# Spatial Orientation in Weightlessness and Readaptation to Earth's Gravity

Abstract. *Unusual vestibular responses to head movements in weightlessness may produce spatial orientation illusions and symptoms of space motion sickness. An integrated set of experiments was performed during Spacelab 1, as well as before and after the flight, to evaluate responses mediated by the otolith organs and semicircular canals. A variety of measurements were used, including eye movements, postural control, perception of orientation, and susceptibility to space sickness.*

A novel set of sensory cues is produced by head movements in weightlessness. Voluntary head tilts are no longer confirmed by static changes from the otolith organs signaling head orientation with respect to the vertical. Indeed, with average linear acceleration equal to gravity during free fall, the linear accelerometers of the nonauditory labyrinth transduce only transient linear acceleration and no longer indicate head pitch or roll angle. We hypothesized that vestibular afferent signals, particularly from the utricular and saccular maculae, are centrally reinterpreted, for example, to represent linear acceleration rather than tilt (*1*). We further supposed that this central adaptation underlies the amelioration of symptoms of space adaptation syndrome, a form of motion sickness which afflicts roughly half of all space travelers during the first 2 to 4 days in orbit. In order to localize this presumed adaptation, a set of interrelated experiments was performed on four Spacelab 1 crew members. Pre- and postflight tests of postural control and motion perception, as well as of the inflight protocols, were used to evaluate readaptation to the earth's gravity after reentry.

*Visual-vestibular interaction* (*2*). When viewing a wide field display scene rotating about his sagittal (roll) axis, a subject on the earth with head erect normally perceives a sensation of continuous self-rotation in the direction opposite to the field motion (circularvection) combined with the paradoxical perception of a steady angle of tilt. This has been attributed to graviceptor signals, particularly those from the otolith organs, which do not confirm the visual input suggesting continuous roll rate (*3*). Visually induced tilt is enhanced when the head is placed in positions other than the erect (*4*) and can be continuous about a vertical axis when a subject lies supine. In weightlessness the absence of any inhibiting otolith signals might be expected to produce stronger and more compelling visually induced roll, although the absence of confirming signals from the semicircular canals might be expected to delay the onset of circularvection. Subjects viewed the polka-dot–patterned inside of a drum (dome) which rotated at speeds of 30°, 45°, or 60° per second about their roll axis. The head was fixed by a bite board, and ocular torsion (*5*) was recorded by a video camera. (Torsion results are not yet available.) The subject's body alternately floated free or was restrained by standing against stretched elastic cords, which created an upward force on the feet. Self-rotation illusion was manually indicated by magnitude estimation with a potentiometer and by qualitative descriptions from each subject. There was considerable variability among the four crew members in their reactions on the ground as well as in space. There was evidence for some degree of enhancement of the vection during weightlessness, relative to ground erect or supine tests, for at least three of the four subjects. Reactions varied from a sense that the subject and Spacelab together were rotating about a stationary dome to feelings of incomplete vection. Latency to onset of vection and average intensity of the self-motion indication generally confirmed the subjects' reports of stronger visual effects in Spacelab than on the ground.

Early in the mission, elastic cord loading produced inhibition of visually induced tilt in two of three subjects. By MD 5, the inhibitory influence of these localized somatic cues disappeared. Body sway and neck torque in response to dome rotation was sensed by two subjects, but clearly visible only in one, whose trunk and legs rotated slowly by up to 30° in the direction opposite to dome rotation. On closure of the eyes for three of four subjects, circularvection unexpectedly ceased immediately, despite the absence of any sensory cues to signal body deceleration. Its onset was hastened by free-rolling head movements. During postflight rotating dome experiments, two subjects indicated self-motion illusions not previously experienced lasting for up to 5 days after flight.

Visual cues concerning orientation appear to take on an increasing role in weightlessness. Localizable tactile cues, which may partially substitute for static otolith cues early in the mission for some subjects, no longer seem to play this role once vestibular adaptation has taken place.

