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Simulating believable forward accelerations on a Stewart motion platform

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Abstract. Here we present a study where human participants rated the believability of forward accelerations simulated with a hexapod motion platform equipped with a projection screen. Visual forward accelerations were presented together with brief forward surge translations and backwards pitches of the platform, and synchronous random up-down movements of the camera in the visual scene and the platform. The magnitudes of all of the parameters were varied independently across trials. Even though we found a high variability between participants, most believable simulation occurred with strong visual accelerations combined with backwards pitches of the platform which approximately matched the visually simulated acceleration. This was contrary to a previous study, which had found most believable simulation when the platform movements simulated a much smaller acceleration than what was shown visually. Furthermore, surge translations increased believability if they qualitatively matched the magnitude of visual acceleration. The acceleration-deceleration profile of the surge translation and the magnitude and frequency range of the up-down movements had little effect on the believability. When strong visual acceleration cues were given, most participants reported trials as realistic even when the platform tilt rate was above thresholds for the vestibular canals reported in literature. These results can be used to optimize motion cueing algorithms for the simulation of linear accelerations in motion simulators.

1 Introduction

It is still an unsolved problem how to optimally simulate self-motion using motion simulators, despite the fact that self-motion simulation is an essential part of all commercial flight and driving simulators [1]. Flight simulators used for pilot training and also most driving simulators try to simulate motion trajectories which are considerably larger than the actual range of the physical simulator device. To do this, motion cueing algorithms attempt to mimic the accelerations which act on the body during self-motion. While a larger range of movement allows for more accurate motion cueing, increasing the number of degrees of freedom and enlarging the movement range of the simulator raises the costs of the device considerably, and there are also technical limits to what kind of trajectories can be performed in a simulator due to the limited motion envelope and actuator power. It is therefore important to find techniques to believably simulate large trajectories using smaller movements, which are within the limited movement range of the simulator. It is still unknown how to move the simulator optimally, so that the simulated trajectory is most *believable* for a human observer. Presenting believable physical accelerations is also an issue for psychophysical experiments which investigate the perception of self-motion in motion simulators.

1.1 Influence of visual and inertial cues on self-motion and self-orientation perception

Several senses provide information about self-motion, the most important being vision and the sensation of inertial body movements (vestibular and somatosensory/proprioceptive senses) [2]. It has been known for a long time that the different sensory modalities interact in the perception of self-motion, but how exactly the brain estimates body orientation and self-motion from these cues is still a matter of debate [3, 4]. See [5, 6] for recent models.

The perception of body orientation in space can be influenced by vision. This is well illustrated in the rod-and-frame test, where participants are asked to adjust the orientation of a line (the rod) such that it points straight upwards against gravity. If this line is surrounded by a tilted visual frame, observers typically orient the rod towards the same side as the visual frame (for review, see [2]). If participants are exposed to a tilted full visual surround (a furnished room), the illusion is even stronger [7]. In these experiments, visual cues had more influence on the perceived orientation in space than the sensed direction of gravitation.

The phenomenon ofvection (a visually induced illusion of rotational or linear self-motion) shows that the perception of self-motion can be induced by purely visual stimulation. Typically, the onset ofvection is delayed for a few seconds after the onset of the stimulation [8, 9, 10]. There is, however, a large inter-individual variability of

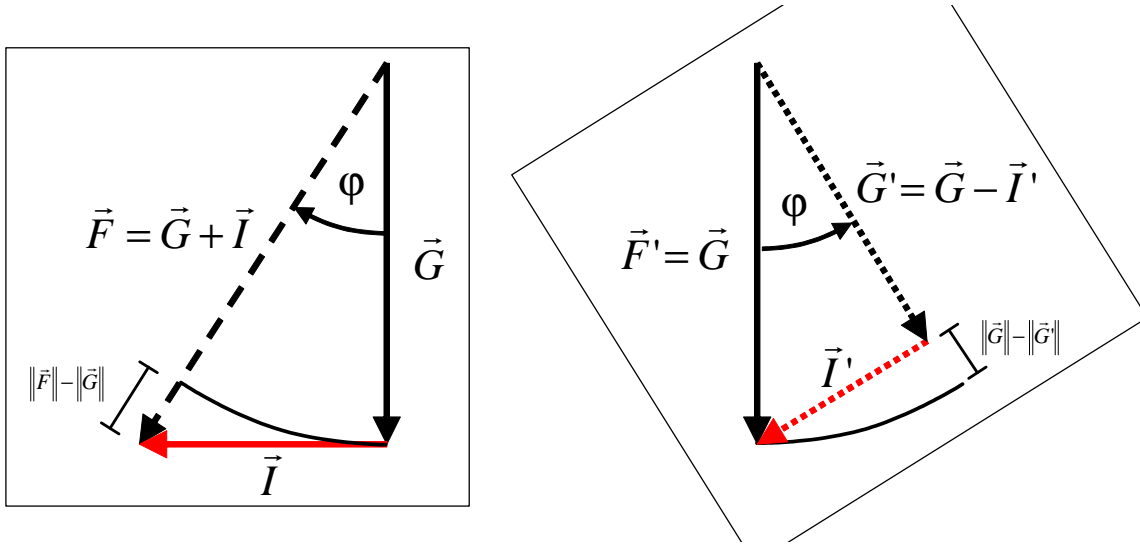


Figure 1: Tilt coordination for the simulation of forward accelerations by tilt. *Left:* during a real acceleration, the resulting gravito-inertial force vector \vec{F} is the sum of gravitational force \vec{G} and inertial force caused by the acceleration, \vec{I} . The additional acceleration causes a rotation of the force vector direction by an angle $\varphi = \arctan(\vec{I}/\vec{G})$, and increases its magnitude. *Right:* When the acceleration is simulated by tilt coordination, the participant is rotated in space by the angle φ , so that the gravitational force vector \vec{G} points (in the local coordinate frame) in the direction of the simulated gravito-inertial force \vec{F}' . Even though the direction of the gravito-inertial force vector \vec{F}' is then correct, the magnitudes of the simulated gravitational force \vec{G}' and inertial force \vec{I}' are reduced, compared to a real acceleration.

vection onset latencies. A reason for this might be due to individual differences of vestibular sensitivity: Lepecq et al. (1999) [11] found a negative correlation between individual vestibular thresholds and vection onset latency for translatory movements along the vertical axis. This corroborates models which propose that the delay of the onset of vection is related to the perception of a conflict between visual and vestibular cues of self-motion [12, 13]. According to these models, the lower the vestibular threshold, the longer a visual-vestibular conflict can be perceived and the longer vection is delayed.

Even though visual vection can be very compelling, the rather long vection onset latencies prevent immediate perception of self-motion, and this method is thus not sufficient for self-motion simulation. In cases where observers are exposed to a true physical movement, perception of self-motion arises immediately. Therefore, inertial cues of self-motion should help to reduce the onset latency of vection. It has indeed been shown that concordant inertial cues can speed up the onset of the illusion of self-rotation in a rotating optokinetic drum [14].

1.2 Motion cueing algorithms

For the simulation of sustained forward accelerations, visual and inertial cues need to be provided in a way so that the observer believes that he is moving forward, even though he is not. For this, it is common to use a short initial forward translation, referred to as "surge" motion, in combination with a backward tilt of the platform that presses the participant into the seat [15]. It is assumed that for a good simulation of a linear acceleration, the whole-body angular velocity should be below the threshold for the vestibular canal system which detects rotational motion. Under these circumstances, evidence of a rotation is minimized and the interpretation of the change of direction of the gravito-inertial force vector as an acceleration is facilitated. The surge translation should have an acceleration above the sensory threshold and a deceleration below that threshold, such that the participants notice the acceleration but not the deceleration. A visual forward acceleration and a stable horizon are visual cues that support the perception of a physical forward acceleration.

Figure 1 shows how a backward tilt can be used to align the simulated gravito-inertial force vector with the direction of gravity, with the goal of making the observer interpret the rotation of this vector as due to forward acceleration (a method termed "tilt coordination"). Horizontal linear accelerations cause a change of the direction of the gravito-inertial force vector because of force vector addition (Figure 1, left). The same change of direction can be caused by a rotation of the observer (Figure 1, right). A forward linear acceleration of $a \text{ m/s}^2$ corresponds

to a backwards pitch of an angle $\varphi = \arctan(a/9.81)$, or inversely, a pitch of angle φ simulates an acceleration of magnitude $a = \tan(\varphi) \cdot 9.81 \text{ m/s}^2$.

