Large Excursion Rotary Tracking of Target and Target Light in a Space Station Simulator Revolving at 7.5, 10.0 and 12.0 RPM

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Twenty-four professional engineers, sedentarily employed, volunteered as test subjects to perform a rotary tracking test within a space station simulator revolving at 7.5, 10.0 or 12.0 RPM and aligned with the inertial resultant.

Pretrained to asymptotic performance, they could be considered a select group only as to intelligence, motivation and histories of low motion sickness susceptibility. Exclusion of data on 11 of the subjects due to illness increased the selectivity of the results. It may be assumed, however, that the personal qualifications of a prospective astronaut for a similar task would be considerably greater.

All RPM's showed minimal decrement, with rapid adaptation, following Spinup and Spindown of the simulator. Performance at 10.0 RPM was significantly better than at the other two RPM's.

This observed perceptual-motor ability, within a test format designed to elicit untoward Coriolis effects, suggests that satisfactory hand-eye coordinations can be performed in space vehicles rotating at velocities substantially above the tentative 4 RPM ceiling.

RELIABLE PREDICTIONS of the effects of long exposures to zero gravity cannot be made at present. Ground simulations are bound by unavoidable artifacts. Clinical data from confinement asthenias relate only speculatively to the consideration of weightlessness. Actual exposures, in air- and spacecraft, have been of limited duration and number. Estimates of the biological effects of two or more weeks of such existence continue to appear in the professional literature. Predictions range from decubitoid asthenia[1-3] to inertial release phenomena of salutary quality.[4-6] The question can only be resolved empirically. Prior to that space vehicles designed for protracted missions will possess a rotogravity (artificial gravity produced by rotation of vehicle or vehicular module) capability. This capability will be used as a biological necessity, a performance desideratum or a precautionary backup. The following work and associated studies[7-9] assume such an inertial design in the future generation of space vehicles.

Vehicular rotation introduces certain unique problems that also require preflight evaluation. Movements of head, hands or other body parts relative to the vehicle spin axis produce varying degrees of untoward effects that have been generally termed Coriolis phenomena.[10] Their nature and magnitude in human subjects have been studied in a variety of test environments including functional aircraft,[11,12] human centrifuges,[13,14] modified Barany chairs,[15,16] and the USN "Slow Rotation Room" at Pensacola.[17-19] None of these were intended nor could be interpreted as revolving space station simulators, making extrapolation of their data to the applied situation correspondingly difficult. It is submitted that a test room revolving on a centrifuge arm and free to align itself with the inertial resultant of gravity and centrifugal acceleration does form a reasonable simulation of a revolving space station. Such a device was used in this study.

To evaluate performance decrement within this environment a perceptual-motor test was chosen. This form of psychophysiological evaluation is particularly sensitive to an altered force field. An individual's ability to position a limb, to orient himself or parts of himself, to manipulate tools or to perform piloting tasks are dependent on vestibular and kinesthetic cues.[20] Perceptual-motor tests have been used in the Vostok[21] and Mercury[22] programs for this reason.

A form of perceptual-motor test widely used by experimental psychologists is the rotary tracking test.[23] A number of instrumental variations are and have been used but most utilized is that introduced by Koerth.[24] This consists of a small brass target near the edge of a revolving turntable, the subject being scored on the amount of time he can keep his stylus in contact as the target revolves. This form of test apparatus was used in this study as the apparatus variables which influence rotary tracking behaviour have been explicitly stated[25] and explored[26] and the apparatus could be sized to force major excursions of head and hand and reflect their reaction with the environment in the quantitative effect upon the tracking performance of practised subjects.

The results of this study suggest that the tested form of perceptual-motor performance is refractory to rotogravic decrement, that subjects show rapid adaptation to abrupt and major force field changes and that the tentative angular velocity ceilings of 4 RPM[27] or lower[28] may be too conservative.

PROCEDURE

Subjects. The test sample consisted of 24 volunteers from the professional engineers employed by astronautics. They were Caucasoid males of 37±4.6 years of age and height 5′ 10±3.1″. The total sample was randomly divided into six groups of four subjects each and the six groups randomly assigned to fill the three 7.5 RPM, two 10.0 RPM and one 12.0 RPM test positions. All subjects were trained daily on the tracking apparatus, with the test simulator static, for two weeks prior to their day of experimental performance. This training brought their tracking ability to well-defined

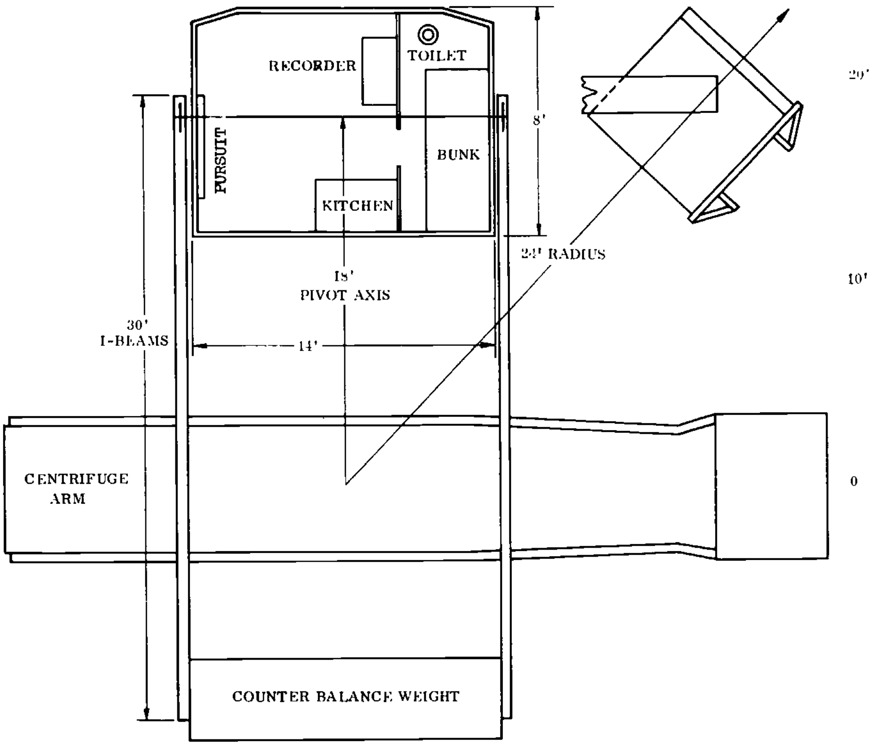

Fig. 1. MRSSS test complex.

and consistent plateaus of performance.

Before being exposed to the environment of the dynamic test simulator the subjects were required to pass an airman's third class medical examination. None of the subjects had histories of undue susceptibility to kinetoses.

No special instructions were given to the subjects regarding diet or rest preceding their day of experimental performance and they were allowed to eat and drink when and what they chose during the test.

