Personal visual-vestibular coherence and simulator sickness

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Abstract *– Simulator sickness can be explained by a conflict between visual and vestibular self-motion cues. In real life, retinal image- and physical self-motion are equal but opposite. Most moving-base simulators, however, apply less physical motion than visually displayed, the ratio (gain) between visual and vestibular motion being fixed. It has, however, been shown that for linear motion the optimal gain was about two on average, and varied largely between subjects. We accordingly posed the question whether this gain could explain individual differences in simulator sickness. We then exposed subjects to a continuous physical linear sinusoidal motion with fixed amplitude on a sled, and presented the corresponding visual motion in a virtual environment using VR goggles. This visual motion was in phase with and opposite the physical motion, except for its amplitude that subjects had to adjust by handheld buttons until it matched their perceived physical motion best. After determining each subject's optimal gain, we then exposed them to separate sessions using their optimal gain and a three times smaller gain while rating motion sickness. Results confirmed the reported large individual variability in optimal gains as observed previously, but did not show an effect of the visual-vestibular gain on their sickness scores.*

Keywords: *visual-vestibular coherence, personalised motion cueing, simulator sickness.*

Introduction

Real vehicle motion as used to render the visual imagery of a simulator is typically (much) larger than the physical motion that can be realised by a simulator motion platform. At the same time, Correia Gracio et al, (2014) showed that when exposing subjects to linear motion with a fixed amplitude and congruent virtual (visual) motion, except for its amplitude, they subjectively prefer a (much) larger visual amplitude. In their experiment they used sinusoidal (surge, sway, and yaw) motion, with a physical amplitude of 2 m (4 m peak-peak) and 20° (40° peak-peak). They presented the opposite visual motion (e.g., forward physical motion inducing backward optic flow) and subjects were instructed to manipulate the amplitude of the visual motion using buttons such that the visual motion subjectively matched the physical motion best. The latter condition is also referred to as 'coherent'. They defined the observed personal ratio as the 'visual-vestibular gain'. In real life conditions this gain can be assumed 1[1]. Although slightly larger for surge than for sway, their experiment showed an average gain of about 2 for linear motion and 1 for yaw. More importantly, they observed large individual differences, ranging from less than 1 to over 14 for linear motion and substantially less variability in yaw. In addition they found larger gains for larger FoV and when more objects were included in the imagery, which effects were studied in addition. The latter effects, again were only observed for linear motion and not for yaw. They explained these results by assuming ambiguities in visual linear self-motionperception only, having a bigger effect with reduced image 'quality' as inherent to artificial images. To this explanation the assumption can be added that individual differences in neuronal weighting of visual and vestibular cues likely explains the individual differences. In contrast with these observations, it is a matter of fact that most, if not all simulators apply fixed gains, assuming one-size-fits-all.

In addition it is the case that simulator sickness varies largely between subjects. To explain motion sickness in general, Reason (1978) assumed a neural mismatch between integrated sensory information and a (cognitive) expectancy or prediction about this information. When visual cues are present, the mismatch can be modulated by a visual-vestibular conflict, then also explaining simulator sickness in

[1] Note that for sinusoidal motion, this gain is equal for considering position, velocity and acceleration (and jerk, etc.).

particular (Bos et al., 2008; Bos et al., 2021). Simulator sickness too varies largely between people, which variability may be related to the same individual differences in neuronal weighting of visual and vestibular cues. It is the aim of the experiment described here to elaborate on that assumption.

Given the results found by Correia Gracio et al. (2014) with the largest variability of personal gains observed in surge motion, we here limited our study to surge motion only. Given the availability of a sled with a relatively large length, we took the opportunity to also study a possible effect of physical motion amplitude by including a larger than 2 m motion.

If the relationship between individual gains and simulator sickness could be established, (part[2] of) the interindividual variability in simulator sickness can then be explained by assuming a large proportion of people having a different personal gain as actually applied when exposed to fixed-gain moving base simulators. This would then also offer a way to reduce simulator sickness by considering that personal gain, to create personalised motion filters.

