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Lubeck, A.J.A.

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Chapter 5

Framing visual roll-motion
affects postural sway, the
subjective visual vertical and
motion sickness

Lubeck, A. J. A., Bos, J. E., & Stins, J. F. (under revision). Framing visual roll-motion affects postural sway, the subjective visual vertical and motion sickness.

Abstract

Objective. Effects of visual roll-motion on postural sway, the subjective visual vertical (SVV), and motion sickness, is often studied using mechanical devices, while electronic displays offer cheaper and more flexible alternatives. These devices typically emit and reflect light scattered by the edges of the screen, providing Earth-fixed cues of verticality. These cues possibly decrease effects of rotating stimuli, what has not been studied explicitly in one experimental design.

Methods. We exposed sixteen participants to a visual dot pattern, either stationary, or rotating in roll, that was or was not surrounded by a visible Earth-fixed frame. To eliminate unintended visual cues, the experiment was performed in complete darkness and participants wore neutral density goggles passing only 1% of light. Postural sway was measured using a force platform, SVV measurements were obtained from a visible rod, and motion sickness severity was obtained with an 11-point rating scale.

Results. Results showed that the presence of an Earth-fixed frame significantly decreased the effect of the rotating pattern on postural sway, SVV deviations and motion sickness.

Conclusions. Therefore, when studying subjective verticality related effects of visual stimuli it is imperative that all visual Earth-fixed cues are not just minimized, but completely eliminated. The observation that an Earth-fixed frame significantly decreased the effect of the rotating pattern on all variables points towards a common neural origin, possibly involving a neural representation of verticality. Finally we showed that an electronic screen can yield similar effect sizes as those taken from the literature using mechanical devices.

5.1. Introduction

In order to correctly identify “up” and “down” with respect to the Earth gravitational field, it has been suggested that our central nervous system uses a neural representation of the Earth-vertical (see e.g.^{135,136}, or more recently¹²). Such a neural representation can be described as a vector with a magnitude and orientation. In this experiment we focus on the orientation of this vector, further referred to as the neural representation of verticality. Previous research has shown that this neural representation is essential to orient behaviour with respect to the Earth vertical^{11,12,137}. For the most veridical neural representation of verticality, it is continuously updated with integrated cues from the visual, vestibular and somatosensory systems^{2,8,138}. Visual Earth-fixed cues are thought to aid a veridical representation, while visual tilt or motion, without accompanying physical motion, is thought to cause a deviation thereof^{2,138,139}. By measuring behaviours that arguably use the neural representation of verticality, effects of such visual stimuli can be quantified.

Studies using static tilted stimuli, such as a tilted furnished room or just a tilted luminous square, have shown that postural control, i.e. “the act of maintaining, achieving or restoring a state of balance during any posture or activity”²², is affected whilst viewing a tilted frame^{30,31,140}. Besides postural control, subjective visual vertical (SVV) estimates of a straight line are ‘attracted’ by the tilted frame, a phenomenon known as the Rod-and-Frame effect^{30,71,141–145}.

Similar postural excursions and SVV deviations can be induced by viewing a dynamic visual stimulus, e.g. a pattern rotating in roll as used in the Rod-and-Disc test^{30,31,146}. Viewing a stimulus in roll is thought to cause a tilt of the neural representation of verticality, in this case in the direction of the stimulus rotation^{2–4,138,139}. This can be inferred from both postural sway and the SVV, typically both deviating in the direction of stimulus rotation^{30–32,89}.

In addition to postural sway and SVV deviations, such rotating stimuli are known to be provocative with respect to motion sickness, or in this case, visually induced motion sickness (VIMS). Interestingly, motion sickness, whether induced physically or visually, is also assumed to be affected by a deviation of the neural representation of verticality².

Besides serving a scientific interest, rotating visual stimuli have been proposed to be beneficial in the clinical context of vestibular rehabilitation. The idea behind this approach is that repeated exposure to visual motion can reduce the severity of disturbances caused by visual motion in certain vestibular patients^{30,87,102,147,148}. This kind of therapeutic intervention can be facilitated by using electronic screens instead of previously used mechanical devices^{67,147–150}.

