N95- 32422

THE ROLE OF THE VESTIBULAR SYSTEM N MANUAL TARGET LOCALIZATION

Final Report
NASA/ASEE Summer Faculty Fellowship Program -- 1994
Johnson Space Center

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Date Submitted: September 2, 1994

Contract Number: NGT-44-005-803

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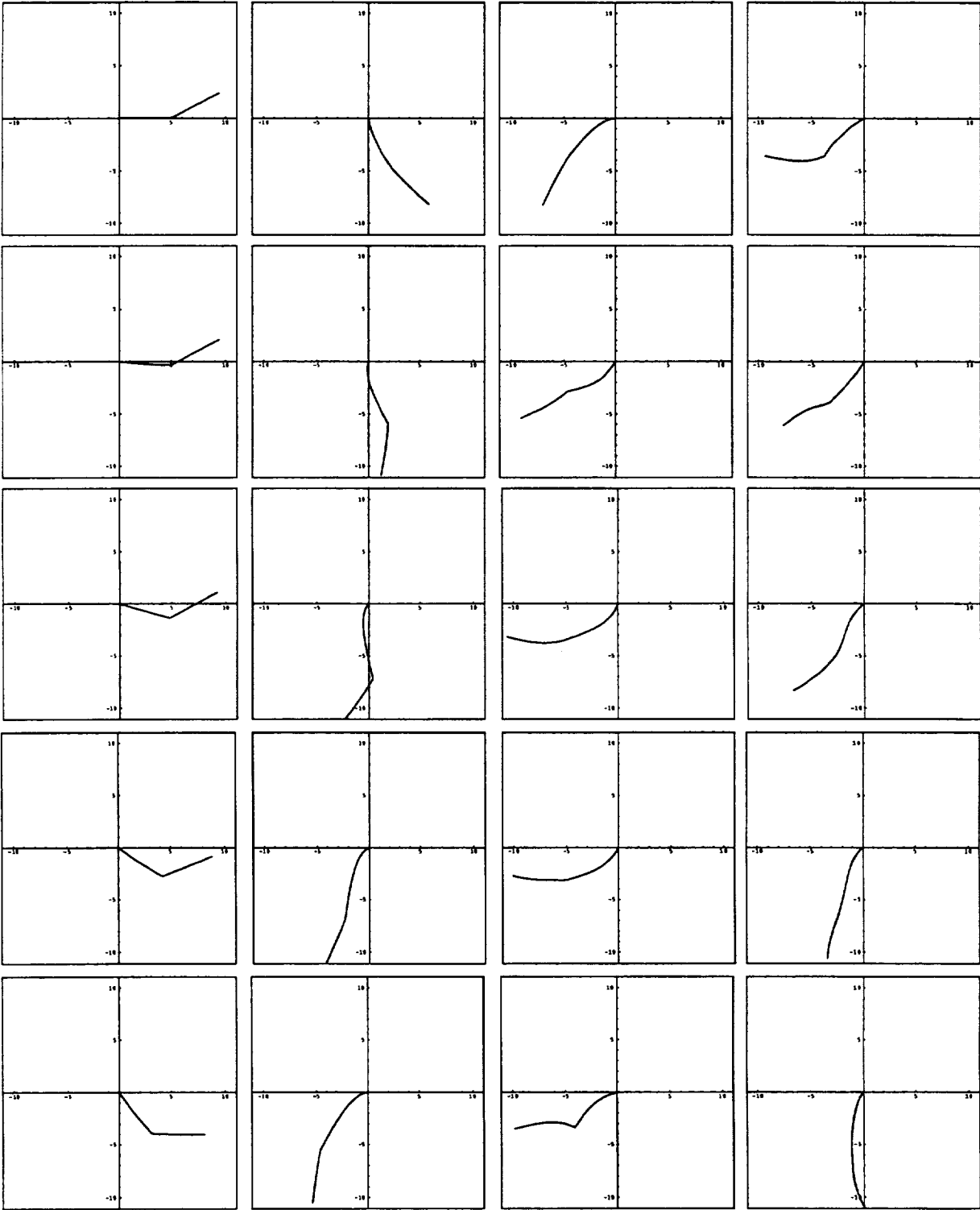
Date Approved: _____Sept. 2, 94_____

Figure 3: Two Link Flexible Manipulator–High Elastic Energy

ABSTRACT

Astronauts experience perceptual and sensory-motor disturbances during spaceflight and immediately after return to the 1-g environment of Earth. During spaceflight, sensory information from the eyes, limbs and vestibular organs is reinterpreted by the central nervous system so that astronauts can produce appropriate body movements in microgravity. Alterations in sensory-motor function may affect eye-head-hand coordination and, thus, the crewmember's ability to manually locate objects in extrapersonal space. Previous reports have demonstrated that crewmembers have difficulty in estimating joint and limb position and in pointing to memorized target positions on orbit and immediately postflight.