When a visual acceleration is presented together with a platform pitch, we can compare the acceleration specified by the visual scene and the acceleration specified by platform pitch, and define a physical motion *gain* as the acceleration cued by platform pitch relative to (divided by) the visual acceleration. A gain of 1 means that the acceleration specified by the platform pitch corresponds to the visual acceleration. A gain below 1 indicates that the acceleration specified by platform pitch is smaller than the visual acceleration, and a gain above 1 results if the physically simulated acceleration is larger than the visual acceleration.

The change of the direction of the gravito-inertial force vector caused by linear accelerations or rotations is sensed by the somatosensory system and by the otoliths of the vestibular system [16]. The brain can use signals from the vestibular semicircular canals and the somatosensory system as well as visual cues to determine whether the force vector direction change is caused by a rotation or by a linear acceleration. This process is called "tilt-translation disambiguation". Under the right conditions, the human brain can interpret at least parts of an actual tilt as linear acceleration [3]. In aviation this can lead to powerful illusions, for example the somatogravic illusion, in which pilots experience a backwards pitch during long-lasting forward acceleration. If pilots pull down to compensate, this can cause fatal accidents, especially during catapult takeoffs from aircraft carriers under bad visibility conditions [17]. Visual cues can also influence tilt-translation disambiguation [18]. In that study, visual pitch specified by a horizon and visual acceleration specified by optic flow influenced both pitch and acceleration judgements of human observers.

Some neurophysiological experiments suggest that the nervous system indeed uses vestibular canal signals and other body receptors that sense rotations and accelerations to disambiguate tilts and linear accelerations. For example, Angelaki et al. (2004) [19] showed that some neurons in the vestibular nuclei and the cerebellum can distinguish between body tilt and linear acceleration in darkness, possibly by combining information from linear and rotational inertial motion sensors. Since the vestibular nuclei also receive visual optic flow signals [20] and somatosensory signals from the neck and other parts of the body [21, 22], these signals could in principle solve the tilt-translation ambiguity already at the level of the vestibular nuclei.

Several algorithms have been developed to optimize motion cueing for aircraft simulation in training simulators. Earlier approaches focused on generating force cues which are as close as possible to the to-be-simulated forces (e.g., the nonlinear "adaptive algorithm", reviewed in [23]); other algorithms use knowledge about the characteristics of the human motion senses, in particular the vestibular system, to optimize the accuracy of the elicited sensory signals (e.g., the "optimal algorithm", see [24]). Recently, also a combination of both methods has been proposed [23]. However, what is perceived as realistic does not necessarily depend directly on the accuracy of the elicited vestibular sensory signals. For example, it has been reported that pilots prefer classical and adaptive motion cueing to the "optimal algorithm" [25].

The ultimate judge for the believability of a given simulation is the human observer. Psychophysical experiments are therefore the optimal means to examine how movements need to be simulated so that observers accept them as realistic. Since typical motion platforms have a very limited physical motion range, large or sustained accelerations can only be presented if one finds an intelligent way to deceive the human senses to perceive self-motion. What method can be used to achieve this depends on how the different sensory channels are fused into a percept of self-motion and self-orientation.

Groen and Bles (2004) [26] investigated the simulation of sinusoidal translatory motion (forward-backward) by using a visual stimulus showing forward-backward motion and whole-body tilt rotation of different frequencies and magnitudes. They found that pitch rotations below a threshold of about $3^\circ/\text{s}$ were interpreted by the participant as translations, whereas they were perceived as rotations above this threshold. Interestingly, the threshold depended on the amount of visual acceleration. Higher visual accelerations allowed larger pitch rotation speeds before body rotations were perceptible.

Another study by Groen and colleagues investigated the effect of short forward "surge" translations and backwards pitch rotations of the platform on the perceived realism of a simulated aircraft takeoff acceleration which was also presented visually [27, 28]. Here, participants judged the realism of the simulation in the initial and the later phase of the trial independently. The study found a dependency of the believability of the initial phase of the acceleration on the platform surge motion, with good judgments only for small surge motions. Large surge motions did not blend well with the subsequent pitch simulation of the acceleration. In the later phase of the trial, believability ratings were dominated by the pitch velocity. Pitch rotations which were much smaller than the corre-

sponding visual accelerations were rated best. Optimal amplitudes for surge translations and pitch rotations were found to be approximately 0.2 and 0.6 times the ones that would correspond to the visual acceleration, respectively.

The study by Groen et al. (2000) [27] has a number of limitations: First, they introduced a strong conflict between the visual and the body acceleration cues in all their trials, by using gradually increasing body acceleration cues, while keeping constant visual acceleration. Second, the visual scene did not contain any clearly perceptible size cues. The physical motion simulation gains far below 1 which they found might be explained by a misperception of the size of the scene, even though a collimated display was used. An alternative explanation could be the influence of an *idiotropic bias*: If humans have to rate the direction of "up" in a gravitation-free environment, they prefer a direction aligned with the longitudinal axis of their body [29]; see also [18].

In the study reported here, the visual scene contained clear size cues and was viewed monocularly by the participant to eliminate the vergence cue for distance. Contrary to the study of Groen et al. (2000) [27], we used increasing accelerations both for the visual display and the physical simulation of acceleration by body tilt, instead of combining a constantly accelerating visual scene with an increasing physical acceleration cue.

1.3 Aim of our study

Many motion simulators use hexapod Stewart platforms, which can be rotated and translated in all directions in a certain range. For the simulation of forward accelerations, these platforms can simultaneously perform a backward pitch (for tilt coordination), a surge translation, and also up-down translations to simulate movements over uneven ground. To explore how to best use the available motion range to simulate believable forward accelerations on such a simulator platform, we examined the effect of the following six parameters on the reported believability of the simulated acceleration:¹

- Amount of platform pitch,
- Size of forward (surge) translation,
- Acceleration-deceleration timing of the forward translation,
- Magnitude of correlated up-down movements of platform and visual display and
- Frequency thereof, and
- Amount of visual acceleration.

Platform pitch and surge translation are standard procedures for forward acceleration simulation. The acceleration-deceleration timing was manipulated to investigate whether a strong acceleration with a weak deceleration really makes the forward acceleration more believable, compared to a weaker acceleration with a more noticeable deceleration. Since the translation motion range of Stewart motion platforms is usually very limited, and acceleration and deceleration have to fit in the available motion range together, the weaker the deceleration, the stronger the acceleration has to be, and vice versa.

Our motivation to manipulate up-down movements of the platform and the visual scene which are synchronous and consistent was to increase the binding between visual and inertial cues for self-motion (similar to the Gestalt principle of common fate) and thus increase the believability of the simulated acceleration. We tested this by manipulating both magnitude and frequency range of concordant up-down movements of the observer in the visual scene and the platform.

Finally, the visual acceleration was varied between trials so that we could investigate what range of acceleration magnitudes can be simulated believably, and which platform movement parameter combinations are most believable for a given visual acceleration.

2 Materials and methods

This study was performed in the Motion Lab of the Max Planck Institute for Biological Cybernetics. The setup consists of a hexapod Stewart motion platform (Maxcue platform, *cueSim*, England) with a seat mounted on top and a custom-built projection system (JVC DLA-SX21S projector, flat projection screen). Participants were seated on the platform and viewed a computer-generated visual scene that showed a randomly textured ground plane and sky (Figure 2) [30]. To define absolute size to allow scaling of distances, velocities and accelerations, billboards

¹Parts of the results of this study have been presented previously on a poster at the VSS 2004 conference in Sarasota/Florida.