A potential confounding factor when using such techniques is that most displays provide unintended visible Earth-fixed cues of verticality. Light emitted and reflected by objects in the “completely darkened”

experimentation room, can result in unintended visual cues, which may affect the representation of verticality. A particular source of reflection concerns the edges of the display itself. As shown by the Rod-and-Frame effect, these Earth-fixed cues may influence our neural representation of verticality, thus possibly affecting the variables of interest. If, for example, a rotating stimulus failed to elicit an effect, this might have been due to the (unintended) presence of visible Earth-fixed cues instead of another assumed reason. Despite this issue having been recognized and efforts having been described to reduce or eliminate these Earth-fixed cues (e.g.^{60,143,151}), the question remains how influential these Earth-fixed cues actually are.

We therefore performed an experiment with the main objective to scrutinize the effect of a visible Earth-fixed cue – in this case a rectangular visual frame – on three variables that are arguably controlled, or at least affected by the neural representation of verticality during exposure to visual roll-motion. The three variables are postural sway, the SVV and VIMS. In particular we assume that the influence of visual roll-motion on these variables is smaller when the rotating stimulus is presented together with a static, visible, rectangular frame.

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5.2. Method

5.2.1. Participants

Sixteen healthy young adults participated voluntarily after signing an informed consent form. Due to technical difficulties during the experiment, data of two participants were discarded, leaving 14 participants for further analyses. Participants were students at the Faculty of Human Movement Sciences of the VU University, 8 males and 6 females, with a mean age of 20.6 years ($SD = 1.4$ years). Ethical approval was provided by the Ethics Committee of the same faculty in accordance with the Declaration of Helsinki.

5.2.2. Apparatus

Participants were, in a completely darkened room, exposed to stimuli shown on a 40 inch TV-screen (Samsung LE40B620; 88 x 50 cm; width x height) in high definition resolution (1920 x 1080 pixels) with a monitor refresh rate of 60 Hz. In order to block the edges of the screen and eliminate other unwanted visual Earth-fixed cues, two precautions were taken. First, the edges of the screen were covered using a removable low reflective cardboard cover, leaving a circular viewing area with a radius of 25 cm. Second, participants wore neutral density (ND) glasses passing only 1% of light. As a result, all Earth-fixed cues made visible by scattered light were eliminated, while maintaining visibility of the actual stimulus. Participants stood at a distance of 70 cm from the screen, yielding a field of view (FoV) of 40 x 40°.

The stimulus consisted of two components, a computer generated dot pattern and a computer generated frame. The dot pattern, as shown in Fig. 5.1, consisted of 88 non-overlapping dots, each dot subtending a FoV of approximately 1.5° . In case the pattern was rotating (see procedures, below), the pattern rotated with an angular velocity of $30^\circ/\text{s}$ (one revolution per 12 s). The pattern enclosed the complete circular viewing area (area left uncovered by the cardboard). In a subset of trials, the dot pattern was surrounded by a 50 cm yellow square frame with an edge width of 0.24 cm. When the frame was present, the cover with the circular viewing area was removed. The TV-screen was carefully positioned Earth-horizontal to assure unbiased SVV measurements (see below).

During exposure, participants were standing on a custom made 1 x 1 m strain gauge force plate, recording the Centre of Pressure (CoP) at 100 Hz. Participants stood with their arms hanging comfortably by their sides and their feet positioned with the heels together with a 30° angle between the feet as marked on the force plate.

SVV measurements involved aligning a computer generated rod to the perceived vertical. The rod consisted of eight small dots, subtending a visual angle of approximately 5° , which were placed on an imaginary line to minimise quantization visibility (Fig. 5.1). The orientation of the rod was adjusted by using a hand held keypad with a roughened structure on two buttons, representing clockwise (CW) and counter clockwise (CCW) rotation. The rod was presented with an initial angular offset between 30 and 70° leftward or rightward of the Earth-vertical, and rotated with a speed of $10^\circ/\text{s}$ with incremental steps of 0.17° when a button was pressed. Participants were allowed to correct the rod in order to align it with their perceived vertical as long as the rod was visible. Participants held the keypad in both hands when the rod appeared on the screen for SVV measurements, and kept it in their right hand in between SVV measurements.

