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DESIGN CRITERIA FOR THE SPATIAL ORIENTATION TRAINER

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FOREWORD

This work was accomplished by personnel in the Vestibular Research Section, ENT Branch, under task No. 775508, between January and June 1967. The paper was submitted for publication on 6 July 1967.

This report has been reviewed and is approved.

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ABSTRACT

Spatial disorientation continues to cause at least 4% of the aircraft accidents in the Air Force. At the USAF School of Aerospace Medicine, the Spatial Orientation Trainer has been designed to help eliminate such accidents. The more deadly of the vestibular illusions of flight (namely, the Coriolis illusion, the oculogravic illusion, and the graveyard spin) can be reproduced and used to stress the pilot while he is performing a simulated mission in the trainer. Such exposure gives him practice in overcoming the sensory conflicts that result in disorientation and practice in proper aircraft control in spite of disorientation. The methods by which the illusions of flight are to be produced and the criteria upon which effectiveness of the trainer is to be judged are discussed in detail.

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I. INTRODUCTION

Spatial disorientation accidents still happen. In 1959 Nuttall and Sanford (1) revealed that 14% of the fatal aircraft accidents and 4% of all major aircraft accidents in the USAFE were caused by spatial disorientation. According to data available from the Inspector General of the Air Force (2), approximately 4% of aircraft accidents currently suffered by the Air Force are still "definitely or probably" caused by spatial disorientation. At the recent U. S. Navy Symposium on Vertigo as a Problem in Aerospace Medicine, Luehrs (3) pointed out that during the eight-year period from 1958 to 1966, losses of 395 Navy aircraft were "ostensibly due to spatial disorientation" at an estimated cost to the Navy of at least $150,000,000.

Even more recently, Smiley (4) reported the results of a survey of 224 Canadian military pilots, which showed that spatial disorientation was by far the most common aeromedical occurrence which causes pilots "real concern for safety of self or aircraft." These data serve to augment the findings of Smith (5), who concluded that spatial disorientation was responsible for more than half of aircraft accidents in the Royal Air Force not caused primarily by mechanical failure. Smiley's results likewise tend to reinforce the statement by Nuttall (6) that disorientation of the pilot is involved in more than 25% of major aircraft accidents in the US Air Force in which physical, physiologic, and pathologic factors are implicated.

Through the years, diverse devices have appeared with the purported purpose of making the pilot less susceptible to spatial disorientation. For many years the Barany chair has been a favorite tool of the flight surgeon for demonstrating some of the vestibular illusions to pilots. Link Trainers—specifically, dynamic flight simulators such as the Link C-8—have been and still are a real boon to flight instructors and students. In the Link Trainer, the trainee is given the chance to develop and practice his instrument cross-check, and is often given the chance to develop and fight some types of pilot vertigo, as well. Somewhere in oblivion is a unique device which represents the product of some early thinking on the problem of spatial disorientation. Bonner (7) in 1963, published this statement: "Zim recommended in 1943 that the United States adopt the Ruggles Orientor [*sic*] for training in disorientation. As we know, nothing came of this." A check on Zim (8) reveals that he has encaptioned a picture of a contorting, gimbaled, three-axis machine: "This device, the Ruggles Orientator, duplicates any position of the pilot in flying and has aided in understanding the problems of balance and airsickness." It further appears that Zim's "recommendation" was only inferred. The search for information on the Ruggles Orientator took us finally to Bauer's *Aviation Medicine* (9), published in 1926. Bauer has this to say about the Ruggles Orientator:

> The hypersensitive (with respect to vestibular tests) individual is very easily confused by rapid changes in position in respect to his environment. Consequently when he goes into the air and does acrobatic work he is apt to become very confused following a spin, tight spiral or other stunts and be unable to right his machine in time to escape accident. The experienced flier not only becomes used to his sensations but his sensations become less marked and he is not easily confused. As already stated, the test pilot becomes immunized to rapid changes in motion; dizziness and vertigo disappear and he is able to interpret his sensations so that he shows little reaction to rotation or other rapid

> changes in motion. The whirling dancer, for instance, is able to stop suddenly without falling, whereas the novice will fall.
>
> With this in mind, an apparatus was developed during the war (World War I) known as the Ruggles Orientator. Briefly the apparatus consists of a cockpit of an airplane suspended in three concentric rings. It is operated by motors and is controlled by a stick and rudder in the cockpit or by a stick and rudder in the instructor's chai- on the ground. By a combination of movements of the stick and rudder, the Orientator can be put through any evolution that a plane can be put through except straight forward, or up and down motion. In other words, it can be looped, rolled, spun, put through a tight spiral, an Immelmann, etc. These movements are similar to those made by a plane except that they are made at a greater angular velocity. The effects, therefore, will be more severe than those experienced in a plane.
>
> The original idea was to train a man in the Orientator in conjunction with his flying training, accustoming him to rapid changes in his position in space with respect to the horizon, so that when he actually went into the air he would be less confused and less apt to have an accident during his early training. The Orientator came into disrepute because some claims were made that it would teach a man to fly. This, of course, it will never do. Recently at the primary flying school of the United States Air Service, the Orientator has again been used in connection with the flying instruction, purely for the purpose of shortening the period of training, and an effort has been made to pick out men who are slow reactors and will not make good pilots.

The fate of the Ruggles Orientator was sealed soon after the above material was published, as it was subsequently proved that tests on the Ruggles Orientator were completely invalid measures of flying aptitude (10). Examination of several photographs of the Ruggles Orientator reveals that, although it has 360° of freedom about three orthogonal axes, it is incapable of providing the trainee with control responses that would be anywhere near analogous to the control responses of an aircraft in flight; in fact, the more unusual the attitude of the cockpit, the more distorted is the control response (see discussion of this phenomenon in section II). It would appear that the Ruggles Orientator was not the final answer to the problem of spatial disorientation, which had barely been recognized in this early era of flight, and could hardly be expected to be resolved so soon.

In 1964, a new tack was taken in the endeavor to defeat spatial disorientation. The Spatial Disorientation Demonstrator (SDD) (figs. 1 and 2) was built at the USAF School of Aerospace Medicine for the purpose of demonstrating to pilots, in a relatively inexpensive and completely safe ground-based vehicle, the more important illusions of flight (11). The SDD is, in effect, a very inexpensive short-armed centrifuge, the cabin of which travels along a circular (10-ft. diameter) track at angular velocities up to 25 r.p.m. (2.6 radians/sec.). The cabin can be rotated continuously about its vertical axis and positioned to face any direction relative to the hub of the apparatus. The vertical axis of the cabin itself can be tilted ±15° about a tangential axis, so as to allow the cabin to pitch or roll, depending upon the direction which the cabin is facing. The inside of the cabin resembles an F-100 cockpit and contains a functioning attitude indicator. The pilot, riding in the cabin of the SDD, can be subjected not only to constant angular velocities up to 25 r.p.m. (2.6 radians/sec.) in the main yaw plane with concomitant linear (centripetal) acceleration up to 1 g, but also to various other angular velocities and angular accelerations in the pitch, roll, and planetary yaw planes. By proper manipulation of the controls, the operator can cause the pilot to experience some of the vestibular illusions common to flight, which the pilot can recognize as illusory by comparing his sensations with the true attitude information on the gyro horizon. The SDD has served well as a demonstrator of spatial disorientation, and much has been learned from it with respect to stimulus requirements, reproducibility of illusions, and similar parameters. But it has become obvious that the SDD lacks certain characteristics and capabilities that the ideal disorientation training device must possess.