Apparatus. The revolving space station simulator constructed for this and future studies consists of a 14′ x 7′ x 8′ room mounted by trunnions on the end of an 18′ centrifuge arm. Figure 1 is a drawing and Figures 2 and 3 are photographs of the simulator complex. Figure 4 represents the interior arrangement of the test room. The interior walls are insulated and covered with ½″ acoustical tile. A plywood bulkhead 5′ from one end of the room divides it into two compartments, with an interconnecting door. Both compartments are light-tight for testing that may require this accommodation and are provided with running water and drainage facilities. The smaller compartment is provided with a toilet and two double bunks. The larger compartment contains tables, chairs, cupboard space, freezer and food-preparation and washing facilities. The room will accommodate six adults and allow the running of two or more tests simultaneously. Monitoring facilities include an onboard polygraph and hardware, FM telemetry and closed-circuit TV communication with the outside. Air-conditioning maintains temperature and humidity within desired comfort limits.

Fig. 4 shows the position of the rotary tracking appa-

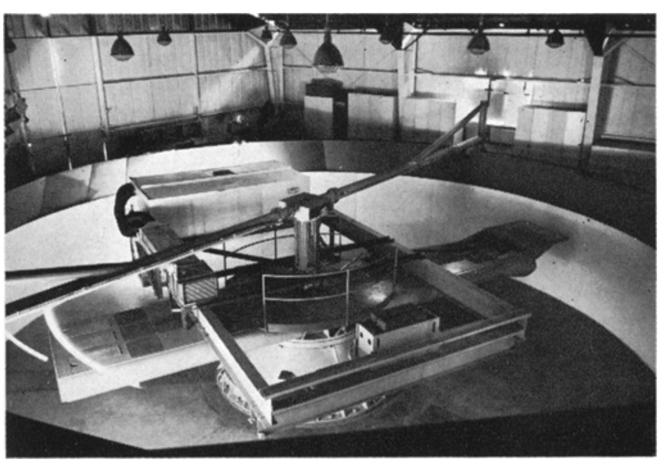

Fig. 2. MRSSS test complex.

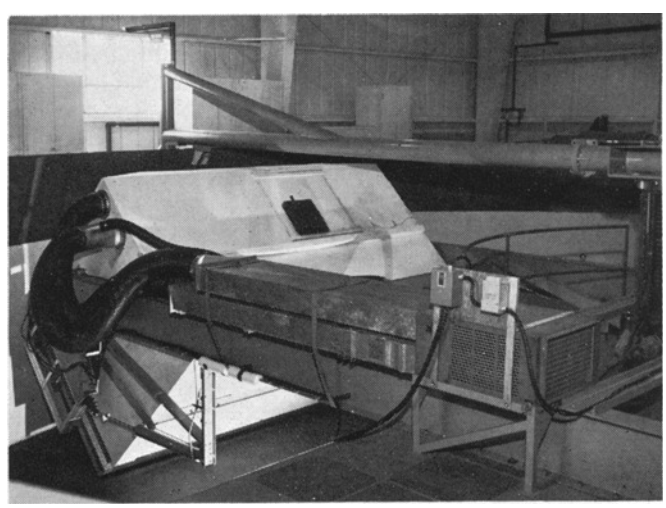

Fig. 3. MRSSS at 12 rpm (inclination = 44°).

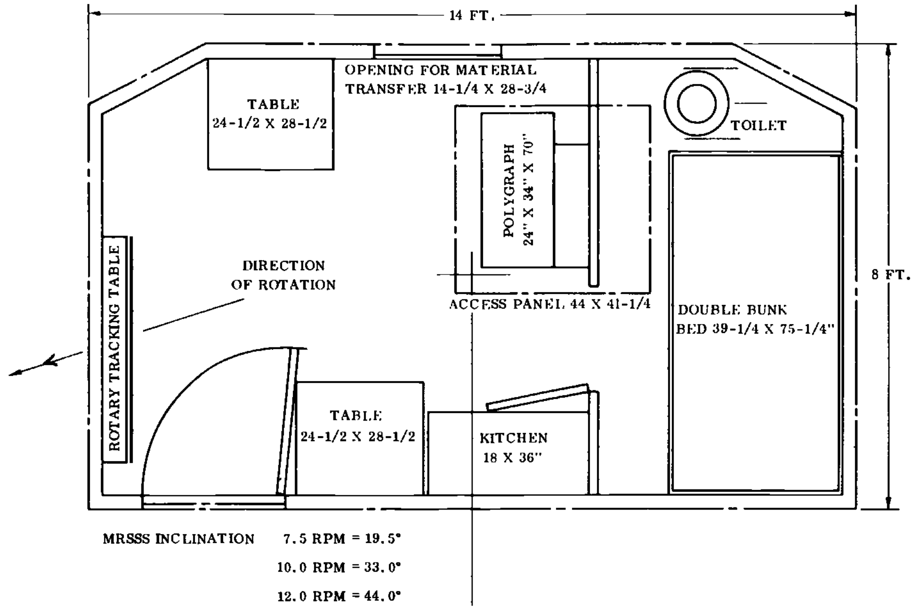

Fig. 4. MRSSS interior arrangement.

ratus in the larger compartment. It consists of a target turntable, tracking stylus and scoring clocks.

The plywood turntable is 1.15 meter in diameter and mounted on a wood base (Figure 5). It is driven by a variable speed Globe 28-volt DC motor. For this study the turntable speed was maintained at a constant 28 RPM. Set flush in the turntable's surface and 70 mm. from its periphery is a 92 mm. diameter copper target (Figure 6). The target is divided into an 18.4 mm. diameter bullseye and four 8.6 mm. wide concentric rings by four 0.6 mm. wide rings of phenolic resin. The target contains a 0.5 watt light source which may be switched on and off by the test conductor. The light is transmitted by the rings of phenolic resin, producing a non-glare outline of the target rings but leaving adjacent areas unilluminated. The turntable was mounted against the leading (in direction of room rotation) bulkhead of the larger compartment, its center 55½" from the deck or approximately three inches below the average subject's shoulder level.

The stylus (Figure 7) consists of a wooden handle 14 cm. long and 2 cm. in diameter to which is attached

Fig. 5. Subject tracking target.

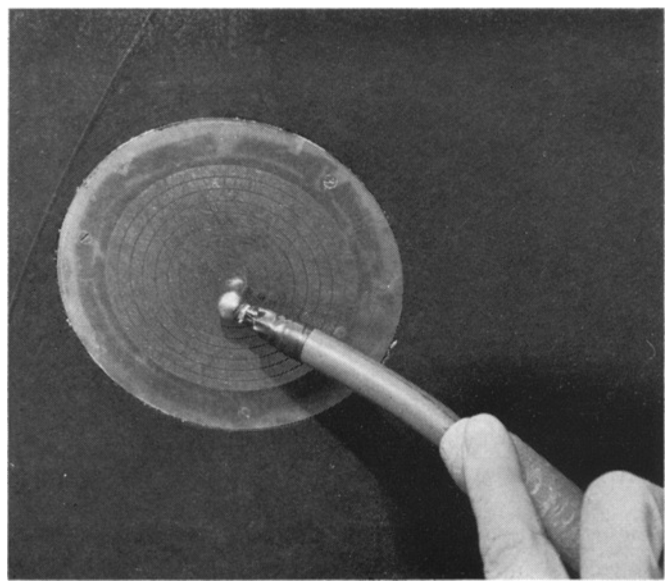

Fig. 6. Stylus on target.

