PERCEPTION OF SPATIAL ORIENTATION IN DIFFERENT G-LEVELS

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INTRODUCTION

Human spatial orientation depends to a significant extent on gravity. On earth it is even more important than vision, as experiments with tilted visual scenes have shown (1). To estimate the direction of gravity during and after whole body movements, interaction of the vestibular sense organs, the otoliths and semicircular canals, is necessary. Gravitational and translatory linear acceleration, both sensed by the otoliths, cannot be measured separately. Therefore, other sources of information must be used to determine the direction of gravity. Without vision, the angular velocity sensed by the semicircular canals as well as the knowledge about the constancy of the direction and amount of gravity with respect to earth can help to correctly locate the direction of "up" (2,3).

On earth, when one is briskly tilted with respect to gravity, a fast change of the direction of gravity as well as the accompanying angular velocity of the tilt is sensed by the vestibular system. The perceived direction of gravity follows without delay and is quite correct (4). However, when the fast change of the direction of the resultant acceleration is not accompanied by an appropriate "natural" semicircular canal input, as occurs in the "Oculogravic Illusion" experiment performed on a human centrifuge, the perceived direction of gravity follows only with a delay of about 20 sec (4,5).

In microgravity, the appropriate accompanying otolith stimulation is not available, since there is no gravity vector. Therefore, during whole body turns without vision, subjects always have only the angular velocity information supplied by the semicircular canals to estimate their body orientation. This is similar to a whole body turn around an earth vertical axis under 1g conditions. As in microgravity, the angular velocity information has to be integrated by the central nervous system to provide an estimate of self-orientation. However, the question remains whether such a path integration task can be performed in microgravity.

In order to evaluate the possible influence of the missing gravity vector on the perception of spatial orientation, experiments were performed during the MIR94 space mission and during parabolic flight. A ground control experiment was performed to compare the spatial orientation abilities in the microgravity environment with those on earth.

METHODS

MIR94 mission : Two subjects participated in the inflight experiment which was performed on flight days 3, 4, 5, 13, and 30. Subjects were passively turned around their body x-axis (approximately at the height of their hips) by another astronaut. Directional noise from the station was masked by headphones. After remembering their initial orientation within the spacecraft, subjects closed their eyes or covered them with one hand. The instruction to the subject was to point towards the ceiling of the spacecraft during the turn or after the turn had stopped (see Fig 1A). The experiment was recorded on HI-8 video tape for off-line analysis. The video tapes were digitised using an SGI workstation with a frame rate of 5 Hz. The video files were then analysed on a PC by means of software which allows the examiner to view the video data frame by frame and to mark the body and pointing directions for each frame interactively.

Parabolic flight : Two control subjects participated in the experiment; the protocol and analysis procedures were the same as for the space flight experiment.

Ground experiment : Two control subjects (one of them also participated in the parabolic flight experiment) were tested. To achieve a similar situation as in the microgravity experiments, subjects were rotated around their body x-axis while lying on their back (see Fig. 2A) in a computer-controlled two-axis rotating chair (SEGA). Subjects were instructed to remember the initial starting direction and during the turn to adjust by remote control a luminous line, which was visible on a video screen above their face, to the initial starting direction. Turning velocity was set at 22 deg/s, the average velocity measured in the microgravity experiment. No other visual or auditory information was available during the turn. The chair and line position was recorded on-line with a sampling rate of 125 Hz.