*Space sickness monitoring experiment* (*6*). Symptoms and signs of space sickness and fluid shift were observed and documented by four specially trained crew members during this physically demanding flight. An example of one subject's overall discomfort during the first flight day is shown in Fig. 1. Three of four crewmen experienced persistent overall discomfort and vomited repeatedly on the first or second day. Symptoms diminished by the end of the third day, but still could be elicited with vigorous head movements through days 4 and

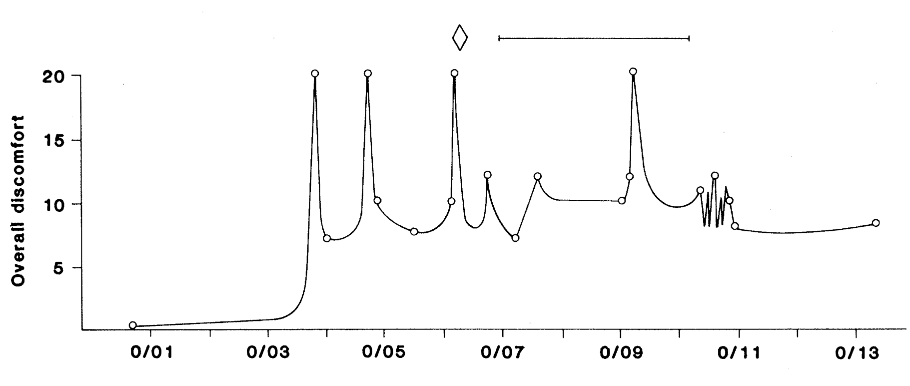


Fig. 1. Magnitude estimate of discomfort (*6*) for one subject during the first 14 hours in orbit. A score of 20 indicates vomiting. Curves between data points were interpolated by the subject. Diamond represents medication (scopolamine and dexedrine), followed by horizontal bar representing period of presumed maximal effectiveness.

5. One subject who explored different types of head movement found pitching and rolling head movements particularly provocative. However, on MD 8 he was asymptomatic after performing 5 minutes of vigorous head-to-knee movements. Two subjects wore head-mounted accelerometers, but quantitative analysis of head movement data is not yet complete.

Symptom pattern was generally similar to that seen in the same individuals before flight, except that prodromal nausea was brief or absent in two of three cases, facial pallor and cold sweating were usually absent, and one subject experienced uncomfortable "stomach elevation" and subjective difficulty burping. There is evidence that "sudden" vomiting is characteristic of long-duration motion sickness, and also of the responses of relatively resistant subjects (7). We tentatively attribute absence of pallor and sweating to physiological fluid shift and to the cool, dry environment of Spacelab, respectively. Subjects reported that symptom intensity was clearly modulated with head movement, and was exacerbated by reorientation illusions caused by ambiguous visual cues (as when assuming—or viewing another crewman in—an unusual orientation or when traveling through the tunnel connecting Spacelab with the orbiter). Tactile and proprioceptive contact cues provided by wedging the body into a corner or a bunk cubicle were palliative, as was closing the eyes, provided these contact cues were simultaneously present. Drugs (0.5 mg scopolamine and 2.5 mg Dexedrine or 25 mg promethazine and 25 mg ephedrine) known to be effective in preventing motion sickness were eventually taken by all, and were judged helpful in reducing discomfort with only minimal side effects. One subject was asymptomatic. Among the others, only 2 of 12 vomiting episodes occurred during the presumed period of maximal drug effectiveness. Although all reported persistent head fullness and congestion, and "fluid shift" faces were evident throughout the mission, subjects denied difficulty with hearing or clearing their ears. Altogether, we believe these results support the view that space sickness is a form of motion sickness.