II. THE SPATIAL ORIENTATION TRAINER

The problem confronting flight surgeons, physiological training officers, and others interested in eliminating spatial disorientation

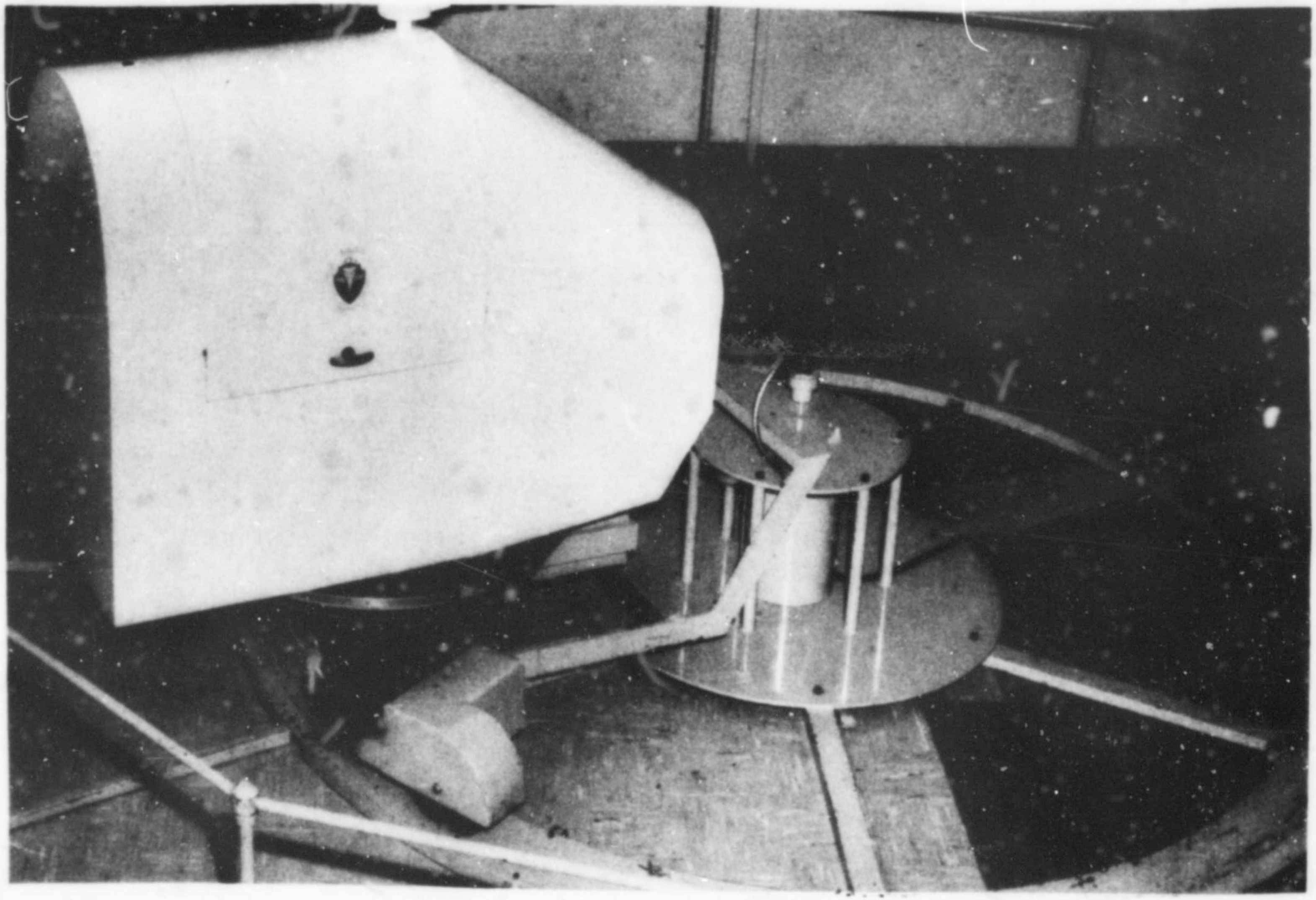


FIGURE 1

The USAF Spatial Disorientation Demonstrator (SDD).