RESULTS

Microgravity experiments : There was no difference in the results of the first days of space flight and the parabolic flight experiments. All subjects showed a very similar, poor performance of spatial orientation ability during and after the turns. The direction indicated as being the ceiling of the space craft or plane was very close (max. difference approx. 20 deg) to the initial direction before the turn, or to the longitudinal body z-axis (see Fig 1B, lower plot). For example, after a 90 deg turn from the initial left-ear-down position to upright, the subject pointed at an angle of 70 deg on his right side, i.e., 20 deg away from the initial direction of the ceiling. In another case, starting from upright, the subject pointed to the floor after a 180 deg turn, again,

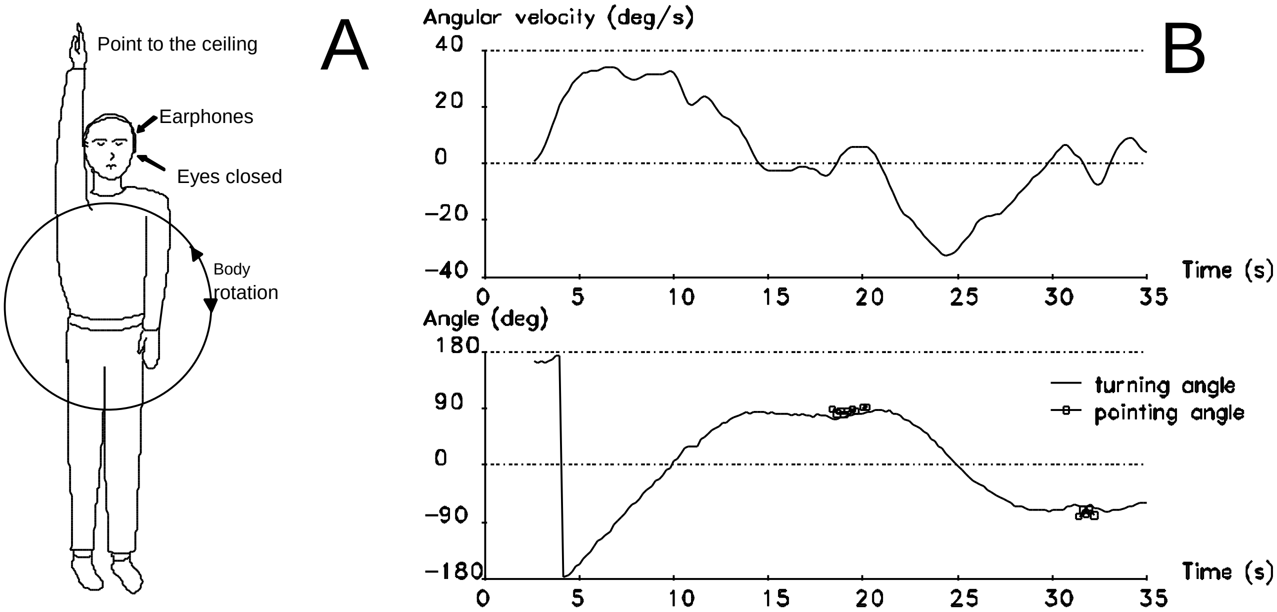

Figure 1. A: Setup of inflight experiment. The subject, standing upright at the beginning, had to point to the direction of the ceiling after whole body turns around the body X-axis. B: Example of inflight results (flight day 4). Upper plot, solid line: angular velocity of whole body turn. Lower plot, solid line: angle of turn of the subject. Squares: pointing angle as indicated by the subject. Note: correct pointing would require the pointing angle to coincide with the narrowly dashed 0 deg line.