5.2.3. Visually induced motion sickness

VIMS is considered a complex condition that includes not only symptoms of nausea, but also oculomotor and disorienting symptoms evoked by viewing visual motion⁴¹. To monitor the occurrence of VIMS, participants were asked to rate their subjective misery using the misery scale⁸², which is an 11-point scale ranging from 0 to 10. This scale exploits the knowledge that symptoms of nausea are generally preceded by symptoms from the oculomotor and disorientation subscale⁸². Absence of symptoms is represented by 0; any symptom except nausea is scored between 1 and 5 (; a score of 6 or higher is given whenever feeling nauseated; 10 representing vomiting. The experiment was discontinued if a MISC rate of 6 or higher was reported.

Anticipating the results, no differences were found between CW and CCW trials and an average over these trials was computed for the MISC rates.

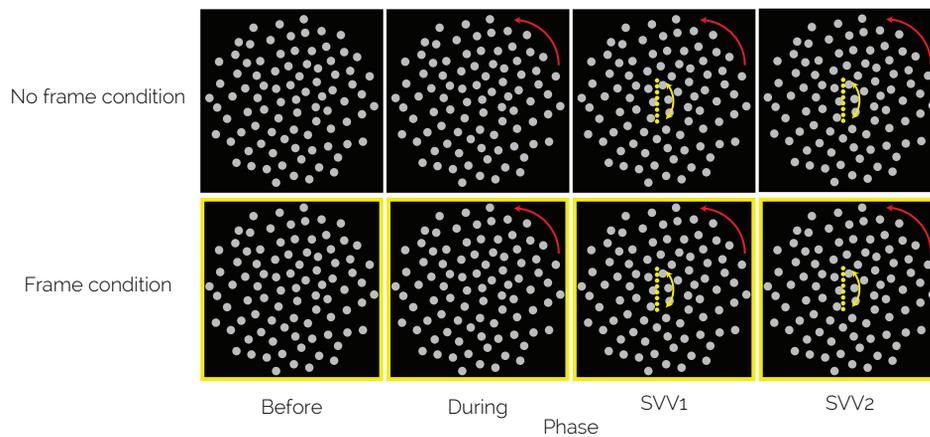


Figure 5.1. Overview of the procedure. The rows represent the two conditions, the No Frame (NF) and Frame (F) condition, respectively. The columns represent the phases during each trial; before, during, SVV1 and SVV2 phase respectively. Each condition consisted of three stimulus types. In one stimulus type the dot pattern remained stationary. In the other two stimulus types the dot pattern rotated clockwise and counter clockwise from the during phase until the end of the stimulus type. Here examples of the counter-clockwise stimulus type are depicted. During the SVV1 and SSV2 phase participants were asked to adjust a rod to match their subjective visual vertical, which appeared once rotated leftward of the Earth-vertical and once rightward of the Earth-vertical in each trial. For the postural sway only data from the before and during phase was included.

5.2.4. Procedure

Before the start of the experiment, participants were informed about the procedure, were familiarized with the MISC, and signed an informed consent form. Participants were asked to put on the ND glasses and to stand on the force plate as depicted. During exposure, participants were instructed to stand as quietly as possible, to continuously look at the centre of the monitor, and to only take a step to prevent falling (which never happened).

The experiment consisted of two conditions with three trials each, and each trial was divided into four phases as explained in the following. The conditions differed as regards the presence of the frame. In the Frame condition (F), the frame was displayed surrounding the dot pattern, while in the No Frame condition (NF) the frame was absent (Fig. 5.1). In the three trials the dot pattern did not rotate (still), rotated clockwise (CW), or rotated counter clockwise (CCW). Each trial lasted 108 seconds and was divided into the following four phases. In the first, "before" phase, the dot pattern was shown motionless for 12 s. In the second "during" phase that lasted 48 s, the pattern remained either stationary, or rotated in CW or CCW direction. In the third "SVV1" phase, lasting 24 s, a rod appeared with a leftward or rightward angular offset from the Earth-vertical that participants aligned to their perceived vertical. Pattern rotation and presence or absence of the frame remained the same as in the during phase. After this phase, the

adjusted rod disappeared from the screen. The fourth, "SVV2" phase was identical to the previous SVV1 phase, except that a new rod appeared with a random angular offset with an orientation that was to the opposite side of the Earth-vertical. After each trial, participants were asked to rate their misery using the MISC. Between conditions, participants were asked to sit down for a two minute rest to avoid fatigue.

