Perception of Upright under Created Gravity – Wo ist Oben? – Messung der Wahrnehmung des Perceptual Upright (PU) mit Hilfe des OCHART-Tests unter den wechselnden Gravitationsbedingungen in einer Zentrifuge

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1. Introduction

Maintaining an upright posture in a low gravity environment is not easy. NASA documents abound with examples of astronauts falling on the lunar surface [1] [2]. Even on the most recent moon visit (Apollo 17, 1972), Astronaut Harrison Schmidt fell over as he worked on the lunar surface. The perception of the relative orientation of oneself and the world is fundamental not only to balance [3] [4] [5] [6] [7] [8] but also for many other aspects of perception including recognizing faces and objects [9] [10], and predicting how objects are going to behave when dropped or thrown [11]. Indeed, recent emerging studies suggest that a functioning vestibular system may be required for depth perception [12] [13] and even for higher aspects of cognition such as the identity of self [14]. Misinterpreting the upright direction can lead to perceptual errors for example misinterpreting the orientation of a vehicle, and can threaten balance if a person uses an incorrect reference orientation to stabilize themselves. It is therefore crucial to understand how the direction of up is established and to establish the relative contribution of gravity to this direction before journeying to environments with gravity levels different to that of Earth.

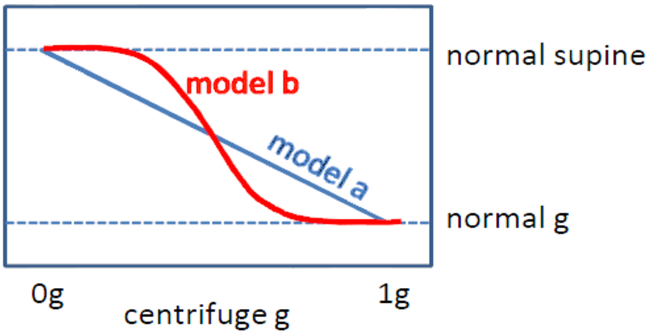

Figure 1: The influence of visual cues at 0g and 1g has already been studied. This study will examine the area between those two states. At least two models are conceivable for the perception of the relative orientation of oneself with varying centrifugal force.
Model a: The perception will adapt linear to changes in the centrifugal force
Model b: The perception will adapt non-linear to changes in the centrifugal force

The perception of upright depends on visual, gravitational and bodily cues [15]. However, the weighting of those cues vary both individually and are dependent on a person's context. Gravity typically contributes about 20% to the perceptual upright with the remainder coming from visual cues and the orientation of the body [16]. When leaving an upright position, visual cues (like distinct horizontal and vertical structures in our busy environment) become significantly higher weighted, though it is not certain how those changes in weight behave in particular (e.g. linear, based on a threshold meaning "everything or nothing" principle, sigmoidal, etc.; See Fig. 1). It is the goal of this study, to systematically explore the connection and correlation between visual and gravitational cues. Furthermore it was evaluated to what extent memorizing of 3D orientations of objects depends on gravitational conditions under which they have been learned or recalled. In doing so, it is tested if the quality of the reconstruction will be influenced by a change of gravitational conditions between learning and recalling.

2. Experiments

To determine the relative contribution of varying gravitational forces, experiments were run using the Short Arm Centrifuge Facility (SAHC) provided by the European Space Agency (ESA) situated at the Deutsches Zentrum für Luft- und Raumfahrt (DLR) Institute of Medicine in Cologne, Germany. In total, ten subjects (5 male, 5 female; average age of 29.9 ± 7.2 yrs) took part in the experiment.

The participants lay on their backs (supine position) in a nacelle with their head towards the axis of rotation. In front of the subject's head, an earth-horizontal screen (12 x 12.8 cm, 1024 x 768 @ 60Hz) was positioned 20 cm above their faces (See Fig. 2). The screen was mounted inside a light-proof hood to obscure the participant's view of the external environment; the room lights in the centrifuge room needed to remain on while the centrifuge was spinning for safety reasons. The screen could be viewed through a circular aperture (with a diameter of 12.2 cm, 34°) to avoid orienting cues from the edges of the screen.