One set of internal cues that may assist in the manual localization of objects is information from the vestibular system. This system contributes to our sense of the body's position in space by providing information on head position and movement and the orientation of the body with respect to gravity. Research on the vestibular system has concentrated on its role in oculo-motor control. Little is known about the role that vestibular information plays in manual motor control, such as reaching and pointing movements. Since central interpretation of vestibular information is altered in microgravity, it is important to determine its role in this process.

This summer, we determined the importance of vestibular information in a subject's ability to point accurately toward a target in extrapersonal space. Subjects were passively rotated across the earth-vertical axis and then asked to point back to a previously-seen target. In the first paradigm, the subjects used both visual and vestibular cues for the pointing response, while, in the second paradigm, subjects used only vestibular information. Subjects were able to point with 85% accuracy to a target using vestibular information alone. We infer from this result that vestibular input plays a role in the spatial programming of manual responses.

INTRODUCTION

Astronauts experience perceptual and sensory-motor disturbances during spaceflight and immediately after return to the 1-g environment of Earth (Young et al., 1984). During spaceflight, sensory information from the eyes, limbs and vestibular organs is reinterpreted by the central nervous system so that astro-nauts can produce appropriate body movements in microgravity. Alterations in sensory-motor function may affect eye-head-hand coordination and, thus, the crewmember's ability to manually locate objects in extrapersonal space. Previous reports have demonstrated that crewmembers have difficulty in estimating joint and limb position and in pointing to memorized target positions on orbit and immediately postflight (Watt et al., 1985).

The ability to point or reach toward an object or perform other manual tasks is essential for safe Shuttle operation and may be compromised particularly during re-entry and landing sequences and during possible emergency egress from the Shuttle. An understanding of eye-head-hand coordination and the changes produced during space flight is necessary to develop effective countermeasures. This summer's project expanded upon last summer's research on the sensory cues used in the manual localization of objects.

Last summer, we determined that people use an egocentric, as opposed to an allocentric, reference frame to point toward a target. In an egocentric reference frame, the object is localized in relation to the position of the subject's body while in an allocentric reference frame, the target is localized in relation to other objects in the external visual world. Thus, people use internal, egocentric cues, such as the direction of gaze and the position of the limbs, to locate objects in extrapersonal space. One set of internal cues that may assist in the manual localization of objects is information from the vestibular system. Since central interpretation of vestibular information is altered in microgravity, it is important to determine its role in this process.

Vestibular receptors include the otolith organs and semicircular canals located in the inner ear. This system contributes to our sense of the body's position in space by providing information on head position and movement and the orientation of the body with respect to gravity. Along with visual, auditory and proprioceptive cues, vestibular input contributes to an internal spatial map within the central nervous system of body position

Healthy human subjects can use vestibular information to estimate, without the aid of vision, the magnitude of self-angular displacement when briefly rotated about an earth-vertical axis. Bloomberg et al., (1991) demonstrated that subjects, who are rotated in total darkness, can make accurate saccadic eye movements back to a previously seen earth-fixed target. Since the rotation and the saccadic eye movements occurred in total darkness, vestibular cues must have been used to update the internal spatial map, code the target position in space, and generate accurate eye movements. Research on the vestibular system has concentrated on its role in oculo-motor control.

Little is known about the role that vestibular information plays in manual motor control, such as reaching and pointing movements.

This summer, we determined the role of vestibular information in a subject's ability to point accurately toward a target in extrapersonal space.

Subjects were passively rotated about the earth-vertical axis and then asked to point back to a previously-seen target. In the first paradigm, the subjects used both visual and vestibular cues for the pointing responses, while in the second paradigm, subjects used only vestibular information. Subjects were able to point with 85% accuracy to a target using vestibular information alone. We infer from this result that vestibular input plays a role in the spatial programming of manual responses.

METHODS

Subjects:

Eight healthy subjects, five males and three females, ranging in age from 21 to 40 were tested. Five subjects were right-handed while three were left-handed.

Experimental set-up:

In order to measure pointing accuracy, subjects were seated in a rotatable chair located two meters from the center of a screen. The target was illuminated on the center of the screen at a height of 56 inches, average eye-level for a seated subject.

A laser for pointing was mounted onto a plastic finger splint. The tip of the laser rested on a ball joint so that it could be rotated in any direction. The laser was secured onto the index finger of the dominant hand of the subject with VelcroTM straps. For each test, subjects practiced pointing with the finger-tip laser at the illuminated target on the screen and adjusted the position of the laser. Subjects were able to match the laser beam location with the perceived pointing location.

The target was initially displayed on a computer monitor and then projected onto the viewing screen using an overhead projector equipped with a special display panel (Proxima Corporation, San Diego, CA.). The display panel possessed an auxiliary scanning device that was used to record the laser beam spot on the display screen when the subject pointed with the laser at the remembered target position. The display window had a resolution of 640 units horizontal and 480 units vertical. Software was written by Dr. William Huebner to display the target momentarily on the screen and then to record the coordinates of the laser spot.