Participants were exposed to the two conditions (F and NF) in a random, counterbalanced order. The initial rotation direction (CW or CCW) was randomly chosen at the start of the experiment and then alternated to avoid possible accumulation effects. Each condition always started with the baseline trial (still stimulus type) followed by two trials with rotation (CW and CCW; rotation stimulus type).

5.2.5. Data analysis

For assessment of postural sway, CoP time series collected in the "before" and "during" phase were included. CoP time series were first filtered using a 2nd order low-pass Butterworth filter with a cut-off frequency of 5 Hz. Due to a small delay between the start of the CoP data collection and start of exposure, the last second of each CoP time series was discarded, leaving a before phase of 11 s and a during phase of 47 s. Because the pattern rotated in the frontal plane, it elicited the largest CoP displacements in the mediolateral (ML) direction. We therefore limited the analyses of the CoP time series to this direction. Anticipating the results, no significant differences were found between CW and CCW trials. For this reason CoP data for the CCW direction time series were mirrored along the ML-axis, and an average CoP-ML time series was calculated. We thus calculated postural sway parameters for the two stimulus types (still and rotation) with averaged (over CW and CCW rotation trials) values for the rotation stimulus type.

Two parameters were calculated from these CoP time series for each phase: the mean moving window standard deviation (MWSD), and the lean. The MWSD was calculated by taking SDs for 1 s non-overlapping time windows of 100 data points each, which were then averaged, providing a MWSD for each phase⁴⁵². The MWSD was favoured over the standard deviation taken over the entire phase, because of substantial CoP shifts in ML direction – anticipated and observed – to which the MWSD is insensitive. The lean was defined as the average positional shift of the CoP in ML direction in the during phase relative to the mean CoP position in the before phase. Positive values denote a postural deviation into the direction of rotation and negative values denote a deviation in the opposite direction.

The SVV deviation was defined as the angular difference between the orientation of the adjusted rod and the Earth-vertical in degrees. Anticipating the results, no differences were found between initial rod offset orientation angles with respect to the Earth-vertical (CW and CCW) and the

CW and CCW rotation trials. Therefore, first an average was calculated over the SVV deviations collected in the SVV1 and SVV2 phase for each trial. Second, the SVV deviations for CCW rotation trials were mirrored along the vertical axis, and an average over the CW and CCW trials was calculated. Positive values denote a deviation into the direction of rotation and negative values denote the opposite.

5.2.6. Statistical analysis

IBM SPSS Statistics 21 was used for statistical analysis. The assumption of normality for postural sway parameters and SVV deviations was checked with Shapiro-Wilk tests, and inspection of q-q plots. Effects of stimulus type (still, rotation) and frame (F, NF) on MISC rates were studied using four non-parametric Wilcoxon Signed Ranks tests with a Bonferroni correction ($p = .0125$). Effects of phase (before, during), stimulus type (still, rotation) and frame (F, NF) on the MWSD were examined with a $2 \times 2 \times 2$ repeated measures (RM) ANOVA. To determine whether the lean in the during phase was significantly different from the before phase, for all combinations of stimulus type and frame, four one-sample t-tests with the test value set at 0 (representing the mean position in the before phase) were performed. Second, a 2×2 RM ANOVA was conducted on the lean values to study effects of frame and stimulus type.

The statistical analysis of the SVV employed the same factors as the analysis of the lean. First the SVV deviations were compared to the Earth vertical (0°) using four one-sample t-tests. Second, to analyze effects of frame and stimulus type, a 2×2 RM ANOVA was used. Significant main effects were followed up with pairwise comparisons. Significant interaction effects were followed up using planned contrasts and inspection of interaction plots. To determine effect size partial eta-squared (η_p^2) was calculated. The significance level was set at 0.05.

5.3. Results

5.3.1. Postural sway

Fig. 5.2 shows the grand averaged CoP for the F and NF condition. This figure reveals that the CoP clearly deviated into the rotation direction in the NF condition whilst rotation and not in the F condition. In other words, when exposed to CW and CCW roll-motion in the absence of a frame, participants gradually shifted their CoP to the right and left, respectively.

