Findings on American Astronauts Bearing on the Issue of Artificial Gravity for Future Manned Space Vehicles

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This paper reviews findings for American astronauts which may indicate some alteration in vestibular response related to exposure to zero gravity. Of 25 individuals participating in Apollo missions 7-15, nine have experienced symptomatology that could be related to the vestibular system. The apparent divergence between these results and Soviet space program experiences, which initially appears great, may reflect the greater emphasis given by Soviet investigators to vestibular aberrations. Presently the incidence of motion sickness, long known as an indicator of vestibular disturbance, seems too low to warrant any positive statement regarding inclusion of an artificial gravity system in future long-term space missions. Where motion sickness has occurred, adaptation to weightlessness has always resulted in abatement of symptoms. In the absence of biomedical justification for incorporating artificial gravity systems in long-term space flight vehicles, engineering considerations may dictate the manner in which the final ballot is cast.

ONE OF THE major purposes of the biomedical effort in support of the Mercury, Gemini, and Apollo manned spaceflights has been to evaluate the adaptation of astronauts to weightlessness. In general, adaptation has proceeded much more smoothly than some had predicted. For example, concern was expressed about a decreased tolerance to gravity, or to increased gravity forces, following weightless flight. The Gemini 4 crew sustained a peak of 8.2 G during the reentry phase without adverse effects. Apollo reentry forces on return from lunar missions have reached levels near 6.7 G. All of these acceleration levels, which had been previously experienced by the crews during centrifuge training, were well tolerated.[4]

Medical and performance data available at the present time do not support a requirement for artificial gravity systems in spacecraft. In the view of spacecrews to the present time, artificial gravity systems are unnecessary for task performance. Crews have learned to live in a zero-g state and feel very confident in that state. Many have, in fact, expressed a preference for a zero-g environment since the absence of gravity increases the effective volume of what would otherwise be rather confined work spaces.

On the other side of the coin, the provision of artificial gravity would undoubtedly increase the habitability of spacecraft. Eating would become a simple affair, and locomotion would proceed nearly as it does in the earth-bound environment. With artificial gravity, everyday activities in spacecraft could be carried out as easily and simply as they are in one's own home. Where engineering considerations are concerned, design tasks would be simplified in that restraint systems and locomotion aids would no longer be required. On the other hand, the engineering tasks associated with designing the artificial gravity system itself are formidable and they could be costly.

The issue of the need for artificial gravity in spacecraft of the future is no more clearly resolved among Soviet scientists than it is in the United States. Valyavski[6] summarizes the Soviet position by stating that investigations of the problem of weightlessness may indicate that man can form adaptive mechanisms to the weightless state. However, he goes on, until this is proved, technology will continue in the Soviet Union to attempt to create artificial gravitation. This is a problem which is "much in the forefront of modern cosmonautics." In discussions by the author with various Soviet space medical authorities, it has been indicated that the Soviet medical community finds no basis for requiring artificial gravity, but it is still a question of concern to Soviet space system designers.

Performance of the vestibular system is one good index of man's adaptive response to the weightless environment since this sensor system is exquisitely sensitive to gravitational effect. In view of this consideration, close attention has been paid to the function of the vestibular apparatus in weightless space flight. The relationship between the function of the vestibular system and motion sickness is well established, and so this phenomenon has been regarded as an indicator of vestibular dysfunction.

The object of this article is to review the response of astronauts in the American space program to the weightless environment using performance of the vestibular system, as indicated principally by the motion sickness phenomenon, as an index of adaptation to zero gravity, and to attempt to draw inferences from these findings related to the need, or lack thereof, for artificial gravity for future space operations.

EARLY EXPECTATIONS CONCERNING VESTIBULAR FUNCTION IN WEIGHTLESSNESS

At the time of the first Mercury mission, there was considerable concern regarding the possibility of inflight motion sickness. Consequently, anti-motion sickness drugs have been included in the onboard medical kit since this early manned mission. They were carried in both injectable and oral form. The drugs included were Tigan and Marezine. To the surprise of many, these drugs were not needed. For experimental purposes, attempts were made to provoke vestibular responses by performing head movements in the spacecraft. Crews were instructed to perform head movements cautiously while reaching for or pointing to specific areas in the spacecraft to demonstrate whether perceptual-motor impairment had been provoked. Again, no problem was noted.