The subjects were seated in a rotatable chair whose movements were controlled by a servo-motor and computer. The chair was rotated at a rate of 40 degrees per second to displacements of 0 degrees, +/-10 degrees, +/-20 degrees, or +/- 30 degrees. In each experiment, the chair was rotated ten times to each of the seven possible displacements for a total of seventy rotations. The order of the displacements was random but consistent across

subject population. A search coil system was used to verify the position of the chair before and after each rotation.

During the experiment, the subject was placed in a comfortable head restraint to prevent any head movement independent of the movement of the chair. The subject wore earphones to receive verbal cues during the trials, such as when to fixate the target and when to point. The earphones also masked outside auditory signals in the room which might have given the subject cues as to rotational displacement or where to point.

Experimental protocols:
Each subject was tested in two experimental paradigms.

Paradigm one: The subject was asked to fixate his/her gaze at the target on the illuminated screen. The chair was then rotated while the subject maintained his/ her gaze at the target. The projector light was then extinguished, and the subject used the finger-fixed laser to point back at the remembered location of the target on the screen. For each displacement, the subject pointed three times at the remembered target location. Second and third attempts were corrective motions.

Paradigm two: The subject was asked to fixate the target on the illuminated screen. The projector light was then extinguished. The chair was rotated in total darkness, and, after rotation, the subject pointed back to the remembered location of the target. For each displacement, the subject pointed three times at the remembered target location.

For all eight subjects, paradigm one was always tested before paradigm two. At least two days elapsed for each subject between tests.

In both paradigms, the subjects received minimal feedback of how accurately they had pointed. In paradigm one, however, the subject could use both visual and vestibular cues to locate the position of the target during rotation. In paradigm two, the subject could use only vestibular cues during and after rotation to locate the position of the target and to point.

Data analysis:
For each pointing trial, the linear deviation of the laser point from the x-axis of the target was measured. These data were used to calculate angular deviation from the target given a constant distance form the chair's center of rotation to the target (Figure 1). This deviation was defined as the pointing error. The values of pointing error for the first pointing attempt at each displacement in a given experiment were averaged. Mean pointing errors were calculated in an identical fashion for the second and third pointing attempts. Data are displayed as mean pointing error +/- standard error of the mean. Mean values of pointing error were compared using a two-tailed Student's T-test. A p value of less than 0.05 indicated a significant difference between the means.
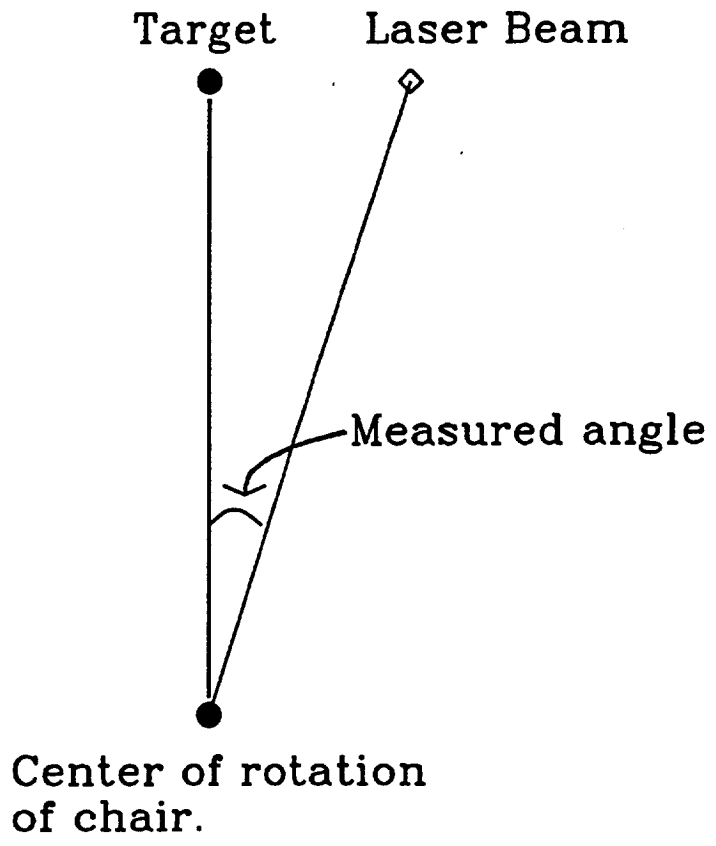
Figure 1.— Angular deviation of laser beam relative to target.

RESULTS

For both paradigms, subjects were rotated both clockwise and counterclockwise for 10, 20 or 30 degree rotations. Thus, following 50% of the rotations, the subjects pointed away from their body to aim at the remembered location of the target. For the other 50% of trials, the subjects pointed across their bodies to aim at the target position. No significant differences were found in pointing accuracy between crossed and uncrossed pointing movements. No differences in performance were noted between left-handed and right-handed subjects.