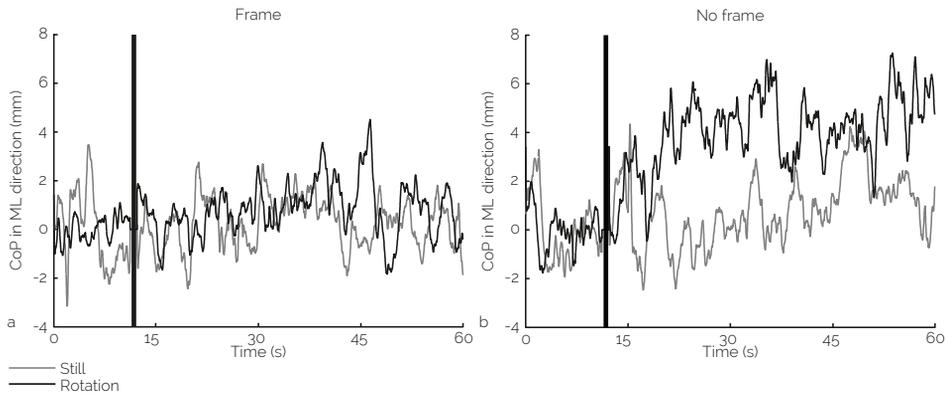


Figure 5.2. The grand averaged (GA) CoP traces in ML direction for the still stimulus type and rotation stimulus type (averaged over CW and CCW after mirroring of CCW data) **a.** GA CoP in the Frame condition. **b.** GA CoP in the No-Frame condition. The black vertical bar represents the transition from the before phase to the during phase.

Table 5.1. Results RM ANOVA's for the MWSD, lean and SVV

| Source | df | F | η_p^2 | p |
|---------------------------|----|-------|------------|--------|
| MWSD | | | | |
| Frame | 1 | 2.66 | .17 | .127 |
| Phase | 1 | 3.35 | .21 | .09 |
| Stimulus Type | 1 | 4.37 | .057 | .25 |
| Phase×Frame** | 1 | 9.64 | .43 | .008 |
| Frame×Stimulus Type ** | 1 | 15.87 | .55 | .002 |
| Phase×Stimulus Type *** | 1 | 31.20 | .71 | <.0001 |
| Phase×Frame×Stimulus Type | 1 | .264 | .02 | .616 |
| Lean | | | | |
| Frame* | 1 | 5.65 | .303 | .034 |
| Stimulus Type | 1 | 3.94 | .23 | .07 |
| Frame×Stimulus Type | 1 | 3.57 | .215 | .08 |
| SVV | | | | |
| Frame*** | 1 | 24.65 | .66 | <.0001 |
| Stimulus Type ** | 1 | 17.39 | .57 | .001 |
| Frame×Stimulus Type ** | 1 | 18.56 | .59 | .001 |
| Error | 13 | | | |

* $p < .05$. ** $p < .01$. *** $p < .0001$.

Effects of the frame and stimulus type were statistically present in our two CoP parameters. Fig. 5.3 shows the mean MWSDs before and during rotation, separately for the still and rotation stimulus types, and for the F and NF conditions. Statistical analysis revealed three significant two-way interaction effects for the MWSD (all statistics are reported in Table 5.1). As expected, the interaction between phase and stimulus type showed that only in case of rotation (rotation stimulus type) the MWSD increased significantly in the during phase ($Mean = 1.095 \text{ mm}$, $SE = .072 \text{ mm}$) compared to before ($Mean = .825 \text{ mm}$, $SE = .056 \text{ mm}$), $p = .008$. More importantly, the significant interaction effect between phase and frame revealed that during rotation, the MWSD was significantly increased compared to the before phase in the NF condition, while no such increase was present in the F condition, $p = .002$. A significant influence of the frame was also revealed by the significant interaction between frame and stimulus type. The MWSD was significantly elevated ($Mean = 1.101 \text{ mm}$, $SE = 0.084 \text{ mm}$) in case of rotation compared to a stationary pattern for the NF condition ($Mean = 0.796 \text{ mm}$, $SE = 0.074 \text{ mm}$), but not in the F condition, $p < .0001$.