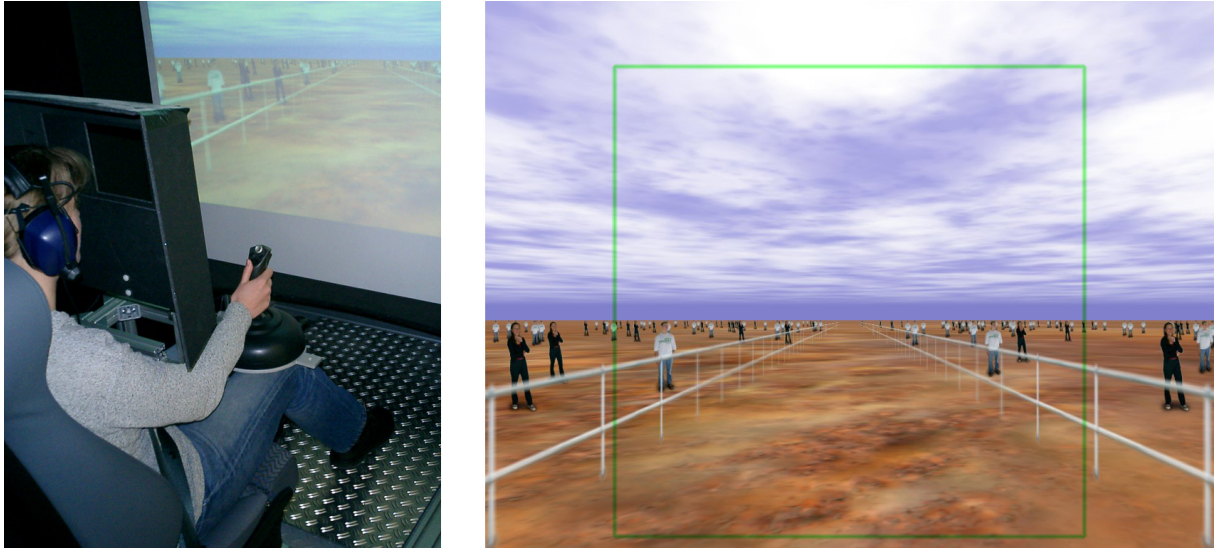


Figure 2: *Left*: Participant on the motion platform, looking through the aperture at the projection screen. *Right*: Screen shot of the visual scene. The green frame shows the approximate field of view through the aperture.

showing people and a fence were placed on the ground plane. The simulated height of the observer's eye was set at about 1.8 meters above the ground, slightly varying with up-down movements during the acceleration. Since the platform hardware contains low-pass motion filters which introduce a phase shift, resulting in an effective delay of approximately 200 ms with respect to the visual display, we delayed the visual motion by 200 ms so that platform and visual motion were synchronous for the participant.

The participants were seated with their eyes at a distance of 1.16 meters from the projection screen (Figure 2). They viewed the screen with the right eye only, so that they could not use stereoscopic distance cues. An aperture was mounted directly in front of the participant's face and adjusted so that they could not see the edges of the projection screen. This was done in order to make the participants less aware that they were looking at a screen. The visible field of view was approximately 50° horizontally and vertically. We adjusted the seat so that their eye height was exactly level with the horizon and they had the impression of looking at an exactly horizontal ground plane. Participants wore headphones presenting noise (a mixture of sounds recorded from the motion platform and other sources) so that they could not hear the platform motors. Additionally, shakers mounted under the foot plate and the seat were used to cover vibrations caused by the platform legs.

2.1 Stimuli

In each trial the simulated acceleration was shown to the participant for six seconds (four seconds of acceleration build-up, followed by two seconds of constant acceleration). Then the displayed scene was faded out to black and the platform returned to zero in another six seconds (in darkness). Values for the six parameters (listed above) were chosen randomly in the following range for each trial:

Final visual forward acceleration: $0 - 1.5 \text{ m/s}^2$ (resulting trajectories are shown in Figure 3, lower middle and right plots). During the first four seconds, the visual acceleration was faded in linearly from 0 to the chosen maximum acceleration, and then held constant during two more seconds.

Final platform backwards pitch: $0^\circ - 15^\circ$ (Figure 3, lower left). For platform pitch, a raised cosine curve (π to 2π) was used to move the platform to its maximal angle within four seconds. This ensured smoothness of the trajectory, compared to pitching the platform with constant angular velocity, where platform pitch would start and stop abruptly. During the last 2 seconds, platform pitch was held constant. The pitch rotation axis was at the platform floor (at foot level for the participant), slightly in front of the body axis, to maximize the platform motion range for rotations and translations. This resulted in small head translations, which were however far below detection threshold.

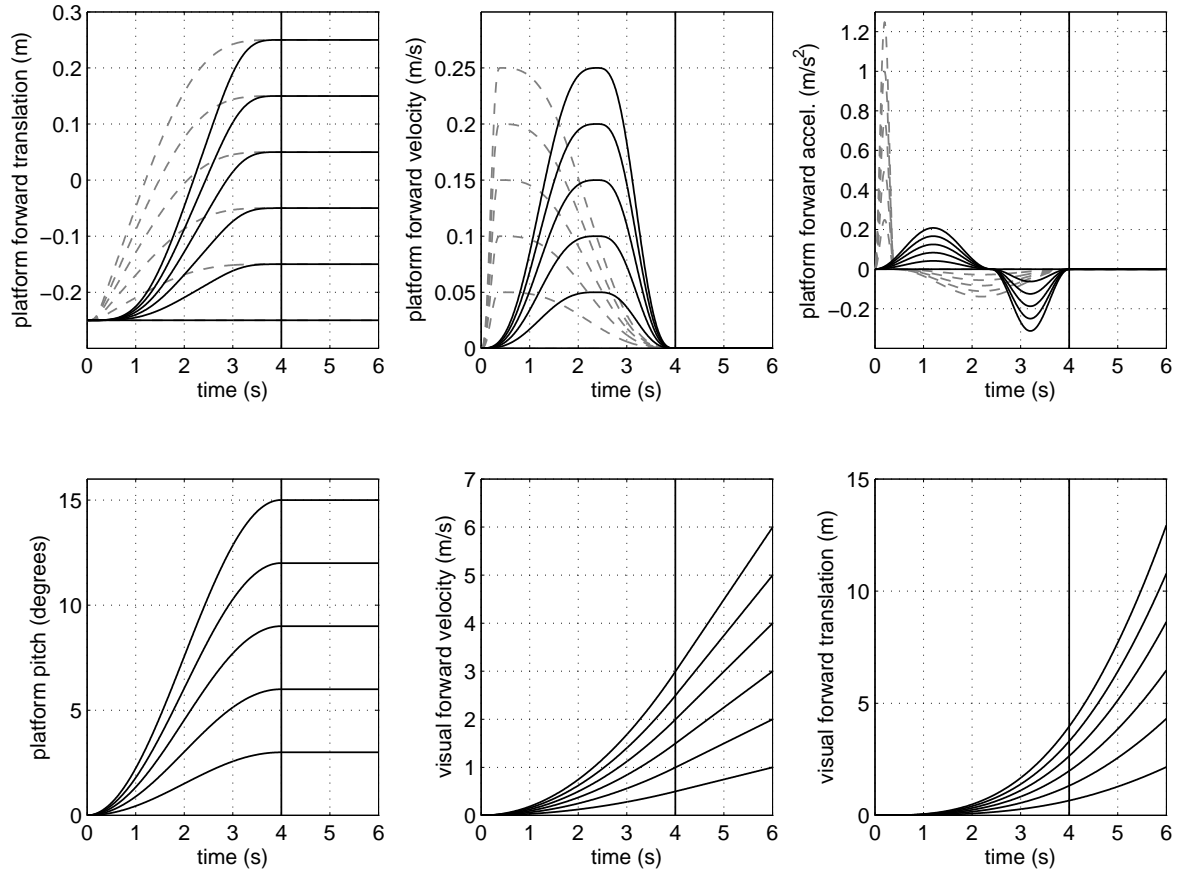


Figure 3: Motion trajectories used. Different lines show example trajectories for different parameter values in the range used for this experiment. *Upper row*, left to right: Distance, velocity and acceleration trajectories of the physical forward (surge) translations. Trajectories with different target distances in the specified range are shown. The two different trajectory bundles in these subfigures (grey dashed and black solid) show the extreme cases of the acceleration/deceleration ratio. *Lower row*, left to right: Platform pitch, visual forward velocity, and visual forward displacement over time. The simulated acceleration builds up over the first four seconds and then stays constant for two seconds.