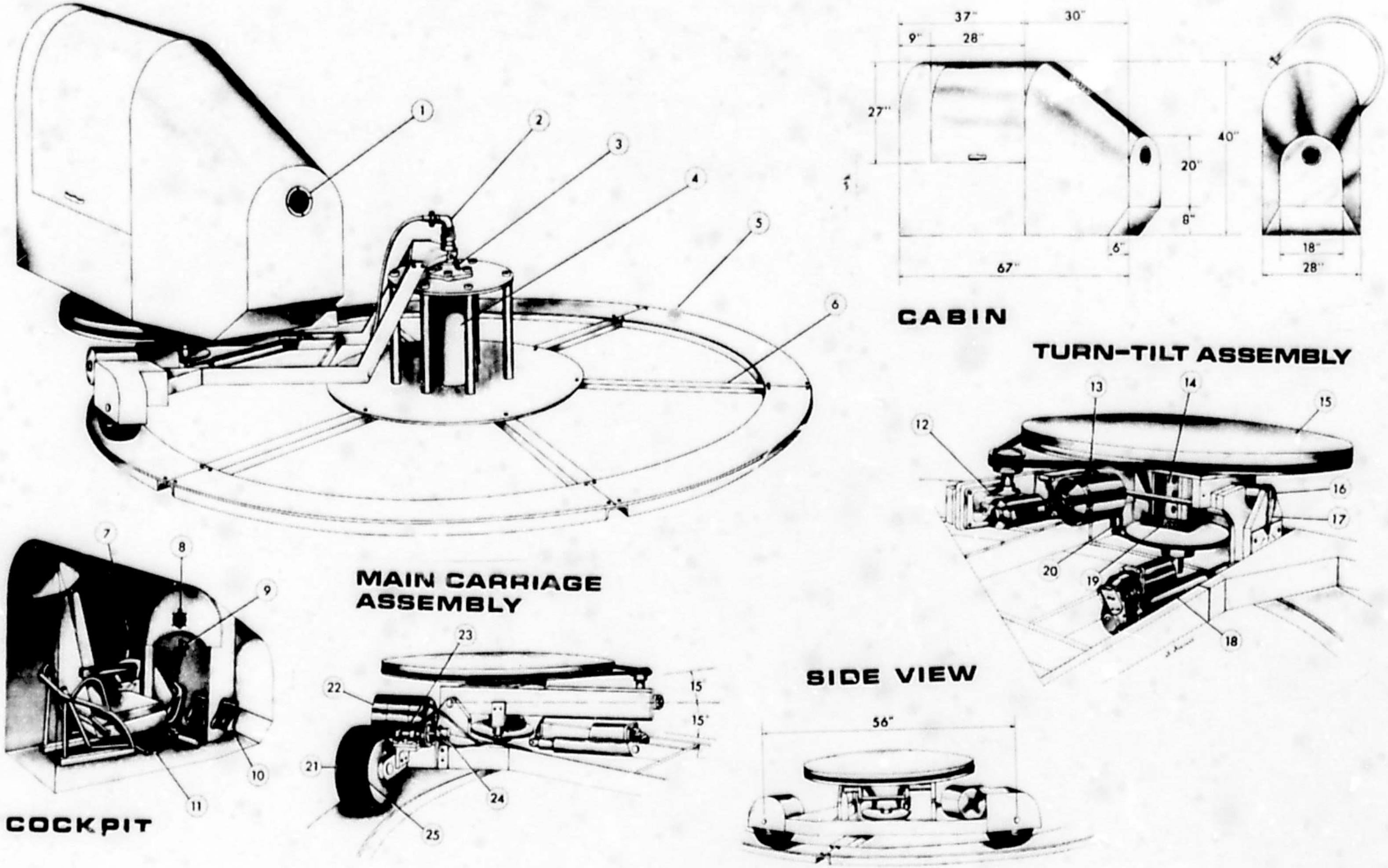


FIGURE 2

Details of construction of the SDD. The key to the numbers is available in SAM-TR-65-7.

accidents has been threefold. First, we would like to be able to demonstrate effectively to pilots that spatial disorientation can happen to anyone. Second, we would like to be able to discern, through testing, which pilots might be prone to lose aircraft control under disorienting conditions. Third, we would like to be able to offer pilots a means by which they can become resistant to the effects of disorienting influences. The Spatial Orientation Trainer (fig. 3) is currently being developed by the Air Force to attack the problem of disorientation from all three aspects.

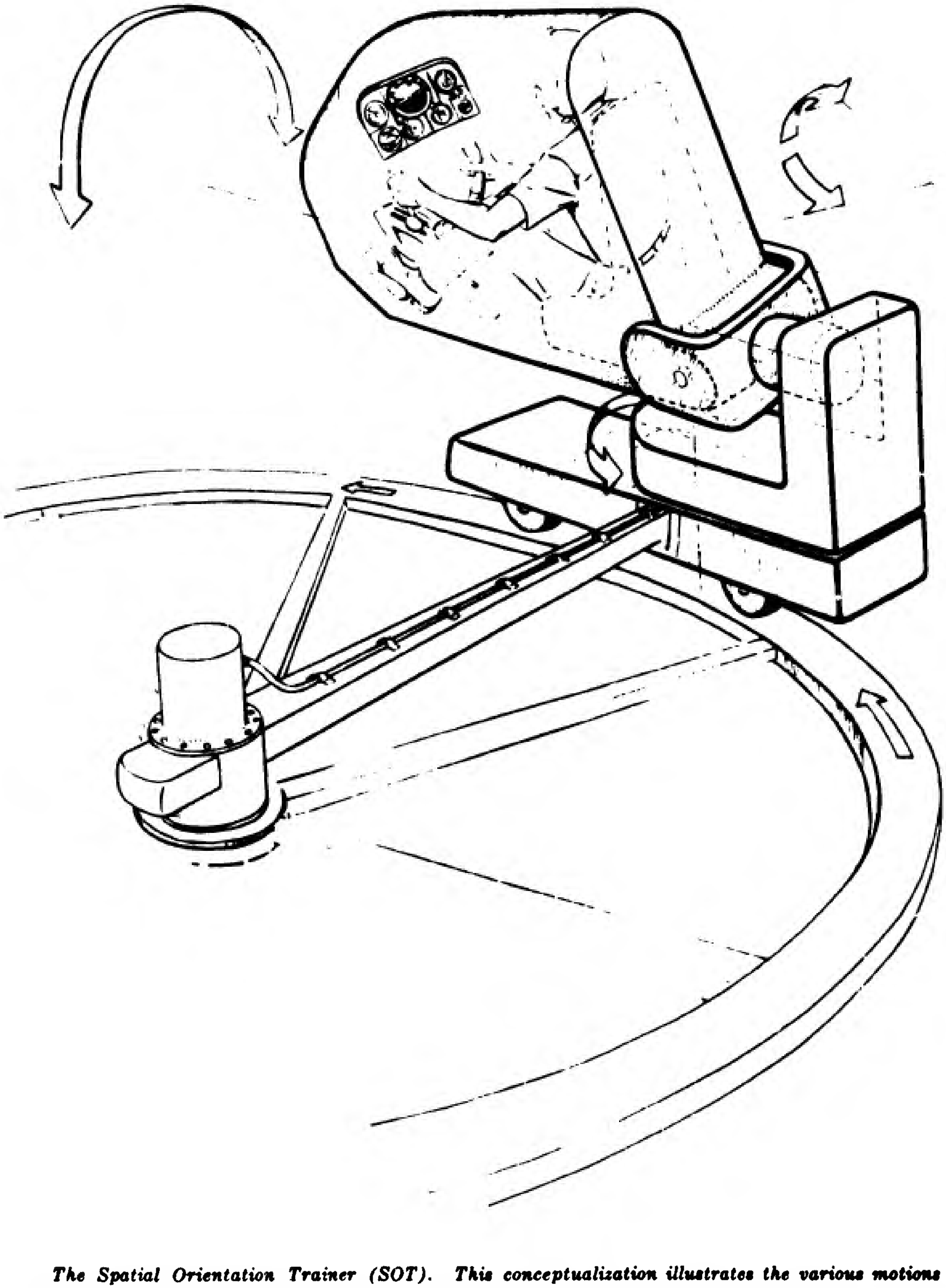
Nature of the Spatial Orientation Trainer

At this point we should review the types of spatial disorientation which have not only been proved to be the most deadly to pilots but also have been found to be the most amenable to study and reproduction. These are the oculogravic illusion, the Coriolis illusion, and the illusion of rotation that results in the graveyard spin (12).

The oculogravic illusion results from inadequacies of the otolith organs and proprioceptive system in the airborne environment (fig. 4). The oculogravic illusion occurs when the inertial force of a large linear acceleration combines with the force of gravity to form a resultant force which is falsely construed by the pilot to be acting in the same direction as the force of gravity. If the pilot then controls his aircraft with reference to the perceived vertical rather than the actual one, he will put the aircraft into a dive. The oculogravic illusion is common during night and weather takeoffs in high-performance aircraft, and the all-too-frequent result of the illusion is a full-power crash several miles from the end of the runway. The Spatial Disorientation Demonstrator owes much of its success to the fact that it can produce the oculogravic illusion by generating up to 1 g in the longitudinal direction when it is revolving with the nose of the cabin facing the hub of the apparatus. The oculogravic illusion has exacted a high tribute from the Air Force in pilots and aircraft, and is second only to the Coriolis illusion on the list of most dangerous and devastating types of disorientation.