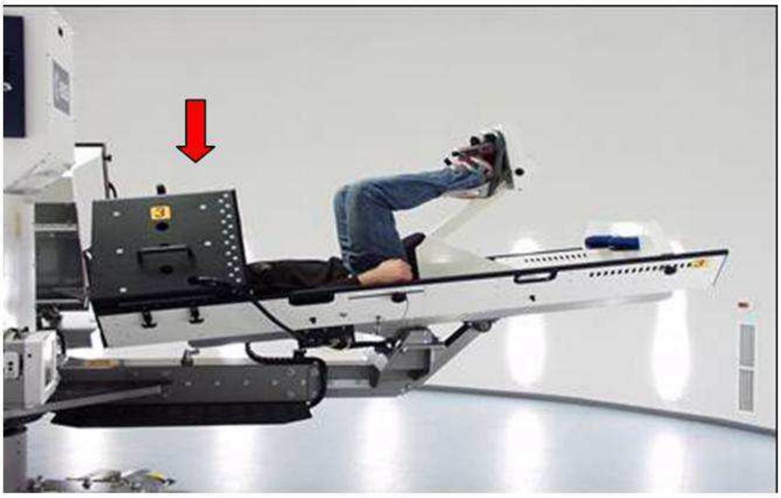

Figure 2: The experiment as realized on the short arm centrifuge. The subject is lying on his back (supine position) in a sitting position (to reduce the effect of the gravitational forces on the circulatory system of the subject). The screen (mounted in the hood; red arrow), in which the visual stimuli are presented, is positioned in front of the subjects face.

To run the software needed for the experiments, a laptop (MacBook Air 11") was fixated to the centrifuge and connected to the screen and an additional input device (Logitec Trackball) to enable feedback from the participant. During the experiments the laptop could be accessed remotely from the control room.
In addition, a gyro sensor was installed on the centrifuge on earlevel. Thus, for each input given by a subject, a log entry together with the current gravitational force could be written. After running the experiments, this enabled an automatic evaluation of the logfiles.

The perception of upright was measured using an "Oriented Character Recognition Test" (OCHART). This test uses a stimulus consisted of the character "ᓂ" that could be presented at any orientation under control of an adaptive algorithm (PEST [17]). The algorithm searched for the orientation at which the participants chose the interpretations "p" and "d" equally. The characters were presented on highly-polarized visual backgrounds that were tilted 112° to the left or right of the body midline. These orientations have been found to shift the perceptual upright maximally [16]. A third visual background of a neutral grey was also used to estimate the perceptual upright when visual orientation cues were not present.

The rotational speed of the centrifuge was altered between separate instances of the OCHART-Experiment to simulate gravitational forces between 0g and 1g. In total, nine centrifugal accelerations were simulated (0, 0.02, 0.04, 0.06, 0.08, 0.1, 0.2, 0.6 and 1g). The corresponding rotation speeds were calculated for each participant to take into account small variations in the distance of each person's head from the axis of rotation (between 73cm and 76cm). Participants lay in the centrifuge with their legs bent as if they were sitting lying down which reduced the distance of the body extremities from the centre of rotation and hence reduced the gravity gradient along the body.

A total of ten subjects had been investigated during the study. Participants held an emergency stop button in their left hand mounted on the end of a hand grip which could be operated by their left thumb in the case of an emergency.

2.1 OCHART-Experiment

The OCHART-Experiment (Oriented Character Recognition Test) was designed to measure the perceived upright of a human subject. In this experiment the symbol p is shown in various orientations. In addition a background, also with arbitrary orientation, which includes various vertical and horizontal structures can be shown (See Fig. 3).
After showing the symbol for a short period of time (ca. 500ms) the participant has to decide, whether a “p” or a “d” was perceived.

Figure 3: Example of the presentation of the symbol p/d within the OCHART-Experiment including a tilted background image.

In previous experiments it could have been shown that the transition of the perception of the symbol from “p” to “d” happened roughly in the real horizontal when running the experiments in an upright body position without any background shown. Also a rotated background has only little influence on the orientation of this threshold. On the other hand, while running the experiments in zero gravity (0g) it could be shown, that the orientation of this threshold and therefore also the perception of upright was influenced more heavily by the visual misinformation given by a rotated background.
This leads to the question, how big the influence of visual information is for gravitational forces between 0g and 1g, which will be examined in this project.

2.2 3D-Orientation Experiment

For the 3D-Orientation experiment, we tested the hypothesis whether the correct reconstruction of a previously learned 3D-orientation of an object will be affected by alterations of gravitational forces.

For this, a two stage experiment has been designed. In the first stage, a three-dimensional object with a unique 3D-orientation was presented on the screen to the subject (see Figure 4, left). The subject's task was to memorize the 3D-orientation of the object for a retention period of up to one hour.