In paradigm one, subjects were rotated while they maintained gaze on the stationary target. After the rotation was complete, the target light was extinguished, and the subjects pointed back to the remembered location of the target. For the first attempt following a ten degree rotation, subject pointing error averaged 1.3 +/- 0.3 degrees; for a twenty degree rotation, pointing error averaged 1.6 +/-0.2 degrees, and for a thirty degree rotation, pointing error averaged 2..4 +/- 0.5 degrees (Figure 2). Since subjects pointed three times with each chair rotation, we were able to observe whether any improvement occurred with subsequent pointing attempts. For the ten and twenty degree rotations, a significant improvement was found in pointing accuracy between the first and second attempts for paradigm one.

Pointing error was also normalized against the angle of chair rotation. For a ten degree rotation, subjects erred by 0.13 degrees per degree of rotation. For both the twenty and thirty degree rotations, subject erred by only 0.08 degrees per degree of rotation (Figure 3).

In paradigm two, subjects fixated on the target as in paradigm one. However, the target light was extinguished before rotation, and the subject pointed back to the remembered location of the target once the rotation was complete. Pointing error was greater in this paradigm. For a ten degree rotation, subject pointing error averaged 2.1 +/- 0.4 degrees; for a twenty degree rotation, pointing error averaged 3.1 +/- 0.6 degrees; for a thirty degree rotation, pointing error averaged 4.7 +/- 0.6 degrees (Figure 4). In contrast to paradigm one, no significant improvement in pointing accuracy was observed with subsequent pointing attempts.

Normalized pointing error were 0.21 degrees per degree of rotation for a ten degree rotation and 0.15 degrees per degree of rotation for both twenty and thirty degree rotation (Figure 5).

For both paradigms one and two, subjects tended to undershoot the target. This was true regardless of whether crossed or uncrossed pointing movements were used.

