Locomotion and Cargo Handling in Simulated Artificial Gravity

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Performance of selected tasks was evaluated experimentally during rotation at 3, 4, or 5 rpm. Test subjects were suspended in the artificial *g* vector while climbing ladders radially, and walking tangentially. The walking cargo-handling experiments were performed at radii of 20, 40, 60, and 70 ft, at *g* levels between 0.06 and 0.58. Radial transfer was also evaluated in an elevator between radii of 10 and 65 ft. The experimental conditions did not prove unduly stressful to the test subjects, and it is concluded that selection and indoctrination will enable the majority of men to comfortably live and perform in an artificial *g* environment. Restraints may be required on elevators in space to counteract lateral coriolis forces in the presence of diminishing artificial *g* forces. Ladder climbing was, subjectively, an acceptable mode of radial transfer. Tangential locomotion and cargo transport were reported to be better when walking in the pro-spin direction as compared to the anti-spin direction, due in part to the "flat floor" configuration. It was concluded that crew orientation did not seriously affect crew performance at radii of 40 ft or more. However, all performance was seriously degraded at a radius of 20 ft. Cargo handling was affected somewhat by the radial location, but more significantly, by the rotational rate.

Introduction

THE desirability of providing a more "Earth-like" environment in the living quarters of scientist-astronaut personnel on long duration space missions has resulted in a requirement to evaluate the impact of the rotating environment on crew performance and spacecraft design. It is recognized that the necessity or desirability of an artificial *g* environment will only be established after longer duration missions have been experienced in the weightless environment. However, in view of the fact that artificial *g* may be necessary, the effects of rotation must be determined so that mission planning and spacecraft development will not be delayed because of a lack of adequate design information.

There is a requirement for a critical analysis of the effects of the peculiar environment, as compared to the acceptable aspects of everyday living and working. In the artificial *g* environment, crew performance may be modified by the cross-coupled angular accelerations, coriolis forces, gravity gradients, variations in traction, rates of accommodation, and the susceptibility of the individual to oculo-vestibular stimuli. Human tolerance to these conditions will determine, in part, the acceptability or inadequacy of the habitability aspects of an artificial *g* vs the weightless environment. Some individuals contend that the advantages of weightlessness far outweigh the disadvantages inherent in restraint systems, lack of postural stability, and other manipulative problems associated with crew activities. On the basis of both in-flight and postflight results, certain representatives of the USSR strongly advocate the requirement for an artificial *g* environment for long duration space flights.[1,2]

Past studies have shown that the movement of man within a rotating environment result in stimulations of the vestibular, visual and proprioceptor systems, producing conflicting sensations relative to the immediate environment. The interaction of the environmental stimuli on these three sensory systems may produce symptoms of vertigo, disorientation, visual illusions, lassitude, postural abberations, or ultimately nausea.[3] The turning or nodding of the head in a rotating environment generates cross-coupled angular accelerations that induce motion of the fluid within the semicircular canals, not normally stimulated by such head movements in a stationary environment. This results in illusions of bodily or environmental motion.[4,5] The intensity and duration of the symptoms appear to be related to the vehicular rotation rate, head movement rate, and the tolerance threshold of the individuals to the vestibular stimuli. In addition to the angular stimulation of the semicircular canals, the otolith organs are subjected to coriolis forces, which are generated by linear movement within the rotating environment. The magnitude of the coriolis force is directly related to the angular velocity of the vehicle and the rate of linear motion of the individual or mass, either radially or tangentially relative to the direction of rotation. Linear axial motion (i.e., locomotion parallel to the axis of rotation) does not produce excessive coriolis forces or other disturbing stimuli.[6,7]