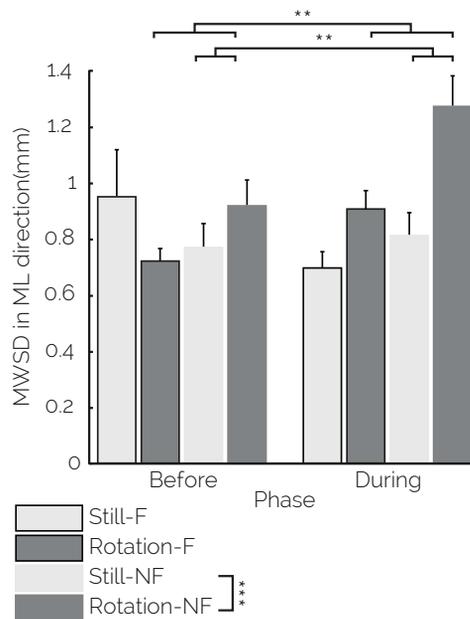


Figure 5.3. Mean MWSD (in mm, $\pm SE$) for the frame and no frame conditions. 'Before' indicates the phase before rotation. 'During' indicates the phase with rotation, but only for the rotation stimulus types. Significant differences at $p < .01$ and $p < .0001$ are indicated with **, and ***, respectively.

Fig 5.4. shows the average lean for both stimulus types and conditions. One-sample t-tests revealed that the lean was only significantly different from 0 (i.e. the before phase) during rotation in the NF condition, implying that the CoP shifted into the rotation direction compared to before rotation,

$t(13) = 2.82, p = .014, r = .61$. The RM ANOVA revealed that rotation and the interaction between rotation and frame affected the lean in a similar way as the MWSA, but failed to reach significance (Table 5.1). Only the frame significantly suppressed the lean (Table 5.1).

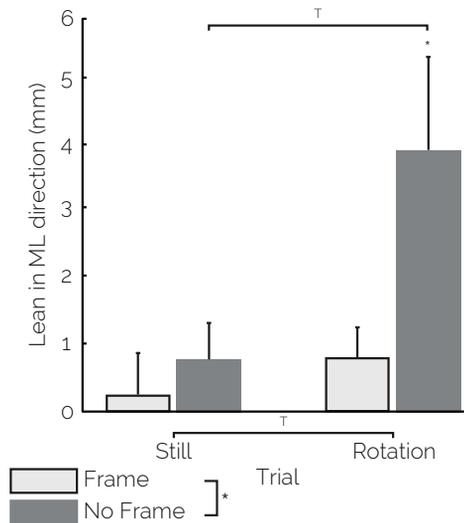


Figure 5.4. Mean lean in ML direction (in mm, \pm SE) for the frame and no frame conditions. Positive values indicate a lean in the direction of rotation. Negative values indicate a lean in the direction opposite to the rotation direction (if there was rotation). Significant differences at $p < .05$ are indicated with *. Trends at $p < .08$ are indicated with T.

5.3.2. Subjective visual vertical

Fig. 5.5 shows mean SVV deviations in degrees ($^{\circ}$) for all stimulus types and conditions. First, one-sample t-tests showed that only in case of rotation the SVV deviated significantly from 0 in the direction of rotation, $t(13) = 3.16, p = .02, r = .66$ and $t(13) = 4.64, p = .0005, r = .62$ for the F and NF conditions respectively. Second, the RM ANOVA revealed that (1) presence of a frame significantly reduced the SVV deviation; (2) rotation of the dot pattern significantly increased SVV deviation; and (3) rotation had a significantly larger effect on SVV deviations in the NF condition compared to the F condition (Table 5.1). In other words, the SVV deviated significantly more from the Earth-vertical when the pattern rotated without a frame ($Mean = 6.57^{\circ}, SE = 1.42^{\circ}$) than during rotation with a frame ($Mean = 1.13^{\circ}, SE = 0.425^{\circ}$), $p = .001$.