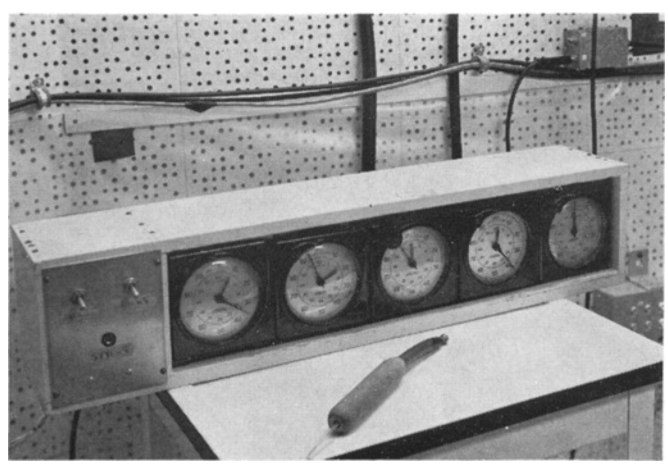

Fig. 7. Stylus and scoring clocks.

a rubber shaft 9 cm. long and 1.2 cm. in diameter. The stylus is tipped with a 1 cm. diameter stainless steel ball, whose electrical lead passes through the hollow cores of the shaft and handle. The elastic quality of the shaft allows definitive direction of the tip but collapses under pressure to prevent "locking in" of target by the subject. When tracking the stylus provides a 10 to 11 cm. extension from the subject's hand to the target. The stylus weighs 100 grams.

Five Standard Electric chronometers are used as scoring clocks (Fig. 7). Each clock is connected to the stylus lead and to one of the five scoring areas on the copper target. Clock #1 registers time on bullseye, Clock #2 registers time on the adjacent target circle and so on to Clock #5 and time on the outermost circle of the target. Touching of the stylus tip to any of the five areas actuates its respective clock. Clock totals at the end of a tracking trial provide data for calculating *Total Time on Target, Total Time on Bullseye* and *Average Distance of Stylus Tip From Target Center.*

Experimental Design. The subjects were tested in groups of four, one day for each group. A day's program started with pre-test physical examinations and the donning of nylon flight suits and rubber-soled shoes. Subjects were then conducted to the MRSSS where they were tested with the simulator stationary *(Prespinup Testing).* Following spinup of the simulator to the required RPM at the rate of 0.2 radians/sec.,[2] the subjects were tested a second time *(Postspinup Testing).* Near the end of four hours of continuous rotation at the selected RPM the subjects were tested a third time *(Prespindown Testing).* A fourth and final testing *(Postspindown Testing)* was done immediately following spindown to stop. Table I shows the trials making up each testing sequence and their chronological order. For each phase of testing each subject performed six 30-second tracking trials, three with the room light on and the target light off and three with the room light off and the target light on, each of the former always succeeded by one of the latter.

The experiment was designed to provide the following information:

Pre-spinup Testing: a baseline static performance for comparison with subsequent stressed testing. In all subjects baseline performances correlated with previous training plateaus.

Post-spinup Testing: performance before any significant adaptation to the altered inertial field could take place. Particular attention to be directed to initial decrements and any adaptation during this first rotational test sequence.

Pre-spindown Testing: with approximately 3½ hours having elapsed since the previous testing, evidence of additional adaptation (improved performance) and tracking data for comparison with post-spindown testing.

Post-spindown Testing: evidence of decrement due to retention of rotational adaptation into postrotational period. Rapidity of readaptation to static environment.

Alternation of each trial tracking conventional target in lighted room with a trial tracking lighted target in dark room was designed to potentiate any oculovestibular disorientation, and consequent performance decrement, that might occur from cross-coupled accelerations produced by head rotation within the revolving test room. Comparison of decrements for both test modes would then suggest relative inputs from perceptual and motor Coriolis effects.

To limit distraction while tracking a subject donned sound-dampening muffs. He then took a standing position twenty inches from the vertical plane of the turntable, stylus in hand and feet comfortably apart. He began to track the target bullseye the moment the turntable started rotating and continued until it stopped. He was allowed to rotate his body and head but not flex his knees or hips or move his feet. Complete freedom of head, eyes and arms was allowed.

The test conductor started scoring five seconds after the beginning of the turntable rotation, allowing the subject that much time to get on target. The turntable was stopped after the 30-second scoring period ended.

TABLE I. MRSSS ROTARY TRACKING TEST TRACKING SEQUENCE

TARGET SPEED = 28 RPM
▣ ROOM LIGHT, TARGET DARK
◘ ROOM DARK, TARGET LIGHT

MRSSS:	STATIC			4 HR. ROTATION (7.5, 10.0 OR 12.0 RPM)			STATIC
TESTING:	PRESPINUP			POSTSPINUP		PRESPINDOWN	POSTSPINDOWN
	SUBJECT	TARGET	DURATION				
	A	▣	30 SEC.	REPEAT		REPEAT	REPEAT
	A	REST	10 SEC.				
	A	◘	30 SEC.				
	B	▣	30 SEC.				
	B	REST	10 SEC.				
	B	◘	30 SEC.				
	A	REPEAT ABOVE					
	B	REPEAT ABOVE					
	A	REPEAT ABOVE					
	B	REPEAT ABOVE					
	C & D	REPEAT A & B'S SEQUENCE					

TABLE II. MRSSS ROTARY TRACKING TEST: 7.5—10.0—12.0 RPM

Trial	Room Light On: Target Light Off														
	7.5 RPM (N=5)					10.0 RPM (N=4)					12.0 RPM (N=4)				
	TOB		TOT		STTTC	TOB		TOT		STTTC	TOB		TOT		STTTC
	X	SD	X	SD	X	X	SD	X	SD	X	X	SD	X	SD	X
1	20.8	2.6	29.0	1.3	7.7	21.7	1.4	28.5	0	6.7	23.8	2.7	28.7	2.2	6.3
2	21.8	2.7	29.4	1.6	7.3	20.5	4.7	29.2	2	7.5	23.3	1.1	28.3	0	6.4
3	22.0	1.7	29.2	1.8	7.2	22.5	2.5	29.0	2	6.8	23.3	1.9	28.8	0	6.5
4	16.4	1.7	27.2	1.7	10.1	18.0	3.6	28.5	1.7	8.3	15.5	3.1	26.3	0	9.5
5	16.8	3.0	27.4	1.5	8.6	19.2	4.5	28.2	2.2	7.7	17.3	3.7	27.2	2.5	8.8
6	21.0	3.2	28.4	1.1	7.4	22.2	2	28.0	1.7	6.6	21.5	3.4	28.5	1.2	7.1
7	19.0	3.1	28.2	1.9	8.0	20.7	2	28.7	2.2	7.4	21.8	1.6	28.3	0	6.7
8	19.6	3.3	28.4	2.3	7.3	21.8	1.4	28.2	2.4	6.9	22.0	2.7	28.2	2.6	6.8
9	21.0	2.6	28.6	2.0	7.4	23.2	1.7	28.7	2.2	6.4	22.2	3.5	28.0	6.6	6.6
10	21.2	3.4	28.4	0.9	7.3	21.2	2	29.0	1.4	7.2	20.5	3.3	28.3	0	7.2
11	22.2	4.6	29.2	1.6	7.0	21.3	2.2	28.5	1.4	7.1	23.0	2.5	29.3	0	6.5
12	24.2	4.1	29.4	1.7	6.5	22.3	0	29.0	1	6.8	24.0	3.2	29.3	0	6.5

Legend: Trials 1 through 3 are PreSpinUp
Trials 4 through 6 are PostSpinUp
Trials 7 through 9 are PreSpinDown
Trials 10 through 12 are PostSpinDown

TOB = time on bullseye, in seconds
TOT = time on total target, in seconds
STTTC = mean distance from stylus tip to target center, in mm.