It has been predicted that the maximum stresses in the rotating vehicle will be encountered by individuals moving radially between areas of high-*g* forces and low *g*, or weightlessness, and back again, such as would be encountered in moving from the living area of the space base to the weightlessness laboratory and back. Although relatively few data existed with respect to the tolerance of man to locomotion within the rotating environment at long radii, it was hypothesized that the magnitude of the stresses might be minimized through techniques of configuration design, or crew operational procedures. In addition, the response might be modified through crew selection and indoctrination. On the basis of the forces generated by crew movement, the configuration of all equipment and aisles in an axial arrangement should reduce the number of crew motions that result in adverse effects.[6] However, since the programing of activities to eliminate all stressful stimuli is not practical, regardless of design configuration, the determination of the optimum design, development of crew operational procedures, and a better comprehension of the impact of the rotational environment on crew performance must be established. The program discussed herein was conducted to provide human performance

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data for the development of crew operational procedures and design criteria, with specific tasks designed to evaluate the differential effects of cross-coupled angular accelerations, coriolis forces, and g gradients on locomotion and cargo handling during artificial gravity simulation.

Approach

The artificial-g simulation tests were conducted on the Rotational Test Facility, which is composed of a control center, and a 160-ft-long rotating beam. The beam is 80-in. wide, protected along its length by 7-ft-high walls. The crew module, located at a mean radius of 75 ft, is 10 ft wide and 40 ft long. The floor automatically cants to provide a walking surface normal to the induced g vector. The Crew Module is equipped with a quick-opening hatch and a stairway to permit ingress and egress while the beam is in motion. The living area is comprised of four bunks, a head, shower, lavatory, kitchen-recreation area, and a test area. Adequate sewage, and potable water storage capacity is available to permit continuous testing with a crew of 4 men for 30 days, without resupply. The hollow bearing at the hub permits ingress and egress on to the facility while it is rotating.

An overhead trolley system has been installed 20 ft above the surface of the beam between two ladders, to permit orientation of the test subject in the artificial-g vector while supported in a sling system designed to reduce the effects of the Earth's g field. The ladders have been located 30 in. apart, and extend from approximately 10 ft to a radius of 65 ft. A chain-driven cart (elevator), adjustable for speeds up to 8 fps, has been installed between the ladders. At the opposite end of the beam, a moveable enclosure (walking room) is cantilevered from the trailing edge of the beam and may be positioned at radii of 20, 40, 60, or 70 ft. The walking room is equipped with a sling system similar to that utilized with the ladders. The walking surface is 15 ft long and permits the test subject to walk tangentially while facing either the prospin or antispin direction and while carrying cargo. Because of the cantilevered configuration, the artificial-g vector varies along the floor from the back-end of the room to the other end over the beam. The surfaces of the floor and wall are carpeted with 12-in. squares, permitting evaluations of locomotion with respect to body angle, stride length, etc. A cargo storage cabinet is located at the prospin end of the room, from which boxes can be removed from one bin, rotated, and placed in an alternate cubicle.

Test Protocol

Volunteer engineering personnel were screened to serve as test subjects on the basis of a successful completion of a FAA Class II equivalent medical examination and physical fitness test battery. Those individuals were then sent to the Naval Aerospace Medical Research Laboratories in Pensacola, Fla., for evaluation and calibration of the auditory, visual, proprioceptor, vestibular systems, and susceptibility to motion sickness.

Each test subject was randomly exposed to all of the experimental conditions for each of the tasks evaluated. This procedure was employed to reduce or eliminate individual differences as a source of error in the resultant data. The test subjects were arbitrarily assigned identifying letter symbols, which were applied to the helmets to facilitate individual identification during television monitoring and in film documentation. Individual logs of performance time subjective comments, debriefings, and other comments were maintained.

One-Day Tests

The 12 one day tests were performed at the rate of two per week, with alternate days used for data reduction, facility modification and maintenance. The tests were performed during rotation at 3, 4, and 5 rpm, with the walking room moved each week to radii of either 20, 40, 50, or 70 ft. Each test day was divided into five major periods. The first period of each day was utilized for facility preparation, test subject medical evaluation, and the collection of baseline performance data prior to facility spin-up. Three periods were radomized with respect to psychomotor and gross locomotion activities, with the final period of each test day allocated to administration of the postural equilibrium test battery immediately after cessation of rotation.