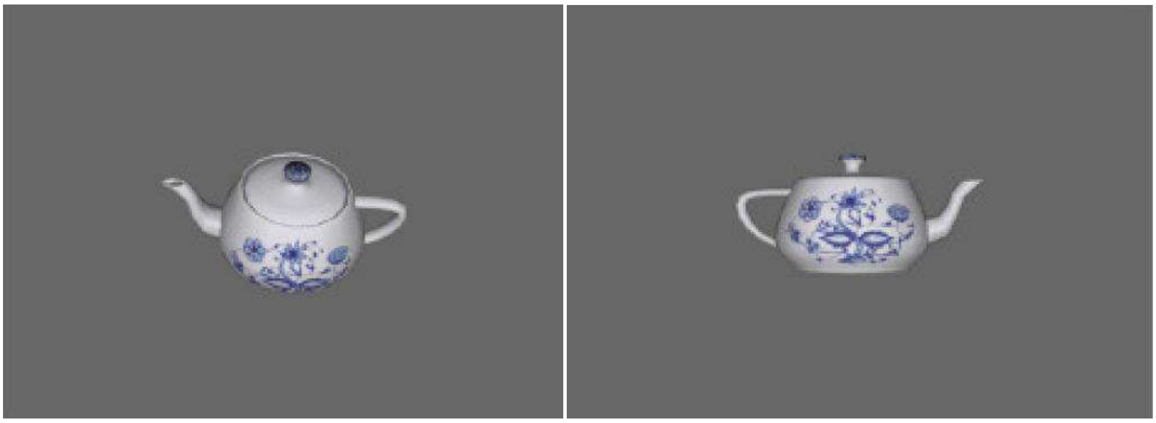

Figure 4: Example of an object, which was used for the 3D-Orientation experiment.
Left: An orientation that had to be memorized;
Right: The object in its neutral position from which the memorized orientation had to be reconstructed

In the second stage of the experiment, the task for the subject was to reconstruct the previously memorized orientation. For this, the corresponding object was shown to the subject in a neutral position (see Fig. 4, right). By using a trackball, the subject could alter the object's orientation in roll and pitch until it had assumed the previously memorized 3D-orientation.

This second stage of the program was performed at the highest g-level exposure of a given session (0.6g or 1g) and as a control after halting the centrifuge (0g).

2.3 Protocol

In the course of two test-sessions within one day, eight different gravitational forces were simulated using the short-arm-centrifuge (0.02g, 0.04g, 0.06g, 0.08g, 0.1g, 0.2g, 0.6g and 1g; each measured at ear level). For each session, four of those gravitational forces were realized (see Fig. 5).

The OCHART experiment was executed once at each g-level and, to simulate 0g, before the first and after the second session when the centrifuge was stationary. In addition, control experiments were run for each subject on each day before and after the experiments on the centrifuge within a separate room, once in an upright sitting and twice in a lying position (once lying on the left side, once on the right side).

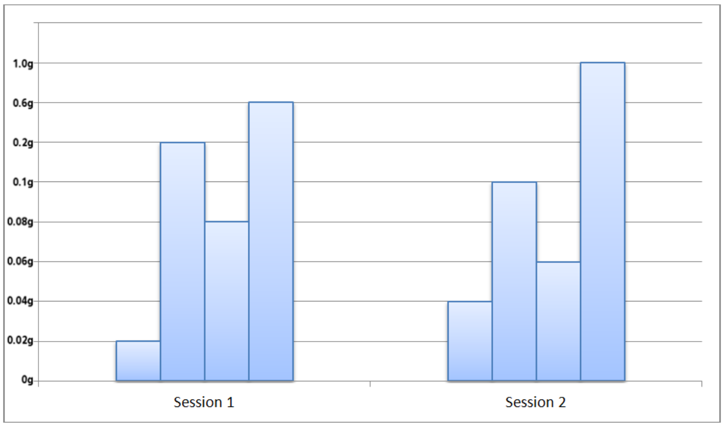

Figure 5: Sequences of realized gravitational forces within session 1 and session 2.
Session 1: 0.02g – 0.2g – 0.08g – 0.6g
Session 2: 0.04g – 0.1g – 0.06g – 1.0g

For the orientation experiment, the subjects were asked to memorize the 3D-orientation of nine of a total of 18 objects before each session, when the centrifuge was still stationary. When reaching the highest g-level of a session and after performing the OCHART experiment, the subject was then asked to reconstruct the previously learned 3D-orientation. In theory the subject had no time limit for the reconstruction of the task. Nevertheless, it was recommended to complete the reconstruction task quickly because of the high physical stress a body is exposed to under those high g-levels. After that, the centrifuge was brought to halt and the second part of the 3D-orientation-experiment was repeated.

