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APPARENT INSTRUMENT HORIZON DEFLECTION DURING AND IMMEDIATELY FOLLOWING ROLLING MANEUVERS

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NAVAL AEROSPACE MEDICAL RESEARCH LABORATORY
PENSACOLA FLORIDA

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SUMMARY PAGE

THE PROBLEM

The present study was the result of recent reports by pilots of apparent visual bending or bowing of instrument horizons during and immediately following ascending rolling maneuvers in the F-14 aircraft, and it investigates the probability that normal reflex actions may partially account for these reports.

FINDINGS

The results of these tests suggest that the vestibulo-ocular reflex (VOR) can produce an apparent deflection of the instrument horizon (actually an apparent flicking back and forth) during and after roll maneuvers involving high peak angular velocities. This perceptual aberration could be disturbing to a pilot attempting to use his instrument horizon and could lead to suspecting instrument malfunction if the pilot were unaware of this phenomenon. The reported distortions of the instrument horizon could be the result of the VOR which tends to stabilize the eye relative to the Earth during angular acceleration of the head, and therefore reflexly displaces the eye relative to objects such as flight instruments that move with the head.

INTRODUCTION

Several years ago Melvill Jones (7) showed that disorientation effects on inflight visual control can be strong. He recommended that to maintain a clear sense of orientation during rolls, "A maximum angular velocity of 200° per second should not be exceeded... (and) that not more than three consecutive rolls should normally be undertaken..." The present study was the result of recent reports by pilots of apparent visual bending or bowing of instrument horizons during and immediately following ascending rolling maneuvers in the F-14 aircraft, and it investigates the probability that normal reflex actions may partially account for these reports.

During roll maneuvers with the pilot looking forward, the induced vestibulo-ocular reflex (VOR) resulting from angular acceleration of the head is about the corneoretinal axis; i.e., the x-axis as defined by Hixson et al. (6). Blurring of vision as a result of x-axis VOR has been reported to be weak in comparison to that resulting from similar accelerations in the y- and z-axes (3). The limited blurring in the x-axis was probably due to the fact that this type of rotational eye movement produces very little displacement of visual images relative to the fovea.

These and other studies of visual blurring from vestibular stimuli have not addressed the question of whether the VOR about the x-axis might distort the pilot's visual perception of flight instruments, such as instrument horizon, irrespective of blurring effects.

PROCEDURE

Two groups of subjects were tested on separate devices with a slight variation in head orientation. The first group of subjects (N = 16) was tested on a modified Stille-Werner rotation device in a seated position with a downward head orientation (Figure 1a). This group was exposed to two ambient lighting conditions: no ambient lighting and low ambient lighting (2.1×10^{-3} foot candles). The low light condition exposed a head-fixed background that moved with the subject. The second group of subjects (N = 10) was tested on a short-arm centrifuge in a semisupine position with an upward head orientation (Figure 1b). This group was tested with no ambient lighting available. Both groups of subjects were positioned so that their head x-axes (6) were centered on the axis of rotation.

For both groups the lighted horizon line (0.3 fL) was positioned approximately 470 mm from the subject's head. Length of lighted line was 97 mm, subtending a visual angle of 11.8 deg. All accelerations (and decelerations) were 15 deg/sec^2 and maintained for 12 sec to achieve a velocity change of 30 rpm,* as depicted in panel A of Figure 2. The stimulus profile was a simple ramp function with 90 sec constant velocity

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*Roll rates considerably higher than 30 rpm can be produced in F-14 aircraft.