If a subject became too ill to take his regular turn he was excused from that test sequence, the remaining subjects being tested on schedule. If the skipped subject and the medical monitor felt he was capable of being tested during the next sequence he took his regular turn. His data, however, were not included with those of the subjects completing all trials.

During the time the subjects were not being tested they were encouraged to be active and move about the test room. They could eat, drink, throw darts, converse, read or relax at will.

RESULTS

Of the 24 subjects 11 missed one or more *in rotation* test trials due to illness. The distribution of illness was:

RPM	N(Initial)	N(Ill)	N(Final)
7.5	12	7	5
10.0	8	4	4
12.0	4	0	4

N = number of subjects

Two subjects, one at 7.5 and one at 10.0 RPM, missed only *Pre-spindown* trials. The other nine subjects missed both *Post-spinup* and *Pre-spindown* trials. Illness in all cases included one or more episodes of vomiting. Usable data for 13 subjects remained.

Three tracking parameters were determined for each RPM: TOB (Total Time on Bullseye), TOT (Total Time on Target) and STTTC (mean distance of Stylus Tip to Target Center). Table II contains the mean values and standard deviations of these parameters for usable data collected at each RPM for trials with the room light on and the target light off. Table III contains the same data for trials with the room light off and the target light on.

Figures 8, 9, 10 and 11 present graphically the mean values of these parameters as a function of test trial.

Inspection of tabulated and graphed data reveals an expected decrement in performance following spinup and spindown. Rapid adaptation appears to occur, however, and in one to three trials maximum tracking efficiency is regained. For all parameters decrement at 10.0 RPM appears to be at least and more rapidly compensated for. Tracking performance with room light out and target light on is lower for all trials than with the room light on. Decrement for tracking of target light, however, appears to be not significantly

TABLE III. MRSSS ROTARY TRACKING TEST: 7.5—10.0—12.0 RPM

Trial	Room Light Off: Target Light On														
	7.5 RPM (N=5)					10.0 RPM (N=4)					12.0 RPM (N=4)				
	TOB		TOT		STTTC	TOB		TOT		STTTC	TOB		TOT		STTTC
	X	SD	X	SD	X	X	SD	X	SD	X	X	SD	X	SD	X
1	16.0	2.8	27.6	1.8	9.0	14.5	2.5	27.8	0	9.6	18.0	3.0	28.3	0	8.4
2	15.2	3.6	27.2	2.2	9.2	15.5	2.3	28.8	0	9.3	18.8	3.2	27.8	0	7.9
3	14.6	2.8	27.4	1.2	9.5	17.5	3.5	28.3	1.3	8.4	17.8	2.6	27.5	2.2	8.2
4	12.0	2.3	27.0	3.8	10.6	14.1	0	27.2	2.3	9.5	12.3	3.6	26.2	2.6	11.2
5	11.4	3.7	26.4	0.9	9.7	16.0	3.5	28.5	1.6	8.9	14.5	2.3	27.0	1.6	9.5
6	13.0	3.3	26.6	0	9.8	16.3	3.5	28.8	1.1	9.0	16.0	2.1	27.3	1.5	8.9
7	14.0	1.8	27.2	0	9.4	15.5	1.6	28.0	1.4	9.2	14.8	2.9	26.8	0	9.7
8	11.8	2.7	26.0	2.3	10.3	17.0	1.4	28.3	0	8.5	15.5	1.6	27.5	2.1	9.0
9	13.0	2.6	27.2	1.5	9.8	17.8	1.8	28.5	1.2	8.4	15.2	2.2	28.1	0	9.0
10	15.4	10.6	28.4	2.2	9.5	17.8	4.2	28.5	1.6	8.4	18.3	1.3	28.8	2.9	8.5
11	16.6	4.0	28.0	1.8	8.7	17.8	1.1	28.5	1.4	8.4	17.3	1.8	28.5	1.4	8.5
12	16.4	3.9	28.0	1.9	9.0	19.3	0	28.3	0	7.7	18.5	2.6	28.7	2.5	8.2

Legend: Trials 1 through 3 are PreSpinUp
Trials 4 through 6 are PostSpinUp
Trials 7 through 9 are PreSpinDown
Trials 10 through 12 are PostSpinDown

TOB = time on bullseye, in seconds
TOT = time on total target, in seconds
STTTC = mean distance from stylus tip to target center, in mm.

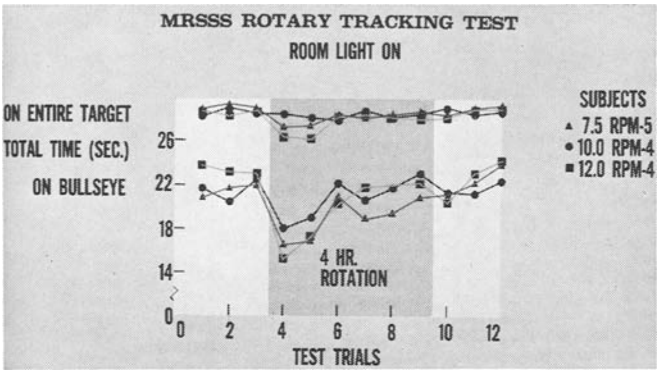

Fig. 8. TOB and TOT per test trial with room light on.

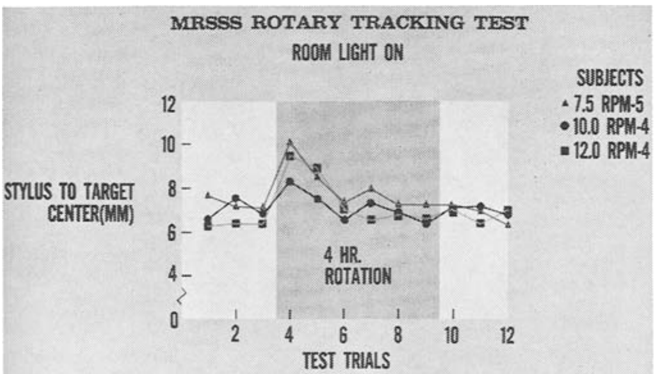

Fig. 9. STTTC per test trial with room light on.