2.4 Participants

Ten participants took part in the experiment (5 female, 5 male, average age 29.9 ±7.2 yrs). To reduce external influences during the experiments, the subjects were chosen by the following characteristics:

- Good state of health; participants were screened for diabetes mellitus, rheumatism, muscle or joint diseases, laser eye surgery, herniated disc, chronic back pain, claustrophobia, heart disease and orthostatic intolerance using anamnesis, clinical chemistry, urine analysis, ECG and through self report of general health.
- No vestibular disorders in the past
- Normal or corrected-to-normal vision
- Preferably experiences with experiments on a centrifuge

Participants completed an informed consent agreement that conformed to the ethical guidelines of York University, Deutsches Zentrum für Luft- und Raumfahrt (DLR), and the Declaration of Helsinki. During the centrifugation the following physiological signs were continuously monitored by a medical team: ECG, heart rate, SpO_2, sphygmomanometric and finger blood pressure, and thoracic impedance. They were also under continuous visual observation via an infrared camera system monitored by qualified medical personnel.
Each participant completed two sessions per day with four g-level each. These sessions were repeated on a second day in an altered sequence. Therefore the centrifuge was used on a total of 20 days for data collection.

2.5 Equipment

To ensure the smooth execution of the experiments, special equipment was needed and had to be bought before the start of the study.

Laptop (MacBook Air, 11", 1.7GHz, 128GB SSD)	A laptop was needed to run the experiments on the centrifuge. It had to run the experiment's software (video output of the OChart- & Orientation-experiments as well as logging the input given from the subject) and establish a remote connection to the desktop PC, located in the control room (to control and observe the software). Because of the high mechanical stress on the hardware while centrifuging, it was decided to use a laptop with a SSD instead of a HDD to reduce the risk of malfunction.
Desktop PC incl. monitor & input devices	For planning and developing, as well as controlling and evaluating the experiments, a desktop PC including all necessary hardware was needed.
Trackball (Logitec TrackMan Marble)	To allow immediate response from a subject, an input device had to be mounted on the centrifuge. It had to have two buttons (to decide if a "p" or "d" was perceived as well as to accept a reconstructed orientation) and allow rotating a shown object with minimal hand movement. A trackball was ideal for those demands.
Accelerometer	A accelerometer had been installed on the centrifuge in order to detect and log the current g-level for every interaction a subject made. With this, it was possible to reconstruct a experiment, even if some sort of error would occur (e. g. wrong g-level provided by the centrifuge, software error, emergency shutdown of the centrifuge, power outage, etc.).

3. Results

3.1 OCHART-Experiment

3.1.1 Off-centrifuge effects

In order to obtain the influence of vision and gravity on the perception of upright (PU) in our participants, we first obtained the direction of the PU with the directions signaled by vision, the body and gravity separated by viewing a grey visual background or a background tilted 112° left or right relative to gravity with the person upright, on their side and on their back (on the centrifuge before the centrifuge started to move). The average directions of the PU found for each of these variations are shown in Figure 6. The effect of the background was to tilt the perceptual upright in the direction of vision. When the body was tilted to the left, the PU shifted to the right (relative to the body, i. e., towards the direction of gravitational up) and vice versa. The purpose of this section was to ascertain baseline measures to compare with data collected when forces were applied along the long axis of the body by the centrifuge data.

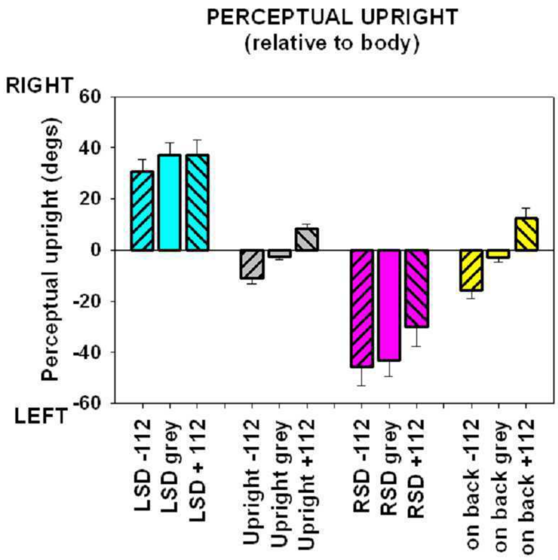

Figure 6: Variation of the perceptual upright in response to body posture (blue: left side down; grey: upright; pink: right side down; yellow: on back) and vision (left hash: 112º left; right hash: 112º right; clear: grey background). Errors are standard errors.

