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Influence of Gravitoinertial Force Level on Apparent Magnitude of Coriolis Cross-Coupled Angular Accelerations and Motion Sickness

James R. Lackner and Ashton Graybiel
Ashton Graybiel Spatial Orientation Laboratory
Brandeis University, Waltham, Ma. 02254, USA
and
Naval Aerospace Medical Research Laboratory
Naval Air Station
Pensacola, Florida 32508, USA

Summary

The Skylab astronauts showed a great decrease in susceptibility to motion sickness during exposure to Coriolis cross-coupled angular accelerations when tested in orbital flight. In fact, none of them reached a motion sickness endpoint inflight although each of them had preflight. We have been attempting to determine whether this decreased susceptibility is related entirely to adaptation or in part to changes in vestibular and sensory-motor function that occur virtually immediately in the microgravity conditions of orbital flight. To resolve this issue we have tested subjects separately in the free fall and high force phases of parabolic flight maneuvers and measured 1) susceptibility to motion sickness during Coriolis stimulation as a function of force level and 2) the perceived intensity of Coriolis cross-coupled angular accelerations as a function of force level. The findings are clear cut: subjects exhibit fewer and less severe symptoms of motion sickness when tested in free fall than they do for the same Coriolis stimulation in 1G; they exhibit much earlier and much more severe symptoms when tested in 2G. Ratings of the apparent intensity of Coriolis stimulation show the same pattern: subjects find that executing head movements in free fall at a particular velocity of rotation is much less stressful than in 1G; in 2G, the perceived intensity and associated discomfort are greatly increased. We conclude that part of the Skylab astronauts' inflight decrease in susceptibility to Coriolis stimulation was related to alterations in vestibular and sensory-motor control that occur immediately during exposure to microgravity force levels.

Introduction

We describe here how variations in gravitoinertial force level affect the experienced magnitude of Coriolis cross-coupled angular accelerations and the elicitation of symptoms of motion sickness. Cross-coupled stimulation of the semicircular canals occurs when a rotating individual makes head movements out of the plane of his rotation. The intensity of stimulation is dependent on the rotary velocity of the body, ω_1, the velocity of the head movement, ω_2, out of the plane of body rotation, and the angle, ϕ, between the ω_1 and ω_2 axes. Descriptions of the physical basis of Coriolis cross-coupling effects have been provided in particularly useful form by Guedry and Benson (1), Benson (2), Guedry (3) and Jones (4). Because of cross-coupling, a rotating individual who makes a head movement will experience aberrant motion of his head about an axis roughly orthogonal to ω_1 and ω_2. For example, an individual who tilts his head toward his right shoulder while being rotated counterclockwise at constant velocity will experience a forward pitching motion about the transverse plane of his head. It has long been known that Coriolis stimulation, when intense, will elicit dizziness, nausea and vomiting. The ability to withstand exposure to Coriolis cross-coupled angular acceleration has formed the basis for a test of motion sickness susceptibility that has been of value in predicting susceptibility during aerial maneuvers, the Coriolis Sickness Susceptibility Index Test or CSSI test (5).

The CSSI test was one of the procedures conducted as part of the Skylab M-131 experiment on vestibular function in weightlessness (6,7). Eight of the nine astronauts who participated in the three manned Skylab missions were evaluated with the CSSI test preflight, inflight, and postflight. The first inflight tests for the different astronauts took place between mission days 8 and 12. At the time of their first inflight evaluation and during subsequent inflight tests, all of the astronauts showed a marked decrease in susceptibility compared to their preflight scores. Even when the velocity of the rotating chair was increased beyond the ground-based test velocities to 30 rpm, all of the astronauts completed the maximum possible number of head movements in the test without reaching a motion sickness endpoint; in fact, all of them were virtually symptom free. The decreased susceptibility of the Skylab astronauts to Coriolis cross-coupled angular accelerations persisted into the postflight period; only over a period of days, and even in some cases weeks, did susceptibility on the CSSI test gradually return to preflight level (6,7).

The origin of the decreased susceptibility to cross-coupled angular accelerations inflight has significance for understanding the etiology of space motion sickness and for gaining insights into the nature of vestibular function in the altered gravitoinertial conditions of space flight. One question of immediate concern is whether the decreased inflight susceptibility resulted from some form of adaptation process, an adaptation which once achieved then persisted for some period postflight and gradually decayed, or whether it resulted at least in part from immediate changes in vestibular function related to the effective lifting of the G force in free fall.