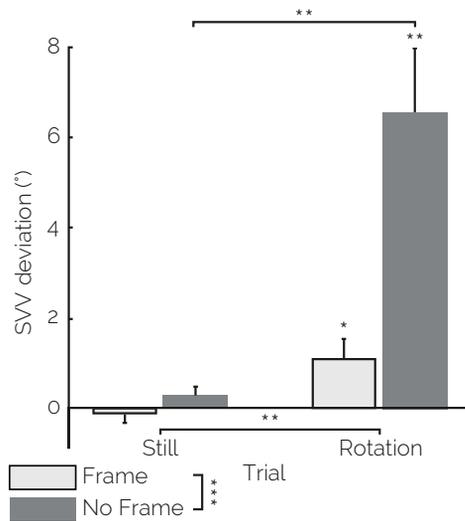


Figure 5.5. Mean SVV deviation (in $^{\circ}$, \pm SE) for both conditions. Positive values indicate a SVV deviation in the direction of rotation. Negative values indicate a SVV deviation in the direction opposite to the rotation direction (if there was rotation). Significant differences at $p < .05$, $p < .01$ and $p < .0001$ are indicated with *, **, and ***, respectively.

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5.3.3. Visually induced motion sickness

The maximum reported MISC rate was 3, and was obtained in the rotation trials in the NF condition. This implies that the stimuli did cause some subjective misery, but no nausea. Yet, in the NF condition participants reported significantly higher MISC rates after the rotation trials ($Mdn = 1$) compared to the still trial ($Mdn = 0$), $Z = 2.82$, $p = .005$, $r = 0.75$, while no such increase was observed in the F condition, $Z = 2.40$, $p = .016$ (note the Bonferroni corrected significance level of .0125; Fig. 5.6). Moreover, the MISC rates reported after the rotation trial in the NF condition were significantly higher compared to the MISC rates reported after the rotation trial in the F condition, $Z = 2.52$, $p = .012$, $r = 0.67$.

Finally, displaying the MISC rates on a trial-to-trial basis, separated for starting condition showed that these findings were not confounded by accumulation effects (Supplementary Fig. 5.1; see p. 140).

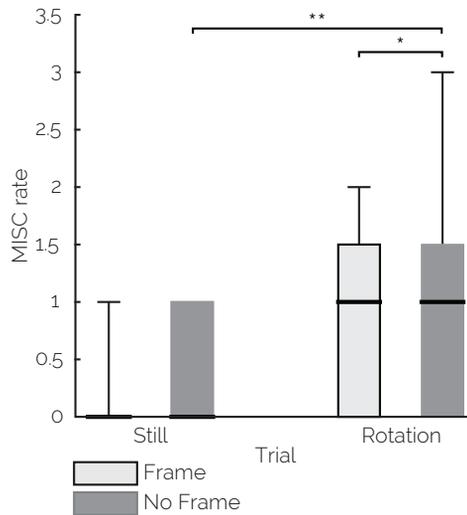


Figure 5.6. Boxplots of the MISC rates for both conditions and stimulus types. The solid black lines indicate the median MISC rate. Significant differences at $p < .05$, and $p < .01$ are indicated with *, and ** respectively.

5.4. Discussion

In this study we investigated the combined effect of an Earth-fixed visual frame and visual roll-motion on postural sway, the SVV, and VIMS ratings. As hypothesized, all three variables revealed that the presence of an Earth-fixed frame surrounding the rotating pattern facilitated upright standing (less variability and less lean), made SVV estimates more accurate (thus, in line with the Earth-vertical), and suppressed VIMS symptoms.

The finding that all variables were affected by roll-motion and the frame suggests that these variables are mediated by one common mechanism, likely involving a neural representation of verticality. First, we observed that postural sway was less variable (MWSD) and showed smaller excursions (lean) in presence of a visible Earth-fixed frame whilst viewing visual roll-motion. Evidence that humans use a neural representation of verticality for postural control has been provided by research in stroke patients with an active lateral tilt of the body¹¹. When interpreting the current postural results as a reflection of the neural representation of verticality, they indicate that the neural representation of verticality deviated less when an Earth-fixed cue of verticality was visible.