3.1.2 On-centrifuge effects

Participants lay on a centrifuge that was then accelerated to various speeds evoking centripetal accelerations at the participant's head from 0 to 1g, as described before. For each value, participants ran three conditions (vision tilted left, vision tilted right and grey background).

When evaluating the data collected by the OCHART-experiment on the short arm centrifuge, a high variation of the results of the different subjects could be observed. Nevertheless, even with a artificial gravitational force of 1g, a loss of importance of visual cues can be shown, comparable with an upright body position, that means that the participants considerably overestimated the artificial gravitation of this experiment.

In addition, it could be shown, that the visual effect decreased systematically by gravitational forces at below 0.2g. It seems that at forces at and below 0.2g a change in the perception happens and therefore, also in the weighting of the different components.

While increasing the g-level from 0g up to 1g, the influence of gravitation to the perception of upright also increased from 0% to 23%. Accordingly the influence of visual cues decreased.

Summarized, the visual effect, defined as the difference between the perceptual upright measured with the background tilted right and tilted left, reduced from 28.1° ± 6.4 when the centrifuge was stationary to 20.9° ± 4.6 when centrifugation produced 1g at the head (p = .036).

The visual effect at the 1g centrifugation was not significantly different from the visual effect measured when upright (19.1° ± 3.5; p=.36).

These effects of vision on the perception of upright under varying gravitational forces are shown in Figure 7.

Analogous to Dyde et al. [16] and the geometrical prediction when removing one of the three vectors, the perceived upright of subjects got influenced more by visual cues while in supine position then when in an upright standing position. This contrasts observations of situations in short periods of zero gravity and lunar gravitational conditions, simulated by parabolic flights, where visual cues generally had less influence. The acceleration, over which an effect occurred, laid considerably over the value which would be expected with linear acceleration thresholds. Nevertheless, further studies and analyses are necessary, in particular to develop models for the evaluation of data with such high individual variability.