In an experiment relevant to this issue, Miller and Graybiel (8) found that in the free fall phase of parabolic flight maneuvers some subjects show a decreased susceptibility to motion sickness during the CSSI test while others show an increase. Many individuals, however, are susceptible to motion sickness during parabolic flight maneuvers simply as a consequence of exposure to periodic variations in gravitoinertial force level, even when they are seated with their heads stationary in relation to the aircraft. It is not known whether the subjects tested by Miller and Graybiel (8) who showed increased sensitivity on the CSSI test are among those individuals who are susceptible to motion sickness during exposure to the parabolic flight force variations independent of Coriolis stimulation, and whether those who showed a decreased susceptibility are insusceptible to the force variations alone.

To resolve this issue we have measured the basic susceptibility of subjects during parabolic flight maneuvers and then have determined how their susceptibility to motion sickness during exposure to cross-coupled angular accelerations relates to gravitoinertial force level. In other assessments, we have had subjects rate the apparent intensity of cross-coupling in situations involving comparable Coriolis stimulation but different gravitoinertial force levels.

Experiment 1

Susceptibility To Motion Sickness During Coriolis Stimulation As A Function of Gravitoinertial Force Level

Materials and Methods

Subjects: Eight individuals took part including one of the authors and seven college students who were paid for their voluntary participation. All had met the medical requirements and undergone the physiological training procedures necessary for taking part in parabolic flight experiments. Each had normal otolithic and canalicular function as measured by tests of ocular counterrolling, ataxia, modified Fitzgerald-Hallpike caloric irrigation, and thresholds for perception of the oculogyral illusion.

Subject Categorization Each subject was categorized in terms of his susceptibility to motion sickness in parabolic flight maneuvers. This was done as follows: in one of a subject's first two flights he was seated with his head restrained and his eyes covered, in the other flight his head was restrained but his eyes were open and he had full sight of the aircraft. Each of these flights lasted 40 parabolas. If a subject scored a total of between 0 and 4 motion sickness points in the two flights, he was assigned to Category I (insusceptible to motion sickness during exposure to periodic variations in gravitoinertial force level; 5-12 points, Category II (moderately susceptible); and 13 or more points in Category III (highly susceptible). The scoring system for assigning motion sickness points was developed by Graybiel, Wood, Miller and Cramer (9) and is presented in Table 1. Four of the eight subjects fell in Category I and four in Category III.

Table I

DIAGNOSTIC CATEGORIZATION OF DIFFERENT LEVELS OF SEVERITY OF ACUTE MOTION SICKNESS

Category	Pathognomonic 16 points	Major 8 points	Minor 4 points	Minimal 2 points	AQS* 1 point
Nausea syndrome	Vomiting or retching	Nausea+ II, III	Nausea I	Epigastric discomfort	Epigastric awareness
Skin		Pallor III	Pallor II	Pallor I	Flushing/Subjective warmth ≥ II
Cold sweating		III	II	I	
Increased salivation		III	II	I	
Drowsiness		III	II	I	
Pain					Headache ≥ II
Central nervous system					Dizziness Eyes closed ≥ II Eyes open III