Finally, there was no significant difference between the pointing error for a zero degree rotation between paradigm one and two. In paradigm one, pointing error averaged 0.85 +/- 0.28 degrees while in paradigm two, pointing error averaged 0.87 +/- 0.21 degrees for the first attempts (Figure 6). In the absence of rotation, the pointing task for paradigm one is identical to that for paradigm two so that the measurements of pointing error should not be and are not different.
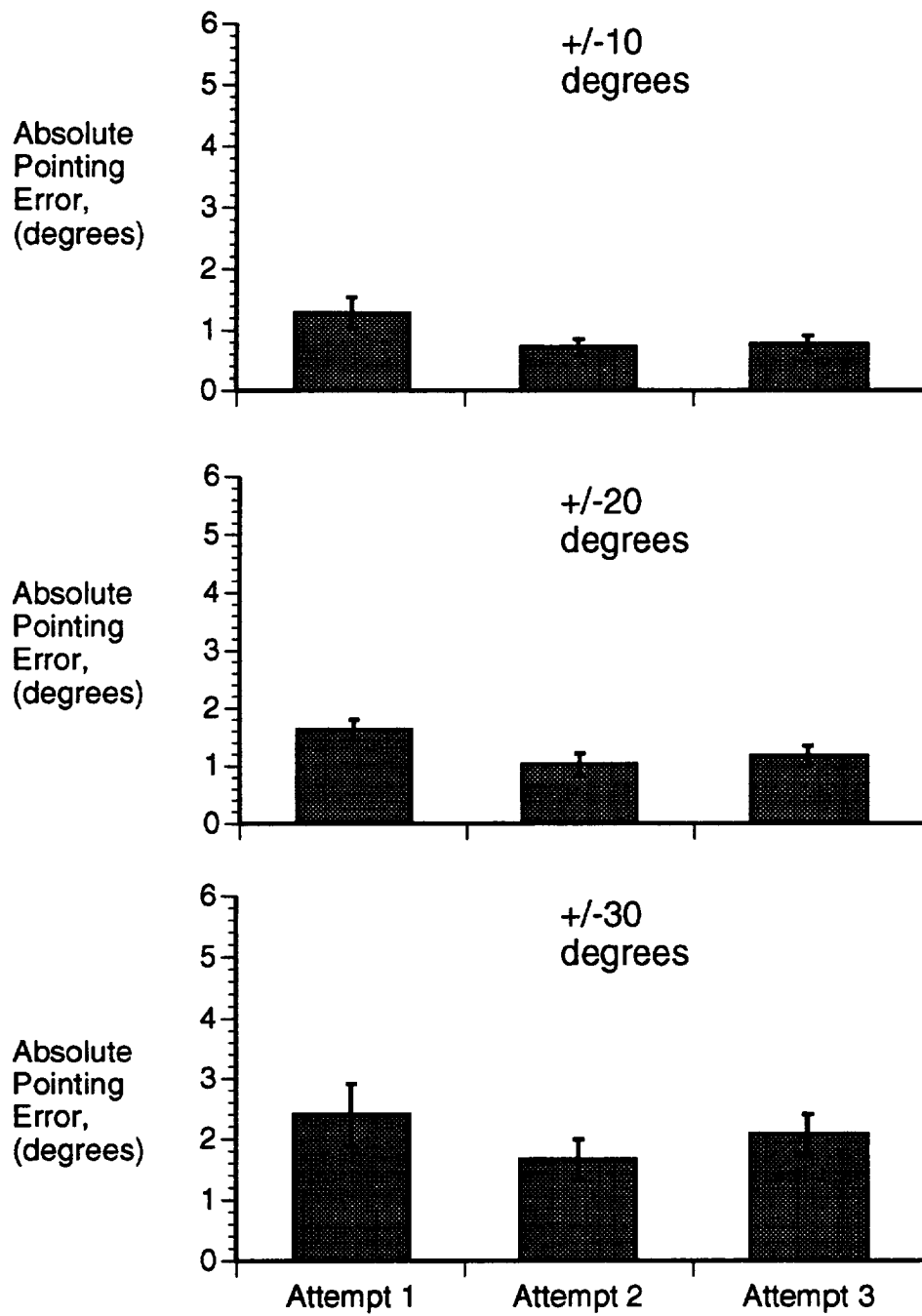