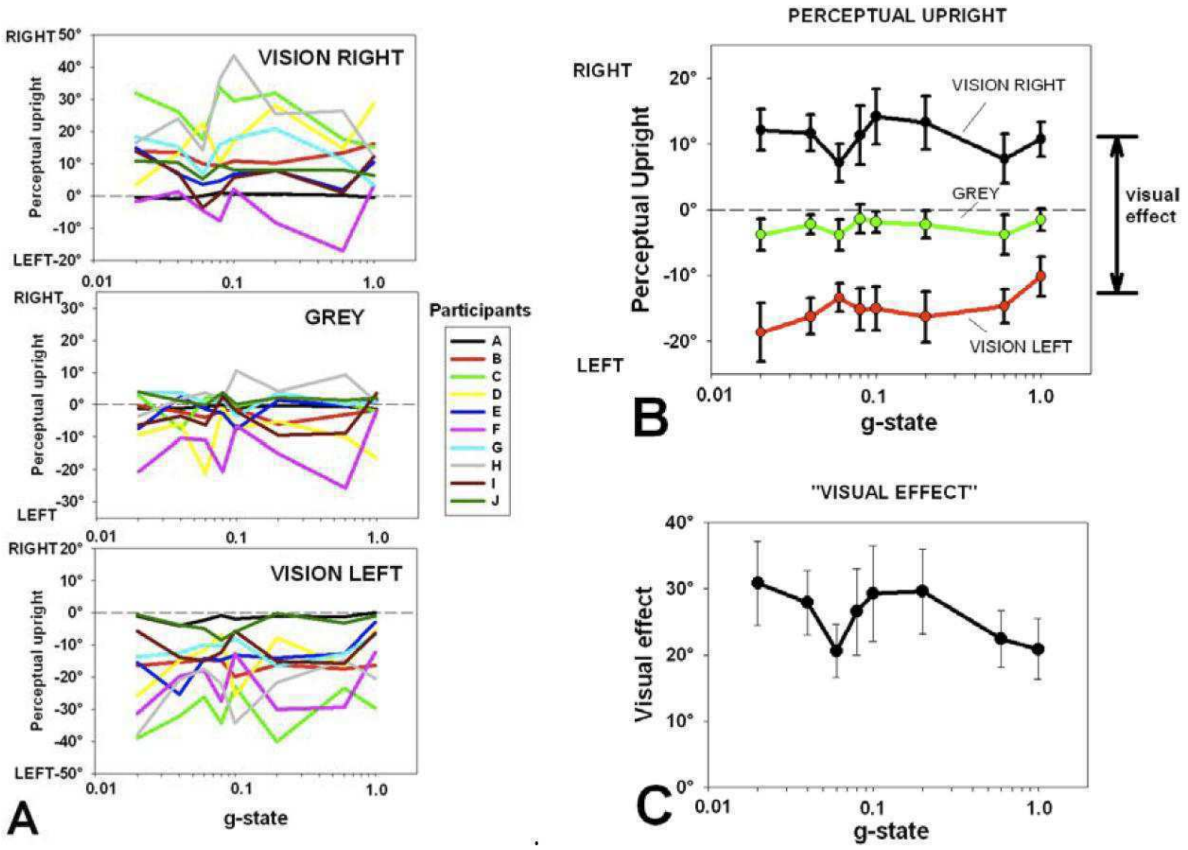

Figure 7: The effect of vision on the perceptual upright during accelerations from 0.02g-1g.
Panel A shows the results from individual participants. Although there was considerable inter-subject variability, panel B shows that, on average, there was a decline in the effect of vision (less tilt away from the body midline, 0º) with increasing acceleration. In order to illustrate this better, the results with vision left (red) were subtracted from vision right (black) for each subject to obtain what we refer to as the "visual effect", which is shown in panel C.

3.1.3 Modeling

We have previously shown that the perceptual upright can be well predicted from a vector sum of vision, the body, and gravity [16]. This model is illustrated in Figure 8 to describe what was expected on the centrifuge. However, because the participant's body was aligned with the centripetal force (as it is aligned with gravity when upright), we were unable to separate the effects of gravity and the body for each centrifugation condition.

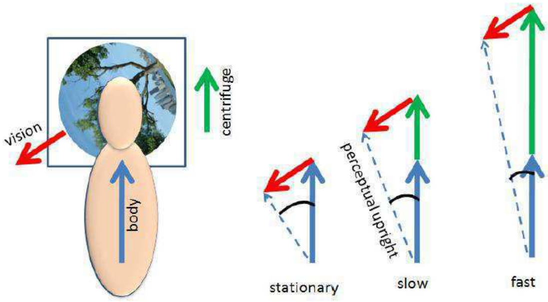

Figure 8: Three vectors are assumed for this experiment: One for the "normal" perception of upright (blue), one for the force applied by the centrifuge (green) and a vector representing the direction of upright in a presented image. By summing up these three vectors, the perceptual upright can be predicted.

We made the assumption that the body and visual vectors remained constant throughout the experiment and only the gravity vector varied. We calculated the lengths of each of these vectors (relative to each other, as only relative measures can be obtained) from the off-centrifuge data using: $\overrightarrow{PU} = v * \overrightarrow{vision} + g * \overrightarrow{gravity} + b * \overrightarrow{body}$ (equation 1)

Where $\overrightarrow{vision}$, $\overrightarrow{gravity}$ *and* $\overrightarrow{body}$ are the directions signaled by each cue, weighted by factors v, b and g respectively. A rotational bias term for the PU was also introduced. The ratio v : b : g using conditions without the spinning centrifuge was 14% : 47% : 39%, as shown in Figure 9, which is similar to that reported in Dyde et al (25% : 54% : 21%) [16] although with more emphasis on gravity and less on vision in this population. People vary enormously in the relative weightings assigned to each vector but the individual weightings are constant over time for each person. Making the assumption that the relative weightings of vision and body remained constant (v/b = 0.29 on average (equation 2)) for each person throughout their centrifuge experience, we then fitted equation 2 and obtained a relative weighting for gravity for each value of added centripetal acceleration (see Fig. 9).