Levels of Severity Identified by Total Points Scored

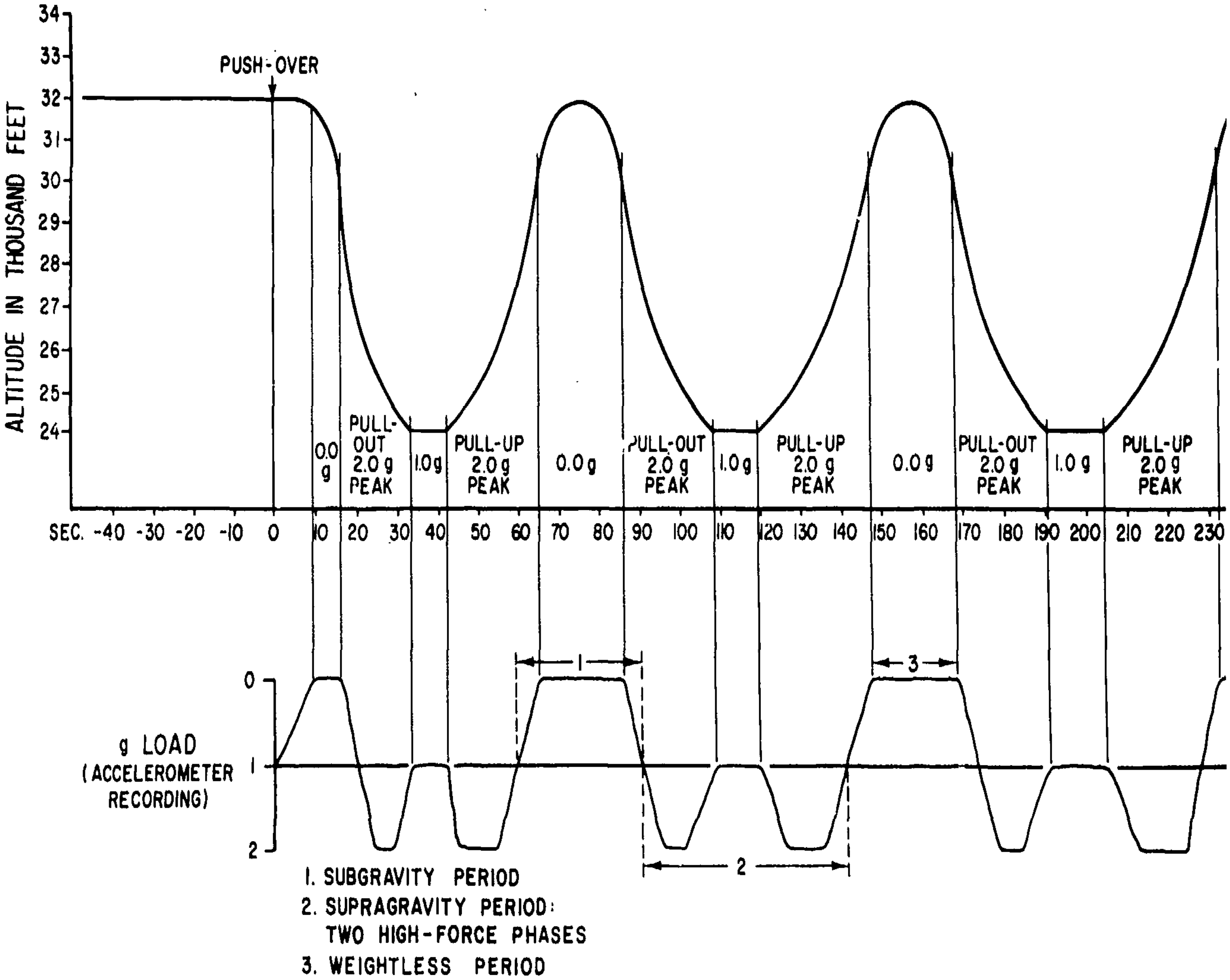
Frank Sickness	Severe Malaise	Moderate Malaise A	Moderate Malaise B	Slight Malaise
(S)	(M III)	(M IIA)	(M IIB)	(M I)
≥ 16 points	8 - 15 points	5 - 7 points	3 - 4 points	1 - 2 points

*AQS = Additional qualifying symptoms. +III = severe or marked, II = moderate, I = slight.

Apparatus: A servo-controlled Stille rotating chair was mounted in the mid-region of the fuselage of the Boeing KC-135 aircraft used in our experiments.

Parabolic Flight Profile: Figure I is a schematic illustration of the flight pattern of the KC-135 aircraft during parabolic maneuvers. The aircraft is flown in a parabolic path to generate alternating periods of increased gravitoinertial force, approximately 2G peak, and of free fall (OG). There are two high force periods in each parabola, and a free fall period lasting approximately 20 sec. In our experiments, the aircraft flies a total of 40 parabolas during each mission. The parabolas are flown consecutively except for turnarounds to gain additional airspace or breaks to assist motionsick subjects.

Figure I



Procedure: Each subject was tested under three conditions involving clockwise rotation at 20 rpm: 1) in the laboratory, 2) in the free fall phases of parabolic flight, and 3) in the high force phases of parabolic flight. In these conditions, the subject was required to make tilting head movements to a tape recorded 1 beat/s cadence. The subject was always maintained at constant velocity for at least 10s before head movements were initiated. The movements involved were a variation on the CSSI test procedure: the subject ventriflexed his head forward in pitch until it touched his chest and then dorsiflexed it until it touched a padded head rest: movement amplitude was 90°, one cycle of movement was completed in 2s for a movement frequency of .5Hz. Eight cycles of movement were carried out, then there was a rest period before the next set of movements, this procedure was repeated until either a motion sickness endpoint of severe nausea was reached or the subject had made 320 cycles of head movement. On the ground, 40s periods separated sets of 8 head movement cycles; in the parabolic flight tests, the minimum separation was 40-45s and the maximum separation was sometimes as long as several minutes or more in the case of a turn around. This maximum interval varied non-systematically across subjects and across test conditions. In parabolic flight, head movements in the microgravity test conditions were initiated in each parabola when a digital accelerameter indicated 0.0G; in the high force condition, when 1.8G had been attained. Ground-based laboratory testing always preceded the parabolic flight evaluations, the order of subject testing in parabolic flight was balanced across subject categories and force levels.