Specifically in the experiment described here we examined two Research Questions:

1. does the visual-vestibular gain depend on the physical motion amplitude
2. does simulator sickness depend on the personal optimal visual-vestibular gain

Methods

In this experiment we largely adhered to the methods used by Correia Gracio et al. (2014), though using a sled allowing larger displacements to also study a possible effect of motion amplitude.

Experimental design

We used a within subjects design with 5 experimental sessions for each subject, realised on 3 days. In Session 1 on Day 1, subjects were tested for their personal gains during 20 minutes of sled-motion at both amplitudes as further described below. In Sessions 2-5, realised on Days 2 and 3, only motion sickness was monitored, while using a 2 and a 7.3 m motion (on separate days) with the optimal personal gain and a gain 1/3 thereof. Whenever possible, conditions were balanced over subjects.

Apparatus

Sled

The sled (Figure 1, top left) consisted of a cabin housing a rally seat with a safety belt (Figure 1, top right), running over rails and pulled by dyneema cables driven by motors at each end of the track. The usable length is 35 m. Peak velocity and accelerations are 14 m/s and 5 m/s^2, respectively. We used two sinusoidal motion profiles, one with an amplitude of 2 m (4 m peak-peak) at 0.17 Hz (as applied by Correia Gracio et al., 2014), and a 7.3 m (14.6 m peak-peak) amplitude at 0.1 Hz. The lower frequency of the larger motion was chosen to cause an equal amount of sickness as the 2 m motion, as estimated by ISO 2631-1 (1997)[3]

Figure 1.The 25 m linear sled (top left), the setup of the interiour of the cabin, also shoing the additional controller attached to the cabin (top right), and the imagery (bottom), as used in the experiment.

VR goggles

To present and manipulate the images for use in this experiment, we created a city road without any car-fixed structure as shown in Figure 1 (bottom). The images were shown through HTC VIVE Focus 3 VR goggles, making use of the Simulator VR Mode (HTC, 2023) and one of the controllers firmly attached to the cabin. The latter allowed for manipulation of the visual-vestibular gain independent of the actual sled motion as sensed by the inertial sensors

[2] Other factors contributing to this variability are, for example, vestibular function per se, habituation, age gender and genetic or ethnic effects.

[3] Table 3 of ISO 2631-1 then lists values for w_f for a number of frequencies. This offers the possibility to reduce both the peak acceleration and sickness by reducing the frequency of the A = 7.3 m motion. When applied to the 2 m, 0.17 Hz motion, $w_{0.17} \approx 1$ and the frequency weighted acceleration $a_w = w_f \times a \approx 2.0$ m/s^2. Considering that $w_f \times a = w_f \times (2\pi f)^2 A$ for sinusoidal motion, it follows that the 7.3 m motion will result in as much sickness as the 2 m motion does at a frequency of 0.1 Hz. Then, $w_f = 0.695$ and $a_w = 0.695 \times 7.3 \times (2\pi \times 0.1)^2 = 2.0$ m/s^2 too. This effectively results in a peak acceleration $a = 7.3 \times (2\pi \times 0.1)^2 \approx 2.9$ m/s^2. Although the ISO sickness estimation formally only applies to vertical motion, Bos et al. (2023) showed that equal weightings apply to vertical, fore-aft, and lateral motion.

of the VR goggles, while still allowing head motion compensated image stabilisation. Because no car-fixed structure were shown, the entire visual environment remained Earth-fixed, except for the longitudinal motion.

Measured variables

Visual-vestibular gain

Optimal visual-vestibular gains (possibly differing between motion amplitudes) were measured in Session 1 by exposing the subjects to continuous sinusoidal motion. During these motions, subjects held a keypad, of which the up- and down-arrow keys were marked with felt and used to in- and decrease the visual-physical gain by 10% per keystroke. Subjects were explained to use these buttons until the visual motion subjectively matched best with the physical motion sensed. When this point was reached, subjects pressed a third button also marked by felt, after which the imagery was set to another initial gain. Each period between starting an adjustment and switching to a next initial gain is further referred to as a trial. Visual vestibular gains were defined as the ratio between the visual motion amplitude reached at the end of each trial divided by the physical motion amplitude tested.