The Coriolis illusion results from inadequacies of the semicircular canals in the airborne environment (fig. 5). The Coriolis illusion occurs during protracted angular velocities when the head is rotated in a plane that cuts across the plane of the protracted angular velocity. The illusion suffered following the coupling of such angular motions is one of undergoing rotation in a plane in which no actual rotation has occurred. If one yaws at a reasonably constant velocity for about 10 seconds, for example, then pitches his head forward while the yaw is persisting, he will experience a sensation of roll; similarly, if he is pitching and then rolls, he will experience the false sensation of yaw. The Coriolis illusion has been blamed, and reasonably so, for a number of aircraft accidents that have occurred during penetration turns, when radio frequency changes and other cockpit duties have required the pilot to make extreme head movements. Coriolis illusions can be generated quite easily in the SDD, the Barany chair, and even in the Link Trainer, when the rider rotates his head in a plane other than the plane of rotation of the device.

The graveyard spin (fig. 6) also results from inadequacies of the semicircular canals in the airborne environment. When a pilot gets into a spin, he undergoes an initial angular acceleration in the direction of the spin, and perceives the rotation of the spin for a short while after the cessation of angular acceleration. After about 10 to 20 seconds, the semicircular canals equilibrate to the rotation, and the pilot perceives no spin. If the pilot then pushes the opposite rudder to stop the spin, he will undergo an angular deceleration which will be monitored by his semicircular canals and interpreted by his central nervous system as representing a spin in the opposite direction. Even though his turn needle indicated to him that he was not spinning, an inexperienced pilot, deprived of external visual reference, may be tempted to make a control correction that puts him into a spin in the direction of the original angular motion. This eventuality is known as the graveyard spin. The false sensations concomitant with the graveyard spin can be generated in the SDD, in the Link Trainer and, of course, in the Barany chair.



The Spatial Orientation Trainer (SOT). This conceptualization illustrates the various motions of which the SOT will be capable. The pilot riding this device will be subjected to the same illusions that the SDD generates, but he will be able to "fly" the SOT by operating the controls.

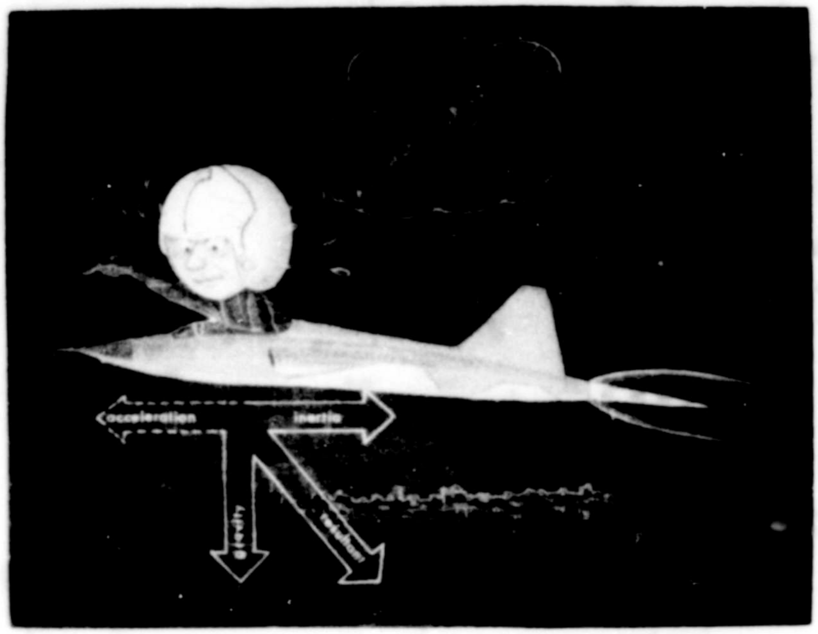


FIGURE 4

The oculogravic illusion. As this high-performance aircraft takes off, the pilot may falsely perceive that the aircraft is in a steep climb.

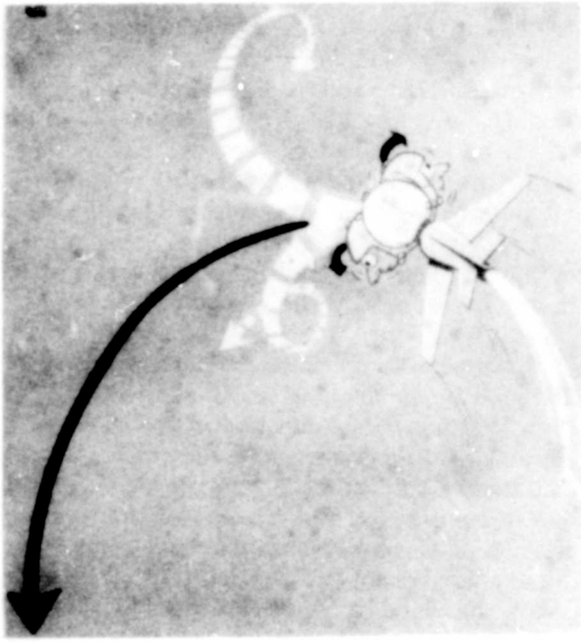


FIGURE 5

The Coriolis illusion. If the pilot moves his head while in a prolonged turn, he may experience false sensations of violent changes of aircraft attitude.

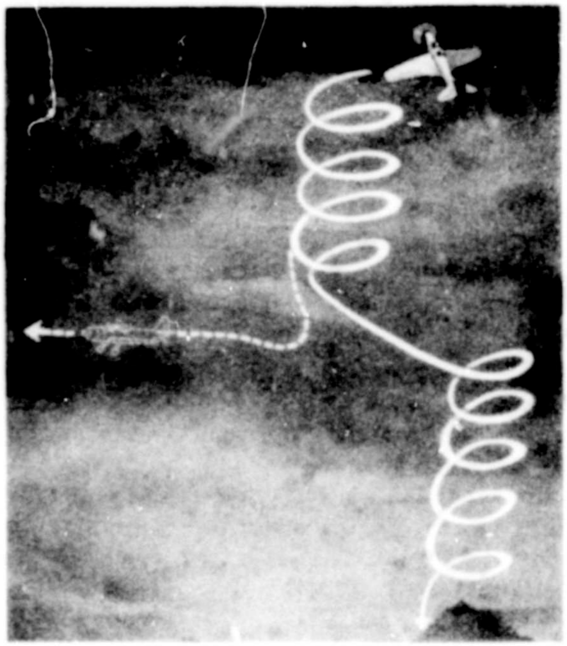


FIGURE 6

The graveyard spin. In recovering from a prolonged spin, the pilot perceives the start of a spin in the opposite direction. Correcting for that false sensation, he enters another spin in the original direction.

Inasmuch as the oculogravic illusion is a large source of concern from the standpoint of flight safety, we feel it is imperative that the SOT be able to generate that illusion in its occupant. We feel also that a radial acceleration of 1 g (resulting in 1 G of inertial force) will be enough to produce an unquestionably adequate oculogravic illusion. An inertial force of 1 G in the horizontal plane combined with 1 G in the vertical direction (downward, due to gravity) will provide a resultant force of 1.414 G's at an angle of 45° up from the true vertical. This displacement of the gravito-inertial force vector will give the occupant of the SOT an illusion of being in a 45° climb while he is actually in level flight. If the same illusion is experienced while the SOT is actually in a 30° nose-up attitude, then the illusion will be one of at least a 75° climb. We say "at least" 75°, because we have discovered that many times the occupants of the SDD have experienced nose-up attitudes of 90° even though the calculated angle between the gravito-inertial force vector and the longitudinal axis of the cabin was somewhat less than 60°. A possible source of the augmented sensory response is the elevator illusion (12).