*Pre- and postflight tests of motion sickness susceptibility (8).* In the past, single preflight tests have not been predictive of space sickness (9). Beginning 4 years before flight, we conducted formal tests of motion sickness susceptibility: horizontal lateral oscillation, heavy water ingestion, a dynamic visual-vestibular interaction test (10), horizontal axis rotation in pitch, and head movements in parabolic flight. The latter two were repeated in the year preceding flight. Modified Coriolis sickness susceptibility tests were conducted by NASA–Johnson Space Center. These tests failed to predict relative susceptibility in flight (11). Four days after flight all four subjects performed more than 140 forehead-to-knee head movements during the 0-*g* phases of parabolic flight without eliciting any symptoms, whereas all had shown some symptoms in one or the other of the preflight tests.

*Otolith-spinal reflex* (12). The burst of gastrocnemius-soleus electromyographic (EMG) activity occurring 50 to 150 msec after the onset of a sudden fall is considered to be predominantly otolith-spinal in origin. It is of short and relatively invariant latency, too early for a voluntary response, and is time-locked to the acceleration stimulus (13). It can also be selectively abolished by labyrinthectomy in cats (14) and baboons (15) and is absent in labyrinth-defective human subjects (16).

Previous studies showed that (i) the size of this otolith-spinal response is proportional to the acceleration stimulus, (ii) the response may be reduced significantly by rotating the gravity vector 90° relative to the body (subject supine) or by free fall, as in parabolic flight in an aircraft (17), and (iii) the response steadily increases in size during prolonged exposure to the supine position (18). The present experiments were designed to measure adaptation and readaptation of the otolith-spinal system during and after prolonged weightlessness.

Before and after flight the subjects were exposed to sudden, unexpected vertical falls of 15 cm, with stimulus amplitudes of 1.0, 0.67, and 0.33 *g*. The lesser accelerations were obtained with a counterweighted parachute harness. Two subjects were tested in orbit, substituting for gravity with suitably adjusted elastic cords running from a torso harness to the floor of Spacelab. The mechanical consequences to the otolith organs of being accelerated downward by elastic cords from free fall are not equivalent to those of being dropped in 1 *g*. Although starting from a different baseline, however, the inflight and ground