Based on Correia Gracio et al. (2014) and anticipating a bias towards the initial setting, we randomly varied initial gains between low (0.5 - 2.5) and high (8.5 - 10.5) values in 8 repeated trials per motion amplitude, i.e, 16 trials per subject in total.

Within each physical motion amplitude, the sinusoidal motion continued over the trials, except for three short pauses, one of which was used to changing the motion amplitude.

Sickness

In Sessions 2-5, we measured the amount of motion sickness subjects experienced using the Motion Illness Symptoms Classification scale, MISC (Reuten et al., 2021), previously also known as the MIsery SCale (Bos et al., 2005). The MISC is shown in Table 1. The MISC is based on a priori knowledge about the order in which symptoms associated with motion sickness generally occur in the first hour of motion exposure.

MISC ratings were verbally asked every minute. To minimise dropout due to excessive sickness, the experimenter stopped the session when a MISC rating of 6 or larger was given. At any moment, the subject could also indicate the wish to stop.

Subjects and procedures

Subjects

Based on Correia Gracio et al. (2014), and to allow for appropriate counterbalancing of experimental conditions, we aimed at including 24 subjects, recruited from TNO's subject data base. Subjects were between 18 and 65 years of age, had experienced at least some symptoms of motion sickness but not excessively in the last 5 years. They also had normal or corrected-to-normal vision, were free of self-known vestibular, neurological, hormonal and cardiovascular disorders, did not suffer from neck or back pain or claustrophobia, did not use sedating medication, were not pregnant and weighted less than 100 kg. The latter was required for fitting in the cabin and not affecting sled performance. All subjects had stereovision as confirmed by TNO's stereo test (TNO, 1972).

Ethical approval was obtained beforehand from the TNO committee on non-medical scientific research with human subjects.

Table 1. The Motion Illness Symptoms Classification scale (MISC; Reuten et al., 2021; Bos et al., 2005).

Symptoms		*MISC*
No problems at all		0
Uneasy (no typical symptoms)		1
Dizziness, warmth, headache, stomach awareness, sweating, ..., ***but no nausea***	vague slight fairly severe	2 3 4 5
Nausea, possibly with symptoms 2-5	slight fairly severe (near) retching	6 7 8 9
Vomiting		10

Session 1

To find the personal gains in Session 1, subjects were continuously exposed to 2x5 minutes of the 2 and 2x5 minutes of the 7.3 m motion.

Upon arrival at TNO on Day 1, subjects were explained the experimental procedure and given the opportunity to ask any questions about the experiment. After signing an informed consent form, subjects were instructed about and familiarised with the adjustment of the visual motion amplitude.

Sessions 2-5

Without revealing details, subjects were explained in Sessions 2-5 to only experience a physical and visual motion with fixed amplitudes, and without further subject interaction. During these sessions, sickness was rated at one minute intervals (see below).

Sessions 2-5 were realised on Days 2 and 3, using the 2 m motion on one day, and the 7.3 m motion the other day. Each motion was used twice with the optimal and the sub-optimal gain of 1/3 of the personal optimal value found in Session 1 on Day 1. A minimum of a 1 hour pause was included in between the two sessions on each day.

Subjects were continuously observed through a web cam. They wore headphones to exclude sounds from outside and to allow communication with the experimenter.

Each Session lasted about 20 minutes or less in case of serious sickness (stop criterion), or at the subject's wish.