The calculation of the radial acceleration that can be generated by the SOT is simple:

$$a = \omega^2 r$$

When a is the radial acceleration, ω is angular velocity in radians/sec., and r is the radius (in this case, equal to 150 cm. or approximately 5 ft.). To find the acceleration in g's, divide $\omega^2 r$ by 980 cm./sec.^{2} when working in the centimeter-gram-second system, or by 32 ft./sec.^{2} if you use the foot-pound-second system. Understanding that every g of acceleration results in a G of inertial force in the opposite direction, we can calculate the magnitude and direction of the force which the subject experiences by adding the G's of inertial force generated by the SOT to the 1 G of gravity, vectorially, of course, with a 90° angle between the two forces. Then the angle of the resultant force relative to the subject in the SOT can be calculated by adding the pitch attitude of the cabin to the angle (ϕ) between the resultant force vector and the true vertical. At 25 r.p.m. (2.6 radians/sec.) of angular velocity in the horizontal plane, the SOT will generate approximately 1 g of radial acceleration and a very adequate oculogravic illusion, as can be verified by working the calculation outlined above.

$$\begin{aligned} a &= \omega^2 r \\ &= 2.6^2 \text{ rad./sec.}^2 \text{ } 150 \text{ cm.} \\ &= 6.76 \text{ rad./sec.}^2 \text{ } 150 \text{ cm.} \\ a &= 1{,}014 \text{ cm./sec.}^2 \\ a &= 1.03 \text{ g in the horizontal plane} \end{aligned} \tag{1}$$

Thus, by vector addition of the inertial force and the force of gravity, the net force on the occupant of the SOT will be 1.42 G at an angle ϕ of approximately 45° from the true vertical. This force environment will result in an oculogravic illusion of at least 45° of nose-high attitude when the cabin is level, and at least 75° (ϕ plus pitch angle) of same when the cabin is pitched up 30°.

There is a certain lag in the development of the oculogravic illusion, as has been reported elsewhere (13), and is borne out by our experience with the SDD. We have observed the lag to be from 15 to 45 seconds, during which time the illusion is gradually building to maximum. We have no means at present of calculating the augmentation (described above) of the oculogravic illusion that we suspect might be caused by the elevator illusion.

Inasmuch as Coriolis illusions are also of extreme importance from the standpoint of flight safety, it is imperative that the SOT be capable of generating these illusions. Three factors are important in the development of the vestibular Coriolis effect: ω_1, the angular velocity of the constantly rotating system; ω_2, the angular velocity of the rotation which cuts across the plane of the rotating system, and t, the time over which ω_2 acts.

$$\text{Coriolis effect} \sim \omega_1 \, \omega_2 \, t \tag{2}$$

states the relationship between the intensity of the vestibular Coriolis effect and the parameters responsible for its development. Our experience with the SDD has shown us that substantial Coriolis effects can be generated at an ω_1 of 15 r.p.m. (approximately 1.6 radians/sec.), even though ω_2 is very low in the SDD—less than 0.1 radian/sec. in the pitch and roll plane.

It should be apparent from the "equation" for the production of Coriolis effects and from the equation for calculating radial acceleration (hence, the magnitude of the oculogravic illusion) that the shorter the radius, the greater the ratio of Coriolis effect to oculogravic effect that will be realized from a rotating device and the greater the savings in structural material and space. The 5-foot value for the radius of the SOT was selected on the basis of our experience with the SDD, which revealed that completely adequate Coriolis and oculogravic illusions can be generated in a device with a 5-foot radius and an angular velocity of 15 r.p.m. (1.6 radians/sec.). Since the SOT will be rotating at 25 r.p.m. (2.6 radians/sec.), the Coriolis effect concomitant with a given head movement performed in the SOT will be approximately 1.7 times the magnitude of the Coriolis effect produced by the same head movement in the SDD.

The Coriolis effect is responsible for another type of illusion which can be generated in the SDD, and although it has no readily recognizable counterpart in operational flying, it nevertheless is extremely disorienting. If the operator pitches the cabin of the SDD upward while it is revolving around the track at a constant angular velocity, the occupant will experience a rolling motion of the cabin which is purely illusory. Similarly, if the cabin is rolled while it is undergoing constant angular velocity, the occupant will feel that the cabin is involved in a pitching motion. The rolling sensation resulting from such a Coriolis effect in the SDD has been estimated to cover 15° to 20°, even though the ω_2 (referring to equation 2) of the SDD is less than 0.1 radian/sec. The angular velocities of pitch and roll of which the SOT will be capable will be nearly equivalent to those of which a high-performance aircraft is capable; i.e., they will approach 2 radians/sec. In addition, the total displacement about the pitch and roll axes of which the SOT will be capable will be considerably greater than that which the SDD can provide: the SOT will be able to pitch 30° up or down to the horizontal and will be able to roll left or right 90° from the vertical, which displacements represent increases over the maximum displacement of the SDD about those axes by factors of 2 and 6, respectively. This means, referring to equation 2 above, that the disorientation related to this type of Coriolis effect will be considerably increased over the effect which the SDD can generate. Let us take $\omega_2 t$ (the angular displacement across the plane of ω_1) to represent the input into the Coriolis effect that is attributable to pitching or rolling motions of the SDD and SOT. The relative magnitude of the Coriolis effect resulting from a maximum pitching maneuver of the SOT can be calculated thus: Since the ω_1 of the SOT can reach 1.7 times the ω_1 of the SDD, and the $\omega_2 t$ of the SOT is 2 times that of the SDD, then the Coriolis effect from the SOT becomes approximately 3.4 times that obtainable in the SDD. A similar calculation shows that the Coriolis effect resulting from a rolling maneuver in the SOT can be approximately 10.2 times that obtainable from a rolling maneuver in the SDD. It must be pointed out, however, that these results derived from the use of equation 2 are in error by an undetermined amount because certain factors that relate to the trigonometry of the angle of displacement, to the viscous damping of the endolymph in the semicircular canals, and to the sensory enhancement and diminution functions of the central nervous system, have not been (and cannot be, owing to our limited knowledge in this area) considered in our calculations. The graveyard spin, although we do not believe that it is as significant a problem from the standpoint of flight safety as it once was, is a classic example of what can happen when false sensory impressions betray the aviator; and every pilot should experience the false sensations that lead to the graveyard spin. To produce the sensation of spinning, the SOT will be positioned with the nose of the cabin facing away from the hub of the apparatus and will be in a 30°-down pitch attitude. The device will then be accelerated to a constant angular velocity around the track and maintained at that velocity for approximately 10 seconds. As the "spin" is stopped, the occupant of the SOT will feel the start of a spin in the opposite direction. If he corrects for this illusory sensation of rotation, he will put the trainer in a "graveyard spin" (i.e., in a spin in the original direction).