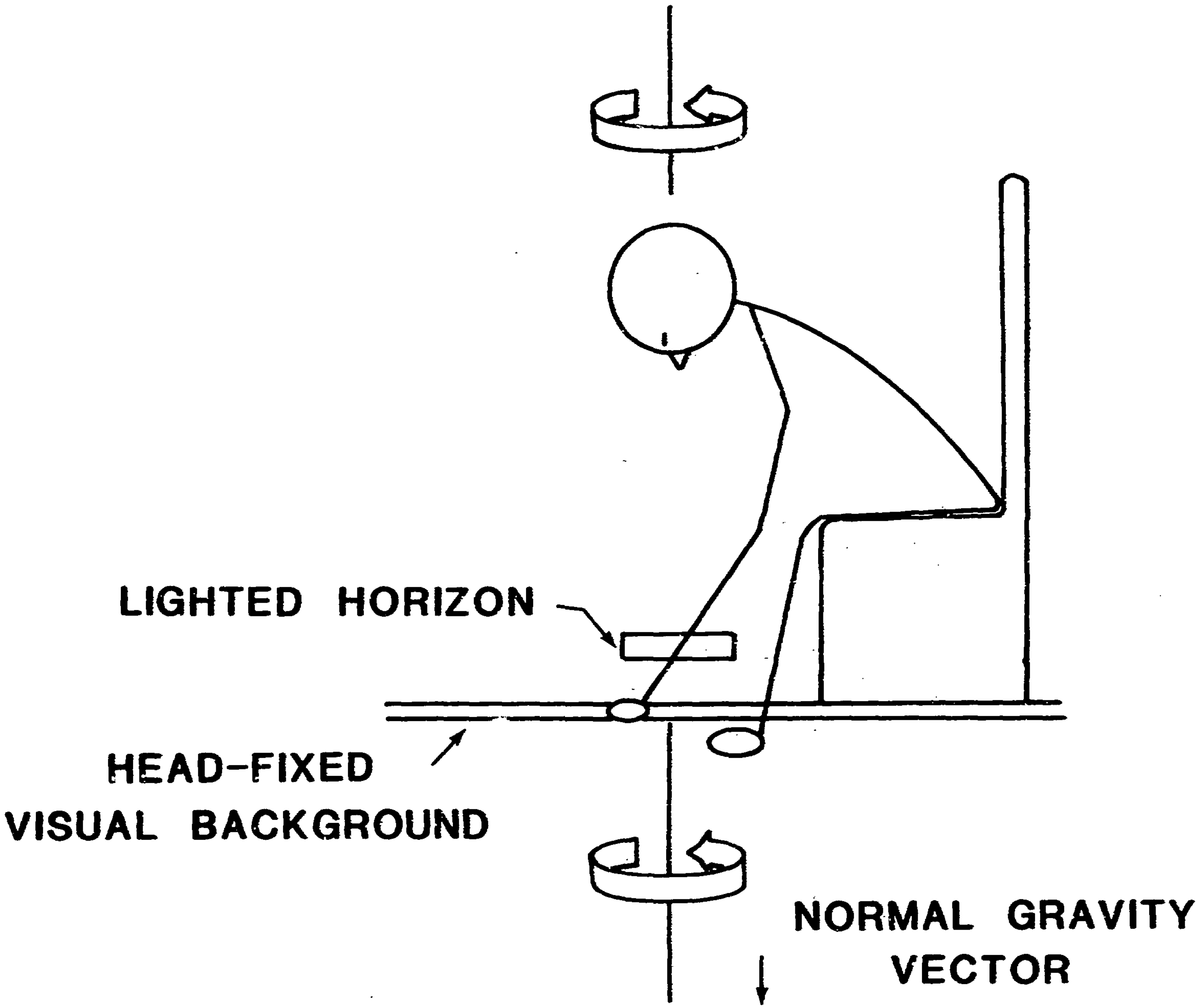

Figure 1a

Group 1 subjects were tested in a seated position with a downward head orientation. During half of the trials for this group, low ambient lighting exposed a head-fixed background that moved with the subject.