Data analyses

Visual-vestibular gain

A final visual-vestibular gain was determined for each subject and each motion amplitude as follows. Because of the large variability in settings observed (see Results), in particular biased by the initial gains, we took the median of the gains across the trials separately for the low and high initial gains and averaged these median values, resulting in the final visual-vestibular gain for each subject and motion amplitude. The suboptimal gain for each subject was then chosen to be 1/3 of this final personal gain. Although the 1/3 ratio was chosen arbitrarily, we deliberately chose smaller gains only, because too large gains would result in digital image smear for those with a relatively large personal gain. The alternative to use both a smaller suboptimal gain for those with a relatively large personal gain and a larger suboptimal gain for those with a relatively small personal gain might result in opposing effects, was therefore not considered. We therefore concluded to only use smaller gains for the suboptimal conditions.

Sickness

MISC scores obtained over time in Sessions 2-5 were used for further statistical analyses, i.e., at 16 time points per subject and Session. Missing values after abortion of trials due to the stop criterion (MISC = 6) or when the subject wished to, were supplemented with the last observed MISC value.

Research questions

To answer Research Question 1: does the visual-vestibular gain depend on the physical motion amplitude, we performed a non-parametric Wilcoxon signed-rank test (α = 0.05) on the personal visual-vestibular gains as determined for the 2 versus 7.3 m sessions.

To answer Research Question 2: does simulator sickness depend on the personal optimal visual-vestibular gain, we performed a repeated measures ANOVA (α = 0.05) on the MISC scores provided during Sessions 2-5. The independent variables in this analysis are time point (16 levels) and session (4 levels: 2 or 7.3 m motions and optimal or suboptimal gain).

Results

Due to dropout we recruited one additional subject. Of the 25 subjects, four had serious difficulties with the task of adjusting the visual-vestibular gain in Session 1 and were subsequently excluded from the data analyses. All final analyses have therefore been carried out with 21 subjects.

Session 1 - Research Question 1

Figure 2 shows all gain settings per participant as well as the median values for the high and low initial gains, and their averages.

The personal gains varied considerably between subjects: between 0.6 and 5.6 in the 2 m session and between 0.2 and 10.1 in the 7.3 m session. The Wilcoxon signed-rank test indicated that the median personal gain across the sample did not differ between the 2 m (Z = 2.7, IQR = 1.8) and 7.3 m (Z = 1.8, IQR = 2.2) sessions, with V = 167 and p = 0.076. Our results therefore do not indicate that the personal visual-vestibular gain is dependent on motion amplitude.

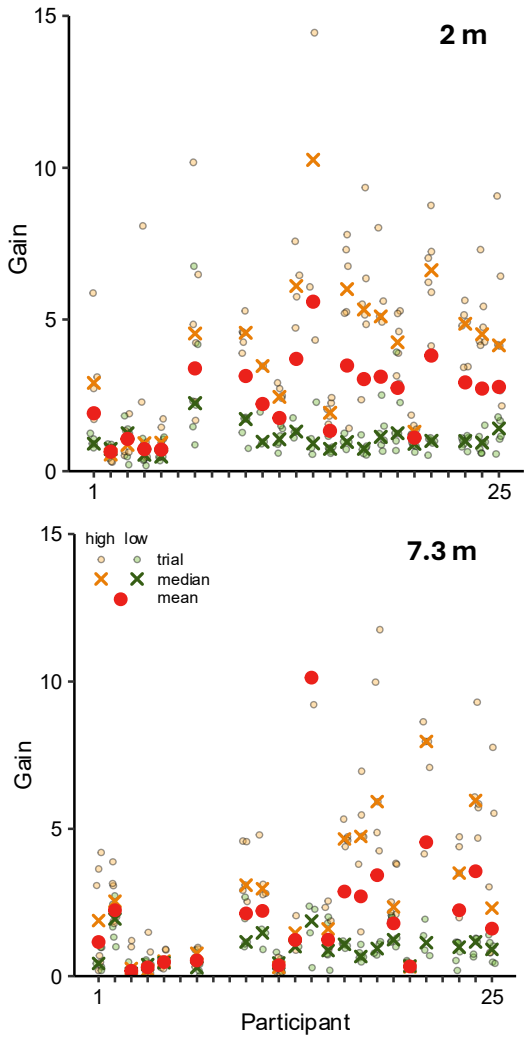

Figure 2. Personal visual-vestibular gains for all trials per subject per physical amplitude (top: 2 m, bottom, 7.3 m). Each final personal gain (red dot) is the average of the two median gains (crosses) over the trials with an initial high (orange) versus low (green) gain. Note that some noise is added to the participant's number to better discriminate between individual gains and there were only two gains of over 15 not shown.