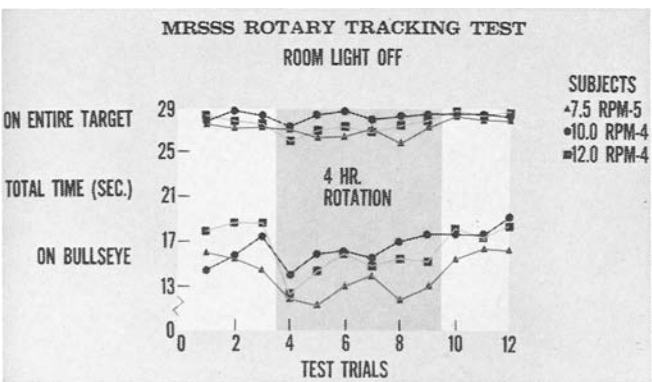

Fig. 10. TOB and TOT per test trial with room light off.

greater than that for tracking the unlit target. For both tracking modes TOB appeared to be the parameter most sensitive to decrement. Therefore, this parameter was chosen for statistical evaluation as to significant differences in tracking ability when different RPM's are compared or when different test sequences or trials are compared within the same RPM.

Two statistical tests for significance were used both tailored for small sample evaluation:

1. The Link and Wallace method for Analysis of Variance[29] and
2. Student's "t" Tests for Correlated and Independent Observations[30]

A *P value* equal to or less than 0.05 was considered significant.

Table IV contains analyses of variance for correlated (intra-RPM) observations and for independent (inter-

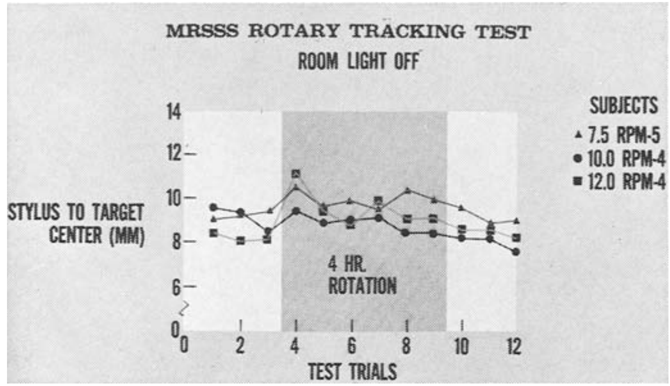

Fig. 11. STTTC per test trial with room light off.

TABLE IV. ANALYSES OF VARIANCE: TOTAL TIME ON BULLSEYE (ROOM LIGHTS ON) INDEPENDENT AND CORRELATED OBSERVATIONS

Independent (Inter-RPM) Observations								
RPM	7.5		10.0		12.0			
N	5		4		4			
Statistic	X	D	X	D	X	D	SR	A(P=0.05)
Trial								
1	20.8	1.1	21.9	1.9	23.8	-3.0		
2	21.8	-1.3	20.5	2.8	23.3	-1.5		
3	22.0	0.5	22.5	0.8	23.3	-1.3		
T	64.6		64.7		70.4			7.1
R		2.4		2.0		1.7	6.1	
4	16.4	1.6	18.0	-2.5	15.5	-0.9		
5	16.8	2.4	19.2	-1.9	17.3	-0.5		
6	21.0	1.2	22.2	-0.7	21.5	-0.5		
T	54.2		59.4		54.3			4.0
R		1.2		1.8		0.4	3.4	
7	19.0	1.7	20.7	0.9	21.8	-2.8		
8	19.6	2.2	21.8	0.2	22.0	-2.4		
9	21.0	2.2	23.2	-1.0	22.2	-1.2		
T	59.6		65.7		66.0			4.7
R		0.5		1.9		1.6	4.0	
10	21.2	0	21.2	-0.7	20.5	0.7		
11	22.2	-0.9	21.3	2.7	23.0	-0.8		
12	24.2	-1.9	22.3	1.7	24.0	0.2		
T	67.6		64.8		67.5			8.0
R		1.9		3.4		1.5	6.8	

Correlated (Intra-RPM) Observations						
RPM	7.5		10.0		12.0	
N	5		4		4	
Statistic	X	Rs	X	Rs	X	Rs
1	20.8	7	21.9	3	23.8	6
2	21.8	8	20.5	12	23.3	9
3	22.0	4	22.5	6	23.3	5
4	16.4	3	18.0	10	15.5	8
5	16.8	7	19.2	10	17.3	10
6	21.0	9	22.2	3	21.5	9
7	19.0	7	20.7	4	21.8	5
8	19.6	9	21.8	3	22.0	7
9	21.0	7	23.2	2	22.2	7
10	21.2	10	21.2	3	20.5	8
11	22.2	8	21.3	7	23.0	6
12	24.2	11	22.3	3	24.0	6
SR		90		66		86
A(P=0.05)	7.0		6.6		8.6	

Legend: X = mean of subjects' scores for each trial
D = differences between adjacent column means
T = Total of means in each test sequence
R = Range of differences for each test sequence
SR = Sum of Ranges

A(P=0.05) = Tabled allowance value for P=0.05
Rs = Range of subjects' scores for each trial

RPM) observations for tracking with room light on (target light off). The analysis for correlated observations compares means of individual trials. The analysis for independent observations compares means of 3-Trial sequences with the same sequence at the other RPM's.

Table V contains comparable analyses of variance for tracking with room light off (target light on).

Table VI contains "t" test results for correlated observations and for independent observations for tracking with room light on (target light off). The tests for correlated observations compare the means of *in rotation* and post-spindown sequences with the mean of the pre rotation sequence. The tests for independent observations compare comparable sequence means for different RPM's.

Table VII contains comparable "t" test results for tracking data with the room light off (the target light on).

TABLE V. ANALYSES OF VARIANCE: TOTAL TIME ON BULLSEYE (ROOM LIGHTS OFF) INDEPENDENT AND CORRELATED OBSERVATIONS

Independent (Inter-RPM) Observations

RPM		7.5		10.0		12.0			
N		5		4		4			
Statistic		X	D	X	D	X	D	SR	A(P=0.05)
Trial									
1		16.0	–1.5	14.5	3.5	18.0	–2.0		
2		15.2	0.3	15.5	2.3	18.8	–2.6		
3		14.6	2.9	17.5	0.3	17.8	–3.2		
	T	45.8		47.5		54.6			10.3
	R		4.4		3.2		1.2	8.8	
4		12.0	2.1	14.1		12.3			
5		11.4	4.6	16.0		14.5			
6		13.0	3.3	16.3		16.0			
	T	36.4		46.4		42.8			8.0
	R		2.5		1.5		2.8	6.8	
7		14.0	1.5	15.5		14.8			
8		11.8	5.2	17.0		15.5			
9		13.0	4.8	17.8		15.2			
	T	38.8		50.3		45.5			9.9
	R		3.7		1.9		2.9	8.5	
10		15.4	2.4	17.8		18.3			
11		16.6	1.2	17.8		17.3			
12		16.4	2.9	19.3		18.5			
	T	48.4		54.9		54.1			6.1
	R		1.7		1.3		2.2	5.2	