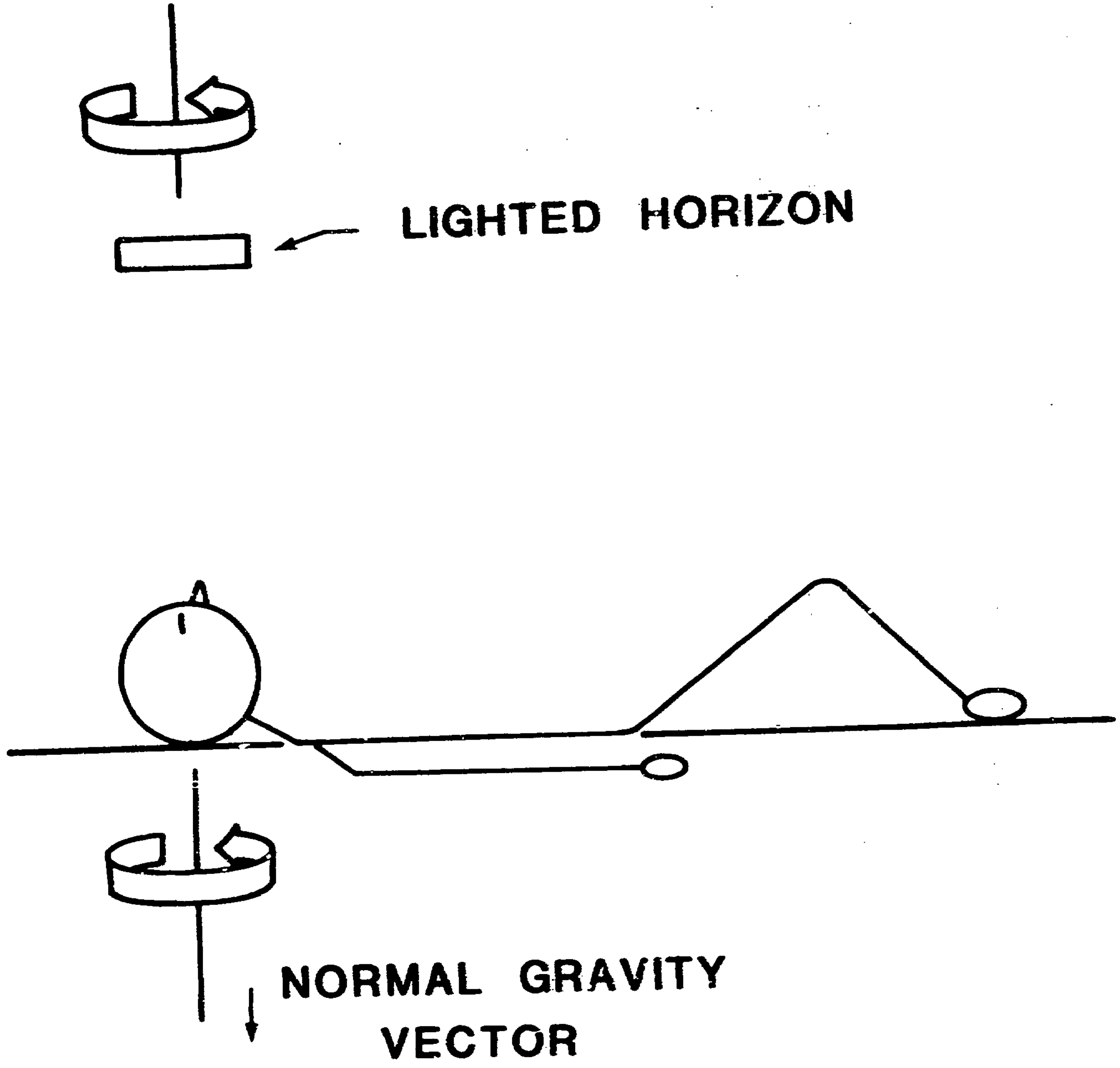

Figure 1b

Group 2 subjects were tested in a semisupine position with an upward head orientation (no ambient lighting)