FIGURE 2.- Absolute pointing error for paradigm one (rotation in the light) for 10, 20, 30 degree displacements. Data represent mean +/- SEM for 8 subjects.
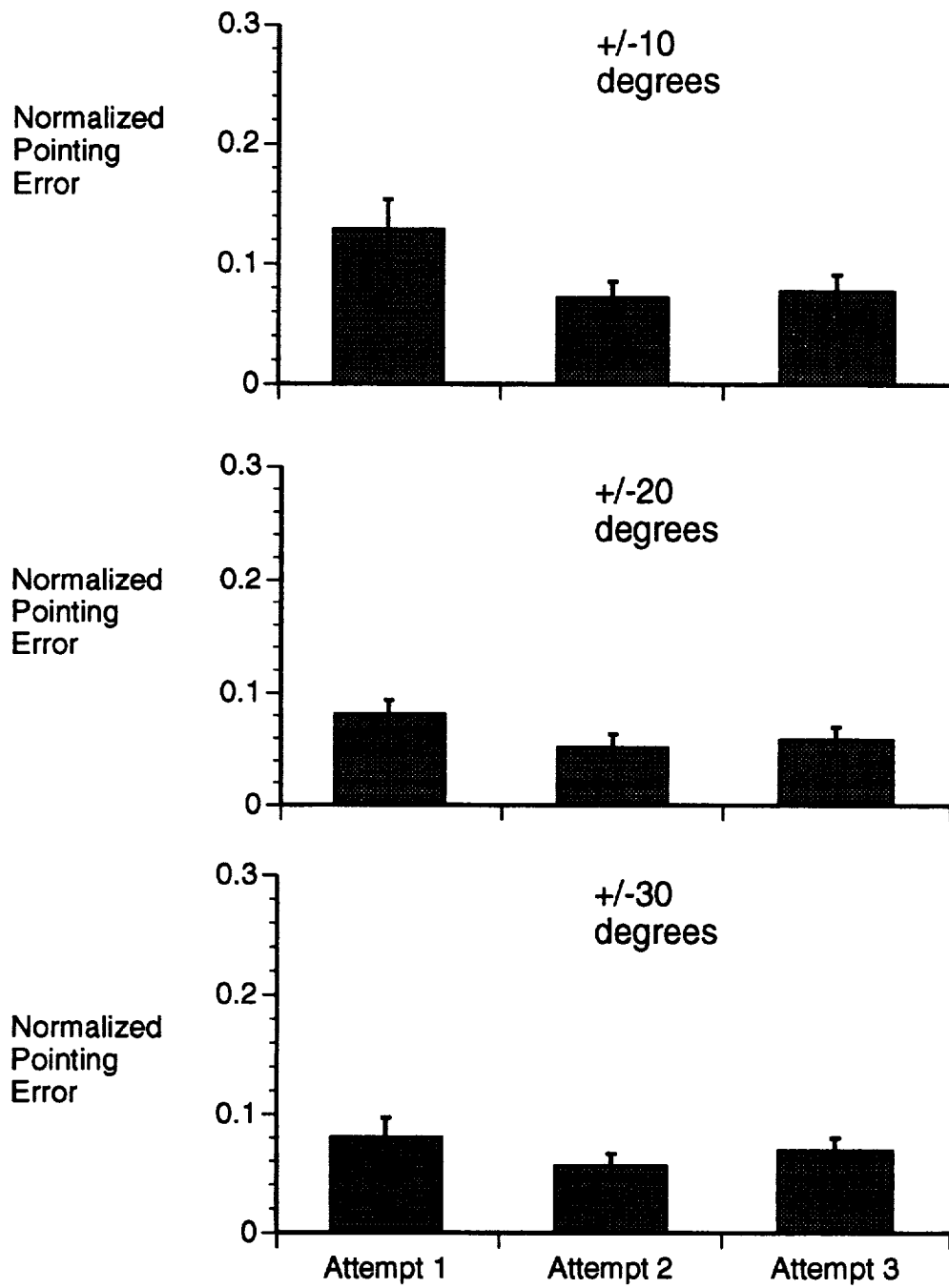
FIGURE 3.- Normalized pointing error for paradigm one (rotation in the light) for 10, 20 and 30 degree displacements. Data represent mean +/- SEM for 8 subjects.
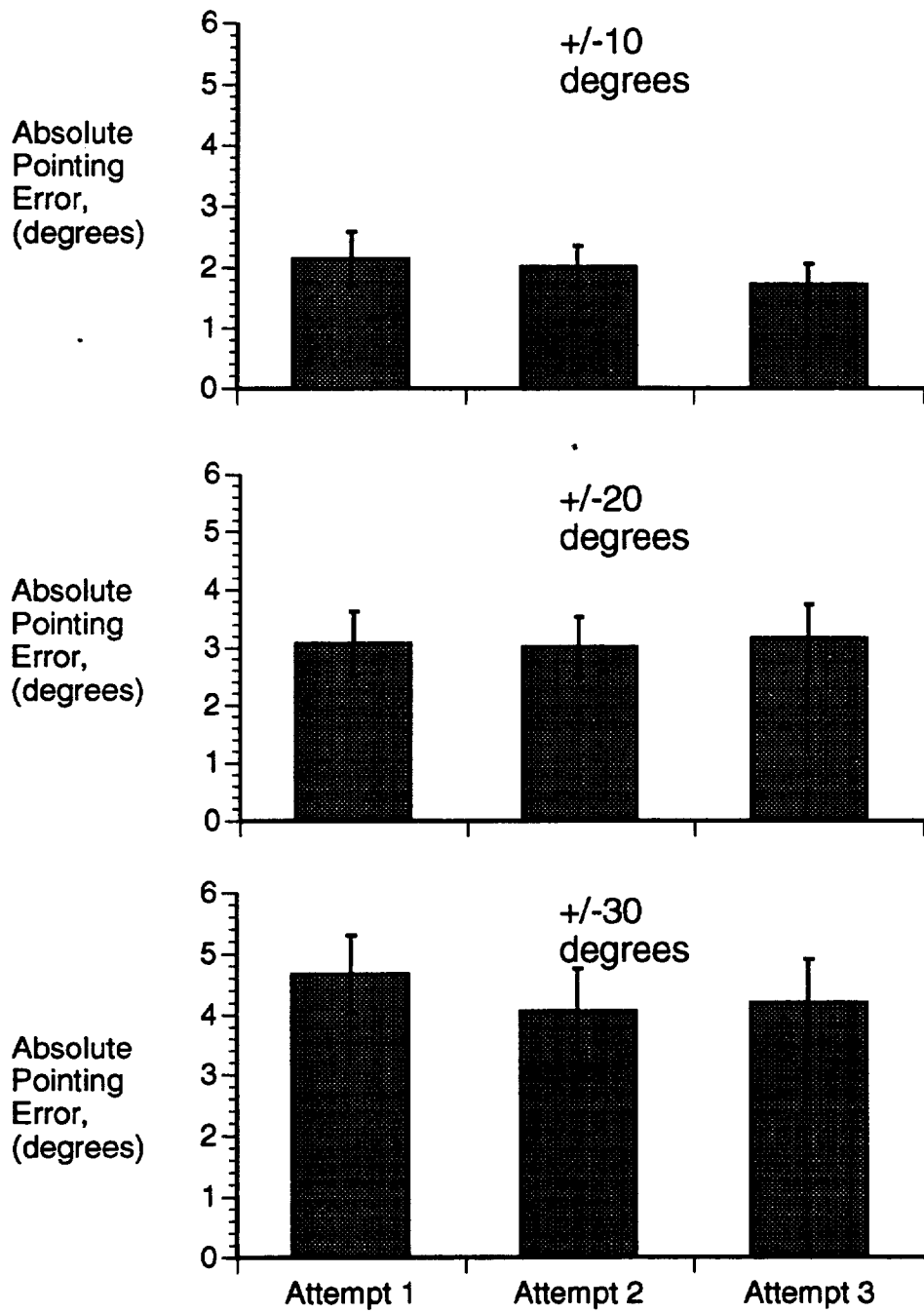
FIGURE 4.