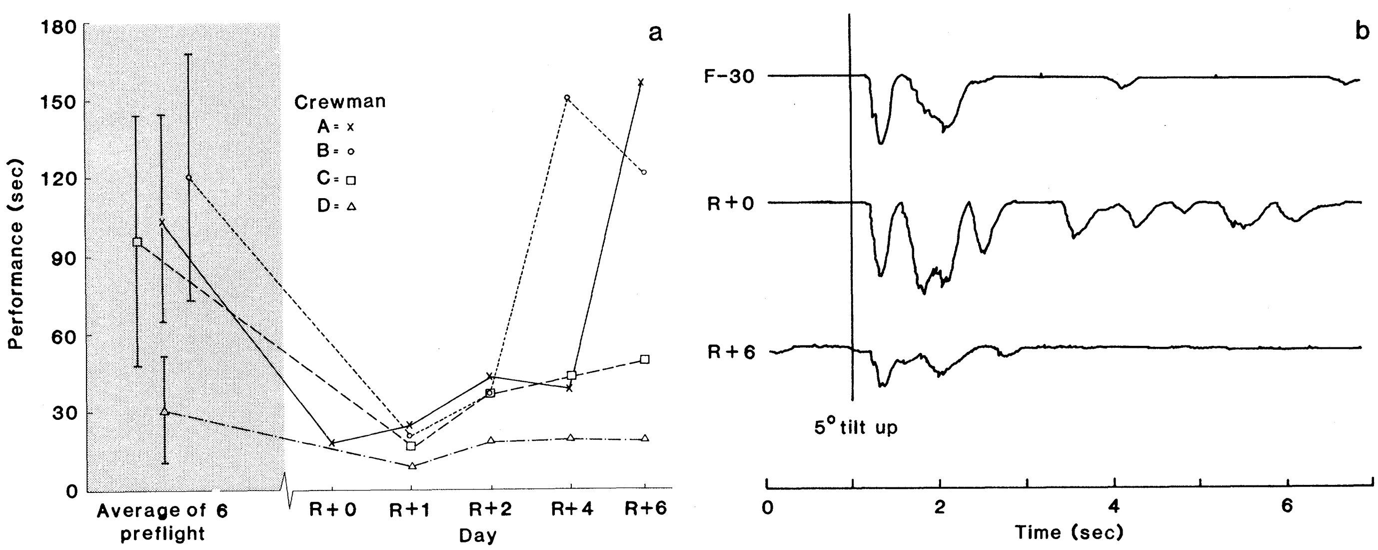


Fig. 2. Posture control with eyes closed, showing marked decrements immediately after flight for standing on a 5.7-cm rail or responding to an unexpected toe-up tilt of a posture platform (6). In (a), modified sharpened Romberg test measured total time standing on rail for the best three of five 1-minute trials. In (b), filtered EMG activity (arbitrary units) from the tibialis anterior muscle of one subject during the first eyes-closed 5° toe-up tilt shows, for R + 0, increased magnitude and duration of the late response. The drop in magnitude below the preflight value was seen for R + 0 but not for the other three subjects.

stimuli involve similar step changes in vertical acceleration.

After flight, all subjects experienced difficulty maintaining balance when landing from falls. This was dramatic initially but returned to normal within a few days. Contributing factors suggested by the subjects included leg muscle weakness, slower reaction to the falls and landings, and some difficulty telling where the legs were, with the result that the feet were often forward of or behind the body center of gravity on landing. The latter phenomena seemed to be present late in the flight as well. At that time, one subject also described "pins and needles" sensations in his legs.

Despite the impressions of the subjects, comparison of pre- and postflight EMG data obtained no earlier than 3.5 hours after landing did not appear to show any significant changes in latency or amplitude of the early otolith-spinal response to sudden falls. These results are compatible with those of ground-based studies on otolith-spinal adaptation to the supine position (*18*). The lack of change after flight could be the result of a readaptation time course too rapid to be detected by the present experiment, including the possibility of a nearly instantaneous readjustment of the response back to normal on return to the familiar 1-*g* environment. It is also possible that postflight changes in otolith function can be demonstrated only by lower frequency stimuli. These results suggest, however, that postflight postural instability is more a reflection of altered proprioceptive or tactile sensation, or possibly muscle wasting, than of modification of the vestibulo-spinal reflexes studied here.

*Awareness of position experiment (19).* Subjects were strapped blindfolded to a flat surface and after 5 to 15 minutes rest were asked to point to preestablished targets and to describe the position of their limbs. If straps were left loose, uncertainty of orientation with respect to the laboratory grew slowly, as might be expected due to the possibility of body drift. However, even with tight straps there was an apparent increase in variability of limb position estimate with muscles relaxed, compared to preflight results. After flight, occasional very large errors in pointing at high-elevation targets were found through R + 5.

*Pre- and postflight posture and orientation (20).* Postflight postural instability, especially with eyes closed, has been noted previously (*21*) and related to the duration of weightlessness. In a sharpened Romberg test, all subjects showed considerable difficulty in standing with their eyes closed after flight and exhibited growing body oscillations before falling off a (5.7-cm) rail. As shown in Fig. 2a, standing time dropped to 25 to 35 percent of preflight value on R + 1 and improved only gradually over the following week. The one subject tested on R + 0 indicated performance even poorer than on R + 1, suggesting a considerable amount of readaptation during the first 12 hours after return, as borne out by the crew's comments on instability in the dark and movement illusions.

Additional experiments were performed with crew members standing, eyes open and eyes closed, on a posture platform which is rotated rapidly and unexpectedly in a step disturbance of 3° and 5° about the ankles. Measurements were made of platform torque, EMG activity from the tibialis anterior and the gastrocnemius muscles, and body position. Four hours after flight, crew members were unsteady; they adopted a wide stance and for the first time lost their balance during step disturbances on the posture platform (tilt up; eyes closed). As seen in Fig. 2b, postflight activity in both muscles was not significantly changed in latency or amplitude up to 250 msec after each tilt, but was stronger beyond 250 msec. By R + 4, EMG responses returned to preflight levels. Despite previous reports of increased spinal activation after flight (*22*), no increase in antagonist EMG was found during platform tilts.