THE FIRST INDICATION OF DIFFICULTY

No problems which might be indicative of vestibular disturbance were noted in the brief American flights which preceded the first one-day flight of the Soviet cosmonaut G.S. Titov in Vostok 2. Titov was reported to have shown transitory vestibular-autonomic nervous system changes, but his "work fitness" was said to be preserved and he was reported to have experienced no "essential physiological discomfort".[7] This first experience of alteration in vestibular function proved to have a rather significant psychological impact on American astronauts who were to follow the Titov flight. One astronaut had become so convinced that he would be ill in flight that he experienced sensations of nausea on the launch pad. However, when this astronaut cautiously performed head movements in flight toward the end of the mission, all went very well and he experienced no real problems.

None of the project Mercury astronauts experienced any vestibular difficulty which could be linked to exposure to weightlessness. Coincidentally, both astronauts Glenn and Shepard were victims of episodes that produced vestibular disturbances some time after their spaceflight exposure, but neither of these incidents was in any way related to the astronauts' weightless experience. Astronaut John Glenn experienced some very marked vestibular disturbances (vertigo, nausea, and nystagmus) after a fall in which he sustained a severe blow to the head in the area of the labyrinth. X-ray examinations indicated that some hemorrhage had probably occurred in the area of the labyrinth. Symptoms, however, cleared over a period of time and he has had no residual problems and has returned to flying. The case of astronaut Alan Shepard was initially less clear-cut. Several years after his first spaceflight exposure he reported episodes of vertigo. The presenting symptoms initially indicated viral labyrinthitus. It later became obvious that the astronaut was in fact afflicted with Ménière's disease. He was, as a result, grounded for a period of time. His therapy at first included medication which was not altogether effective. Twenty-nine months prior to the Apollo 14 flight, the condition was alleviated by surgery which involved the implacement of an endolymphatic shunt, permitting the endolymph to drain into the cerebrospinal fluid. This operation was completely successful, and the crewmember became totally asyptomatic.[2] Astronaut Shepard was evaluated extensively at the Naval Aerospace Medical Institute prior to his participation in the Apollo 14 mission and experienced no difficulty whatever of a vestibular nature prior to, during, or after that mission.

GEMINI RESULTS

Despite the increased internal volume of the Gemini spacecraft which permitted increased opportunity for movement, no disorientation or motion sickness was reported.[3] Normal central nervous system function, including labyrinthine function, was evidenced by the crewmembers' ability to rendezvous with the Agena vehicle, perform extravehicular activity, and execute accurate reentry maneuvers. During the eight-day Gemini 5 mission and the fourteen-day Gemini 7 mission, ocular counterrolling was measured and compared with pre- and postflight responses. Postflight, each pilot maintained his respective preflight level of response, which indicated that no significant change in otolithic sensitivity occurred as a result of the flight.[5]

Another effect which occurred during the Gemini program and which has persisted through all missions since that time is an experience of "fullness of the head" as a result of redistribution of the total circulating blood volume. This phenomenon was unfortunately described by some astronauts as a feeling of "hanging upside down on a parallel bar". As a result of this unhappy choice of words, the notion that an inversion illusion had been experienced became rather widespread. This, however, was not the case. Since the earliest observation of this phenomenon, crewmen have looked for this symptom in themselves and in others and have described it as appearing as a roundness of the face, in some cases with red coloration. In the future, these observations may be verified by photography.

