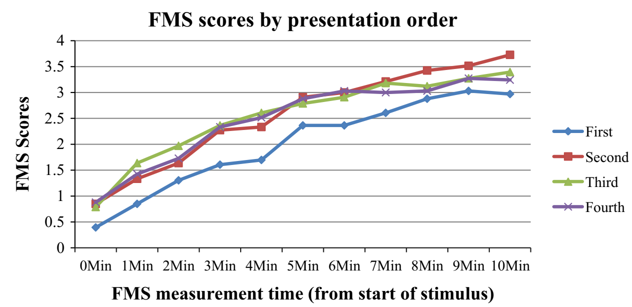


Fig. 7. Mean FMS scores across subjects, grouped by condition presentation order.

3.3. Stimulus sequence effect

Previous studies have shown that sequence effects may occur, that is VIMS levels may rise with each additional stimulus, but possibly plateau or even eventually decline with the onset of habituation effects [17,21]. As expected, scores of the unfolded counterbalanced sequence of all measurements (SSQ, FMS, Balance Board) showed a medium to high correlation with time ($M = 0.77$, ranging from 0.39 to 0.93), with an eventual decline between the third and fourth measurements. An example of such a habituation can be seen in Fig. 7.

As VIMS is known to have a cumulative effect, it could be argued that separating measurement sessions would increase the accuracy of the measurement. As plausible as this may be, the time required for return to baseline after exposure to MS-eliciting stimuli has yet to be agreed upon (for different separations between stimuli compare [30,15]. The separation of sessions is, however, not without its drawbacks. While it can be assumed that VIMS levels will return to baseline when separating sessions by a pre-defined time interval, other confounding variables, such as sleep duration, diet, alcohol consumption etc. could possibly be introduced. Due to these reasons and for practical considerations, we decided to perform all conditions in one session, making sure that subjects returned to their baseline FMS values before proceeding to the next condition, and varying the condition order in a fully counterbalanced design between participants (see Fig. 8).

3.4. Balance board

Because all balance board Center of Pressure (CoP) parameters were likely to be correlated, as they were computed from the same principal set of pressure sensor data, we performed a Principal Component Analysis (PCA) to extract the most important independent factors. The PCA was computed from the complete set of WBB data, containing 165 records (15 variables, baseline +4 measurements for each subject). Only factors with eigenvalues $\geqslant 1$ were considered [13,16]. The Kaiser-Maier-Olkin (KMO) and the Bartlett's sphericity test were used to determine the suitability of the variables for PCA, with a KMO value of greater than 0.6 and the significance of the Bartlett's sphericity test at $p \leqslant 0.05$ as thresholds. The analysis yielded a KMO of 0.743 and $p < 0.001$ for Bartlett's sphericity test, allowing us to continue with the factor extraction. The PCA and scree plot yielded two distinct factors. Because loadings for the highest varimax-rotated factors only differed marginally, we extracted four sway parameters in total for further analysis, namely: mean sway velocity, total sway path length, mean centroid distance and the area of the 95% confidence ellipse. We chose these parameters because they possessed high loadings and best represented the parameters in their factor group. The former two can be classified as trajectory measures while the latter two are measures of dispersion of the CoP. A similar