- Absolute pointing error for paradigm two (rotation in the dark) for 10, 20 and 30 degree displacements. Data represent mean +/- SEM for 8 subjects.
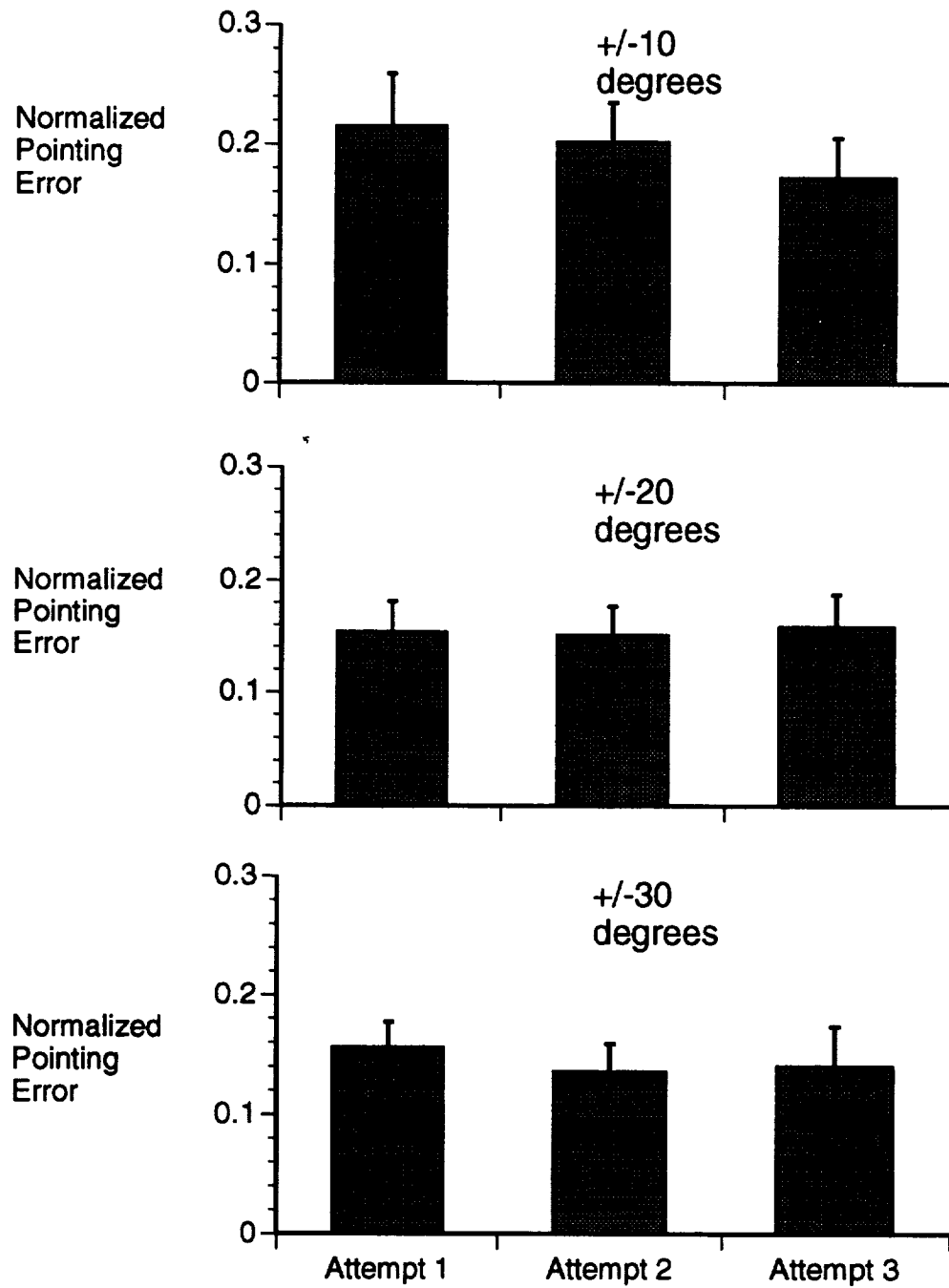
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FIGURE 5.- Normalized pointing error for paradigm two (rotation in the dark) for 10, 20 and 30 degree displacements. Data represent mean +/- SEM for 8 subjects.
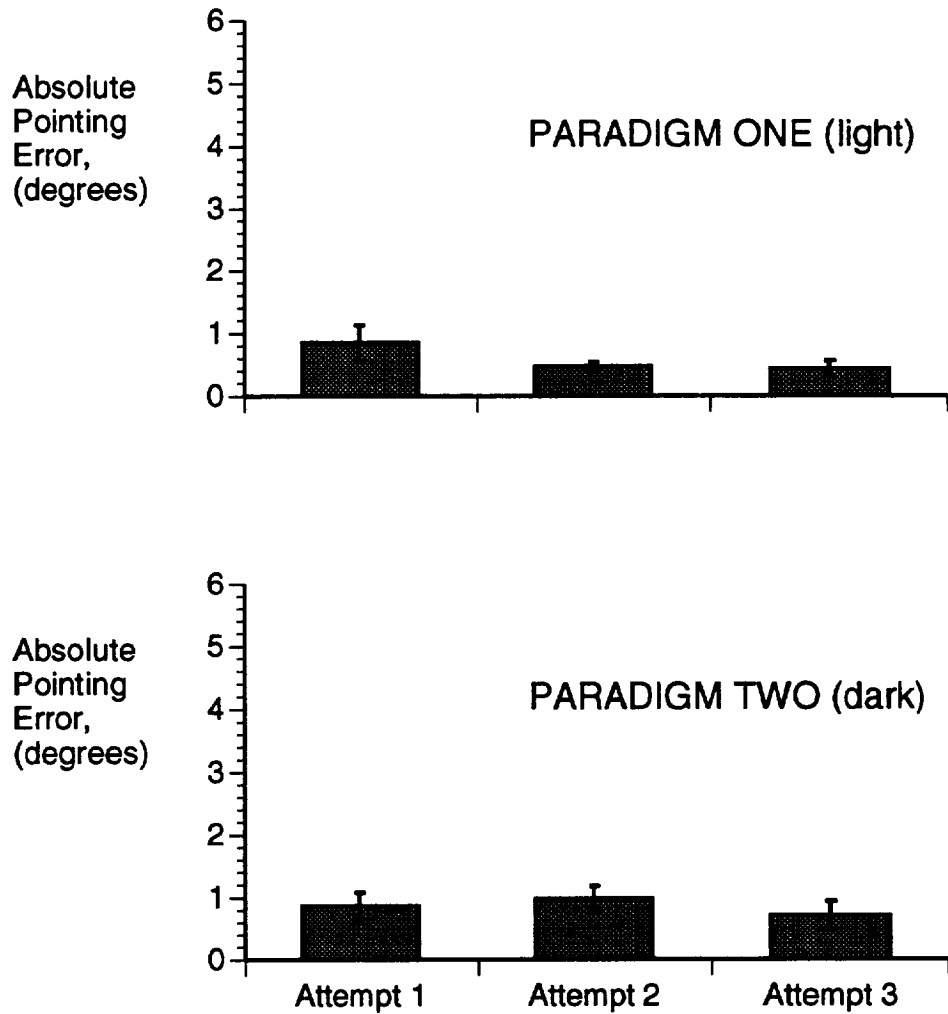
FIGURE 6.- Absolute pointing error for 0 degree displacement for both paradigms. Data represent mean +/- SEM for 8 subjects.