Correlated (Intra-RPM) Observations

RPM	7.5		10.0		12.0	
N	5		4		4	
Statistic	X	Rs	X	Rs	X	Rs
1	16.0	8	14.5	6	18.0	6
2	15.2	10	15.5	5	18.8	9
3	14.6	8	17.5	9	17.8	6
4	12.0	7	14.1	3	12.3	10
5	11.4	11	16.0	8	14.5	6
6	13.0	9	16.3	10	16.0	5
7	14.0	5	15.5	3	14.8	8
8	11.8	8	17.0	2	15.5	3
9	13.0	7	17.8	5	15.2	5
10	15.4	6	17.8	11	18.3	4
11	16.6	11	17.8	4	17.3	5
12	16.4	12	19.3	2	18.5	6
SR		102		68		73
A(P=0.05)	8.0		6.8		7.3	

Legend: X = mean of subjects' scores for each trial
D = differences between adjacent column means
T = Total of means in each test sequence
R = Range of differences for each test sequence
SR = Sum of Ranges
A(P=0.05) = Tabled allowance value for P=0.05
Rs = Range of subjects' scores for each trial

TABLE VI. "t" TESTS: TOTAL TIME ON BULLSEYE (ROOM LIGHT ON) INDEPENDENT AND CORRELATED OBSERVATIONS

Independent (Inter-RPM) Observations

RPM's Compared / Testing Sequence	7.5 to 10.0	10.0 to 12.0	12.0 to 7.5
PreSpinUp	P > 0.4 Lower	P > 0.1 Lower	P > 0.05 Higher
PostSpinUp	P > 0.1 Lower	P > 0.1 Higher	Equal
PreSpinDown	P = 0.05 Lower	P > 0.4 Lower	P > 0.05 Higher
PostSpinDown	P = 0.3 Higher	P > 0.2 Lower	P > 0.4 Lower

Note: P value under each comparison indicates one-tailed significance of X-RPM scoring (higher or lower) relative to Y-RPM.

Correlated (Intra-RPM) Observations

RPM / Comparison	7.5	10.0	12.0
PostSpinUp to PreSpinUp	P < 0.005 Lower	P < 0.025 Lower	P < 0.005 Lower
PreSpinDown to PreSpinUp	P < 0.05 Lower	P = 0.5 Lower	P < 0.025 Lower
PostSpinDown to PreSpinUp	P > 0.25 Higher	P = 0.5 Lower	P > 0.05 Lower
Trial 3 to 6	P = 0.2 Higher	P > 0.4 Higher	P > 0.10 Higher
Trial 9 to 10	P = 0.35 Lower	P > 0.35 Higher	P > 0.15 Lower

Note: P value under each comparison indicates one-tailed significance of X-sequence or X-trial (higher or lower) to Y-sequence or Y-trial.

Figure 12 presents graphically significant decrements (at P = 0.05 level) for correlated observations. Analysis of Variance and "t" test results are graphed concurrently for comparison. The upper half of the graph displays decrements for tracking with room light on (target light off). The lower half displays decrements for tracking with room light off (target light on). A half-unit drop in a line denoting a given RPM indicates that for those test trials or Three-Trial sequences tracking performance was significantly lower than the

TABLE VII. "t" TESTS: TOTAL TIME ON BULLSEYE (ROOM LIGHT OFF) INDEPENDENT AND CORRELATED OBSERVATIONS

Independent (Inter-RPM) Observations

RPM's Compared / Testing Sequence	7.5 to 10.0	10.0 to 12.0	12.0 to 7.5
PreSpinUp	P > 0.3 Lower	P > 0.05 Lower	P > 0.05 Higher
PostSpinUp	P > 0.1 Lower	P > 0.4 Higher	P > 0.05 Higher
PreSpinDown	P < 0.005 Lower	P > 0.05 Higher	P < 0.05 Higher
PostSpinDown	P > 0.05 Lower	P > 0.4 Higher	P > 0.05 Higher

Note: P value under each comparison indicates one-tailed significance of X-RPM scoring (higher or lower) relative to Y-RPM.

Correlated (Intra-RPM) Observations

RPM / Comparison	7.5	10.0	12.0
PostSpinUp to PreSpinUp	P = 0.10 Lower	P > 0.25 Lower	P < 0.005 Lower
PreSpinDown to PreSpinUp	P = 0.35 Lower	P > 0.30 Lower	P < 0.05 Lower
PostSpinDown to PreSpinUp	Equal	P = 0.15 Higher	P > 0.4 Lower
Trial 3 to 6	P = 0.15 Higher	P > 0.3 Higher	P > 0.10 Higher
Trial 9 to 10	P > 0.05 Lower	Equal	P > 0.35 Lower

Note: P value under each comparison indicates one-tailed significance of X-sequence or X-trial (higher or lower) to Y-sequence or Y-trial.

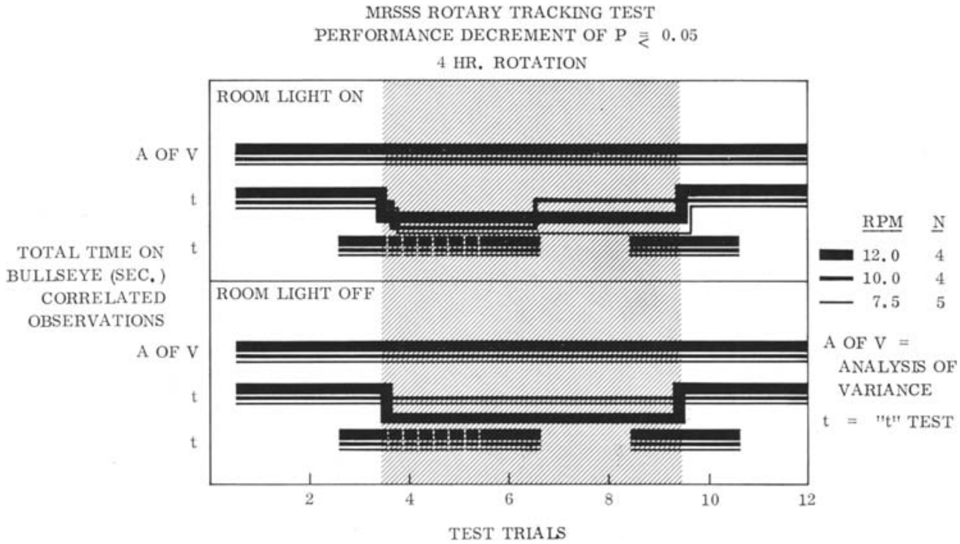

Fig. 12. Significant decrements in TOB: correlated observations for both tracking modes.

control score at that RPM. For both tracking modes 10.0 RPM shows the least decrement, the graph indicating significant decrease only for the mean of the *Post-spinup* testing scores with room lights on. Comparison of Trial #3 with Trial #6, however, indicates that by the third *Post-spinup* trial decrement is no longer significant. 7.5 RPM and 12.0 RPM show increasing decrement, in that order. Only 12.0 RPM shows significant decrement for mean scores of both in rotation test sequences. It appears, therefore, that 12.0 RPM requires additional readaptation following the three hours or more separating the last *Post-spinup* trial and the first *Pre-spindown* trial. All RPM's show recovery from significant decrement by the third trial of the Post-spinup sequence and no significant decrement for the first Post-spindown trial. All RPM's show no significant decrement for Post-spindown sequences.