APOLLO RESULTS

Apollo mission astronauts, like their Russian counterparts who have reported "space sickness" during nearly every mission[8, 9] have experienced motion sickness symptoms on a number of occasions. The divergence of findings between these later American missions and Russian missions and earlier American space missions is difficult to interpret. It should be noted that since vestibular disturbances appeared early in the Russian space program, highly trained observers have recorded even very minimal findings and these have, in turn, been interpreted in this country as more significant than they might actually have been. In support of the point that this divergence may be more illusory than real, it should be noted that electrooculograms recorded during the flight of Vostok 3 and 4, sometimes simultaneously with the administration of special tests, revealed no asymmetry of oculomotor reactions or nystagmus.[1] Moreover, vestibulometric studies did not reveal any change in the otolith apparatus' threshold of sensitivity to galvanic current in the Voskhod 1 cosmonauts, and postflight studies did not reveal any substantial changes in the function of the vestibular apparatus. What then accounts for the difference in responses of the Mercury and Gemini astronauts, on the one hand, and the Apollo astronauts on the other? Many factors, including individual variables such as prior space flight exposure, individual susceptibility to motion sickness, physical condition at the time of flight, and medication taken in flight, may play a part. However, a more obvious difference between the two mission series should be noted before any attempt is made to evaluate these variables. This is the difference in the relative volumes of the spacecraft employed. The larger the volume of a spacecraft, the greater the opportunity for increased and, probably, more rapid movement. Excessive head movements, particularly when such movements occur early in the mission, appear from inflight experience to be directly related to the onset of motion sickness symptoms.

COMPARISON OF MERCURY, GEMINI AND APOLLO VEHICLE VOLUMES

Figure 1 compares the volume of the three Command Module vehicles used to date. The Apollo Command Module, in addition to being much larger than the other two vehicles, afforded still further opportunity for movement when the Lunar Module was first mated to the Command Module for the Apollo 9 mission. For the first time, with the Apollo 9 mission, astronauts were able to move about inside two spacecraft by traversing the tunnel back and forth between the Lunar and Command Modules. Because the Apollo spacecraft was so much larger than the earlier craft, astronauts could move freely using no restraints; they could stand and tumble and exercise. Further, with lunar landings, transitions from zero gravity to one-sixth gravity, and back again, were possible. This, too, may not be without influence on a gravity-dependent system such as the otolith apparatus.

EARLY OBSERVATIONS AND ATTEMPTS AT PREDICTION AND PREVENTION OF MOTION SICKNESS

The first clear-cut case of motion sickness in American space flight was experienced by the Apollo 8 astronauts. All three crewmembers experienced symptoms ranging from stomach awareness to vomiting, lasting for up to five days in the case of one crewman. Motion sickness drugs were taken with mixed results.

Because of these findings, attempts were made to design a prevention program that was to begin prior to flight with the aim of increasing resistance to inflight motion sickness. This program included:

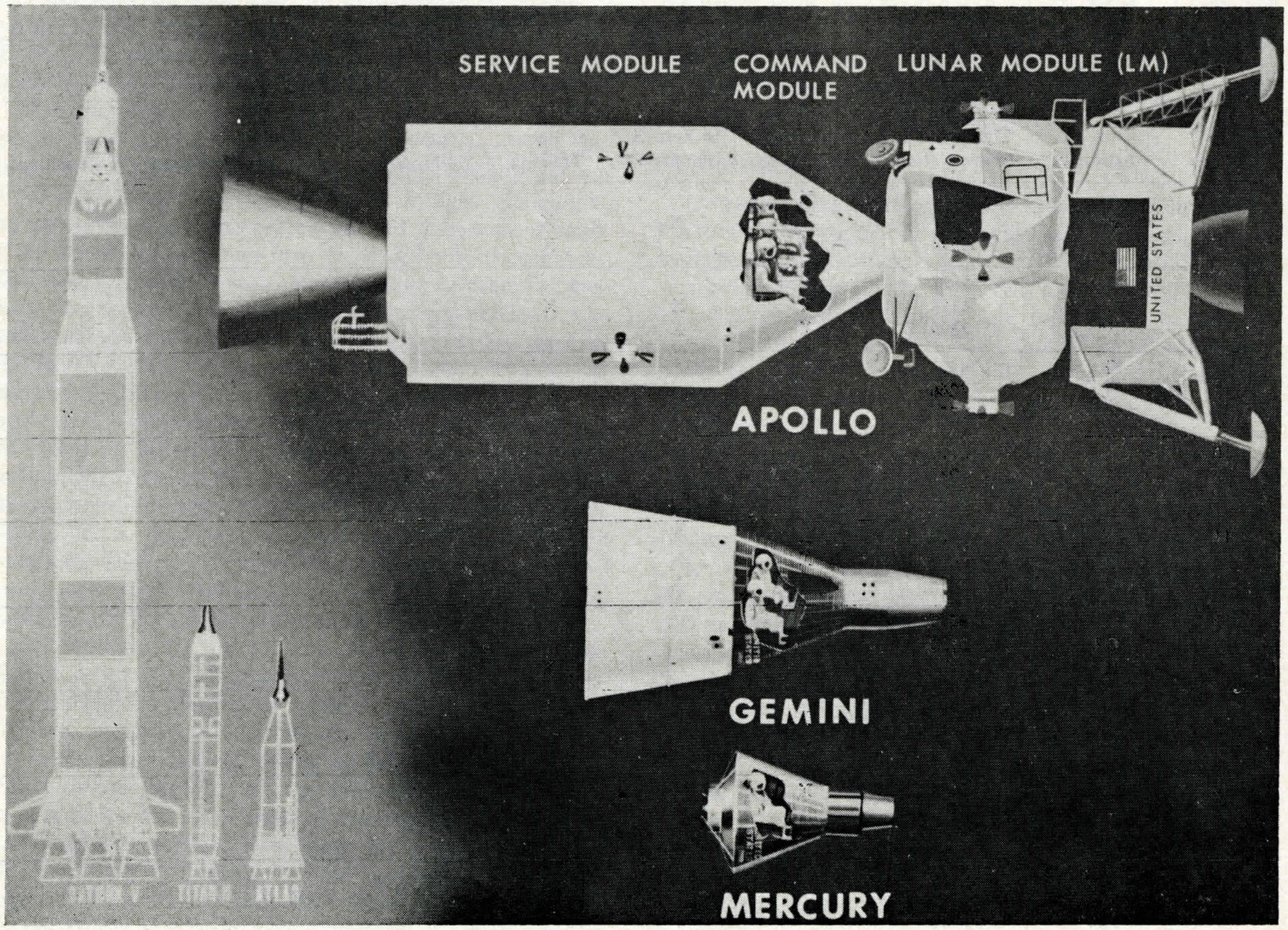

Figure 1. Comparison of Mercury, Gemini, and Apollo Command Module volumes.

1. Instruction in the use of head movements designed to hasten the process of vestibular adaptation to zero g.

2. Substitution of Dexedrine-Hyoscine for the treatment of motion sickness. This substitution was based on findings at the Naval Aerospace Medical Institute indicating that the combination of drugs was more effective than Marezine for the treatment of motion sickness.

3. The initiation of a more rigorous flying profile including aerobatic maneuvers prior to participation in weightless space flight. The above measures were adopted in lieu of more elaborate preflight evaluation because of mission time constraints.

APOLLO SERIES VESTIBULAR EVALUATION

In an effort to understand the significance of inflight motion sickness episodes, detailed histories were compiled for each astronaut in the Apollo mission series. The data points were gleaned from a variety of sources and cross-checked in order to insure that the information was accurate. These histories indicated whether or not an individual crewman had previously experienced motion sickness in automobiles, boats, and aircraft or while flying zero g parabolas or engaging in egress-type exercises during training. Symptoms experienced both during exposure to the provoking situation and after the exposure were noted. Table 1 lists these findings and indicates motion sickness symptoms and vestibular-related illusions experienced during space flight. In addition, the table specifies aircraft flight experience prior to participation in the Apollo mission noted for each crewmember.