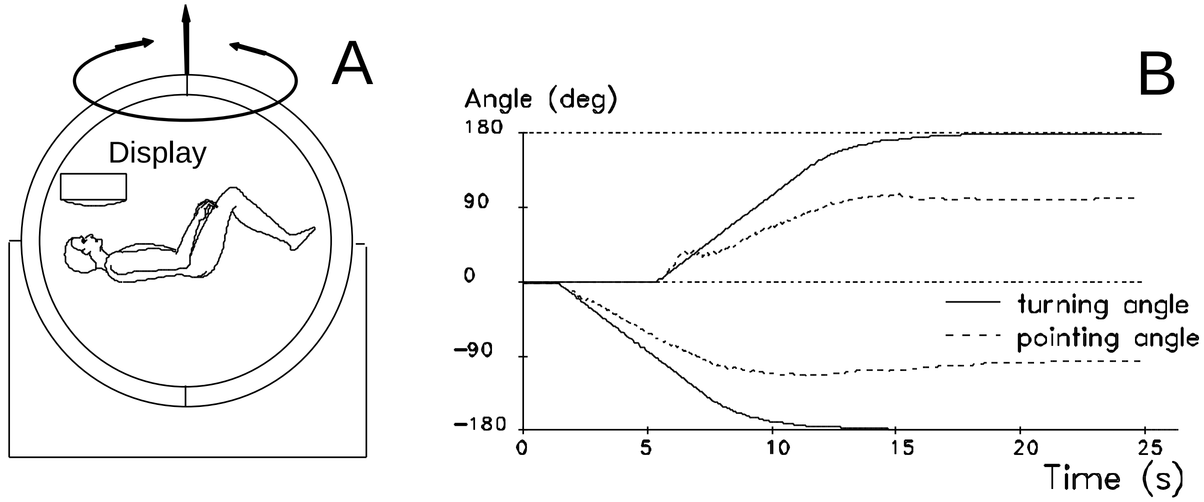

Figure 2. A: Setup of control experiment. The subject, lying supine, had to adjust a line on a display during and after a whole body turn around the body X-axis. B: Two examples of results of 180 deg turns. Solid line: angle of turn of the rotating chair. Widely dashed line: pointing angle as indicated by the luminous line display. Note: as in Figure 1, correct pointing would require the pointing angle to coincide with the narrowly dashed 0 deg line.

pointing coincided with the initial direction of the ceiling, as if the body turn had not been perceived by the subject.

Indeed, some subjects reported that they did not perceive the rotation and consequently suspected that the turning velocity was too slow. However, analysis of the video data showed angular velocities around 20 deg/s, sometimes up to 40 deg/s (see Fig 1B, upper plot), which is well above the threshold of the semicircular canals (approx. 3 deg/s).

On the last day in space, however, the pointing directions of both subjects showed a much greater variability. The deviation of the pointing angle from the body axis ranged from 0 deg to full 180 deg, but, again, in most cases did not coincide with the true direction of the ceiling. Thus, the raw data alone do not allow a conclusion about why subjects perceived such large changes in self-orientation.

Control experiments : Subjects in the control experiments (turning velocity 22 deg/s) were able to adjust the luminous line with a positional gain of about 50%, i.e., at an angle of 180 deg subjects adjusted the line to about 90 deg in the correct direction (see Fig 2B), which is much more than observed during early inflight. Since the axis of rotation was parallel to gravity, the only sensory input available to compute self-orientation was the rotational velocity sensed by the semicircular canals. Therefore, the relevant sensory information was exactly the same as in space flight, except for the amount of gravity (see also Discussion).

MODELLING

To understand the low gain of self-orientation indication in the control experiment, a simple model simulation was performed. With a semicircular canal model consisting of two high-pass filters (10s and 30s time constants) and a threshold followed by a velocity to position integrator, the ground results were quantitatively simulated by feeding the chair velocity into the model. This shows that the transfer function of the semicircular canals together with a threshold is sufficient to explain the low gain of pointing in the control data.

However, when the same model was applied to the early inflight data, the simulation results did not match the experimental data. Therefore, a simple canal model is not sufficient to explain both the control and early inflight data sets.

In contrast, comparison of the simulation of the last flight day experiment with the actual results suggests that a certain amount of adaptation might have happened: the simulated data and the pointing results showed in most cases much smaller differences than for the early inflight data.

DISCUSSION

The experiments performed in early space flight and in parabolic flight show that the perception of self-orientation with respect to the environment during and after whole body rotations in 0g differs significantly from the 1g condition. The question arises as to why such a difference is observed.