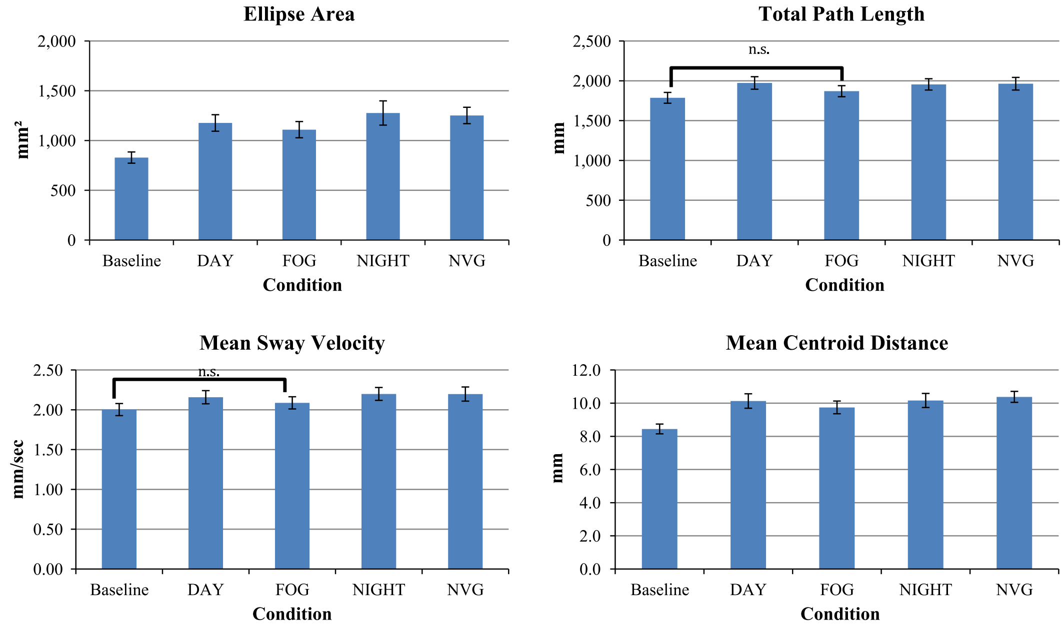


Fig. 8. Mean balance board results for each condition (over all subjects). Each figure details a different balance board parameter. Non-significant differences to the baseline score are labeled. Error bars represent SEM.

approach was taken by Rocchi et al. [33] in the analysis of balance board measurements. The results of the PCA, including short explanations of each measured variable, are presented in Table 3:

A one-way MANOVA was computed on the CoP-parameters, as identified through the factor-analysis ($F[16, 382.52] = 2.60$, $p = 0.001$; Wilk's $\Lambda = 0.729$, $\eta_p^2 = 0.076$). A-priori contrasts revealed that the DAY, NIGHT, and NVG conditions differed significantly from their baseline postural sway measurement, while FOG did not. Out of the four sway parameters, two were not significantly different from the baseline (for total path length and mean sway velocity, FOG was $p > 0.05$, all other conditions were $p < 0.05$). Because comparisons were part of the apriori-hypothesis, no adjustment of the alpha level was necessary. Bonferroni adjusted post hoc contrasts revealed no statistically significant differences between the four conditions (all $p > 0.05$).

3.5. VIMS questionnaires correlations with balance board

To further assess the relationship between postural sway and VIMS questionnaires we calculated the correlations between results of each method for each condition.

4. Discussion

The purpose of the present study was to examine the role of brightness and contrast in the elicitation of MS. We evaluated

Table 3
PCA results including elaborations on the variable measurements.

	Component		Comment
	Trajectory measures	Measures of dispersion	
Mean sway velocity (anterior-posterior)	**0.953**	0.272	The mean anterior-posterior sway velocity, defined as length of the anterior-posterior path component divided by the total measurement time
Mean sway velocity	**0.951**	0.281	The mean sway velocity, defined as path length divided by the total measurement time
Mean sway velocity (mediolateral)	**0.951**	0.280	The mean mediolateral sway velocity, defined as length of the mediolateral path component divided by the total measurement time
Path length (vertical)	**0.913**	0.348	The vertical component of the sum of the Euclidean distance between consecutive CoP points
Path length (total)	**0.913**	0.357	The sum of the Euclidean distance between consecutive CoP points
Path length (horizontal)	**0.912**	0.356	The horizontal component of the sum of the Euclidean distance between consecutive CoP points
Root mean square (mediolateral)	**0.907**	0.294	The root mean square of the mediolateral component of all the path segments[a]
Root mean square (anterior-posterior)	**0.902**	0.264	The root mean square of the anterior-posterior component of all the path segments[a]
Mean centroid distance	0.257	**0.934**	The mean Euclidean distance of each CoP point to the centroid of all CoP points
95%-Confidence ellipse radius (major)	0.216	**0.934**	The major axis of the 95 %-Confidence ellipse of the CoP points
95%-Confidence ellipse area	0.353	**0.922**	The area of the 95%-Confidence ellipse of the CoP points
Variance (anterior-posterior)	0.132	**0.900**	The variance of the anterior-posterior component of all path segments[a]
95%-Confidence ellipse radius (minor)	0.447	**0.741**	The minor axis of the 95%-Confidence ellipse of the CoP points
Area enclosed by a convex polygon of all sway measurements	0.449	**0.741**	The area of a convex polygon created by the CoP points
Variance (mediolateral)	0.488	**0.657**	The variance of the mediolateral component of the path segments[a]