All three crewmembers in the Apollo 8 mission experienced motion sickness symptoms. Each of these individuals had some history of motion sickness and two had prior space flight experience. The crewmember designated "E" had participated in the 14-day Gemini mission. He experienced symptoms of nausea on the first day of the Apollo 8 flight. This crewmember first complained of stomach awareness upon arising from his couch, and felt that motion sickness would be precipitated if he continued to move about freely. These symptoms, he reported, lasted for several hours and then ceased. Astronaut "F" experienced similar symptoms which again abated after several hours. In the case of astronaut "D", parallel symptoms were experienced but appeared to clear. The astronaut used a Seconal tablet to aid sleep, but awoke feeling ill again. He complained of headache and was nauseated. He, therefore, remained in his couch attempting to perform chores from the reclining position. After making a valiant effort to con-

TABLE I. ILLUSIONS AND MOTION SICKNESS SYMPTOMS EXPERIENCED BY APOLLO ASTRONAUTS

			Motion Sickness History			Illusions/Motion Sickness Symptoms in Space Flight			
Mission	Astronaut	A/C Flight Time Prior to Mission Noted	In Land, Air and Sea Vehicles	In Zero-G Parabola	In S/C Egress or Egress Training	Tumbling Illusions	Stomach Awareness	Nausea	Vomiting
7	A	4517	X						
	B*	4107	X	X	X				
	C*	3574	X		X	X			
8	D	5627	X				X	X	X**
	E	4358	X	X	X		X	X	
	F*	3399	X	X			X		
9	G	4323							
	H	4266			X	X	X		
	I*	2279	X	X	X		X	X	X
10	J	5221	X						
	K	4747	X						
	L	2787	X				X		
11	M	6400	X	X	X				
	N	4425	X	X	X				
	O	3676	X	X					
12	P	4057	X						
	Q*	3638							
	R	3914			X				
13	S(E)	4282	X	X	X				
	T*	6249					X	X	X
	U*	6135					X		
14	V	5063	X						
	W*	3594	X						
	X*	4276							
15	Y(H)	4780			X				
	Z*	6715		X		X	X		
	AA*	3370							

*Had no prior space flight experience. **Concomitant illness.

trol the symptoms, even managing to swallow a small amount of vomitus several times, he finally succumbed and vomited into a fecal collection bag. This apparently relieved his discomfort, but it appeared to precipitate symptoms once again in crewman "F". The crewmen expressed the feeling that the symptoms were related to Seconal administration, in conjunction with which they had experienced symptoms of nausea on the ground. In fact, both men had been afflicted with gastroenteritis when they had been medicated and it is likely that the illness rather than the drug precipitated the difficulty.

Of the Apollo 9 crew, two were experienced astronauts. Astronaut "G" alone had no reported history of motion sickness and he, unlike the others, experienced no symptoms whatever during his Apollo mission. Astronaut "H" had experienced Coriolis effects during the Gemini 8 mission when that spacecraft rotated at a very high rate of speed and he was reaching up to switch circuit breakers to correct the situation. Interestingly, when he became aware of the fact that his symptoms were associated with looking for the controls, he simply reached for them but did not look for them, and the Coriolis effects ceased. In the Apollo flight, he experienced stomach awareness which lasted for two to three hours at the beginning of the flight. Coupled with this, he expressed a lack of interest in food which lasted through the second day of the mission. While donning his spacesuit on that day, he experienced a feeling of tumbling and spinning as he bent down to don the suit. During the performance of extravehicular activity, however, he experienced no symptoms.

Astronaut "I" who had had no prior space flight exposure, had more symptoms of motion sickness than any other individual in the Apollo 9 mission. Because he was concerned about the possibility of inflight difficulties, he was given Marezine prelaunch and then took it again after about 1-1/2 hours into orbit. Despite the medication and attempts to restrict movement as much as possible, he experienced stomach awareness and two episodes of nausea, and vomited. He also lost his appetite for the first six to seven days of the mission. Finally, he adapted to the weightless environment and had no further problems. This individual had been tested preflight and exhibited no labyrinthine abnormality, nor did he prove to be highly susceptible to motion sickness during ground testing or while performing nine zero-g parabolic aircraft flights in a postflight evaluation program. In early parabolic flights, he experienced some symptoms, but quickly adapted. Strangely, however, he did not show the same facility for adaptation in space flight.