Three- and seven-day tests

The procedures for conducting the tests in the long-duration tests were basically similar to the one-day tests except that the walking room was located at the 40 ft radius and the rotational rate was maintained at 4 rpm. The test schedules were essentially the same as that for the one day tests. However, additional periods in the morning and evening were programed for toiletry, food preparation, and collection of physiological data.

Tangential locomotion

These tests were performed while the test subjects were positioned in the sling system to align the individual longitudinally with respect to the radial g vector. The purpose of this system was to reduce the effect of the normal Earth g vector while the test subjects walked tangentially on a vertical floor (wall). All tests were accomplished by two-man teams, with each test subject assisting the alternate into and out of the sling system, activating the movie camera, and recording time of performance. The test subjects performed ten traversals of the vertically oriented walking surface per session; i.e., five in the prospin and five in the antispin direction. The test subject was required to back-up or be assisted back to the starting position each time between traversals. The test was self-paced and the measure of performance was time required for each traversal, and subjective comments. Motion pictures were obtained for selected traversals during each day.

Tangential cargo transport

This test was performed in conjunction with, and under the same conditions as described for the tangential locomotion tests. The cargo package was a 1-ft cube weighing 32 lb, suspended by a separate sling system. The test subject carried the package during two traversals of the walking surface, facing both the prospin and antispin directions. He also evaluated the effect of setting down and picking up the package twice and continuing the walk during each of two traversals in each direction. Performance was evaluated as described for tangential locomotion.

Cargo handling

This test was performed with the test subject suspended in the sling system as described for tangential locomotion, except that it was evaluated while facing the prospin direction only. The test procedure consisted in the removal of four, free floating, 1-ft cubes, weighing about 5 lb each, from receptacles in an eight-chambered cabinet, rotation of the cubes about two axes, and reinsertion of the cubes into the receptacle at a higher level, and then reverse the procedure. This task was repeated four times in each direction. The test was self-paced, and the measure of performance was time required for accomplishment of two cycles.

Radial locomotion (ladder climbing)

The test subjects were suspended in the horizontal position and alternately ascended and descended either of two radially-oriented ladders, facing either in the prospin or the antispin direction. Two ascent-descent cycles were performed in each of the two orientations each day. The test was repeated four times at each of the three rotation rates during the one-day test series. The rate of traversal was self-paced, and the measure of performance was time required for each traversal. Motion pictures were obtained for selected ascent-descent cycles. Additionally, during the seven-day test, a rope was stretched between the ladders and evaluated for potential use as a radial ascent-descent mode. The test subject moved hand-over-hand along the rope facing alternately pro- and antispin directions. Subjective comments were recorded.

Passive radial transfer (elevator)

The test subjects passively rode in a powered cart, while lying in the radial g vector. Each individual was exposed to two ascent-descent cycles while facing either the prospin, the antispin, or axial (facing upward) directions, with the cart traveling at linear rates of 2, 4, or 6 fps, during exposure to 3, 4, and 5 rpm rotational rates. No performance measurements, other than subjective comments, were available for this test.

Results

The final test subject pool was comprised of seven men between the ages of 31 and 49. These individuals were found to be clinically normal in all respects. The motion sickness evaluations revealed the following individual responses: 1 "average," 3 "low average," and 2 "far below average" in susceptibility.