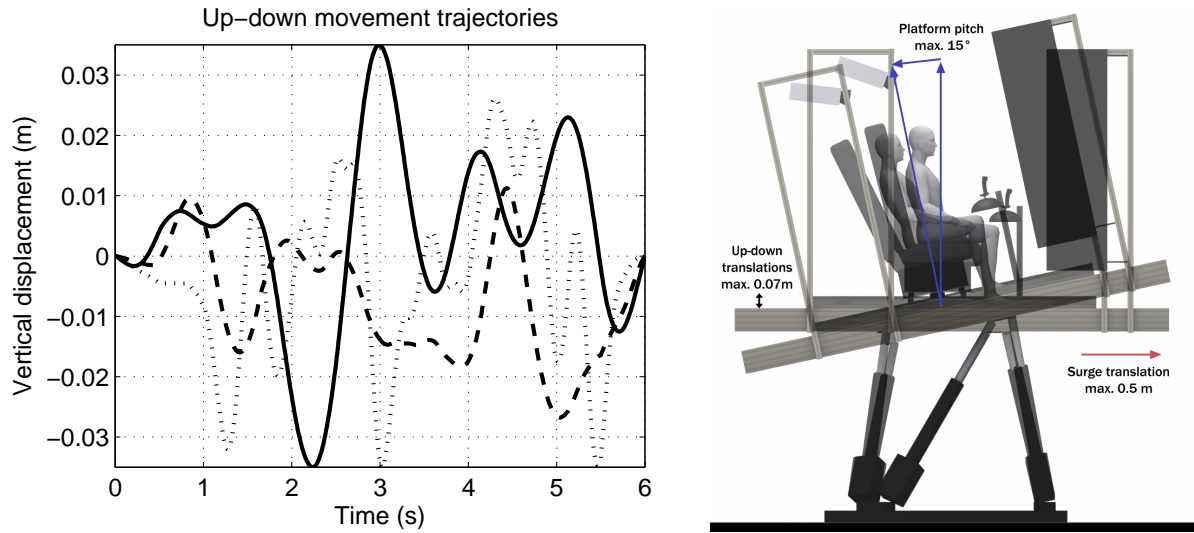


Figure 4: *Left*: example of physical up-down trajectories for three different filters; cosine window of 1.5 s (solid), 1.0 s (dashed) and 0.5 s (dotted). *Right*: Summary of the physical motion cues provided by platform movement.

Amplitude of forward translations of the platform: 0 - 0.5 meters in 4 seconds (Figure 3, upper row). Curves with different peak values show the trajectories generated for different values of this multiplicative parameter.

Ratio of acceleration/deceleration durations for the translations: 0.11 - 1.5 (1/9 - 3/2). The two differently-shaded curve bundles in Figure 3, upper row, show the two extreme ratios. This parameter was introduced in order to compare the effect of translatory movements with hard acceleration and soft deceleration with others which have less strong accelerations and stronger decelerations. Our purpose was to see whether a noticeable deceleration degrades the believability of the simulated forward acceleration. The platform forward translation trajectory over time t (Figure 3, top row) is calculated by the following formula, where d is the duration of the trajectory (4 seconds in this case), w is the time when the deceleration starts, and p is the translation magnitude (final position):

$$f_{d,w,p}(t) = \begin{cases} \frac{p}{w \cdot d} \cdot \left(t^2 + \frac{w^2}{2\pi^2} \cdot \left(\cos\left(\frac{2\pi t}{w}\right) - 1 \right) \right) & \text{if } t < w \\ \frac{p}{d} \cdot \left(2t - w - \frac{1}{d-w} \cdot \left((t-w)^2 + \frac{(d-w)^2}{2\pi^2} \cdot \left(\cos\left(\frac{2\pi \cdot (t-w)}{d-w}\right) - 1 \right) \right) \right) & \text{else} \end{cases}$$

Amplitude of up-down noise, synchronous in visual and platform movements: 0 - 7 cm. This is a multiplicative parameter for the amplitude of the low-pass-filtered white noise trajectory which is used for random vertical movements of the observer during the simulated acceleration.

Frequency range of up-down noise, defined by using a moving-average low-pass filter on white noise:

cosine window, raised cosine from $-\pi$ to π , width 0.5 - 1.5 seconds. White noise was convolved with the cosine window function and then normalized. The final up-down trajectory was computed by multiplying the resulting function with a constant amplitude factor (0 - 7cm; the up-down noise amplitude). Figure 4, left, shows example filtered noise signals for windows of size 1.5 s, 1.0 s and 0.5 s.

The physical movement parameters investigated in this study are summarized in Figure 4, right.

2.2 Task

After each movement, participants were asked to judge how well the perceived body motion matched the visual motion they saw. Additionally, they were asked to rate the trial as 'bad' when they noticed conflicts between sensory cues. For example, they should give a bad rating if they felt and saw different acceleration magnitudes, or when they felt a body rotation while the horizon remained fixed. When no conflict was noticed and they felt like moving through the visual environment, they should rate the trial as 'good'. Thus participants were instructed to rate the believability of the forward acceleration according to the amount of conflict perceived between visual and body cues.

Participants responded by using a joystick to adjust a bar shown on the projection screen (by moving the joystick sideways). Setting the bar all to the left would indicate a 'very bad' simulation, while moving it all the way to the right would mean a 'very good' simulation. Intermediate positions of the bar indicated intermediate ratings, respectively. The participant was asked to set the bar (continuous scale; 256 steps internally) according to the believability of the felt acceleration of the trial and to confirm by pressing a joystick button. Then the next trial was started.

Each participant judged the believability of 180 forward accelerations, presented in two blocks of 90 trials each, with a pause between the blocks.

As noted above, stimuli were chosen randomly from a range for each parameter. Each trial was in that sense unique, and different participants experienced different individual trials, but from the same parameter ranges. It was impracticable to use a full design of all stimulus combinations with several values for each parameter, since we varied six parameters. Instead, we decided to choose parameters randomly for each trial and to analyze the results by computing correlations of perceived simulation quality ("believability") and the simulation parameter values.

We used *Matlab* for correlation analysis and plots, and *SPSS* for multiple hierarchical regression analysis.

15 students participated in this experiment (9 female, 6 male). They had normal or corrected-to-normal eyesight, and no history of neural or vestibular diseases. Participation was voluntary, and they were paid for participation at standard rates. All participants gave their informed consent prior to the start of the experiment. Two participants (not part of the 15 participants) got motion sick, whereupon the experiment was stopped and their data discarded. When asked after the experiment, all participants reported that some of the forward accelerations had been very convincing.