By the time of the Apollo 10 mission, five of nine Apollo mission astronauts had experienced motion sickness difficulties ranging in degree from mild to severe. Of the Apollo 10 astronauts, the individual with markedly fewer aircraft flying hours was the only mission crewmember who felt any symptoms of motion sickness. For the first two days of the Apollo 10 flight, he suffered from stomach awareness and a loss of appetite. He employed programmed head movements in an attempt to hasten adaptation, but these, he reported, produced nausea to a point near vomiting, at which time he terminated the movements. When the head movements were attempted once again on the second day of flight, exacerbation of the symptoms occurred after one minute. After two days of flight, during which the astronaut moved cautiously to minimize symptoms, he adapted completely and experienced no further difficulty. On the seventh day of the mission, he experimented with the head movements once again and was this time able to perform them for five minutes, but, again, the movements precipitated feelings of motion sickness.

Among the Apollo 11 crew, all crewmembers had fairly extensive histories of motion sickness difficulties but none had any difficulties whatsoever during orbital flight or during lunar surface activities. Many predictions had been made regarding the possibility of experiencing disorientation when stepping out upon the lunar surface. However, no such difficulty has been encountered by any of the astronauts performing lunar surface activity.

Only one individual in the Apollo 13 crew had a history of motion sickness and, paradoxically, he alone experienced no symptoms during weightless flight. The other two crewmembers who suffered, in one case, stomach awareness lasting for one day and, in the other, nausea and vomiting as well had had no prior space flight exposure.

The Apollo 14 crew had a mixed history of prespaceflight motion sickness episodes and still no difficulty was noted during weightless flight. None of these crewmembers took any medication at all. In the Apollo 15 crew, one of the two astronauts who encountered no difficulty was the only crewmember with no history of motion sickness. He also had significantly less flight time than the other two crewmembers.

SUMMARY

Of twenty-five astronauts who participated in Apollo missions 7 through 15, nine have shown some sort of inflight symptomatology that could be related to the vestibular system. Of the nine, two have entirely negative histories for motion sickness, four have only one positive history finding, and two have markedly fewer flying hours than the other individuals. Of the seventeen individuals exhibiting no inflight symptomatology, twelve have positive histories.

No trends can be seen here. There appears to be no definite relationship between either flying time or prior experience, or any other variable, and the experience of motion sickness symptoms in the weightless state. Despite individual variables, however, various elements of the space flight environment appear to precipitate motion sickness symptoms. The volume of the spacecraft seems to be important. Increased volume, affording additional opportunity to move about freely, exacerbates the motion sickness problem. This seems to be evidenced by the fact that no astronauts in the smaller Mercury or Gemini capsules experienced any vestibular-related difficulty. It does not appear likely that transitioning from zero gravity to the one-sixth gravity environment of the lunar surface, or the return transition, has any significant effect. Head movements, programmed to hasten otolithic adaptation to zero g, appear to produce motion sickness difficulty in flight. The head movement technique may, however, not have received an altogether fair test since the regimen, which calls for the prior use of medication, has not always been followed explicitly.

Emotional factors cannot be disregarded in the production of motion sickness symptoms. This is clearly demonstrated by the experience of the Apollo 7 astronaut who exhibited symptomatology even before he was airborne. Soviet investigators[8] also believe the emotional state of the individual to bear a definite relationship to motion sickness.

The magnitude of the motion sickness problem experienced by astronauts to date does not appear to clearly suggest the need for design and incorporation of an artificial gravity system in near-future space vehicles. By and large, adaptation to zero gravity proceeds relatively smoothly. In no case has an individual who has experienced motion sickness symptoms failed to adapt to the weightless state eventually, and, this adaptation usually proceeds rather quickly. In general, adaptation occurs more smoothly when movements are made cautiously during the adaptation period. Once adaptation is complete, even violent movements such as tumbling and spinning are possible without provocation of unusual symptoms. Although there is no plain requirement from a medical standpoint for the provision of artificial gravity, other considerations may ultimately lead us in that direction.

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