Visual field dependence was measured by the rod and frame test (*23*), in which subjects set a luminous line to the vertical under the influence of a luminous frame in a darkened room. Figure 3 shows that all four subjects were more field-independent than the population average. The two most field-dependent (A and D) before flight both shifted toward increased field dependence after flight, returning gradually but not completely back toward their baseline by R + 6. Subject A, who showed particularly large variability and asymmetry after flight, also showed large asymmetry in the postflight luminous line test (*24*). The two least field-dependent showed no changes after flight. An increase in time to make judgments of the vertical was noted for all subjects.

Perception and control of lateral acceleration were measured with a servo-controlled sled which provided accelerations up to 0.7 *g* over a 4-m track. The time to detect low step accelerations (0.001 to 0.08 *g*) increased slightly in variability after flight and showed some examples of long delays and direction errors, but presented no consistent trends in either threshold or the time to detection of linear acceleration (*25*). For closed-loop nulling of random disturbances in lateral acceleration on the sled,

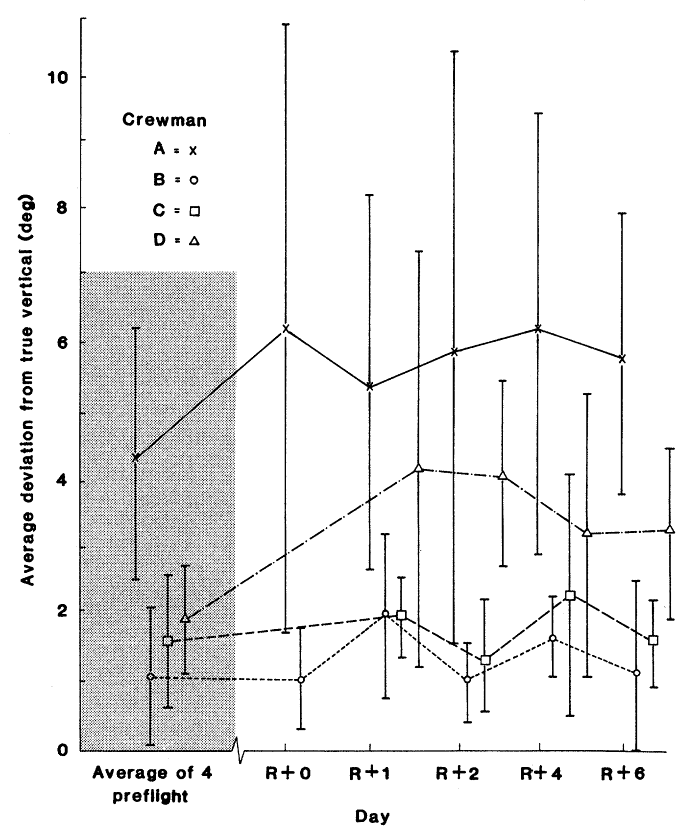


Fig. 3. Rod and frame measurements of field dependence, average absolute deviation, and standard deviations. Subject A also showed increased asymmetry in visual field dependence as well as in body tilt (*24*) after flight.

the two subjects who were tested on the evening of the return performed very accurately using only nonvisual cues. Their performance far exceeded that before flight and approached their accuracy for the task with full visual cues. This ability decayed gradually over the week of postflight testing. Dynamic ocular counterrolling, measured during lateral sinusoidal oscillation at 0.6 *g* (0.42 and 0.83 Hz), appeared to be reduced in gain on R + 0.