Now we come to the topic of what we expect the occupant of the SOT to do when he experiences one of the illusions of flight. When an occupant of the SDD experiences an illusion in that device he can be made aware of the fact that his sensation is illusory by giving him reference to his true attitude (i.e., by allowing him to observe the attitude indicator). The SDD only demonstrates to its occupant the phenomenon of spatial disorientation; it does not require any performance from him other than the recognition and relating of his experience. The SOT, on the other hand, will not only demonstrate the illusions of spatial disorientation to the occupant but will also require him to control the attitude of the SOT in spite of the condition of spatial disorientation which has been imposed. If, for example, the subject is given an oculogravic illusion and is then asked to maintain the SOT in a straight and level attitude, he will have to react in response to the reliable information presented to him on the instrument panel, to the exclusion of the unreliable information presented to him through his vestibular and other proprioceptive sensors. We believe that practice at such a task will develop in the trainee the visual dominance characteristic of the experienced instrument pilot. We make the basic assumption that the more precisely the trainee controls the attitude of the SOT in the face of the stresses of disorientation, the more resistant this man is to the effects of disorientation and, therefore, the safer he will be in the air when conditions conducive to disorientation are prevalent.

The question has come up as to whether we expect practice in the SOT to actually attenuate the illusions associated with disorientation or whether we expect only to train him to respond appropriately and with more efficiency in spite of his illusions. At present we believe that the SOT will promote both of those desirable conditions, but whether such will be the case is actually irrelevant until the beneficial effects of training are demonstrated by improved performance.

Some criticisms and special problems

Some of the thinking that has resulted in the current specifications for the SOT requires explanatory discussion, as questions have arisen regarding the validity of that thinking in several different areas.

The first question that is often raised is: "Why don't you just have the stick control the positions of the various instruments, rather than go to the expense of having it control the actual attitude of the device and then the instruments? After all, that's what the proficient instrument pilot does—ignores his false sensations and concentrates on obtaining the correct instrument reading." The fallacy of this argument is not always seen at first glance; and, in fact, it was on the basis of such thinking that the original model of the SDD (since modified) was developed. In the first model of the SDD, the occupant did not have control over the actual attitude of the cabin of the device, but he did have control, through the stick, over the indication of a dummy attitude indicator which was continually resetting itself to indicate different positions of pitch and roll. The task of the occupant was to move the stick to position the horizon bar in such a way that it would always indicate straight and level, during which time he was being disoriented by the motions of the SSD. We must strongly emphasize at this point that, just because there is a disparity between what is indicated on the dummy attitude indicator and what is communicated to the brain about orientation by the senses of balance, it does not mean that there is a conflict between these two inputs. In the example just given, no orientation information was presented on the attitude indicator, because it was not related to the true attitude, and the occupant of the SDD knew it. Thus, any statement implying that the occupant had a task of discerning between his visual and vestibular information in order to effectively control the device, was completely misleading. Any decrement in the subject's ability to control the attitude indicator while the SDD was in motion was not related to any disorientation of the subject (or "unorientation," to recall a word that has been used to describe the condition generated by the original version of the SDD). The response decrement in the "unoriented" as opposed to the static condition is attributable to what we call kinetosis, which is a state of physiologic and psychologic impairment resulting from the effects of motion in general, not specifically from disorientation. The point is that in order to make spatial disorientation a relevant factor in the attitude control problem, we must make certain that the subject understands that some semblance of attitude control can be achieved through the use of his vestibular and other proprioceptive senses. Furthermore, he must also understand that the information presented to him through the attitude indicator will give him another means by which he can control the attitude of the vehicle. Only then can the situation of sensory conflict (i.e., vertigo) appear, as it does in an aircraft. This is why we maintain adamantly that to have a successful "vertigo trainer," we must have the trainee "in the attitude control loop" as opposed to "out of the loop," as he is in the SDD.

Another criticism of the SOT is concerned with the fact that the motions which the SOT will undergo are not identical to the motions which an aircraft undergoes. The critic asks: "What aircraft flies around in a circle at 25 r.p.m., simultaneously pitching and rolling? Will training on the SOT even transfer to the situation in a real aircraft, and might there be the possibility of negative transfer?" We cannot answer these questions either positively or negatively. We can say only that we are intending not to train a pilot to respond appropriately to specific illusions in specific aircraft, but are trying to instill in him the capability of responding appropriately to the information presented on the instrument panel whether it be to the exclusion of, or in spite of, pilot vertigo of a general nature. Even though it may be necessary to warn the trainee that the illusions he will perceive in the SOT will not be completely identical to those he may experience in various aircraft, we nevertheless believe that the time spent practicing accurate control of the attitude of the SOT will give the trainee some insight into how to accomplish a similar task in an aircraft when he is stressed by factors conducive to spatial disorientation.

A word of explanation is in order as to why we are limiting the pitch freedom of the SOT to ±30° and the roll freedom to ±90°, and as to why we prefer the order of the gimbal axes to be pitch, roll, and finally, yaw, from inside outward. The reasons can be seen if we consider the fact that in an aircraft, when it pitches or rolls to a new attitude, the plane of reference for attitude control purposes is carried with it to its new position. On a gimbaled, ground-based device such as the SOT, the plane of reference for the motions of the vehicle must be related to the surface of the earth, unless great expense is taken to provide computerized solutions to the problem of inappropriate control responses at extremes of attitude. For example, in a flying aircraft when the pilot pushes the stick to the left, the aircraft will roll to the left, no matter what its pitch attitude is; in a gimbaled system, however, a stick motion to the left, in the condition in which the pitch attitude is 90° down from its neutral position, would result not in a roll but in a pure yaw, relative to the observer in the cockpit within the gimbaled system. This happens because the cabin in the gimbaled system is incapable of carrying its plane of reference for control purposes along with it when it obtains its new pitch attitude. Certainly, the problem of inappropriate control responses at extremes of attitude can be eliminated by the application of the Euler-angle equations, solved and applied through special computer systems. Rather than suggesting that the Air Force go to the tremendous expense and added grief of computerizing the SOT, we proposed a compromise—limiting the extent of pitch travel that can be obtained from the SOT—hoping that such will result in the greater cost effectiveness. With a maximum pitch capability of 30° up and 30° down, the amount of yaw that will be obtained on the SOT when a roll maneuver is commanded will be proportionally small and tolerable. Since we could have more than ±30° of angular freedom about either the pitch or the roll axis, but not both, we decided that we could obtain a more effective device, with operational dynamics more akin to those of real aircraft, if we were to specify maximum roll capability and limit the pitch freedom to ±30°, instead of the reverse. We selected ±90° as the optimum amount of roll freedom because such an amount will give the trainee plenty of room in which to develop disorientation but will allow the physical size (and, therefore, cost) of the trainer to remain at a minimum.

After it was determined that roll freedom should be ±90°, it became obvious that the pitch axis would have to be contained within the roll gimbal and not vice versa. Otherwise, pure yaw, rather than pure pitch, would be obtained when the stick is pulled back or pushed forward to initiate a pitching motion while the device is in an attitude of extreme roll. Such an effect would obviously be highly undesirable—hence, the requirement for the gimbaling order to be pitch, roll, and yaw, from inside outward. It can easily be observed that if yaw control were to be given to the trainee through actuation of motors controlled by the rudders, a problematical relationship similar to that which exists between the pitch and roll axes would exist between the roll and yaw axes. For that reason the trainee will not be given control over any yaw motion while the SOT is in normal operation. An exception will be during the spin-recovery mode of operation, during which time the trainee will be given control of the main yaw motion through the use of the rudder pedals. We feel that the absence of yaw control from the trainee's standpoint is further justified by the fact that, except during takeoff and landing, rudders are used very little if at all in the normal operation of jet aircraft.