Results

All of the subjects showed dramatically greater susceptibility to motion sickness during Corolis stimulation when they were tested in the high force phase of flight compared with their susceptibilities in free fall and in the laboratory. Moreover, all of the Category I subjects also showed a marked decrease in susceptibility in free fall compared with their laboratory results; two of the Category III subjects also showed a substantial decrease in free fall while two were more susceptible. Table 2 presents a summary of the data in terms of the total number of motion sickness points scored and the total number of head movement cycles achieved according to subject category and test condition.

It is notable that when tested in free fall 3 of the 4 Category I subjects completed the full 320 cycles of head movements without scoring any motion sickness points, the remaining Category I subject had some symptoms but completed the test. Only one of these subjects had completed the 320 cycles of head movements on the ground and none of them had been symptom free.

T.ble II

SUSCEPTIBILITY TO MOTION SICKNESS DURING EXPOSURE TO A CONSTANT LEVEL OF CORIOLIS CROSS-COUPLED ANGULAR ACCELERATION AS A FUNCTION OF GRAVITOINERTIAL FORCE LEVEL. THE AVERAGE NUMBER OF HEAD MOVEMENT CYCLES COMPLETED (320 = MAXIMUM ENTRY) AND THE AVERAGE NUMBER OF MOTION SICKNESS POINTS SCORED (16 = MAXIMUM ENTRY) DURING TESTING ARE INDICATED. THE EMESIS ENTRIES INDICATE THE TOTAL NUMBER OF SUBJECTS WHO VOMITED IN EACH CONDITION.

Subjects	Gravitoinertial Force Level	Head Movement Cycles	Motion Sickness Points	EMESIS
Category I	1 G	186	8	0
(N=4)	0 G	320	2	0
	2 G	77	10	1
Category III	1 G	122	10	1
(N=4)	0 G	141	8	0
	2 G	24	16	3

Experiment 2

Apparent Intensity Of Coriolis Stimulation As A Function Of Gravitoinertial Force Level

Materials and Methods

Subjects: Fifteen individuals took part including one of the authors. All had met the medical requirements necessary for parabolic flight experiments and were without sensory-motor anomalies.

Procedure: The same apparatus and aircraft were used as described above in Experiment 1. Prior to the onset of parabolic maneuvers, the subject was blindfolded and accelerated at $15°/s^2$ to a constant angular velocity of 120°/s, this velocity was maintained for the duration of the test. During straight-and-level flight, the subject was required to execute a total of three rapid tilting movements of the head: the subject tilted his head to his chest (movement time approximately 1s) kept it there for 10s and gradually returned it to the upright avoiding disturbance. This procedure was repeated twice more while the subject paid careful attention to the experienced magnitude of the Coriolis forces acting on his head during and after the forward pitch movement and the level of subjective discomfort associated with the movement. The subject was instructed to give each of these experiences the reference value 10 and to use smaller or larger numbers as appropriate to rate the levels of cross-coupling intensity and discomfort experienced during head movements in subsequent parabolic maneuvers.

During parabolic flight, the subject was required to make one cycle of head movement in the initial high force phase and one cycle in the free fall phase of each parabola. The subject tilted his head to his chest in approximately 1s kept it there for 10s and returned it gradually to the "vertical". The head movements made in high force levels were initiated when a digital acceleometer indicated at least 1.8G, the low force ones at 0.0G. After the completion of each test head movement the subject gave numerical magnitude estimates of the cross-coupling and the discomfort experienced. If there was a turn around period of straight-and-level flight during a subject's test parabolas, he was required to make an additional 1-g force level, head movement to help maintain his rating standard. The subject was tested until he either reached a motion sickness endpoint of nausea or had rated 10 parabolas.