Tangential Locomotion

Tangential walking and cargo transfer experiments were performed in the walking room to evaluate the fundamental factors of the environment, that may effect performance. These factors are the g level, the coriolis forces and cross-coupled angular accelerations, due to the movement of the individual relative to the rotating environment. Criteria were previously established to estimate the relative effect of these factors on the performance of man in the artificial g. These criteria were based on a knowledge of the physical characteristics of the rotational environment and of objects moving therein. The criteria for tangential walking have been reproduced in Fig. 1, with the measurements performed in this study superimposed as symbols. There are four criteria presented in the figure. The upper curve represents a condition, below which, when walking at 3 fps, 1.0 g would not be exceeded. The value of the next curve is identified as a leg heaviness criterion. During walking, as each foot starts and stops, and with each contact with the floor, the leg and foot have peak velocities relative to the floor that approach twice the walking speed. Because of this, the coriolis forces acting on the foot and leg are proportionally much greater than on the body as a whole. Thus, the legs experience a larger effective artificial-g force than the body. The criterion shown represents a rate below which the legs and feet will not exceed 1 g as the body moves at 3 fps. As discussed in greater detail in Ref. 8, such leg heaviness has been experienced in previous simulations. The 0.1 g criterion shown in the figure is one above which, when walking at 3 fps the artificial weight will not be less than 0.1 g. This was felt to be a minimum g level to provide adequate traction for walking. The last criterion is one above which the apparent change in weight (ΔW) due to walking will not exceed 0.5 of the nominal weight (W) produced by the artificial g force. This ratio ($\Delta W/W$) is the change in weight due to walking in the rotating environment. Some investigators have stated that this ratio should not exceed 0.25 (Ref. 8). The test subject comments and data obtained during the current tests of tangential locomotion indicate a general concurrence with the lower criteria, in that traction was clearly a problem at the shorter radii and during lower rates of rotation. The values of the upper criteria were not reached during the current program.

The variations in the tangential walking rates selected by the test subjects with respect to radius, orientation, and rotational rate are presented in Table 1. An analysis of variance and Newman-Kuels analysis[9] showed that the progressive increase in walking rate with respect to increasing radius was significant at the 0.01 level, while the improvement with respect to increasing rotational rate was significant at the 0.05 level. A similar response was observed during the transport of the 1 slug mass as shown in Table 2. The improved performance at the 20 ft radius was related to slightly improved traction due to the cargo mass and to greater initial acceleration due to the increased inertia produced by "pushing" the block in front of the body when starting the walk. It was assumed that the increased rates were related to increased traction, and consequently, bodily control. In that there were no significant differences in rates with or without cargo, except at the 20 ft radius, a scattergram of the rates as affected by the artificial-g level is presented in Fig. 2. It may be seen that a biphasic curve resulted. Walking rates above 0.3 g are affected more by other factors than increased g. However, the best performance, based on walking rate, occurred at 4 rpm and 70 ft radius ($g = 0.37$) both with and without cargo. There is no readily available explanation for this fact except for the lack of excessive vestibular stimulation and adequate traction and bodily control. Several additional factors influenced the walking rates, including the requirement to start and stop within a 15 ft area, as well as the influence of the flat floors. The flat floors result in varying radii, increasing from the center to the

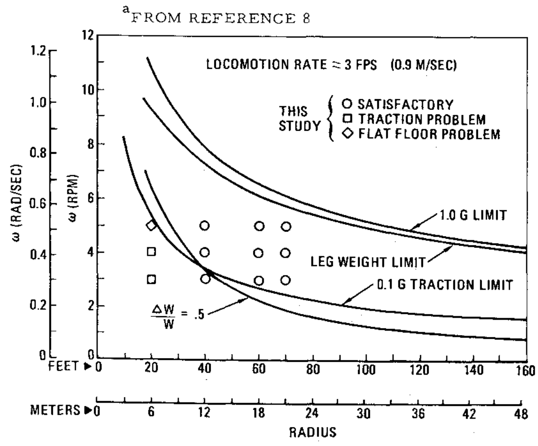

Fig. 1 Predicted boundaries for acceptable tangential locomotion in artificial gravity.