[a] A path segment is defined as the length of one CoP point to the next. Factor loadings >.5 are in boldface.

different measures of MS before, during and after each exposure in adult subjects, using MS questionnaires (SSQ, FMS) and postural sway (PS) measurements (balance board). Subjects did experience simulator sickness to an equal extent in all conditions.

4.1. Overall stimulus efficacy

All conditions resulted in significant differences in reported MS compared with baseline measurements, across all measurement tools. The DAY, NIGHT and NVG conditions also increased postural sway as compared to their baseline measurements. While the FOG condition did show the same trend, two of its four PS measurements yielded non-significant differences to the baseline measurements. Overall, results suggest that subjective MS was elicited, and PS was increased by every stimulus, regardless of stimulus presentation order.

4.2. Brightness

Only anecdotal notes have been published regarding brightness effects on MS elicitation. In their review of MS prediction, prevention, and treatment, Shupak and Gordon [34] suggest that in the attempt to minimize MS, seamen "...use sunglasses during the day to reduce visual stimulation". One potential mechanism would be that reduced brightness lowers the subject's stress level (see [44]. If lower brightness levels were to reduce visual stress, this should facilitate or cause a reduction of VIMS. Contrary to such assumptions, the results of our study suggest that brightness has no direct effects on subjective MS or on PS measurements. Note that this negative finding might not generalize to extremely provocative stimuli that produce high levels of VIMS and stress.

4.3. Contrast and fog

Likewise, contrast variations neither affected the elicitation of subjective MS, nor resulted in differential changes in PS. This finding is in line with a study of Dziuda et al. [11] in which the authors found no effect of fog on MS elicitation both in a fixed and moving based driving simulator. Although the authors did not equate fog with contrast, it is highly probable that their implementation of fog did largely reduce contrast, similar to the daytime low contrast condition in our present study.

Our FOG condition (high brightness, low contrast) differed significantly from the baseline measurement only in two of its four parameters (Ellipse Area and Mean Centroid Distance). This difference between MS questionnaires and PS-data is hard to interpret, as the conflict-theory of VIMS and the postural sway theory make somewhat contradictory predictions in this case. Whereas the postural instability theory postulates that MS can be measured by PS [8,27,39] and even precedes subjective MS symptoms as measured with MS questionnaires [4,35,38,41], other studies [5,26,43] show that PS is a construct that fails to sufficiently explain and predict MS. The correlation results of VIMS questionnaires and PS measurements in the current study tend to agree with the latter (cf. Table 4).

Furthermore, if the fog did in fact induce less sway in comparison to all other conditions (as can be seen from two of its PS measurements), this would imply that the combination of high brightness and low contrast elicits less MS than the other combinations tested. Considering that the NIGHT condition (which differed only in brightness, but not in contrast) resulted in an increased level of MS, it is not possible to isolate the impact solely caused by contrast. The same applies to the analogous brightness condition (DAY – high brightness, high contrast).