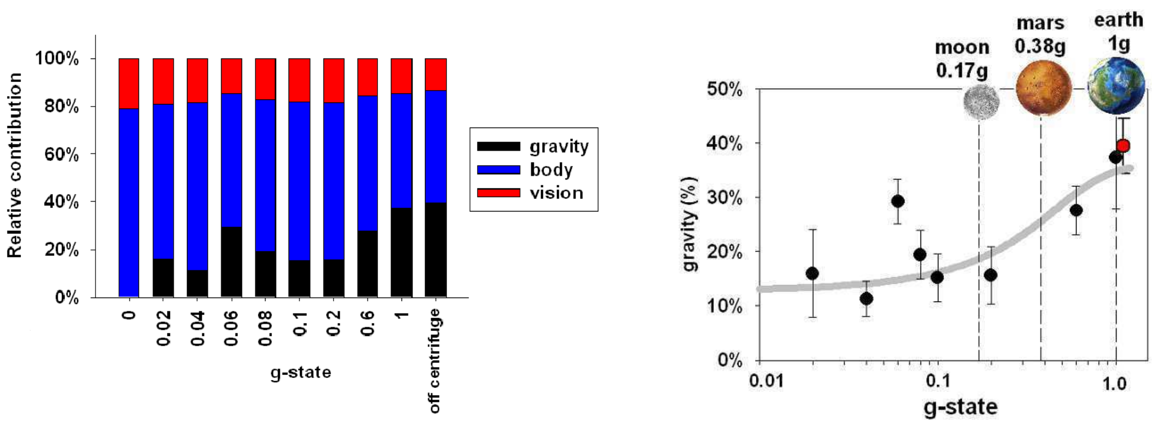

Figure 9: On the left side, the relative weightings of vectors corresponding to vision, body and gravity during centrifugation are shown. On the right side, the weighting of gravity (relative to vision + body) is shown as a function of the imposed g-state. Also included, for reference, are the gravitational fields of the moon, mars and earth. Plotted through the data is a sigmoidal function which suggests a threshold around 0.15g. The red symbol is the value from the off-centrifuge experiments. Errors are SEM.

3.2 3D-Orientation Experiment

The participants' adjustments were transformed into error variables by computing for each axis (pitch and roll) the difference between the actual and the estimated orientation of the objects. We eliminated trials in which the participants were not able to complete their adjustment (due to inadvertently pressing the button, frustration with the difficult trackball interface, or complete forgetting of the initial orientation), as indicated by errors greater than 45° or smaller than -45°. This resulted in a loss of about 30% of the data, indicating that it was in fact a very difficult task. The remaining data were then aggregated across 18 stimuli, resulting in four values per participant (two g-levels x two recall modes). The same procedure was applied to the absolute values of the errors.

A 2x2 rmMANOVA with the dependent variables Error(pitch) and Error(roll) and the factors "g level" and "recall mode" revealed no significant effects (all $p > .05$). To test for non-directional effects, the same 2x2 rmMANOVA was conducted for the variables containing the absolute errors. Again, no significant effects were found (all $p > .05$). This is also shown in Figure 10.

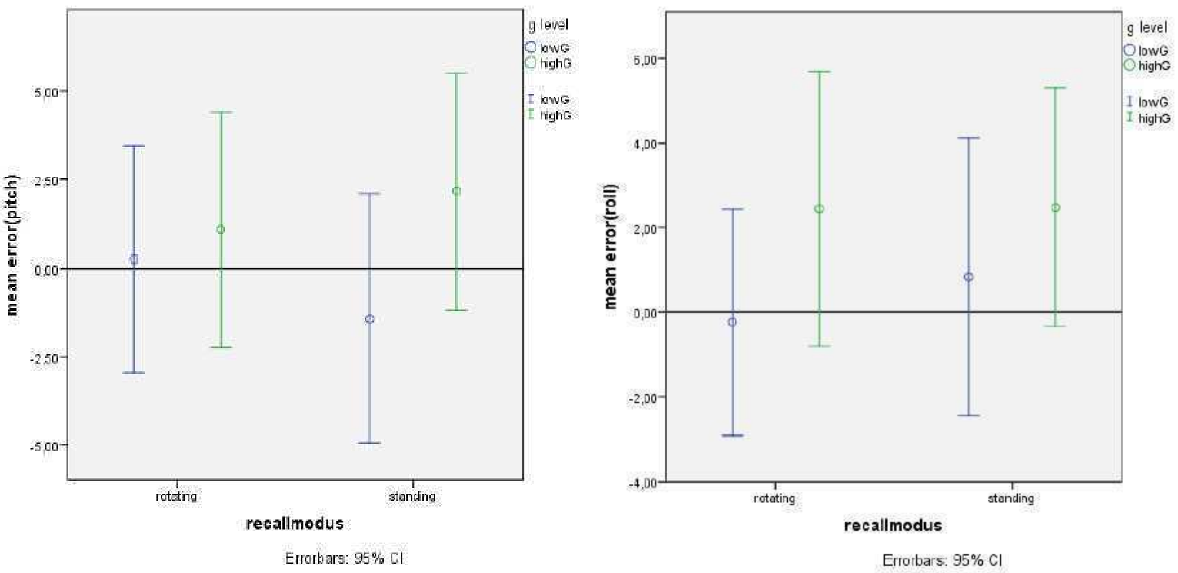

Figure 10: Mean errors for the reconstruction of orientations of 3D-objects for pitch (left) and roll (right) at high (green) and low (blue) gravitational forces. There were no significant effects found (p>.05 each).