Results

The experienced magnitude of a constant level of Coriolis cross-coupled angular stimulation was highly dependent for each subject on gravitoinertial force level. In free fall, relative to straight-and-level flight there was a significant decrease in ratings of apparent intensity, $p<.001$; by contrast, during exposure to high force levels there was a great increase in apparent intensity, $p < .001$. This pattern was characteristic of every subject and all of them also remarked on the great differences experienced.

The same pattern appeared in the ratings of apparent discomfort associated with head movements. The head movements in free fall were reported to be much less stressful than those in straight-and-level flight, and those made in 2G were rated as much more stressful than the 1G standard, $p< .001$ for both comparisons. This pattern was characteristic of every subject.

Table 3 summarizes the experimental findings for apparent intensity and for relative stressfulness of cross-coupling as a function of gravitoinertial force level.

Table III

MAGNITUDE ESTIMATIONS OF SUBJECTIVE INTENSITY AND STRESSFULNESS OF CONSTANT LEVELS OF CORIOLIS CROSS-COUPLED ANGULAR ACCELERATION AS A FUNCTION OF GRAVITOINERTIAL FORCE LEVEL. THE 1 G TEST CONDITION SERVED AS THE STANDARD AND WAS ASSIGNED 10 AS A REFERENCE VALUE. STANDARD DEVIATIONS IN PARENTHESES. N = 15.

	GRAVITOINERTIAL FORCE LEVEL		
	1 G	0 G	2 G
APPARENT MAGNITUDE	10	2 (±1.3)	25 (±3.6)
APPARENT STRESSFULNESS	10	1 (±1.1)	28 (±4.2)

Discussion

The results of our two experiments show unequivocally that the apparent intensity and the relative provocativeness of constant levels of Coriolis stimulation are gravitoinertial force dependent. This finding provides an explanation, at least in part, for the decreased susceptibility of the Skylab astronauts when tested with the CSSI procedure inflight: the same patterns of Coriolis stimulation are less provocative in free fall than on the ground; accordingly, in the absence of other stressful vestibular stimulation, it may be expected that astronauts will be less susceptible to Coriolis stimulation after entry into weightlessness. In addition, however, the continued decreased susceptibility of the Skylab astronauts postflight suggests that some form of vestibulo-motor adaptation also took place inflight. We have described elsewhere how and why this adaptation may occur (10).

Over the past few years, there have been several indications that vestibular responsivity to angular acceleration is gravitoinertial force dependent. Lackner and Graybiel (11) found that the frequency and amplitude of nystagmus elicited in blindfolded subjects by constant levels of angular acceleration were diminished in free fall and enhanced during exposure to greater than 1G force levels. Bludworth, Reschke, and Homick (12), Vesterhauge, Mansson, Johansen, and Zilstorff (13), and de Jong, Oosterveld and Lavooy (14), have recently made similar observations. Together these findings suggest that the gain of the vestibulo-ocular reflex (VOR) diminishes in free fall.

The present findings of a decreased apparent intensity and a decreased provocativeness of Coriolis cross-coupled stimulation of the semicircular canals in free fall relative to terrestrial force levels are in accord with such a decrease in the VOR. The reason for the decrease is uncertain. It has been suggested that the semicircular canals may under some circumstances, such as Z-axis recumbent rotation, be sensitive to linear as well as angular accelerations (15,16). In addition, it is well established that otolithic input can modulate the activity of cells receiving afferents from the semicircular canals. (17,18,19,20,21,22,23,24). This latter possibility seems at present a more likely basis for the effects of gravitoinertial force level on responsivity to angular acceleration. In this context, it should be noted, too, that Igarashi (25) has shown that if the otolith organs are ablated, the intensity of pendular rotation nystagmus is diminished.

Several other factors may influence the apparent intensity of Coriolis cross-coupling accelerations in addition to variations in otolith organ activity related to gravitoinertial level. During exposure to force levels greater or lesser than Earth gravity, alterations also occur in many other aspects of sensory-motor control. These include, for example, changes in the intensity and distribution of touch and pressure stimulation of the body surface, alterations in proprioception, and changes in the levels and patterns of muscle activity associated with making particular body movements. In the last few years, there has been increasing evidence that all of these factors participate in a dynamic sensory-motor calibration of the body to terrestrial force levels. During exposure to non-terrestrial force levels, a variety of illusions occur during body movement, the character of these illusions reveals the existence of the sensory-motor calibrations that otherwise would not be recognized as such (26,27,28,29,30). It seems to us quite likely that the dependence of the apparent intensity of Coriolis stimulation on gravitoinertial force level will be related to these wide ranging functional changes in sensory-motor calibrations as well as to alterations in the central interpretation of patterns of semicircular canal activity.