Table 1 Variations in walking rate relative to radius, orientation, and rotational rate

Radius	meters		6.1	12.2[b]	183[b]	21.3[b]
	ft		20.0	40.0	60.0	70.0
3 rpm	Prospin	m/sec	0.30	0.49	0.61	0.67
		fps	1.00	1.60	2.00	2.20
	Antispin	m/sec	0.34	0.52	0.58	0.73
		fps	1.10	1.70	1.90	2.40
4 rpm[a]	Prospin	m/sec	0.46	0.70	0.70	0.88
		fps	1.50	2.30	2.30	2.90
	Antispin	m/sec	0.37	0.70	0.76	0.91
		fps	1.20	2.30	2.50	3.00
5 rpm[a]	Prospin	m/sec	0.52	0.73	0.79	0.85
		fps	1.70	2.40	2.60	2.80
	Antispin	m/sec	0.46	0.73	0.79	0.79
		fps	1.50	2.40	2.60	2.60

[a] Significant at < 0.05.
[b] Significant at < 0.01.

Table 2 Variations in walking rate, with cargo, relative to radius, orientation, and rotational rate

Radius		meters	6.1	12.2[a]	18.3[b]	21.3[b]
		ft	20.0	40.0	60.0	70.0
3 rpm	Prospin	m/sec	0.42	0.49	0.64	0.73
		fps	1.40	1.60	2.10	2.40
	Antispin	m/sec	0.40	0.40	0.55	0.64
		fps	1.30	1.30	1.80	2.10
4 rpm[a]	Prospin	m/sec	0.52	0.67	0.76	1.01
		fps	1.70	2.20	2.50	3.30
	Antispin	m/sec	0.42	0.61	0.79	0.85
		fps	1.40	2.00	2.60	2.80
5 rpm[a]	Prospin	m/sec	0.64	0.79	0.79	0.82
		fps	2.10	2.60	2.60	2.70
	Antispin	m/sec	0.42	0.76	0.73	0.82
		fps	1.40	2.50	2.40	2.70

[a] Significant at < 0.05.
[b] Significant at < 0.01.

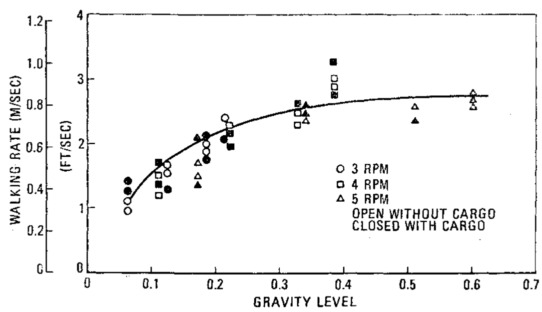

Fig. 2 Variations in tangential walking rate relative to artificial-g level, with and without cargo.

end of the room. This effectively indicates an inclination of the local artificial-g vector relative to the floor, requiring the subjects to lean toward the center of the room to maintain static equilibrium. This effect is greatest at the smallest radius and causes unnatural leaning to initiate walking, further degrading the performance at short radii. Also, of course, walking toward the center of the room represents climbing a slope of varying inclination, whereas walking away from the center represents walking down a slope, requiring more effort and more energy than walking on a level surface. Since the values presented represent an average value for the complete traversal of the room, they should not be interpreted as instantaneous rates under less confined conditions. It was of interest that walking was possible at artificial-g levels as low as 0.06 g. However, starting and stopping on the flat floor configuration was exceedingly difficult and unstable.

The results of walking with and without cargo during the 3- and 7-day test at a 40 ft radius and 4 rpm showed an adaptive effect. There was a significant ($p = 0.05$) improvement in performance between the first day as compared to the remaining test days. This apparent adaptative effect as measured in time of performance agreed with the improving subjective feelings as reported by the crew with time. Also, the results are in essential agreement with the adaptive response of test subjects reported in earlier simulations.[10]

Cargo Handling

The data obtained during free-floating cargo handling tests did not show a marked difference in the time required to perform the test with the size of cargo used in this program (Table 3). The Newman-Kuels analysis indicated that the difference in time of performance at the 5 rpm rate was significant at the 0.05 level when compared to the 3 and 4 rpm rates.