Second, in line with earlier studies^{30–32,89}, it was observed that visual roll-motion caused a significant deviation of the SVV away from the Earth-vertical. Such a deviation is proposed to be possible only if humans possess a neural representation of what is vertical^{3,139}. The observation that the Earth-fixed frame attracted the SVV, comparable to the Rod-and-Frame effect^{30,71,141–145}, also shows that veridical Earth-fixed cues are used to visually estimate what is vertical. Therefore, these findings also support the

idea that the SVV is influenced by a neural representation of verticality. Third, the detailed sensory conflict theory, as proposed by Bles et al.⁴ and Bos et al.², postulates that motion with respect to the Earth-vertical is especially provocative to VIMS. As stated by Bles et al.⁴, "All situations which provoke motion sickness are characterized by a condition in which the sensed vertical as determined on the basis of integrated information from the eyes, the vestibular system and the nonvestibular proprioceptors is at variance with the subjective vertical as predicted on the basis of previous experience". Bos et al.² elaborated on this with respect to visual factors, by adding that "when any pattern with clear horizontal and vertical texture is tilted away from true vertical, a subjective vertical mismatch may arise thus making people sick". On the one hand, and in line with Mittelstaedt¹³⁹ and Bos & Bles³, the current study shows that visual roll-motion does cause a significant deviation of the SVV from the Earth-vertical, which thus may explain the sickness symptoms observed in the current study as well. On the other hand, by adding the Earth-fixed frame, the current study revealed that the SVV deviated less from the Earth-vertical, the above theory thus explaining the observed reduction in sickness too. Although we cannot directly investigate whether humans use a neural representation of verticality, these results do reveal that these variables are being regulated by a common neural mechanism which can be interpreted as a neural representation of verticality.

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In comparison to two earlier studies that used a Rod-and-Disc apparatus^{30,31}, the use of a 40-inch display yielded similar effects of the rotating pattern on postural sway parameters and SVV deviations. Guerraz et al.³⁰ and Pavlou et al.³¹ reported during pattern rotation a mean lean of 5.3 mm and 3.9 mm respectively. In this study we found a comparable lean of 4.01 mm. Also the mean SVV deviation found in this study, being 6.57°, is in agreement with the SVV deviations found in these earlier studies, being 9.78°³⁰ and approximately 6.5°³¹. Although the postural excursions and SVV deviations showed to be comparable and the angular speed was identical (30°/s), the Rod-and-Disc apparatus subtended a larger FoV of 60°^{30,31} than the FoV of 40° subtended by the stimulus in this study. This comparison of results thus provides support for the claim that screens can be used to induce visual disturbances comparable to the Rod-and-Disc apparatus when certain conditions are met.

However, one should take the FoV into account when comparing results. A rotating stimulus that subtended a FoV of 130°, as used by Dichgans et al.⁸⁹, did cause a significantly larger mean SVV deviation of 15°. Moreover, research on vection strength and duration has shown that they increase with an increasing FoV¹⁵³. Further research should test whether the FoV has a similar effect on postural sway, SVV deviations and VIMS.

Although in this study a clear visible Earth-fixed frame was presented, pilot trials in our lab showed that even a minimal visible frame, i.e. only visible after several minutes of dark adaptation, already showed the

limiting effects discussed here. Possibly, even a barely visible Earth-fixed cue, e.g. seeing a part of one's own body through a crack in the goggles or a sub-optimally fitting mask for the screen, may already significantly reduce the effect of the rotating visual stimulus. As a consequence, it is of great importance when using light-emitting stimuli with the purpose of inducing visual disturbances, that no other Earth-fixed cues are visible. In an experimentation room this can often only be realized by completely darkening the room in combination with the use of ND-filters and screen covers to minimize the amount of scattered light perceived by the participant to a sub-threshold level, as shown in the present study. Outside the experimentation room head-mounted displays, such as the low-cost Oculus Rift¹⁵⁴, may be a good alternative. The Oculus Rift subtends a large FoV of approximately 100° and its foam barriers eliminate all visual Earth-fixed cues¹⁵⁴.

Finally, the question how the orientation of the visual frame interacts with the Earth gravitational field in the construction of a perception of verticality during exposure to visual roll-motion remains unknown. A further study in which the visual frame is dissociated from the Earth-vertical is therefore suggested.

In summary, we observed that postural sway, SVV estimates and motion sickness were influenced by the presence of an Earth-fixed cue surrounding visual roll-motion, pointing towards a common neural origin. From a practical point of view, we provided evidence that a commonly available screen is able to induce significant visual disturbances comparable to mechanical devices, when cues of verticality are properly eliminated. Finally, with this study we showed that when studying subjective verticality related effects of visual stimuli it is imperative that all visual Earth-fixed cues are not just minimized, but completely eliminated.