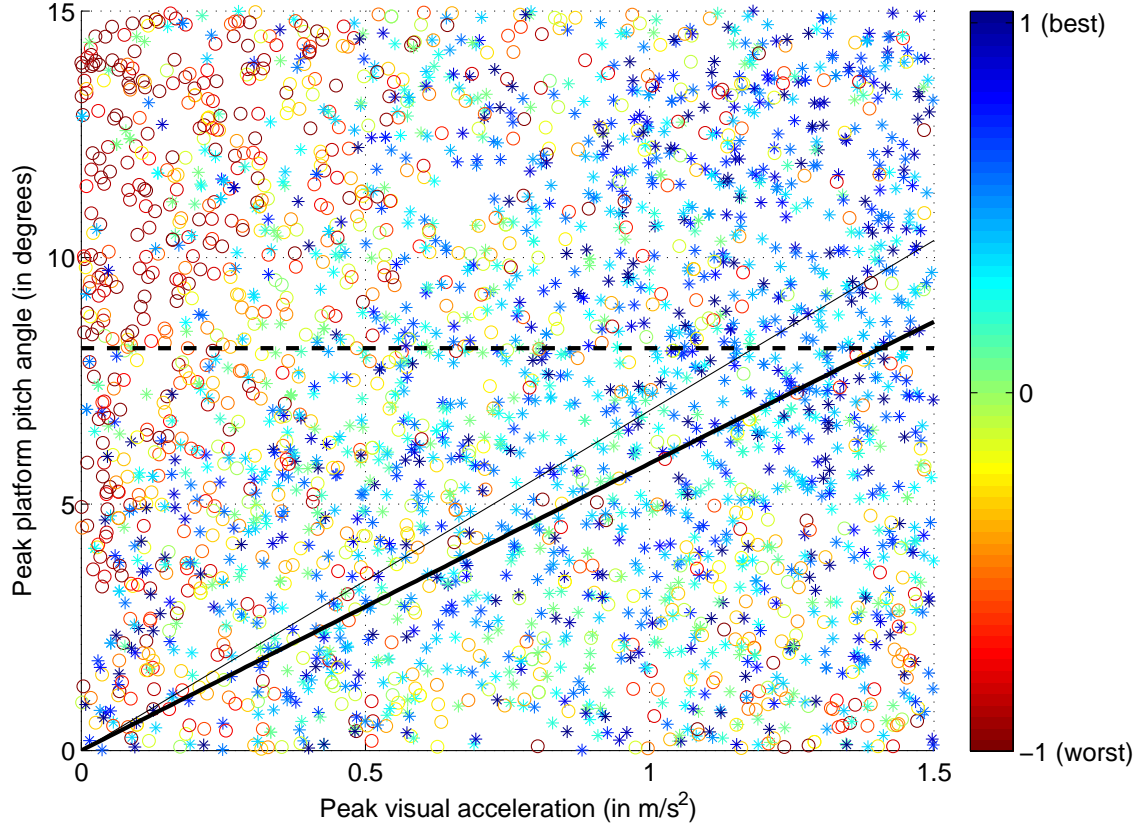


Figure 5: All single responses of all individual subjects, plotted for the factors "visual acceleration" and "platform pitch". Stars mark trials judged as "good" (best are dark blue), circles mark trials judged as "bad" (worst are dark red). The thick solid line shows the corresponding visual acceleration and platform pitch magnitudes (platform pitches which cause the same rotation of the direction of the gravito-inertial force vector as the corresponding visually presented accelerations). The thin black line represents the best regression fit; the best responses were found for a platform gain of 1.19 with respect to the visual acceleration. The dashed line shows a conservative approximate threshold for the perception of angular rotations ($3.25^\circ/\text{s}$ peak velocity). Platform pitch rotations with this peak velocity should be perceptible for approximately 95% of the participants, according to [31].

Subj. nr	Visual accel.	Platform pitch	Surge size	Surge acc./dec.	Up-down amp.	Up-down freq.	Time in exp.
1	0.359***	-0.396***	0.048	0.038	0.022	-0.117	-0.026
2	0.611***	0.171	0.109	0.002	-0.065	0.012	0.034
3	0.246**	0.109	-0.025	-0.043	0.088	-0.097	0.030
4	0.765***	-0.031	0.088	0.073	0.206*	0.031	-0.143
5	0.646***	0.259**	0.147	0.098	0.123	0.140	0.082
6	0.076	-0.057	0.047	-0.053	0.040	0.002	0.096
7	0.694***	0.073	0.020	-0.116	-0.012	0.140	-0.001
8	0.065	0.393***	-0.036	0.019	0.053	-0.189	0.000
9	0.344***	0.128	-0.211*	0.127	-0.071	-0.084	0.087
10	0.188	0.253**	-0.056	-0.055	-0.032	0.040	-0.109
11	0.368***	-0.278**	-0.060	0.056	-0.039	-0.095	-0.015
12	0.476***	-0.413***	0.060	-0.037	0.038	-0.025	0.142
13	0.408***	-0.211*	-0.104	0.030	0.063	0.019	0.084
14	0.426***	-0.704***	0.064	0.145	-0.109	0.087	0.052
15	0.392***	-0.012	-0.006	-0.042	-0.007	-0.101	0.024

Table 1: Correlation coefficients (r -values) of the responses with individual parameters, for each participant separately. Coefficients which are significant (Bonferroni corrected for 7 comparisons) are marked by stars. p -thresholds for one, two and three stars are 0.00714, 0.00143 and 0.000143 respectively.

3 Results

3.1 Individual correlations

To investigate the effect of each individual parameter on the responses, we first computed the correlation coefficients of each parameter with the responses for each individual participant. Results are shown in Table 1. Only two parameters had a clear influence on the ratings of most participants: platform pitch and visual acceleration. Since we asked participants to rate how well the felt physical acceleration matched the visual, the dependency of responses on visual accelerations is surprising. Participants apparently rated trials also according to how compelling the movement was.

Responses for different amounts of platform pitch and visual acceleration are shown in Figure 5. Simulated accelerations were judged best when the visual acceleration was accompanied with an approximately matching platform pitch (gain close to 1, i.e., a pitch which mimics the direction change of the gravito-inertial vector which would result from the visually simulated linear acceleration). Brief forward translations and up-down movements had almost no influence on the responses in this analysis. For none of the participants was there a significant influence of elapsed time in the experiment on the responses. There was a high inter-individual variability, with some participants being much more disturbed by fast pitch rotations than others (see Discussion). It can be seen from Figure 5 that a platform pitch without visual acceleration resulted in a more salient conflict than a visual acceleration without a platform pitch. When a large platform pitch (fast rotation) was presented together with a large visual acceleration, participants often did not report conflicts, i.e., they did not perceive the platform pitch as a rotation, even though it likely was super-threshold for the vestibular canal system (see section 4.2).

3.2 Multiple regression analysis

In order to investigate how much variance of the dependent variable is accounted for by which parameters, we performed multiple hierarchical regression analyses separately for each participant. The results are shown in Table 2. This analysis was performed using SPSS. The multiple regression function was computed in hierarchical order, i.e., the factor exhibiting the highest correlation with the believability ratings was set as the first factor, and further factors were added to the multiple regression equation in the order of the individual correlations. Only factors that significantly increased the adjusted R^2 values were included to the multiple regression function. For 8 out of 15 participants, visual acceleration and platform pitch explain most of the response variance (R^2 values (which are exactly equivalent to η^2) between .07 and .627, see Table 2). The other parameters had significant influences only for some participants, and the sign of the beta coefficient is often inconsistent. For example, one participant found trials with a large surge translation more realistic, whereas another found those less realistic. This variability

Subj. nr	Visual accel.	Platform pitch	Surge size	Surge acc./dec.	Up-down amp.	Up-down freq.	Adjusted R^2
1	.332	-.372					.258
2	.628	.218					.415
3	.265	.144					.070
4	.758				.176		.612
5	.628	.245	.131				.479
6							
7	.691			-.129		.118	.502
8		.375				-.140	.164
9	.352	.140	-.208	.154			.184
10	.169	.239					.082
11	.40	-.318					.227
12	.455	-.388					.370
13	.394	-.179					.190
14	.370	-.673					.627
15	.403					-.136	.162

Table 2: Standardized beta coefficients of the multiple regression analysis and adjusted R Squares for all participants (the latter describes the variance which is explained by all significant factors together, equivalent to η^2). Only values for significant factors are listed.

of positive and negative beta coefficients can also be seen for platform pitch, and also appears in the correlation coefficients. Five participants have negative beta coefficients for platform pitch, while six participants have positive values (see Table 1 and Table 2). Some participants rate small platform rotations less believable than large platform rotations, whereas the inverse is true for other participants.

Often the ratings depend on the combination of both visual acceleration and platform pitch, with best ratings for concordant combinations of the two parameters. Such dependencies are not well captured by correlations of the response with individual parameters. Therefore, we performed further analyses, as described in the next section.

3.3 Parameter correlations for very good and very bad trials

The correlation analysis of the responses with individual parameters cannot reveal how different parameters of the simulated acceleration affect the perceived believability. Figure 5 suggests that our data contains such interactions: good responses fall within a diagonal region in the parameter space spanned by visual accelerations and platform pitch. Participants appear to find the simulation believable if platform pitch and visual acceleration 'match'. We formed two extreme groups of trials, one containing those trials in which participants gave a "very good" response, and a second one containing all trials in which they gave a "very bad" response. Trials in which the participant's rating was above 3/4 on the rating scale were characterized as "very good" trials, and "very bad" trials were those where the participant's rating was below 1/4 on the rating scale. For the extreme groups, we computed correlation coefficients between all independent variables to identify how responses depend on specific combinations of parameter values. For example, we expected to find a high positive correlation between visual acceleration and platform pitch for "very good" responses.

In this analysis, participants were not treated separately, but correlation coefficients were calculated for all individual trials with responses falling in the respective extreme group. From the 2700 overall trials, 794 trials fell in the "very good" group and 491 trials fell in the "very bad" group. We computed all 15 possible pair-wise correlations for the 6 parameters, therefore the resulting significances were Bonferroni-corrected with a factor of 15.