4.4. Will the findings generalize to a more provocative stimulation?

Comparatively low levels of VIMS have been elicited in this study, as can be seen in the different VIMS questionnaires. This could be explained by two main factors: stimulus effectiveness and stimulus exposure duration. Firstly, our simulated flight environment was evaluated by experienced pilots, which found it to be reasonably realistic. However, a fancier simulator—possibly with a moving base—might provide better immersion (see [24] and thereby elicit stronger VIMS. Secondly, it has been shown, that exposure duration is positively correlated with total sickness [18]. A lengthier MS eliciting stimulus, together with a more immersive presentation method (such as stereoscopic viewing) could contribute to higher VIMS in further studies [22]. Thus, with regard to both stimulus effectiveness and realism, future research could

Table 4
Correlations between VIMS measures and PS measures for each respective condition.

PS measure	Corresponding VIMS measures				
	Peak FMS	SSQ total	SSQ nausea	SSQ disorientation	SSQ oculomotor
DAY condition					
Ellipse area	0.048	0.023	−0.086	0.049	0.121
Total path length	0.033	−0.042	−0.078	−0.007	0.031
Mean velocity	0.162	0.070	0.028	0.104	0.123
Mean centroid distance	−0.071	−0.087	−0.162	−0.035	−0.014
FOG condition					
Ellipse area	0.184	0.037	0.031	0.141	0.051
Total path length	0.211	0.044	0.143	0.123	0.044
Mean velocity	0.216	0.041	0.149	0.122	0.039
Mean centroid distance	0.178	0.056	0.019	0.168	0.071
NIGHT condition					
Ellipse area	0.027	0.197	−0.019	0.339	0.198
Total path length	0.178	0.349	0.170	0.450**	0.317
Mean velocity	0.149	0.329	0.154	0.425*	0.304
Mean centroid distance	−0.022	0.199	−0.025	0.321	0.216
NVG condition					
Ellipse area	0.072	0.300	0.119	0.269	0.412*
Total path length	0.168	0.215	0.161	0.173	0.254
Mean velocity	0.150	0.200	0.145	0.160	0.240
Mean centroid distance	0.059	0.279	0.100	0.278	0.369*

** $p < 0.01$.
* $p < 0.05$.

compare brightness and contrast effects on VIMS in high vs. low VIMS environments. Such a comparison would allow to better generalize the findings of this study to the case of brightness and contrast, independent of the elicited level of VIMS.

Comparison of the presented picture in constant contrast, high vs. low brightness levels (FOG vs. NIGHT), shows that while a horizon could be seen in the FOG condition, no horizon was visible in the NIGHT condition. A visible horizon has been suggested to have an ameliorating effect on MS [34,37,42]. As we have shown, the current study did not reveal differences between the conditions in relation to VIMS or PS elicitation. Nevertheless, we suggest controlling the horizon visibility in future studies, where it might become a confounding factor at higher VIMS levels.

Future studies might consider augmenting the FMS-measurements with a post-session SSQ. The combination of FMS and SSQ would enable the researcher to leverage on the FMS's ease of administration while also obtaining symptom-specific details. Alternatively, conditions could be separated by at least one day. This method may provide more accurate baseline measures of VIMS at the price of potential adaptation or contamination by day-specific confounding variables.

5. Conclusion

The present study set out to find whether brightness and contrast affect simulator sickness (VIMS) in virtual reality environments. Using a fixed-base flight simulator, we exposed subjects to four recorded flights, differing in brightness and contrast and measured VIMS as well as postural sway (PS) using a number of converging measures.

5.1. VIMS

Results show that although VIMS was elicited by all conditions, brightness and contrast did not modulate the elicitation of VIMS.

5.2. PS

With the exception of foggy daylight viewing, all other viewing conditions produced an increase in sway after exposure to the visual stimulus. It is rather surprising and of practical importance to notice that low brightness does not prevent increased sway and that low contrast only does so in bright light.

Understanding the role of visual parameters and how they interact to elicit VIMS is important in the design of both real and virtual environments. This study has shown that the potential of simulators to induce VIMS appears to be largely unaffected by brightness and contrast of the inducing visual stimulus. As our subjects tolerated the simulator environment rather well, comparable experiments with more provocative VIMS-inducing stimuli are desirable. Other visual characteristics and their bearing on MS could be evaluated using this methodology and platform.

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