Figure 13 presents graphically significant decrements (at P = 0.05 level) for independent observations. Analysis of Variance and "t" test results are graphed concurrently for comparison. Graph presents both modes (room light on and off) of testing for correlated analyses. To represent inter-RPM decrements a half-unit drop in an RPM line or lines indicates significant decrement relative to the RPM line or lines that rises concurrently. The analysis of variance of tracking with room light on indicates a significant decrement at 12.0 RPM relative to 10.0 RPM. 7.5 RPM tracking shows consistent decrement relative to 10.0 RPM, including some *Post-spindown* decrement. "t" test results for tracking with room light off show 7.5 RPM decrement relative to 12.0 RPM during the Pre-spindown sequence.

To summarize results from the statistical evaluation of tracking data:

1. Tracking at 10.0 RPM shows the least decrement and the fastest adaptation.
2. Tracking at all three RPM's show rapid adaptation, with recovery from the Spin-up and Spin-down inertial changes occurring in from 1 to 3 trials.

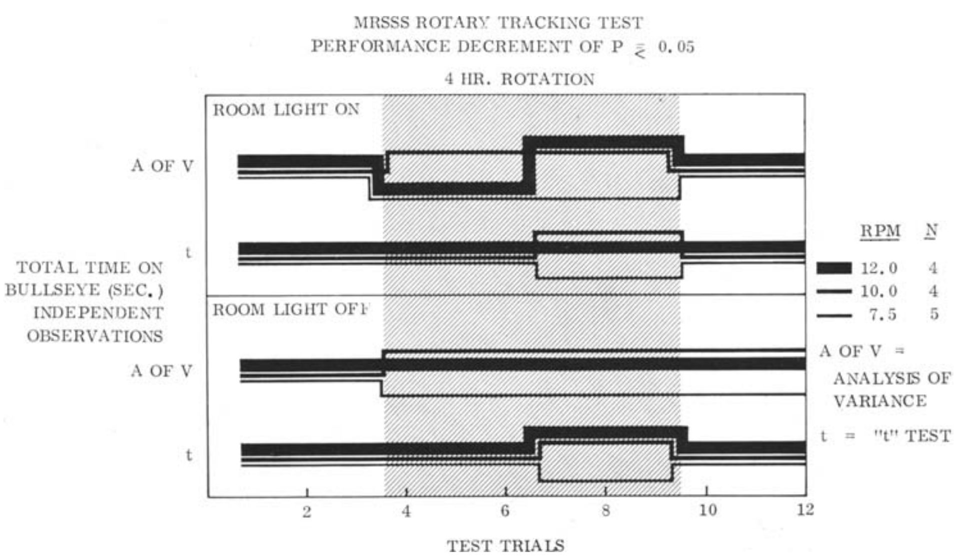

Fig. 13. Significant decrements in TOB: independent observations for both tracking modes.

3. Performance decrements in tracking lighted target in dark room are no greater than those in tracking conventional target in lighted room.

DISCUSSION

As long as no thrust is being applied to a space vehicle, the force acting upon any particle inside can be shown[31] to be described by the expression:

$$F = m\,(a + \omega^2 r + 2\,\omega v \sin \Theta)$$

where: F = total force on the particle
m = mass of the particle
a = linear acceleration of the particle with respect to the vehicle
ω = angular velocity of the vehicle
r = radial distance from the axis of rotation to the particle
v = linear velocity of the particle with respect to the vehicle
Θ = angle between axis of rotation and direction of "v"

The first term within the parenthesis is the acceleration necessary to start an object moving, to stop it or to change its direction and is no different from the acceleration experienced in a stationary environment. The second term is the rotogravity acceleration and is directed away from the axis of rotation of the vehicle. The last term is the Coriolis acceleration.

Two points should be noted in this equation: (1) that while Coriolis acceleration varies linearly with the angular velocity of the vehicle, rotogravity varies exponentially and (2) that Coriolis acceleration is independent of the spin radius, while rotogravity is dependent. These are important considerations in early rotogravity systems. It is desirable from the engineering aspect to have a short radius. With a short radius either the g level must be kept low or the angular velocity high. Reducing the g by shortening the radius has no concurrent effect upon the Coriolis force, thus increasing the critical Coriolis/gravity ratio. Reducing the angular velocity with constant radius produces the same undesirable effect.[31] The practical choice appears to be maintaining the angular velocity at a tolerable maximum, with a spin radius adequate to keep the g level and Coriolis/gravity ratio within satisfactory ranges. As these ranges are not presently known a 1 g environment should be considered the tentative optimum.

The tolerance ceiling for angular velocity will be determined by the magnitude of the generated Coriolis forces and their effects on crew health and performance. The angular velocity (ω) of the earth is only 0.0007 RPM. For 1 g of rotogravity, assuming even a spin radius of 1000 feet, 1.71 RPM is required. This represents a profound enironmental transition.

Coriolis forces act upon all particles in the vehicle moving relative to the spin axis, including crew members' arms, hands and inner ear endolymph. When the head is rotated into or away from the plane of vehicle rotation the lateral portion of the semicircular canals and its endolymph have a greater linear velocity than the medial portion and its endolymph. The consequent inequality of Coriolis forces produces a mechanical couple that causes movement of the endolymph and a cupular impulse. The total effect is the algebraic summation of the couples in all six canals and is maximal when the head is rotated normal to the plane of vehicle rotation. Subjectively, the person experiences a feeling of rotation in a plane approximately orthogonal to the planes of vehicle and head rotation[32,33] The total experience is complex in that the sensations of angular speed and displacement are discordant with information received from otolithic, visual and proprioceptive sensors;[34] the plane of apparent bodily rotation may shift; visual illusions may be perceived; and symptoms, including malaise and nausea, referable to many bodily systems are exhibited.[35]

The effect of these Coriolis forces upon a crewman's psychophysiological responses, such as his accuracy in performing manipulative tasks requiring hand-eye coordination, will be important gauges in defining the tolerable limit of spin velocity.

Cranial precession such as that involved in the rotary tracking test may be resolved orthogonally into two sinusoidal movements, about the Y (bi-temporal) and Z (vertical) cranial axes. Optimal placement of control and display panels in a rotating space station would require either the Y or Z cranial axis of the operator to be parallel with the axis of station spin, reducing the functional probability of disorienting stimuli. A placement against either a leading or trailing bulkhead would accomplish this. Such placement was duplicated in Astronautics MRSSS (Manned Revolving Space Station Simulator) by placing the rotary tracking apparatus against the leading bulkhead.