Only a few parameters correlated significantly for the "very good" and "very bad" trials. For the "very good" trials, we found a significant positive correlation between platform pitch and visual acceleration ($r = 0.29^{***}$). Also the correlation between platform pitch and surge size was positive and significant ($r = 0.11^*$). Another positive correlation between visual acceleration and surge size ($r = 0.09$) was significant before, but not after Bonferroni correction. Good simulation of a forward acceleration does thus combine a platform pitch and a forward surge which match the visual acceleration.

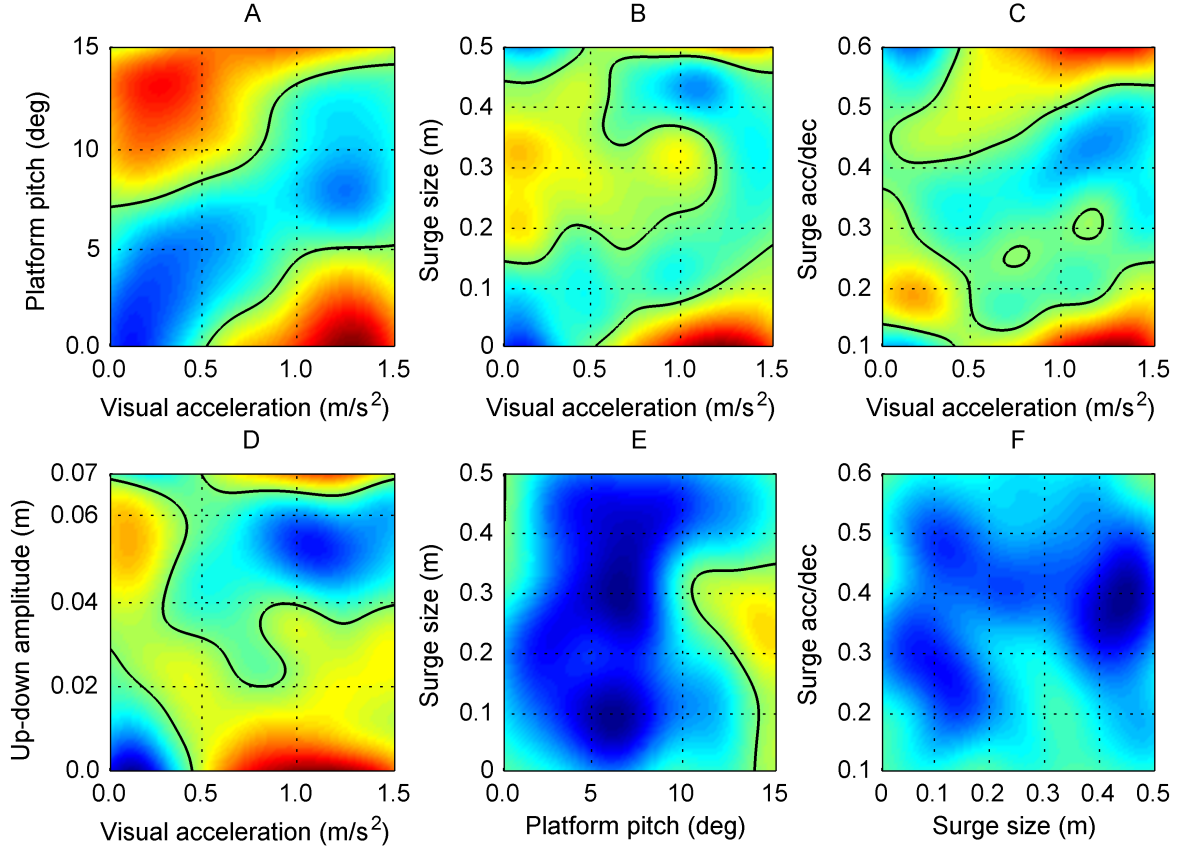


Figure 6 shows how the overall ratings depended on combinations of different parameters. These plots should be interpreted with caution, since some of the effects might be caused by noise (the particular random selection of conditions for the different participants). The 2700 data points – 180 per participant – can only provide a relatively sparse sampling of the six-dimensional parameter space of the experiment. We use these plots to interpret the significant results from the extreme group analysis.

Figure 6A shows the strong dependency of the ratings on a platform pitch matching the visual acceleration, as also evident in Figure 5. Ratings in dependency of platform pitch and surge size are shown in Figure 6E. The peaks for platform pitches around 6° suggest that those platform pitches combined best with the surge accelerations. Figure 6B shows the positive correlation of visual acceleration and surge size for good responses. Particularly small surge sizes are beneficial for small visual accelerations (below 0.5 m/s^2) but decrease ratings for larger visual accelerations.

In the correlation analysis for the very bad trials, we found a significant negative correlation between visual acceleration and platform pitch ($r = -0.18^{***}$; see Figure 6A) and between visual acceleration and up-down amplitude ($r = -0.17^{**}$). Figure 6D shows that for visual accelerations below about 0.5 m/s^2 , very small up-down amplitudes were preferred, whereas for large visual accelerations large up-down amplitudes resulted in better ratings than small ones. This indicates that trials were perceived as unrealistic if a high visual acceleration was paired with a low platform pitch or high amplitude of up-down movements, or if a low visual acceleration was paired either with high platform pitch or low amplitude of up-down movements. A third correlation ($r = 0.09$) between surge acceleration/deceleration timing and surge size was significant before, but not after Bonferroni correction. Figure 6F shows that best ratings occurred for large surge translations, but only if the acceleration/deceleration timing parameter was approximately 0.4 (slightly stronger accelerations than decelerations). Generally, participants did not like very jerky accelerations or strong decelerations. When comparing ratings for different visual accelerations and acceleration/deceleration timing (Figure 6C), it can be seen that jerky accelerations or strong decelerations decreased the ratings particularly for large visual accelerations.

3.4 Optimal gain factor for body pitch

Groen et al. (2000) [27] reported that the perception of sustained acceleration, which is inertially simulated by body pitch, is rated best if the body pitch is about 0.6 times as strong as it should be to match the visual acceleration. Larger and smaller pitch angles were rated as unrealistic. To compute the optimal gain factor of body pitch compared to visual acceleration in our experiment, we used the complete data set of 2700 data points at coordinates (x_i, y_i) . x_i represents the visual linear acceleration and y_i the linear acceleration equivalent to the presented body pitch, and v_i (between -1 and 1) is the response value (believability rating) for trial i . The perpendicular distance d_i of a data point (x_i, y_i) from a regression line with slope s (representing a body pitch gain factor of s) is computed by:

$$d_i = \cos(\arctan(s)) \cdot (y_i - s \cdot x_i)$$

Then, for a given Gaussian kernel with variance σ^2 controlling the smoothness of the measure, we define a believability rating for this slope by:

$$\sum_i (e^{-d_i^2/\sigma^2} \cdot v_i) / \sum_i e^{-d_i^2/\sigma^2}$$

Figure 7 shows believability ratings computed in this way as a function of s . Different lines show results for different values of the standard deviation σ (σ^2 ranging from 1 down to $1/40$). The gain factor for body tilt which produced the best rating was approximately 1.19, and thus much higher than what was reported by Groen et al. (2000) [27]. A "correct" gain factor of 1 (i.e., veridical matching of physically and visually simulated acceleration) was perceived as almost equally believable.