Another problem that has become apparent is that of eliminating from the trainee's cognizance various noises which could give him cues to the attitude of the vehicle. We do not know at the present time how serious this problem might become, but we have specified that potential cueing noises be "adequately" masked by artificially generated cabin noise not to exceed an overall sound pressure level of 100 dB, with a spectral composition similar to that encountered in cockpits of current high-performance aircraft.

A mission in the Spatial Orientation Trainer

At this point we shall present, in dialogue form, what we envision to be a typical training mission in the SOT, for the purpose of describing a possible program for the operation of the SOT. The setting is the physiological training facility at an undergraduate pilot training base. The characters are Second Lieutenant John Jones, the student pilot, and Staff Sergeant Joe Smith, the SOT operator and maintenance specialist.

After appropriate flight planning, Lt. Jones gathers up his charts, dons his crash helmet, and enters the SOT. After communications have been established, Sgt. Smith demonstrates to Lt. Jones that the attitude indicator in the cockpit gives accurate information regarding the actual attitude of the SOT, by pitching and rolling the SOT while the student still has outside visual reference through the open canopy. The canopy is then closed and the SOT is positioned in a straight and level attitude with the nose of the cabin facing the hub of the apparatus. Lt. Jones requests takeoff clearance:

"Phoenix Tower, this is Texas 67, runway 14, ready for takeoff. Request Ramrod 1 departure, over."

"Roger, Texas 67. Ramrod 1 departure approved, cleared for takeoff."

At this point, Lt. Jones pushes the throttle forward, and the SOT begins to accelerate around the track. As angular velocity builds up, the concomitant linear (radial) acceleration builds, forcing the pilot back into his seat.

As rotation speed appears on his airspeed indicator, the pilot applies back pressure on the stick and the nose of the SOT gradually rises above the horizon. During the simulated straight-out departure, Lt. Jones experiences a powerful oculogravic illusion, which gives him the false sensation that he is in a 60° nose-high attitude, even though his instruments tell him he is actually in only a 15° climb. Since the Ramrod 1 departure requires that the pilot maintain 2,000 feet until intercepting the 060° radial of the Webb Vortac, Lt. Jones suddenly applies forward control pressure because he thinks he will overshoot his assigned altitude if he maintains his present apparently nose-high attitude. In doing so, he notices that the gyro horizon indicates a nose-low attitude and that the altimeter is unwinding rapidly. He levels off again at 500 feet and, despite his false sensation of a nose-high attitude, he resumes a normal climb to 2,000 feet. Once established at 2,000 ft. on the appropriate heading to intercept the 060° radial, he reduces power, the SOT revolves less rapidly, and the oculogravic illusion diminishes.

"Texas 67, contact departure control, 294.5."

"Roger, 294.5."

At this point, Lt. Jones reaches down to his right toward the radio frequency selector panel and dials in 294.5.

"Phoenix departure control, this is Texas 67, Ramrod 1 departure, about to intercept the 060° radial of the Webb Vortac at 2,000, over."

"Roger, Texas 67, radar contact. Contact Houston Center on 269.0 when established on the 060° radial, over."

"269.0, Texas 67."

As Lt. Jones closes in on the radial, he applies climb power and rolls to the left to enter a climbing left turn with 30° of bank. After he has set up his climbing turn, albeit with a little difficulty because of the Coriolis reactions resulting from his rolling and pitching maneuvers while the SOT was revolving, he then looks down to the left and reaches for his radio frequency selector panel to dial in 269.0. As he does this, Lt. Jones suddenly perceives the aircraft entering a steep climbing roll to the left, and he controls the aircraft "by feel" for the several seconds he uses to dial in his radio frequency. As he looks back at his attitude indicator, he discovers that he has rolled the plane to the right and is diving at a steep angle. He then maneuvers his craft toward its original attitude, but in doing so he discovers that he feels as though he is overcorrecting violently and cannot make himself follow the attitude indicator for fear he will turn himself upside down. While he is wrestling with this problem, he receives a call from Houston Center: "Texas 67, Houston Center."

"Houston Center, Texas 67. Go ahead."

"Texas 67, squawk code 0500, and ident."

Still wrestling with the problem of putting the craft back into the climbing left turn, Lt. Jones awkwardly reaches to another unlikely spot in the cabin and dials in code 0500 on the transponder, and presses the "ident" button. As he looks back at his attitude indicator he sees that he has again put his craft into a very dangerous attitude, and he resolves firmly to effect the proper control motions this time by monitoring his attitude indicator regardless of what position he thinks he's putting himself into. He then slams the stick over until the attitude indicator finally displays the desired indication, oscillates about that indication for several seconds, and then settles down in the desired climbing left turn. After leveling off at 30,000 ft. on a heading of 060°. Lt. Jones retards the throttle for cruise power and Sgt. Smith slowly stops the rotation of the SOT around the track. Sgt. Smith then positions the cabin of the SOT so that the nose faces away from the hub, and calls Lt. Jones:

"Texas 67, Houston Center. Descend and maintain 5,000. Report passing 10,000."

"Roger, Texas 67 leaving 30.000 for 5,000, report 10,000."

Lt. Jones then further retards the throttle, puts the trainer in a 10° dive, and as airspeed builds up, he puts out speed brakes. Sgt. Smith by then has started the SOT rotating again, and the centrifugal force generated gives the student pilot the sensation that he is in a much steeper dive than he really is. Lt. Jones carefully monitors his attitude indicator at this point and maintains his 10° dive angle. Slowly, Sgt. Smith reduces the rotation rate of the SOT to 0. Eventually Lt. Jones reaches 5,000 ft. and levels off the trainer. Sgt. Smith then queries:

"Texas 67, are you ready for spin recovery training?"

"Affirmative."

"Roger, switch your turn-needle function-selector switch from 'slaved' to 'true.'"

"Roger. switched."

"Fine. Now I will take over control of the aircraft for approximately 30 seconds, and will put it in a spin. When I want you to recover, I will say, 'You have it,' and will relinquish control of the aircraft. You will then have full control of the aircraft and will be expected to recover from the spin using appropriate stick, rudder, and throttle control. Are you ready?"

"Affirmative."

"Roger, retard your throttle to 50% power and give me a 30°-climb attitude."

After Sgt. Smith has ascertained that Lt. Jones has complied with the directions to reduce throttle and put the trainer in a nose-high attitude, he waits for the airspeed to bleed off to stalling airspeed. When he obtains stalling airspeed, Sgt. Smith abruptly lowers the nose of the SOT to full-pitch-down attitude and rolls the cabin sharply to the left. Simultaneously, he brings the SOT up to 20 r.p.m. and then begins to oscillate the trainer between 15 and 25 r.p.m. He announces to Lt. Smith:

"You have it!"

"I have it."