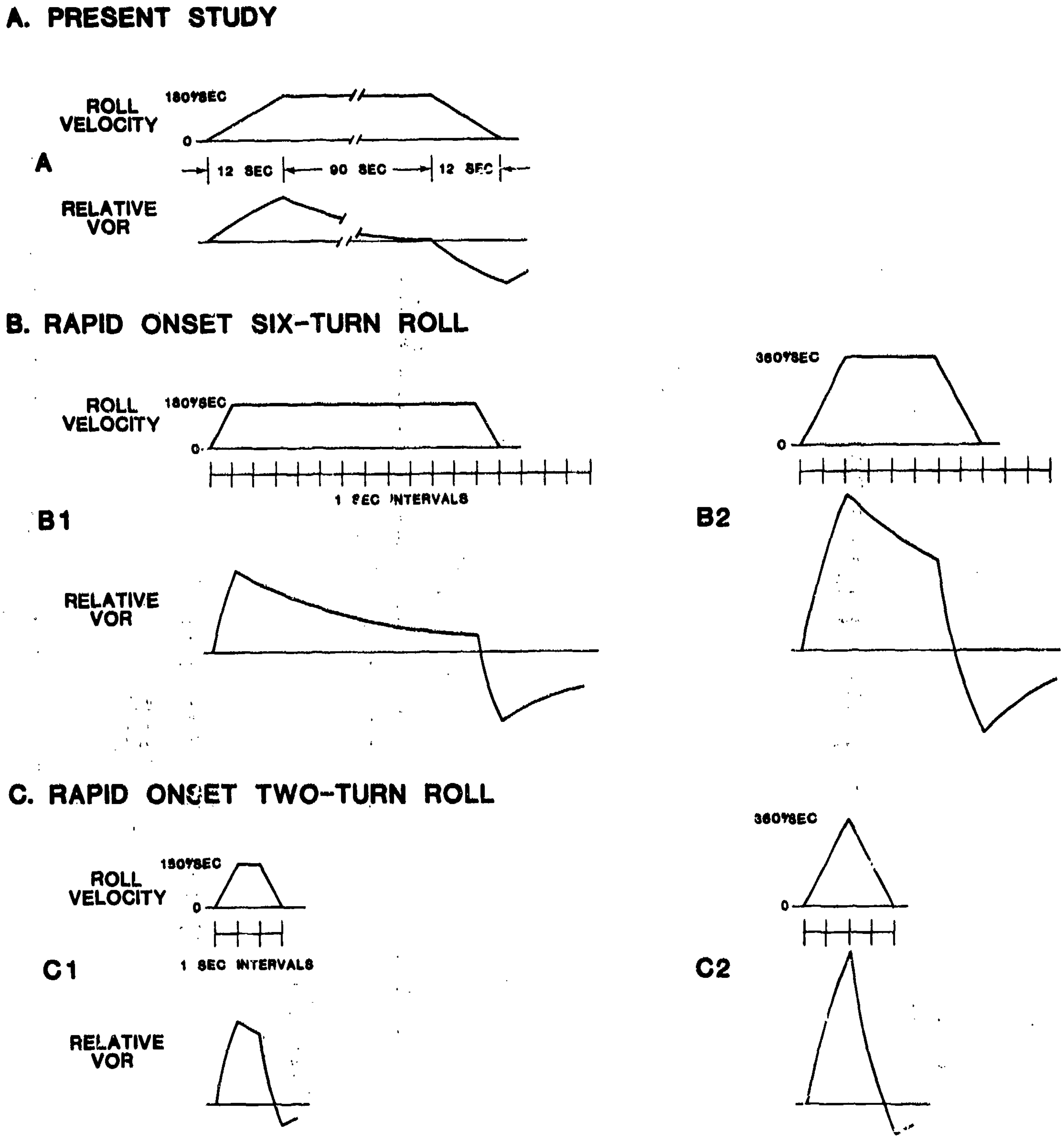

Figure 2

X-axis roll stimuli and associated relative vestibulo-ocular responses for:

Panel A. Stimuli used in the present study
Panel B. An hypothetical rapid onset six-turn roll
Panel C. An hypothetical rapid onset two-turn roll

between each acceleration and deceleration. Prior to the test trials, all subjects were given a practice trial which included the exact acceleration, constant velocity, and deceleration sequence that composed the test sequence.

Half the subjects in Group 1 received an acceleration and deceleration with no ambient lighting, followed by an identical acceleration-deceleration with ambient lighting. The order was reversed for the other half of Group 1. Group 2 was exposed to only one acceleration-deceleration set with no ambient lighting.

After the completion of testing, each subject was requested to describe and estimate the extent of any apparent instrument horizon movement. To simplify this process, a set of potential horizon movements (Figure 3) was shown to each subject. The results from accelerations and decelerations were recorded separately.

Several preliminary runs with laboratory personnel led us to believe that a person's visual focus point might be quite important. As a result, each subject was instructed to concentrate his visual focus on the center of the lighted horizon during all trials.

RESULTS

The incidence of reported horizon deflections and the type of deflection observed are summarized in Table I. When all testing conditions and groups are combined, an apparent instrument horizon deflection was reported in 81 of 84 trials. The type of deflection most often reported is shown in Example E of Figure 3.

Table I

Number of Reported Horizon Deflections

	Group 1		Group 2
Type of Horizon Deflection*	No Ambient Lighting	Low Ambient Lighting	No Ambient Lighting
A	2	2	5
B	1	1	0
C	2	5	0
D	3	7	0
E	18	15	11
F	3	1	2
G	1	0	0
H	0	0	2
None	2	1	0
	32	32	20

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*See Figure 3.