An example of the trajectories of the gravito-inertial (GI) force vector, as simulated visually and physically, is shown in Figure 8. Here all the parameters were set so that the mean rating of the participants would be very good. The trajectories of physical accelerations take the low-pass filter of the platform drivers into account and approximate the actual force vector felt by the participant. The visual trajectories show the 200 ms delay which was introduced to match the timing between visual and platform movements. The graphs of the left side show the direction of the GI force vector in the coordinate frame of the observer on the platform. The increasing visual acceleration causes the visually simulated GI force vector to rotate to a maximal value of, in this case, 7.26° off the vertical. The physically simulated direction of the GI force vector reaches a higher angle, because for the

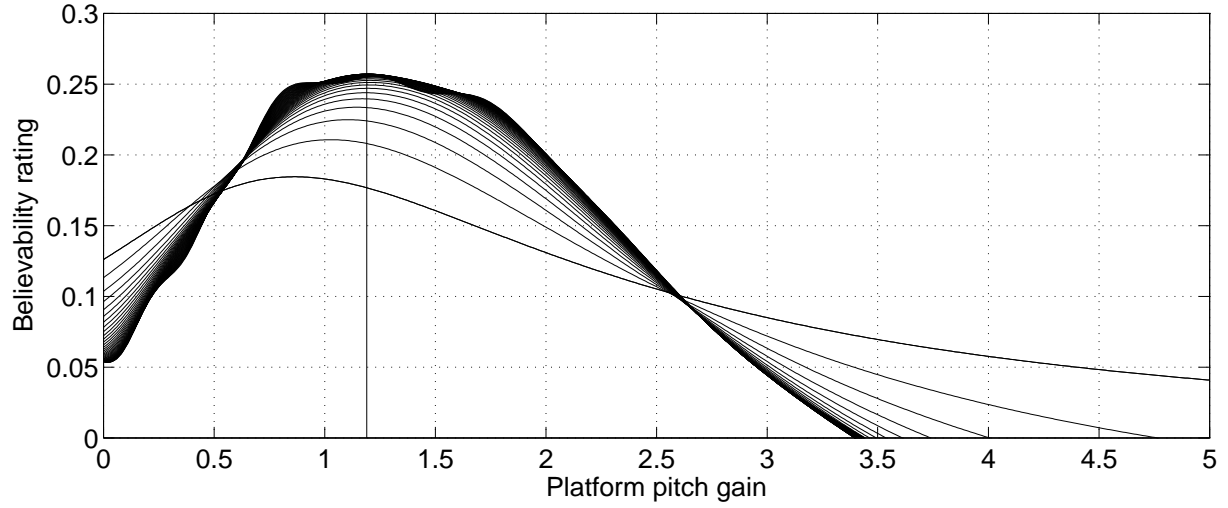


Figure 7: Regression analysis of the body pitch gain in relation to the visual acceleration. Different lines represent different variances of Gaussian low-pass-filtering of the data cloud (σ^2 ranging from 1 down to $1/40$). The best believability rating is reached for a platform pitch gain of 1.19 (vertical line).

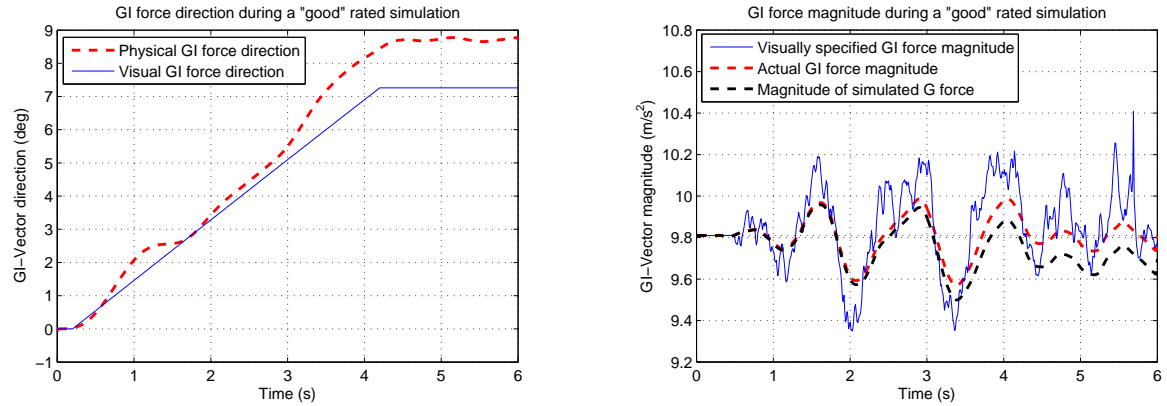


Figure 8: Example of GI force direction (*left*) and magnitude (*right*) during a very good simulation. Parameters were: final visual acceleration 1.25 m/s^2 , surge size 0.45 m , surge acc./dec. 0.4 , platform pitch 8.71° (gain 1.2), up/down amplitude 0.05 m , up/down filter width 1 second . Physical forces simulated by the motion platform are shown as filtered by the low-pass motion filter of the platform drivers and approximate the actual platform movement (see text for more details). Note that this is not measured data, but data simulated from the trajectories and transfer functions.

most believable simulation the platform needed to be pitched more than what would be equivalent to the visual acceleration (factor of 1.2). The surge movement in the beginning of the simulated acceleration can help to produce a quicker onset of the rotation of the GI force vector.

The graphs on the right side show the magnitude of the visually and physically simulated GI force vector. The visually defined GI force vector magnitude is influenced by visual up-down movements. Because platform movement is low-pass-filtered by the platform software, it can only provide the lower frequencies of the up-down movements. This may be a reason why we did not find any effect of the up-down-movement frequency parameter on the responses.

As the platform is pitched, part of the gravitational force is used to simulate a constant forward acceleration. This reduces the magnitude of the simulated gravitational force (Figure 1, right). Since the magnitude change of the GI force vector caused by up-down movements is larger than the reduction of the simulated gravitational force vector caused by pitch, the up-down movements might in this case help to perceptually mask the magnitude mismatch of the simulated gravitational force.

4 Discussion

We analyzed the results using three methods, namely correlations between responses and single parameters (section 3.1), multiple hierarchical regression analysis (section 3.2), and analysis of parameter correlations for trials with extremely good and extremely bad responses (section 3.3). Whereas the first two methods can only identify linear relationships of the responses with the parameters, the third analysis shows how parameters have to be set with respect to each other to produce trials with very good (or very bad) ratings. We found that these correlations were rather weak, even though some of them were significant, and differences between participants were high (see Figure 9).

4.1 Visual acceleration

In this experiment, we asked participants to rate the believability of forward accelerations. Specifically, they were required to judge how realistic the simulation felt that they were moving forward according to the visual stimulus. For 13 out of 15 participants, visual acceleration had a significant effect on their believability ratings – for one of the remaining participants, none of the varied factors had any significant effects, and for the other, platform pitch was the most important factor. Overall, strong visual accelerations were rated more believable than slow visual accelerations. Even though we had instructed participants to rate a realistic non-acceleration also as 'believable', a strong simulated acceleration probably induced a more compelling feeling of self-motion, which may be a reason for higher ratings [32].

4.2 Backwards pitch rotations

Despite the large inter-individual differences, we found that participants rated the simulated forward acceleration as most realistic when a visual acceleration was accompanied by a platform pitch which produced an approximately consistent change of the gravitoinertial force direction, which means that correct to slightly exaggerated body tilt was rated as most believable; see section 3.4. We could not replicate the finding of Groen et al. (2000) [27] that most believable simulation is reached for reduced inertial stimulation. We propose that their finding might have been caused by a misperception of the scale of the visual stimulus. Contrary to their study, we used monocular viewing and size cues in the scene (human figures), which provided an absolute scale of the visual scene, and may thus have counteracted a size misperception of the visual scene which is common in virtual environments [33, 34].

When forward accelerations are simulated by a backwards pitch, two perceptual thresholds are relevant. First, the change of the gravitoinertial force vector direction should be noticeable by the participant. Second, if the pitch rotation is above threshold, so that the participant notices that it is a rotation, this provides evidence against the interpretation that the change of the gravitoinertial force vector is caused by an acceleration and could reduce the believability of the simulation.

Thresholds for very slow tilts (detection of more or less constant deviations from vertical) depend a lot on the availability of somatosensory cues, which are for example impaired when participants are tightly packed in foam. When somatosensory cues are impaired, the detection threshold for slow tilts backwards rises from about 9° from vertical to approximately 20° [35]. Patients with vestibular loss can compensate with other (somatosensory / proprioceptive) signals to perceive body orientation and acceleration in darkness, and can reach perceptual thresholds similar to those of healthy controls [36, 37]. Experiments in microgravity have shown that also pressure cues under the feet can influence the perceived body orientation with respect to gravity [38]. These studies suggest that not

only vestibular signals, but also somatosensory cues are used for the judgment of body orientation and acceleration in space, and that somatosensory thresholds might be lower than vestibular thresholds. In our study pitch rotations of up to 15° backwards were presented, which is supposedly above the perceptual threshold, since our participants were not packed in a body cast and could use somatosensory cues.

To measure perceptual thresholds for the pitch rotation movement, without influence of a change of the direction of the gravito-inertial force vector on the responses, Benson et al. (1989) [31] placed participants sideways on a platform which turned around an earth-vertical axis through the participant's head [31]. They found rotation detection thresholds ranging from about $0.5^\circ/\text{s}$ to $5^\circ/\text{s}$, with a mean of approximately $2^\circ/\text{s}$. In our study, maximal pitch rotation velocity was approximately $5.9^\circ/\text{s}$, therefore the larger rotation movements were probably noticeable for most participants (see threshold line in Figure 5).