In microgravity, no gravitational vector is available to help determine the absolute body orientation with respect to the environment. However, the same is true for the ground control experiment: since subjects were turned around an earth vertical axis, the orientation of gravity with respect to the subject did not change, and the only sensory information available to estimate self-orientation was the angular velocity sensed by the semicircular canals. Moreover, as modelling shows, the poor performance in 0g cannot be explained by the transfer function of the semicircular canals.

In other words, the change of sensory input during the turn is exactly the same in the ground control experiment and in microgravity. Thus, one would expect the change of perceptional output, self-orientation, to also be the same. However, this is not the case. Therefore, the difference between earth and microgravity conditions must be due to the internal processing of the sensory information which interacts in a non-linear fashion.

Recent models of otolith-canal interaction for human spatial orientation (6) postulate the existence of an internal estimate (7) of gravity which determines the perception of self-orientation with respect to gravity. There are different hypotheses of how this internal representation is updated (2,3). Previous microgravity experiments examining the so-called inversion illusion (8) suggested that in microgravity this internal estimate of gravity may be determined by an imbalance or bias of the saccule. According to this hypothesis, the internal estimate would be head- or body-fixed in microgravity, pointing in the positive or negative direction of the head z-axis. During whole body turns around the body x-axis in microgravity, the information from the semicircular canals indicates a change of position, while the internal body-fixed estimate of gravity indicates no change at all. Due to this sensory conflict, the angular velocity information may then be processed incorrectly, which leads to spatial disorientation.

This hypothesis is supported by experiments on a human centrifuge (9), where the otolith stimulus, the resulting gravito-inertial acceleration vector, remained fixed in the direction of the body z-axis. In this case, subjects did not perceive a 60 deg whole body turn with a velocity of about 40 deg/s around their x-axis.

Thus, it can be concluded that in both the centrifuge and the microgravity experiments, the body-fixed direction of the internal estimate of gravity prevents a perception of body rotations around an axis perpendicular to the internal estimate. In contrast, in the ground control experiment, the axis of body rotation and the internal estimate of gravity, as well as the gravity vector, are parallel. Thus, perception of rotation is not prevented, which is in accordance with the model predictions.

Astronauts anecdotally report that they sometimes are completely disoriented after sudden head turns, this happens especially to first-time fliers. The reason for this could be the same as for the disorientation shown in the experiment reported here: the head-fixed internal estimate of gravity leads to incomplete perception of head turns. The gradual accomodation to this phenomenon could, according to our results, indeed be due to a change of internal processing of otolith-canal interaction, as suggested by others (7).

Clement et al. (10) reported misperception of self-orientation in a similar experiment: two subjects were rotated passively around different axes on flight day 7 of a space shuttle mission. In contrast to our study, subjects reported to perceive the rotations around the body y- and x- axis with errors up to 90 deg. This difference may be due to higher angular velocities, which can, however, not be proved, since the actual body movement was not recorded in (10).

To fully confirm our microgravity results, especially possible adaptation, experiments with more subjects and better control of the procedure are necessary. Specifically, higher angular velocities should be applied to fully exclude misperception of changing self-orientation due to threshold mechanisms. This would require a rotating chair with either a visual display or a pointing device to indicate self-orientation with respect to the spacecraft.

CONCLUSION

On earth, using gravity measured by the otoliths as an external reference is an optimal strategy to determine self-orientation with respect to the environment. However, in microgravity, this strategy fails since the external reference is no longer available, but is apparently still assumed to exist by the central nervous system. Therefore, the information about changes of self-orientation detected by the vestibular system can cause a sensory conflict. Both the experimental data presented and theoretical considerations suggest that such conflicting information about the change of direction of gravity either given by otolith input or due to the internal processing, and from the canals about the change of self-orientation, can lead to spatial disorientation and illusions about actual body position and perceived motion. In space flight, such conflicting information may also be one of the many reasons for space motion sickness. The possibly improved self-orientation performance observed inflight after 30 days of exposure to microgravity suggests that there is substantial adaptation of otolith-canal interaction to the new environment, a possibility noted by many researchers (e.g. 7, 10, 11, 12).

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