*Discussion*. The preliminary nature of these findings makes discussion necessarily speculative. Nevertheless, all of the major findings are consistent with the principal hypothesis: during adaptation to weightlessness the nervous system reinterprets signals from the graviceptors (primarily the otolith organs) to represent fore-aft or left-right linear acceleration, rather than pitch or roll of the head with respect to the vertical. Maintenance of this reinterpretation during the postflight period is maladaptive, resulting in postural instability with eyes closed, increased reliance on visual information for orientation, and improved ability to null lateral linear motion.

Independent refinement of the otolith reinterpretation hypothesis was proposed by Parker *et al*. (*26*) to explain their findings with STS-8 and STS-11 astronauts. Self-motion reports and eye reflexes during roll motion showed primarily linear translation and reduced ocular counterrolling after flight, relative to before launch. The adaptation is presumably not reflected at the more peripheral end organ responses or in fast reflex loops such as the otolith-spinal reflex. One consequence of the presumed linear acceleration sensor reinterpretation in flight is the increased use of local visual cues for spatial orientation and, at least early in the flight, increased attention to tactile and proprioceptive information on both body orientation and sense of body movement.

LAURENCE R. YOUNG
CHARLES M. OMAN
*Man-Vehicle Laboratory,*
*Massachusetts Institute of Technology,*
*Cambridge 02139*
DOUGLAS G. D. WATT
*Department of Physiology,*
*McGill University,*
*Montreal, Canada H3G 1Y6*
KENNETH E. MONEY
*Defense and Civil Institute of*
*Environmental Medicine, Downsview,*
*Ontario, Canada M3M 3B9*
BYRON K. LICHTENBERG
*Man-Vehicle Laboratory,*
*Massachusetts Institute of Technology*

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27. We gratefully acknowledge the outstanding cooperation of the Spacelab 1 science crew and support from NASA (NAS 9-15343), the Defense and Civil Institute of Environmental Medicine (Canada), and the Medical Research Council (Canada). We are grateful for the guidance and assistance of G. M. Jones, F. Guedry, A. Weiss, R. Donahue, and especially R. Clark and G. Salinas. We also thank W. Mayer, project manager, and the staff of the Laboratory for Space Experiments at the MIT Center for Space Research. A. Arrott directed the sled protocols and R. Renshaw coordinated the MIT activities in the Baseline Data Collection Facility (BDCF); S. Modestino ran the rails and the rod and frame tests, R. Kenyon the posture platform, and M. Shelhamer the rotating dome experiment. BDCF tests were performed 152, 122, 65, 44, and 10 days before flight, on the day of landing, and 1, 2, 4, and 6 days after return. Several eye movement experiments require further data processing and are not covered in this report. The horizontal vestibulo-ocular reflex was measured during angular oscillation, post rotatory-nystagmus and pitch down nystagmus dumping. Ocular torsion was recorded during eccentric *z*-axis sinusoidal angular oscillation performed at high and low frequencies.

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## Effects of Rectilinear Acceleration and Optokinetic and Caloric Stimulations in Space

Abstract. *During the flight of Spacelab 1 the crew performed a number of experiments to explore changes in vestibular function and visual-vestibular interactions on exposure to microgravity. Measurements were made on the threshold for detection of linear oscillation, vestibulo-ocular reflexes elicited by angular and linear movements, oculomotor and posture responses to optokinetic stimulations, and responses to caloric stimulation. Tests were also conducted on the ground, during the 4 months before and on days 1 to 6 after flight. The most significant result was that caloric nystagmus of the same direction as on the earth could also be evoked in the weightless environment.*

During the European vestibular experiments on the Spacelab 1 mission (experiment 1ES201) crew members performed experiments to explore the effects of exposure to microgravity on vestibular function and visual-vestibular interaction. Tests were also conducted on the ground during the 4 months before and on days 1 to 6 after the flight.

The flight hardware included the vestibular helmet and a collapsible seat and backrest, the body restraint system (BRS) in which the subject was secured by a harness in the yogi position. The helmet was equipped with electro-oculography (EOG) amplifiers and a CCD camera with infrared illumination (EMIR) in front of the right eye. The EMIR device allowed eye movements to be computed in real time for an *x-y*