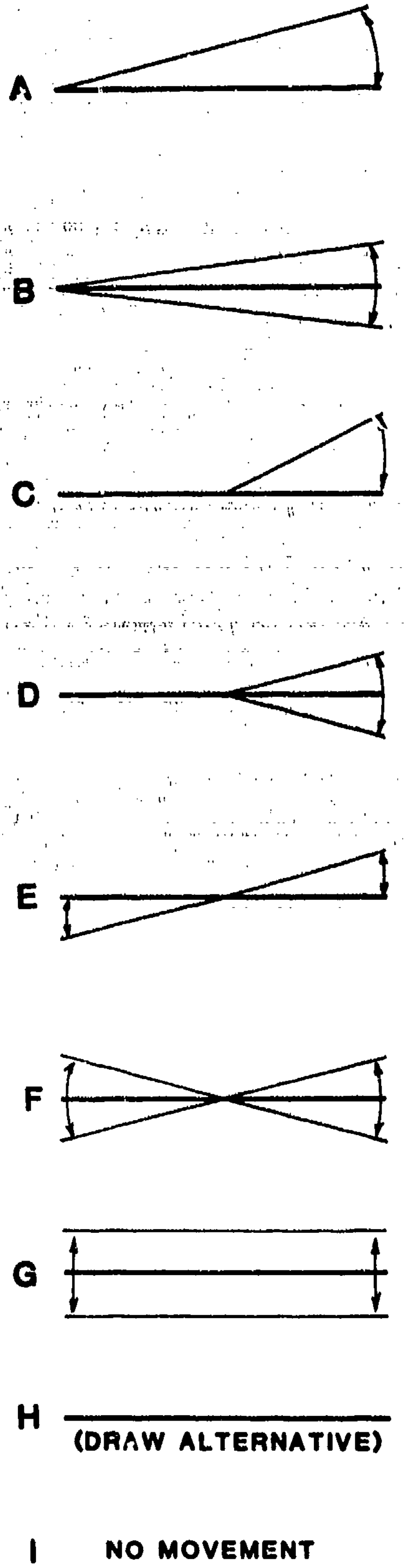

Figure 3

Potential apparent instrument horizon movements as shown to each subject

The types of horizon movement depicted in Figure 3 emphasize movement of the right end of the horizon relative to a true horizon. It should be pointed out that each of the possible right end movements in Figure 3 has a complementary left end movement. In fact, the direction of the canalicular stimulus in almost all cases determined which end of the lighted horizon was above or below a true horizontal setting. For instance, when Example E was reported, the leading edge of the horizon (relative to the direction of canalicular stimulus) was always above the true horizon (i.e., right end up with clockwise rotation, left end up with counterclockwise rotation).

The magnitude of the reported deflection in Group 1 ranged from 0 deg to 30 deg, with a mean of 7.95 deg (S.D. = 7.16) in the low-ambient light condition and a mean of 7.47 deg (S.D. = 5.16) in the no-ambient light condition. For Group 2, the deflections ranged from 5 deg to 37.5 deg, with a mean of 17.40 deg (S.D. = 10.97). There were no significant differences between accelerations and decelerations with regard to the magnitude of deflection (t for related measures: Group 1, t: dark = 1.60, light = 1.48, df = 15, p = N.S.; Group 2, t = 0.19, df = 9, p = N.S.). Within Group 1, the low-ambient light reports were not significantly different from the no-ambient light reports (t for related measures: t: accelerations = 0.27, decelerations = 0.31, df = 15, p = N.S.). The mode or most frequently reported deflection for all data was 5 deg.

DISCUSSION

The results of these tests suggest that the VOR can produce an apparent deflection of the instrument horizon (actually an apparent flicking back and forth) during and after roll maneuvers involving high peak angular velocities. This perceptual aberration could be disturbing to a pilot attempting to use his instrument horizon and could lead to suspecting instrument malfunction if the pilot were unaware of this phenomenon.

The reported distortions of the instrument horizon could be the result of the VOR which tends to stabilize the eye relative to the Earth during angular acceleration of the head, and therefore reflexly displaces the eye relative to objects such as flight instruments that move with the head.

The stimulus waveform in the present study was selected for convenience in obtaining simple observations from subjects. The long periods of constant velocity separating the low-magnitude angular acceleration stimuli provided two fairly sustained intervals (associated, respectively, with the acceleration and deceleration) for observing effects for each period of rotation. This particular stimulus waveform would occur rarely, if ever, in flight, but the dynamics of the VOR have been sufficiently established to extrapolate our findings to motion waveforms that are common occurrences in flight. The VOR is primarily dependent upon the response of the semicircular canals to angular acceleration. The dynamic characteristics of the semicircular canals (narrow lumen and high viscous torques) are such that they act as approximate integrators of angular acceleration for short duration waveforms (4,5,10).