Lt. Smith feels the violent, whipping spin for approximately 10 seconds before he is given control of the trainer. The instrument panel no longer seems as blurred as it was at the beginning of the spin and his sensation of spinning has diminished somewhat. In fact, he no longer distinctly feels the spin but feels instead a rocking motion to the right and left. Observing that his turn needle is pegged to the left, he presses hard right rudder to center the turn needle. He then feels a violent spin to the right and, reflexly, he pushes hard left rudder. When he looks again at his turn needle, it is still pegged in the left direction, and he notices his altimeter passing quickly through 3,000 ft. He again pushes hard right rudder and this time keeps it depressed until the turn needle reaches the no-turn position. The violent sensation of spinning to the right, however, is more than Lt. Jones can cope with, and he again tries to stop the spin by pushing hard left rudder until his sensation of turning ceases. When he notices his turn needle is pegged to the left again, he realizes that he has not stopped the spin and for the third time initiates the application of right rudder. He applies less pressure this time and the needle slowly comes back to the upright position. He releases the rudder pressure, and in spite of his sensation of spinning, he holds the needle upright by returning it to the vertical position with rudder pressure every time the needle appears to fall off to the left. Since he is already in a nose-down attitude, he applies full throttle and as airspeed builds, he starts to pull back on the stick. He notices, however, that his altitude is now 1,200 ft., and he is still descending, although more slowly than he was while he was spinning. He does not recall the exact elevation of the ground at this point, but he suspects he is close to it, and eases back on the stick a little more firmly. With that, the nose drops violently down again as the words "accelerated stall" flash through his mind. Two seconds later, the altimeter stops at 850 ft., the airspeed indicator reads 0, and the red light on the panel informs Lt. Jones that the trainer is no longer flying.

III. EVALUATION OF THE SPATIAL ORIENTATION TRAINER

The obvious method of evaluating the SOT would be to compare statistics on aircraft accidents caused by spatial disorientation before and after the institution of a large spatial disorientation training program utilizing many SOT's. Variables which cannot be controlled make this an unrealistic approach, and such a method would involve unwarranted expenditure of funds on an unproved system. Several less imposing methods of evaluating the SOT can be suggested, however.

A very appropriate evaluation could come from the verbal or written reports and critiques of instructor pilots who could be asked to ride the SOT. Although not necessarily a valid method of determining the actual effectiveness of the SOT, this technic would still provide some insight into how well the SOT would be received and utilized in the field.

The concept of *res ipsa loquitur* can be invoked for some degree of validation of the SOT. If one trainee consistently loses control of the vehicle during disorienting conditions, while another learns rapidly how to adjust for disorientation, we believe it can be argued that the former student would be considerably less safe in the air than would the latter. Although we believe such results would indicate which pilots would not be safe in the air, we do not mean to imply that a pilot's demonstrated competence in the SOT guarantees that he will not have a spatial disorientation accident. We do believe, however, that demonstrated incompetence would put a pilot in a poor-risk category, as far as susceptibility to spatial disorientation is concerned.

Perhaps the most fruitful means of evaluating the SOT would involve an experiment utilizing two groups of student pilots, one being exposed to X hours of basic flight training and Y hours of training in the SOT, and the other being exposed to X plus Y hours of basic flight training or X hours of basic flight training and Y hours of training in a static simulator. Pilots in both the experimental and control groups would then be subjected to Lt. Crawford's in-flight disorientation profile (14) and rated on their ability to regain aircraft control after the disorienting episodes. Differences between the two groups in their ability to perform the task of regaining and maintaining aircraft control would be attributable to the effect of the training in the SOT, if other relevant factors were rigidly controlled.

IV. UTILIZATION OF THE SPATIAL ORIENTATION TRAINER

Assuming the SOT will be successfully validated, the next step will be to determine how many trainers to procure and at what price. This task will, of course, be left to the "cost-effectiveness" people. We believe, however, should the SOT prove to be an effective means of training out susceptibility to the effects of spatial disorientation, that an SOT could be justified at every undergraduate pilot training base in Air Training Command. A long-range guess is that we would recommend from two to four hours of training in the SOT to be included in the undergraduate pilot training curriculum. SOT's might also be justifiably located at the training bases of other commands, such as Tactical Air Command and Air Defense Command. At these bases the training in the SOT might consist of short (one-half hour or less) disorientation refresher sessions. Ideally, provisions would be made for pilots to utilize the SOT's on an informal basis whenever they decide they need additional experience with vertigo.

One of the SOT's will have a unique utilization. That will be the first unit, which will be delivered to the USAF School of Aerospace Medicine for the development of the training profile and the evaluation of the potential of the machine. After those tasks have been completed, the SOT will, we believe, become a valuable research tool for studying spatial disorientation in a more meaningful way than has heretofore been possible in the laboratory. Several specific problems that could be studied on the SOT would be: How does interruption of the instrument cross-check contribute to the development of disorientation? What is the relationship between the magnitude of various stresses and the magnitude of the development of spatial disorientation? Does the proficient instrument pilot actually experience less vertigo in a given disorienting situation, or is he just more capable of maintaining aircraft control in spite of his illusions of attitude and motion? What are the parameters of a training regimen that are most important for developing resistance to spatial disorientation? What effects do alcohol, drugs, and loss of sleep have upon susceptibility to spatial disorientation? Another realm of research that should be undertaken includes such problems as determining the feasibility of combining a cockpit procedures trainer and an operational static flight simulator with an SOT to produce a device of maximal realism and effectiveness.

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY *(Corporate author)* USAF School of Aerospace Medicine Aerospace Medical Division (AFSC) Brooks Air Force Base, Texas	2a REPORT SECURITY CLASSIFICATION Unclassified 2b GROUP

3 REPORT TITLE

DESIGN CRITERIA FOR THE SPATIAL ORIENTATION TRAINER

4 DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Jan. - June 1967

5 AUTHOR(S) *(Last name, first name, initial)*

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6 REPORT DATE October 1967	7a TOTAL NO OF PAGES 16	7b NO OF REFS 14

8a CONTRACT OR GRANT NO. b. PROJECT NO. c Task No. 775508 d	9a ORIGINATOR'S REPORT NUMBER(S) SAM-TR-67-90 9b OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10 AVAILABILITY/LIMITATION NOTICES

This document has been approved for public release and sale; its distribution is unlimited.

11 SUPPLEMENTARY NOTES	12 SPONSORING MILITARY ACTIVITY USAF School of Aerospace Medicine Aerospace Medical Division (AFSC) Brooks Air Force Base, Texas

13 ABSTRACT

Spatial disorientation continues to cause at least 4% of the aircraft accidents in the Air Force. At the USAF School of Aerospace Medicine, the Spatial Orientation Trainer has been designed to help eliminate such accidents. The more deadly of the vestibular illusions of flight (namely, the Coriolis illusion, the oculogravic illusion, and the graveyard spin) can be reproduced and used to stress the pilot while he is performing a simulated mission in the trainer. Such exposure gives him practice in overcoming the sensory conflicts that result in disorientation and practice in proper aircraft control in spite of disorientation. The methods by which the illusions of flight are to be produced and the criteria upon which effectiveness of the trainer is to be judged are discussed in detail.

DD FORM 1 JAN 64 1473

Unclassified
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Vestibular illusions of flight Spatial orientation trainer Spatial disorientation Coriolis illusion Oculogravic illusion Graveyard spin Vertigo						

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