Table 3 Rate of handling cargo relative to radius and rotational rate

Radius	Feet	20	40	60	70
3 rpm	Seconds	75.2	73.1	55.8	74.6
4 rpm	Seconds	63.8	61.3	61.5	77.1
5 rpm	Seconds	56.4	65.7	65.1	53.1

[a] Significant at < 0.05.

The lack of improvement in performance as a result of increasing g with increasing radius cannot be explained at this time. The great variation in individual scores may indicate a basic inadequacy with the procedure. However, the stability of the subject in performing a task is a function of the traction available to him at the particular g level. At three rpm, at 20 and 40 ft radii, and again at four rpm at the 20 ft radius, each subject had the tendency to leave the floor, thereby requiring more energy expenditure for completing the test in a time reasonably close to tests performed at greater g levels. It can be said, however, that manipulation of cargo of the size studied can be accomplished at these lower g levels with a mild degree of inconvenience. All subjects reported experiencing the effects of cross-coupled angular acceleration on the cargo elements, when the elements were rotated, especially at the higher rates of rotation. These effects were of little concern for the size of cargo used in these experiments; however, handling of heavier cargo packages may present problems in this respect. The impact of adaptation was demonstrated by a significant decrease in performance time from a mean of 60 sec on the first day to a mean of 55 sec through the remainder of the test period during the 3- and 7-day evaluations.

Ladder Climbing

The values for radial locomotion on the ladder are presented in Table 4. The mean locomotion rate for traversing the foot ladders was approximately 2.7 fps with a slight advantage of descent in comparison to ascent. There was no significant difference in orientation nor time of day on performance. The "time" measurements were determined to be secondary to the subjective data, which may well provide insight to the operational and design problems associated with ladders in a rotating space vehicle. The following is a summary of the subjective comments relative to the ladder-climbing studies.

1) At 3 rpm the artificial-g forces were not sufficient to warrant the use of feet on the ladder rungs from a radius of 10 ft (0.03 g to approximately 30 ft (0.09 g). The use of the ladder required additional efforts by the test subject to accomplish foot placement in these low-force fields. Therefore, it was felt that the requirement for rungs at low-g forces may be superfluous, except for maintaining body position. Between 30 ft and 65 ft radii (0.09–0.19 g), the forces were of

Table 4. Rate of ladder climbing relative to orientation and rotational rate

Rate	Orientation		Descent	Ascent
3 rpm	Pro	m/sec	0.76	0.91
		fps	2.50	3.00
	Anti	m/sec	0.76	0.98
		fps	2.50	3.20
4 rpm	Pro	m/sec	0.76	0.88
		fps	2.50	2.90
	Anti	m/sec	0.76	0.79
		fps	2.50	2.60
5 rpm	Pro	m/sec	0.82	0.79
		fps	2.70	2.60
	Anti	m/sec	0.82	0.79
		fps	2.70	2.60

sufficient magnitude to warrant use of the rungs for locomotion.

2) Any difficulty experienced in transfer along the ladder appeared primarily attributable to the constantly changing magnitude of the artificial g force vector. The subjects postulated that climbing effort would be reduced significantly by progressive spacing of the ladder rungs; i.e., greater spacing close to the center of rotation on low-g levels, and closer spacing as the g forces increase.

3) Transfer along the entire length of the ladder at 4 rpm (0.05–0.34 g) was reported to be the most acceptable of the three rotational rates studied. Although the transition, relative to centrifugal force change, at the 25–30 ft radius was still noticeable, the various forces were not considered uncomfortable at any radius. Although the forces at radii of less than 30 ft were minimal, foot placement and over-all stability could be maintained without excessive effort.