Thus the magnitude of the VOR and of the visual distortion as well would follow the angular velocity waveform of the roll fairly closely for rolls through small angles, say, 180 deg or less, and there would be little or no aftereffect. However, for multiturn rolls, aftereffects persisting for several seconds can approach the magnitude of onset effects. Equations which predict responses to various stimulus waveforms are based upon a model (4,5,8,10,11) which likens the cupula-endolymph system of the semicircular canals to a heavily damped torsion pendulum (9). Many experiments involving a variety of driving functions and a variety of response measures (including the VOR) have demonstrated that this model provides a generally acceptable approximation of response dynamics. Figure 2 depicts the predicted magnitude and course of the VOR in the stimulus profile of the present study and in several other stimulus profiles more likely to occur in flight, assuming a long time constant for responses from vertical canal stimulation to be 7.3 sec (2).

Panel A of Figure 2 shows the slow build-up of the stimulus and response and the separate and equal magnitude responses to the accelerations and decelerations of the present study. Panel B of Figure 2 shows two rapid onset rolls, each of six turns, and hence, with shorter intervals between the acceleration and deceleration than occurred in the present study. In B_1, a rapid onset achieves a roll rate of 180 deg/sec and produces an onset response considerably greater than that of the present study, but because of the shortened interval of constant velocity in the six-turn roll, the deceleratory effect is of relatively lower (but still substantial) magnitude. In B_2, rapid onset achieves a roll rate of 360 deg/sec (approaching the maximum roll rate achievable in flight). This yields a much stronger onset response than occurred in the present study, but the interval for completing six turns is even shorter than in B_1, so that the deceleratory response is relatively more diminished than the B_1 after-response. Panel C shows two rapid onset rolls, each through 720 deg or two complete revolutions. In C_1, a roll rate of 180 deg/sec is achieved, there is very little time (1 sec) between the onset acceleration and the deceleration, and so the onset response is the same as in B_1, but the deceleratory response is very weak. In C_2, the onset response is strong and equal to that in B_2, but the deceleratory response is negligible because there is zero interval between the acceleratory and deceleratory phases of the stimulus profile. As the interval between acceleration and deceleration is reduced, the effect of the deceleration is progressively diminished because it simply serves to null out the offset produced by the acceleration. From an engineering point of view in which systems are sometimes evaluated in the frequency domain, the progressive transition in response characteristics from Panel A through B_1, B_2, C_1 to C_2 illustrates that in a low-frequency range this system tends to be "on acceleration" and so there is an aftereffect, whereas in a higher frequency range it is "on velocity," and there is no aftereffect. For a more formal engineering systems analysis treatment of this system which provides ready quantitative prediction of responses under any stimulus waveform, the reader is referred to other sources (5,8,10,11). Note that even in short roll waveforms, the reflexive disturbance will be present during the roll but it will not persist after the roll.

Our observations were made on a turntable with an Earth-vertical axis. Rotation about an Earth-horizontal axis would produce slightly stronger per-rotatory responses because the semicircular canal input would be augmented by otolithic and somatosensory inputs. However, according to one theoretical viewpoint (1), postrotatory responses may be suppressed since the fixed gravity vector after stopping would be roughly in the plane of responding semicircular canals, resulting in position information from the otolithic and somatosensory systems inconsistent with a continuing rotation signal from this set of canals. In flight, the pilot's head is not necessarily centered on the axis of roll. When the head is at some radial distance, even a few feet, from a high-rate roll, then a significant centrifugal acceleration vector will develop which may serve to reduce the distortion effects somewhat. Also, the flight path during a roll may be anywhere from near horizontal to a steep climb. Thus, many of these conditions would involve rotation of some component of gravity relative to the pilot's head, which would tend to augment the VOR and the distortion effects. From this discussion it is clear that fairly accurate information must be obtained about the time-dependent changes in all linear and angular acceleration vectors impinging upon the pilot during flight maneuvers and that utilization of this information to predict responses in aircraft depends upon the sensorimotor and perceptual consequences of interaction among the sensory detectors of motion in complex conditions. Present data are sufficient to predict fairly confidently that a variety of aircraft maneuvers will produce distortion effects as strong as or stronger than those we have observed. We, of course, cannot say with confidence that the vestibulo-ocular reflex was the primary causal factor in the distortion of the horizon indicator reported by some F-14 pilots during high-rate roll maneuvers. The degree to which pilots become habituated to such phenomena so that VOR effects become routine and are disregarded is unknown. Yet, in view of the exceptional maneuverability of modern aircraft, it is timely to remind pilots that normal physiological responses to high-rate rolls can yield distorted visual information that may mimic malfunction of flight instruments.

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