At angular velocities of 7.5, 10.0 and 12.0 RPM the inclinations of the MRSSS with the inertial resultant are 19.5°, 33.0° and 44.0°. As subjects were positioned so as to require equal amplitudes of cranial displacement in the two orthogonal planes inclination of the room to the plane of rotation would have no net effect on Coriolis phenomena, reductions about the Z cranial axis being compensated for by additions about the Y cranial axis. For simplicity of calculation the inclination was ignored and rotations of the head about its Z axis considered to be maximal and the sole contributor to vestibular stimulation.

To follow the 28 RPM target with foveal perception the subjects rotated their heads about the Z axis through an average arc of 75° or 1.2 radians/sec. With the room rotating at a constant angular velocity of 0.75, 1.0 and 1.2 radians/sec., the cross-couple product equals 0.9, 1.2 and 1.4 radians^2/sec.,^{2} each in excess of the empirical figure for nausea threshold (0.6 radians^2/sec.^{2}) propounded by Clark and more than one order of magnitude above his threshold estimate of 0.06 radians^2/sec.^{2} for Coriolis awareness.[36] It should be noted that the 0.9, 1.2 and 1.4 radians^2/sec.^{2} are rms values, corresponding to peak products of 1.3, 1.7 and 2.0 radians^2/sec.^{2} Calculations for sinusoidal oscillations of the head with a double amplitude of 75° and a period of 2.14 seconds suggest cupular displacement exceeding 40° in a normal subject.[37]

In view, however, of minimal decrements observed in

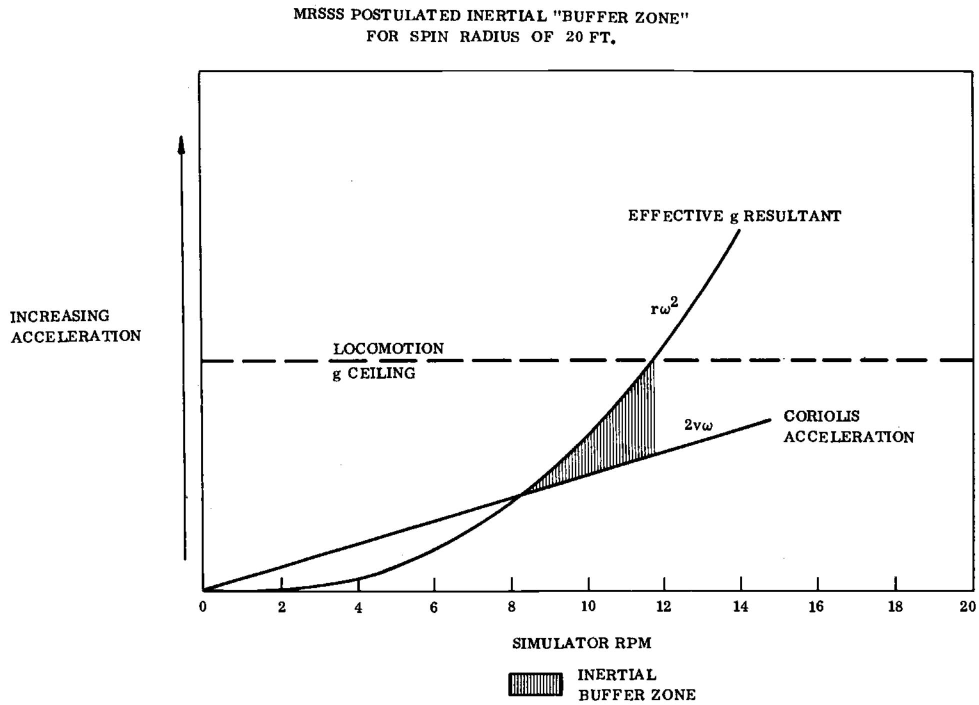

Fig. 14. MRSSS postulated inertial "buffer zone" for spin radius of 20 feet.

tracking at 7.5, 10.0 and 12.0 RPM, in tracking target light compared with target and in tracking at 5.0 RPM in a preceding study,[38] it is suggested that periodic turnings of the head at intervals that are small (a few secs.) relative to the accepted period of the normal cupula (20-30 seconds) produce little vestibular response after the initial turn. This postulate would explain the lack of performance decrement noticed in other studies involving repetitive head turnings of comparable frequency[39,40] at orientations that should produce strong vestibular stimuli. It appears that in these situations the above calculated cross-coupled stimulation is not applicable. A cupulaendolymph system damped against such unusual perturbations has been already suggested.[41]

A second factor involved in the kinematics of rotary tracking is the Coriolis acceleration acting upon the hand, arm and stylus as they move toward or away from the centrifuge spin axis. While tracking the 28 RPM test target on its 0.58 meter radius the subject's hand and stylus described movements of approximately 1.8 m/s, within the range of typical hand translation rates measured by various investigators.[42,43,44] Again ignoring room inclination to simplify computation tracking with the MRSSS revolving at 7.5, 10.0 and 12.0 RPM subjected the subject's hand and stylus to rms (and peak) accelerations of 1.75 (2.47), 2.32 (3.29), and 2.80 (4.24) m/s^2. These accelerations were toward the plane of the turntable as the subject tracked inboard and away from the plane of the turntable as he tracked outboard. During every 1.07-second half-rotation of the target the subject's hand and stylus experienced an algebraic change of acceleration equaling rms (and peak) 3.50 (4.94), 4.65 (6.58) and 5.98 (8.48) m/s^2 for the three test RPM's.

Considering the calculated stresses—qualified even by the suggested absence of excessive vestibular stimuli —the recorded tracking performances, with rapid adaptation to abrupt force field changes, indicate a perseverance of perceptual-motor ability at levels of environmental rotation above predicted ceilings. Of interest are the significantly better performances at 10.0 RPM than at 7.5 or 12.0. Frequent reference in the literature to the dependence of Coriolis effect upon environmental g[27,28] led to the postulation of an inertial "buffer zone" as diagrammed in Figure 14. This concept results from the speculation that with the g increasing exponentially and the Coriolis forces linearly as the angular velocity rises, an area may exist between 7.5 and 12.0 RPM in the MRSSS at a 20-foot radius where the g attenuates the effect of the Coriolis forces to a greater degree than it retards performance. Of course, the inertial resultant at 10.0 RPM in the MRSSS is not 1 g or less but 1.2 g. This exceeds the tentative space vehicle ceilings of 0.9 g or less. To continue this speculation even further, it has not been proved that a rotogravity exceeding 1.0 is unrealistic. As a constant or intermittent physiological conditioner in space it may have definite advantages.

An explanation for the lack of illness at 12.0 RPM cannot be defined with any assurance. Two pertinent statements can be made. *First,* that there was little observable continuity between episodes of nausea at the various RPM's and actual tracking. Subjects quite often became ill before any *in rotation* tracking. Others vomited during the long interim between *Post-spinup* and *Pre-spindown* tracking. Observations by onboard examiners and subjects suggest more discomfort from random motion within the MRSSS when not being tested. *Second,* that the decreased voluntary locomotion of subjects at 12.0 RPM, due at least partly to the higher g (1.4), may have prevented overt illness in the subjects.

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