4. Conclusions

We have shown that centripetal force applied along the long axis of the body is as effective at contributing to our sense of the perceptual upright as when standing with normal gravity. This is despite the fact that participants on a centrifuge actually experience a summation of the centripetal force and gravity (a combined acceleration of $13m/s^2$). The lack of effect of the component of gravity outside the plane of the screen is also supported by the larger visual effect found when participants were lying supine (without centrifuge movement) both here and in previous studies [16]. Our data suggest that a gravitational field of about 0.15g is necessary to provide effective orientation information. This is close to the gravitational force on the Moon of 0.17g (see Fig. 9).

For whole-body linear acceleration, the vestibular threshold is around $0.1m/s^2$ (although studies have reported values ranging from $0.014m/s^2$ to $0.25m/s^2$) [18] and so the lunar value of $1.6m/s^2$ should be well above threshold. These values are compatible with Homick and Miller's conclusion, that lunar gravity is an adequate stimulus for the otolith organs to define a gravitational vertical and to guide posture control [19]. Their conclusion, however, was based on anecdotal reports from Apollo astronauts indicating that they experienced no disorientation on the lunar surface [1]. Our quantitative assessment suggests otherwise. We find that, even though the added gravitational force was above the acceleration threshold, it was only effective at influencing the perceptual upright at much higher levels: the gravitational force on the moon would only barely be able to provide adequate gravitational cues necessary for orientation.

Conducting human experiments with simulated gravity requires considerable consideration of participant safety. This is particularly true of higher g-states which are associated with greater risk to the subject. Although the curves shown in Figure 9 and others show a clear trend between 0g and 1g, the lack of data points at high g-states make it difficult to be specific in terms of the shape of the transition curve. Such fitting is also complicated by the variability encountered at lower g-states. Future experiments hope to capture additional higher g-state data to help reduce the uncertainty in the shape of the transition curve between 0g and 1g. A lower contribution of gravity corresponds to a higher relative significance applied to vision.

Such an increase has also been observed in medicated Parkinson's patients [20] and might partially account for the reported balance problems both for Parkinson's patients and that have been associated with arrival on the moon [21]. When the cues that define the perceived upright are misaligned, for example when the body or visual reference plane is tilted relative to gravity, an unusual pattern of sensory weightings could potentially pull the perceived direction of upright more in the direction of the relatively higher weighted cues and thus threaten the reliability of processes that rely on the perceptual upright.

5. Future Work

To get further data for the situation at the threshold of 0.2g, more specific experiments have to be made. In the second half of 2014, further studies are planned to examine the influence of gravitational forces on the perceptual upright more isolated.

To do so, a tactile instrument will be used to evaluate the perceived upright of a subject (see Figure 11). It is planned to install a tactile instrument in form of a small, touchable but not seeable rod, which orientation can be altered by a servo motor.

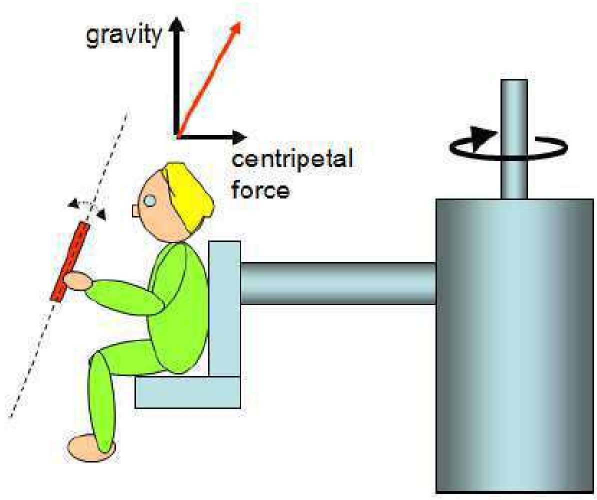

Figure 11: Subject on the SAHC with installed tactile instrument. Subject can feel the orientation of the rod and has to decide, if it is tilted towards or away from his/her felt vertical axis.

The subject has to decide, if the rod is tilted towards or away from his/her body under various gravitational forces. Similar to the OCHART-experiment, the orientation of the rod will be adjusted by an adaptive algorithm until a participant chooses the options “tilted towards me” and “tilted away from me” equally.

Like in the previous experiment, the participants view will be obstructed by a hood with an implemented screen. On this screen, a virtual plane will be shown, which can be tilted horizontally to alter the visual vector.

6. Publications

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