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DISCUSSION

BLES: We know you can motivate the vestibular Corolis effect by adding congruent somatosensory stimulation in which case you would diminish the effect, or adding incongruent somatosensory stimulation which may result in an enhancement of the Coriolis effect. I wonder, if it is possible in your set-up to split out what the influence of the somatosensory information is and what the influence of the otolithic stimulation is?

LACKNER: The story with regard to the influence of the otolith organs in this situation is a very complicated one; in fact, I think many investigators would have predicted just the opposite patterns of results that we have obtained. We have good reason for believing that in addition to the changes in otolith activity there are other factors that change during gravitoinertial force variations in parabolic flight, and contribute to the patterns we have observed, e.g. the loading of the head on the neck changes and the patterns of muscle spindle feedback from the neck musculature are altered. We know, for example, that by vibrating neck muscles to create abnormal levels of spindle activity we can elicit illusory changes in head posture. The point is that we have a sensory motor control system dynamically calibrated to 1G and when we go into high force levels or free fall we are altering much more than just the vestibular receptor system. In fact, skeletal-muscular control and the proprioceptive and somatosensory systems are also being modulated systematically.

MILLER: I know that you've also reported changes in the gain of the vestibular ocular reflex at different force levels. Could you correlate that with the changes you see in susceptibility to cross-coupling?

LACKNER: The changes that we saw in cross-coupling would be in accord with the decreased gain of the VOR that we observed in free fall. From this standpoint the relative effectiveness of a constant pattern of angular acceleration would presumbly be diminished in free fall and augmented in 2G.

HAWKINS: I would like to ask about the influence of outside visual reference on the effect of Corolis stimulation and the visual confusion which may follow it. Fighter pilots in their combat maneuvers frequently make large head movements under very high force levels. I recently saw a case of a pilot who made a fairly gentle pull-up but with a completely empty visual field and he couldn't see his instruments for the next 30 to 40 sec. presumbly due to nystagmus. He did not notice any problems when he had a good outside visual reference. Did your subjects who were making head movements while rotating have a clear visual reference or were they shut in a cabin and unable to see any outside horizon?

LACKNER: Our subjects were blindfolded. In the case to which you refer, one would expect with reduced visual reference and roll head movements to get a rotary nystagmus that would make it very difficult for your pilot to maintain clear view of the instruments, whereas with a full visual field, the nystagmus would be much less. Fred Guedry described an effect several years ago that he referred to as the G excess illusion which I think is related to what you are describing. Essentially in the G excess illusion the pilot is banking his aircraft and there isn't much angular acceleration involved, so there is very little cross-coupling during head movements, but there is a greater then normal G force and this would alter the gain of the vestibulo-ocular reflex, producing rotary nystagmus and apparent deflection of the instrument panels during roll head movements.

GUEDRY: The cross-coupled vector lies in the plane of rotation. Did the head movements of your subjects in parabolic flight involve trunk movement so that a centripetal vector was introduced? The centripetal vector would be aligned with the cross-coupled vector.

LACKNER: We have done the cross-coupling studies both with simple head tilts in pitch, approximately 90° amplitude, and with full head and torso pitch forward. The results are very similar for the two test situations.

JONES: Why is cross-coupled stimulation so rare and so unpredictable in operational high-performance jet flight, given the high-G environment and the frequent head motions of the aircrew?

LACKNER: I think Fred Guedry knows more about this issue than anyone else.

GUEDRY: Most maneuvers in aircraft do not involve sustained high angular velocity spins or turns which are required to induce strong cross-coupled illusory effects from head movements. However, head movements made in a high-G field, 2G and above, can produce disturbing illusory effects often referred to as "G excess" effects, possibly due to excessive feedback from the otolith system in high-G fields. This was shown in several studies in high-speed aircraft making level high-G turns at turn rates so low that cross coupled stimulation of the semicircular canals would be negligible, yet illusory and nauseogenic effects were produced. Experienced pilots and aircrew undoubtedly learn "the feel of maneuvers" and their anticipation of effects from head movements in high-G fields serve to reduce effects. Pilots also sometimes intellectually override such effects, e.g., an experienced pilot reported a 20-30° nose down attitude as a result of a head movement in a 2G field, but said that he was not disoriented because he knew the true condition of the aircraft, which was in a level bank and turn.