Sessions 2-5 - Research Question 2

Figure 3 shows the average MISC scores over time in Sessions 2-5, in which the effects of an optimal personal gain versus a suboptimal gain (1/3 of the optimal gain) for the two profiles are shown.

The results of the repeated measures ANOVA with the MISC scores as the dependent variable and time and session as the independent variables showed a significant main effect of time, implying that the MISC scores increased during the sessions ($F(1,18) = 29.9$, $p < 0.001$). However, there was no significant main effect of session ($F(3,54) = 0.10$, $p = 0.961$) nor of an interaction ($F(3,54) = 1.72$, $p = 0.173$). This implies that the MISC scores did not develop differently over time between the sessions, not with respect to the optimal personal gain versus a suboptimal gain, nor, with respect to the motion amplitude.

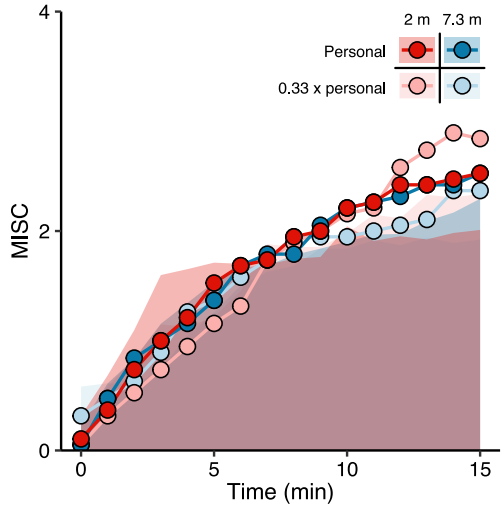

Figure 3. The development of MISC scores over time, averaged across subjects for each of the four sessions. The shaded areas represent standard deviations.

Discussion and conclusions

With the experiment described in this report we took up the challenge to elaborate on the assumption that a personalized optimal visual-vestibular coherence, i.e., a subjectively matching visual and physical self-motion in a moving-base simulator, also results in the least simulator sickness for that person. The hypothesis was prompted by the observation that the ratio, or gain, of optimally matching visual and physical self-motion in a moving-base simulator was shown to vary between subjects considerably, i.e., less than 1 to over 14 as reported on by Correia Gracio et al. (2014). In normal life this gain can be assumed to be 1, while it is (considerably) larger than 1 in moving base simulators (e.g., Sadraei et al., 2018), which Correia Gracio et al. ascribed to the fact that artificial images fall short of real visual environments. This is an additional reason that simulators sickness differs from motion sickness in, e.g., cars, even if the motion platform would be able to realise the real motion 1:1 (see also Bos et al., 2021). This observation is in contrast with the fact that in most, if not all moving base simulators this gain is fixed, assuming a one-size-fits-all solution.

Aligning with the methods used by Correia et al. (2014), we performed an experiment focussing on the relationship between the two factors: personal gain and sickness. Most moving base simulators are rather limited in their displacements, while in real life large(r) displacements are at issue. We therefore also included a larger motion amplitude, i.e., of 7.3 m (14.6 m peak to peak) in addition to the 2 m (4 m peak to peak) profile as used by Correia Gracio et al. The frequency of the larger motion was decreased to cause sickness equal to the smaller motion.

The data show that we succeeded with respect to the latter, because, indeed, no differences in sickness were observed between the 2 m (at 0.17 Hz) and 7.3 m (at 0.1 Hz) sessions.