4) At 5 rpm the rungs were necessary for traversing the full length of the ladder. The forces were considered to be comfortable from 10 ft to 30 ft radius (0.08–0.25 g), but "more work" was required for traversing the ladder at radii greater than 30 ft (0.25–0.55 g).

5) No performance could be established relative to orientation, i.e., facing prospin or antispin, but it was the concensus of opinion that a ladder would serve as an acceptable method for radial transfer.

6) Radial locomotion evaluated by means of a rope suspended between ladders during the seven-day test was found to be unacceptable. The coriolis forces tended to produce torque on the suspended test subject, making climbing difficult and subjectively hazardous. The climb at the higher simulated artificial-g levels made rope climbing similar to that experienced in a normal Earth environment, being deemed too difficult and uncomfortable.

Elevator

The subjective comments of the test personnel produced a consensus opinion that the elevator provided the best mode of transfer between levels of different radii. The test subjects reported that the body motions induced by coriolis and centrifugal forces were not at all uncomfortable with respect to vestibular stimulation during the traverse. It was noted, however, that for elevator speeds of greater than 6 fps, it will be necessary to place handholds or other restraints on the elevator walls to insure personnel stability and safety while riding at the lower g levels, wherein the lateral coriolis exceed the artificial-g forces.

Conclusions

This test program was designed to survey a number of parameters in an effort to develop reliable criteria relative to the capability of man to perform gross and fine motor tasks within the rotating environment. A large number of development areas were observed that will inquire additional work to determine the ultimate or potential impact on vehicle design wherein artificial g is to be provided. The work discussed herein has been limited to the evaluation of locomotion. Although this study was not designed to answer the question of whether artificial g is more desirable than weightlessness, all test subjects were able to function in the rotational environment with a high degree of proficiency, demonstrating good morale and cooperation, without incurring a significant degree of performance degradation due to motion sickness. Some symptomology was experienced in the early phases of the 1-day and 7-day tests, described by the test subjects as the "blahs," which included reports from mild fatigue to slight stomach awareness. The great concern for the potential of recurring nausea resulted in great care in both subject selection and task design. The lack of significant motion sickness in the test population during the first few tests permitted the inclusion of more provocative tasks coupled with scheduled head movements. Although the total reactions of the test subjects varied, in many instances, the performance of head movements, rather than degrading perception and performance, frequently resulted in increased rates of accommodation and improved over-all task performance. This effect would be modified significantly at relatively high-g forces or rotational rates. The subjective opinions of whether individual performances were good or bad was borne out by much of the objective data.

It was demonstrated that both radial and tangential locomotion can be readily accomplished at rotational rates of 3, 4, and 5 rpm during artificial-g simulations. Although the evaluations at the shorter radii in this study fall outside of the predicted values for acceptable performance,[8] the tasks could be accomplished in the lower forces fields at reduced rates. The performance of tangential locomotion and cargo transport could be accomplished with relative ease at the 40, 60, and 70 ft radii even on the flat floor configuration. However, at the 20 and 40 ft radii and 3 rpm, bodily control was somewhat difficult while walking in the antispin direction, especially with respect to stopping before contacting the rear wall, due to the lack of traction and the "tilted" floor effect caused by the difference in radius.

Radial locomotion was readily accomplished without eliciting motion sickness symptoms, utilizing either a ladder system or an elevator. There was no strong preference for facing either the prospin or antispin direction during ascent or descent. However, the utilization of the rope as a means of ascent or descent was considered to be excessively difficult and potentially dangerous.

It is concluded, on basis of the results of this study, that a program of crew selection and indoctrination will permit men to perform with a high degree of competence in the artificial-g environment. There was a strong indication in this study that exposure of men to a number of short 1-day exposures enhanced the rate of acclimation to the continuous exposures of 3–7 days.

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