4.3 Surge translations

We did not find any consistent correlation of reported believability with surge size in this study (only one out of fifteen participants showed a significant effect). The acceleration/deceleration ratio of the surge translation also did not have a significant effect on the ratings. However, there was a tendency that surge motions with relatively strong decelerations were rated worse (see Figure 6F). Maybe in that case the decelerations were noticeable (see below). Analysis of very good trials revealed best ratings of the believability if large surge motions were combined with high simulated accelerations and small surge motions with low accelerations (Figure 6B).

Velocity thresholds for pure linear acceleration have been found to be in a range between 0.07 m/s [39], 0.135 m/s [40] and $0.08\text{-}0.2 \text{ m/s}$, depending on the motion trajectory used (in particular the magnitude of acceleration and jerk) [37]. Benson et al. (1986) [41] reported an acceleration threshold of $0.02\text{-}0.065 \text{ m/s}^2$ for linear accelerations. In our experiments, forward surge translations with up to 0.25 m/s , accelerations up to about 1.25 m/s^2 and decelerations up to about -0.31 m/s^2 were used (see Figure 3, upper row). Larger translations with a rapid onset were therefore clearly above the sensory detection threshold, whereas smaller translations with a soft onset were probably below threshold. Stronger decelerations were probably also above threshold.

Groen et al. (2000) [27] had found that the initial accelerations were rated bad if fast surge translations were presented. Their surge range was larger than the one of our setup (about 1.5 m , vs. 0.5 m in this study), and the inertial acceleration and deceleration they used were also larger (up to 3.5 m/s^2 peak acceleration and -0.5 m/s^2 peak deceleration). The deceleration of larger surge motions might therefore have been noticeable for many participants. This is consistent with the fact that the participants in Groen et al. (2000) [27] rated the transition between initial and sustained acceleration as bad for faster surge platform movements.

4.4 Up-down movements

Up-down movements had only a mild influence on the responses. We found that they were rather responsible for a decrease of the perceived realism if high up-down amplitude was combined with low visual acceleration, than for an increase of realism if high-amplitude up-down movements were combined with high visual acceleration. Figure 6D shows that the influence of the amplitude of up-down movements on the rating depends on the visual acceleration: For accelerations below approximately 0.5 m/s^2 , very small up-down movements were clearly preferred, whereas for higher accelerations large up-down movements got better ratings. The frequency of up/down movements had no significant influence on the responses, maybe because, for the physical movements of the platform, the higher frequencies were strongly attenuated by the low-pass filters of the platform controller, and changing the filter parameter had little effect on the actual movement of the platform. We did not try to increase the frequency of up-down movements with increasing velocity (which would be expected in a real vehicle). Maybe this parameter could be tested in future experiments.

4.5 Measuring individual thresholds of tilt-translation discrimination

Thresholds for the perception of slow tilts depend on whether participants are tilted backwards or forwards, whether they are in an upright or supine position, and how much somatosensory cues are impaired by the experimental setup [35]. These additional influences are likely to be responsible for the high variability of the measured thresholds between different studies. In addition, there is a high variability between participants. This might be because of individual differences of vestibular thresholds [11], or possibly because different attentional strategies are used by different participants.

In this study we also found large differences between participants concerning whether or not faster/larger rotations were perceived as realistic (Figure 9). It would be interesting to know whether the participants who rated large

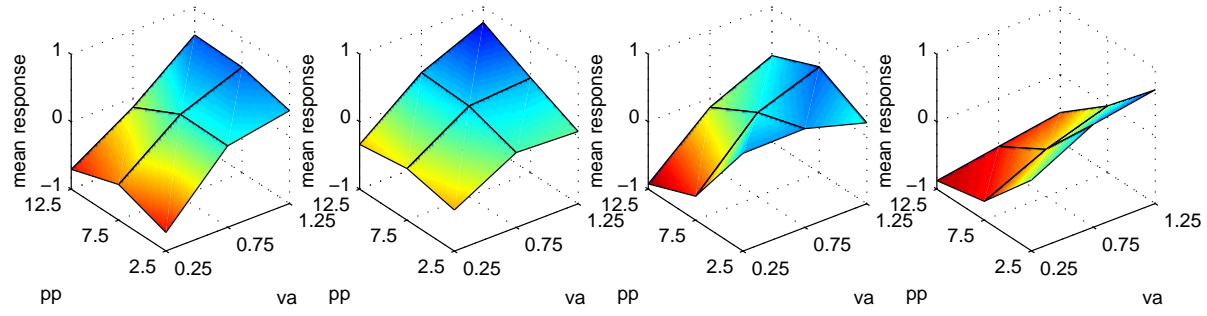


Figure 9: Four examples of responses of individual participants, for different platform pitches (pp) and visual accelerations (va). From left to right participant 4, 5, 12 and 14.

pitch rotations as unrealistic are also those who have a relatively high sensitivity for discriminating whole-body linear accelerations and pitch rotations (without visual cues). We attempted to measure this on the motion platform by having the participants discriminate forward-backward-translations from series of four rotations, which produced the same pattern of change of the gravito-inertial force vector, in darkness. The two motion sequences can also be combined so that the direction of gravito-inertial force with respect to the body does not change during the trajectory [19]. Preliminary experiments, however, showed that the two movements can be easily discriminated on the basis of somatosensory perception. Forces acting on the feet during forward-backward translations are very different from those during a series of backward-forward-forward-backward pitch rotations, particularly if the axis of rotation is placed in the participant's head and the feet are off-axis by 1 - 1.5 meters while seated. Thresholds for discriminating these forces somatosensorily are apparently much lower than those of the vestibular canal system for equivalent rotations. Also, we could not rule out that participants would use other cues for the discrimination, for example platform vibrations. Therefore, it appeared unfeasible to measure individual perceptual thresholds of translation vs. pitch perception with our setup. This is however an interesting topic which should be explored in further studies.

5 Conclusions

This study investigated how a Stewart platform has to be moved to simulate linear forward accelerations most believably in the presence of visual acceleration.

Visual acceleration and platform pitch had the strongest influence on the responses. Accelerations were rated best if the pitch changed the direction of the gravito-inertial force consistent with the visual acceleration, in contrast to the results of Groen et al. (2000) [27]. Forward surge translations can improve the ratings if large surge translations are presented with strong accelerations and small surge translations with weak accelerations. Acceleration/deceleration timing of the surge translations did not have any significant effects. Also synchronized up-down movements of platform and visual scene had little influence on the reported believability; however, participants tended to rate trajectories with large up-down movements and weak accelerations bad. There were high inter-individual differences in the ratings.

In the light of these results it might turn out to be difficult to simulate forward accelerations realistically for all observers with such stimuli. Still, the results can provide some guidelines for the simulation of forward accelerations. Pitching the platform backwards is a particularly useful inertial cue for forward acceleration. The pitch magnitude should be consistent with the simulated acceleration, at least if the size of the visual scene is not misperceived. Forward surge motion can help, if small surge motions are used for small simulated accelerations (below 0.5 m/s^2) and large surge motions for large simulated accelerations, and the deceleration is not too strong. Large up-down movements should not be used together with very weak visual acceleration.

We conclude that a platform pitch presented together with a consistent visual acceleration can be sufficient for a believable simulation of a forward acceleration to a human observer, possibly even if the angular pitch rotation is above threshold for the vestibular canal system.

It has been proposed that human perception follows a Bayesian estimate based on the available sensory cues and appropriate priors (see [42] for review). This basically means that the human brain will adopt the most likely interpretation of a given stimulus. Optimal motion cueing should therefore stimulate additional sensory cues to enhance the likelihood that the simulated motion is actually true. Our findings are consistent with this

assumption, as we found that simulated forward accelerations were perceived as most realistic when the change of the gravito-inertial force vector direction simulated by body pitch was approximately consistent with the visual acceleration. Since trials with pitch rotation velocities which are assumed to be above detection threshold were still often rated good, a salient visual acceleration paired with a consistent change of the gravito-inertial vector direction can apparently suppress (or draw the attention away from) the perception of conflicting signals from the vestibular canals.

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