Session 1 - Research Question 1

As anticipated, the initial gain settings in Session 1 affected the personal gains considerably, which was the reason to determine the final, personal gains the way we did, i.e., by taking the average of the median values over the high and low initial gain trials.

In the 2 m motion we found a smaller range of gain values (0.6 and 5.6) as compared to the range of values observed by Correia Gracio et al. (2014; <1 to over 14). This may be attributed to the fact that we included a familiarisation trial beforehand. Interestingly, we did not find a significant overall difference between the two motion profiles.

Although these results may accordingly be credible, still three of our subjects had serious problems with the adjustment task. We therefore propose to consider the use a two-alternative-forced-choice method in possible future experiments on this issue. The choice then being whether the visual motion is perceived as larger or smaller than the physical motion, or, the other way round, whether the physical motion is too weak or too strong as compared to the visual motion[4]. Then, every cycle of the motion a choice could be scored. Even at a low frequency motion of, e.g., 0.1 Hz, still 30 choices could be obtained, which

[4] Note that these two options concern different perceptions, visual motion (velocity and position in particular) versus force, possibly leading to different observations because perception does not always obeys the laws of physics.

likely is sufficient to either fit a psychometric function through the observations, or reach a stable value using a staircase method.

Sessions 2-5 - Research Question 2

In Sessions 2 to 5, we investigated whether a personal visual-vestibular gain as determined in the first Session (Figure 2) resulted in less motion sickness compared to a gain reduced by a factor of 3 (Figure 3). Overall our results did not show less sickness in the sessions with an optimal personal gain as compared to the sessions with a reduced gain for either physical motion amplitude. This, however, does not imply that there is no relationship.

A major reason for our not finding an effect of the gain on sickness is likely given by the fact that we only fount moderate levels of sickness, i.e. a maximum of MISC = 2 on average, implying only “vague symptoms” (Table 1). Low levels of sickness give less power to find the effect, in particular when the variability is in the same order of magnitude as the observed levels themselves, as was the case in our data too. Moreover, these low ratings concern symptoms typically preceding nausea, which symptoms do vary largely between subjects and do not only include vestibular effects, but also mere visual effects that even may occur in watching static images (Lubeck et al., 2015). Also headaches and fatigue as two of the included pre-nausea symptoms may not only be induced by self-motion. Experimental follow-up on this matter would therefore benefit from using more provocative stimuli.

The fact that we only found vague symptoms (on average) may be explained by the fact that, different from, e.g., the ISO 2631-1 (1997) which only considers inside viewing conditions, i.e., moving as a whole with the subject, we did apply an Earth-fixed out-the-window view. Moreover, this view was always in phase with the self-motion, in which the amplitude may have only played a subordinate role regarding motion sickness, which subordinate role may have been emphasised by our using a rather flat, sketchy imagery with a limited reality (Figure 1 bottom).

Another reason for our not finding an effect of the gain on sickness may be given by the fact that VR goggles come with a multitude of limitations as compared to real viewing conditions. Limitations regarding field of view, luminosity, contrast, spatial, colour and temporal resolution, and delays, for example (see also Bos et al., 2021), may each affect different individuals in different ways with respect to motion perception and sickness, the latter two possibly in different ways as well. Moreover, whether the visual-vestibular gain as studied here is actually a constant within individuals or a feature that humans can habituate to dynamically is yet another question. If this gain would not be constant that could as well explain the absence of finding the effect at issue and would be worth a future study.

A minor, technical reason for our not finding an effect of the personal gain on sickness may, lastly, concern the use of a new solution to still compensate for head movements while wearing the goggles in a moving environment (the HTC Simulator VR Mode). This solution did not show to be perfect yet, causing some image instabilities that may have added variability to the gains observed (Session1) as well the sickness observed in Sessions 2-5.

Still, from a practical point of view, the question posed here remains of interest, and may even become critical with further development of projection systems and head-mounted virtual reality solutions, which developments may result in more, rather than less sickness as often assumed (Bos, 2013; Bos et al., 2017). The hypothesis posed here therefore still deserves further scrutiny.

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