DISCUSSION

Subjects pointed approximately twice as accurately in paradigm one than in paradigm two. In paradigm one, the subjects were able to track the target visually during rotation, while in paradigm two, subjects were rotated in total darkness; no visual feedback of tracking was possible. Thus, visual feedback of target position during rotation improved pointing performance. Nevertheless, subjects were able to point back to the target in paradigm two with a great deal of accuracy. The pointing error for a 20 or 30 degree rotation averaged 0.15 degrees per degree of rotation. Since the subjects were able to point back to.targets in paradigm two, a vestibularly derived percept of head rotation must have been the primary if not the only source of information to the motor command networks for pointing movements. This vestibular information has derived primarily from the semicircular canals. To our knowledge, these experiments represent the first demonstration of a role of the vestibular system in manual pointing.

In paradigm one, pointing performance improved between the first and second pointing attempts for 10 and 20 degree rotations. Since the subjects pointed in the dark, they must have compared the position of the laser beam after the first pointing attempt with a stored version of target position within an internal spatial map. They were able to adjust the direction of the laser beam to approximate more accurately the remembered position of the target.

In contrast to their performance in paradigm one, subjects did not improve their pointing performance with second pointing attempts in paradigm two. When the pointing error was normalized against the degree of rotation for 20 and 30 degree rotations, the error averaged 0.15 degrees per degree of rotation.

In paradigm two, subjects were primarily if not entirely dependent on the vestibular system for pointing performance. The normalized error of 0.15 degrees per degree of rotation, therefore, may represent a limit to the accuracy of internal perception of rotation obtained with exclusively vestibular information. Alternatively, vestibular input may provide a more accurate estimate of the degree of chair rotation than the normalized error value. The normalized error may indicate other limits of accuracy. These limits are reached as motor output signals are sent to the pointing arm.

In related, similar studies, subjects were asked to make saccadic eye movements back toward an earth-fixed target after a 20 degree rotation in total darkness. In these experiments, the vestibular-ocular reflex was inhibited so that saccades were necessary to bring the eyes back on target (Bloomberg et al., 1991b). As in paradigm two, vestibular input provided most if not all the sensory information used by these subjects to generate saccades. Saccades brought the eyes to within 1.6 degrees of the target. As in our pointing experiments, subjects tended to make saccades that undershot the target. The normalized eye movement error was 0.08 degrees per degree of rotation, about half of the normalized pointing error reported here. Thus, vestibular input may provide a more accurate measure of rotational

displacement than we can measure from the pointing output. The motor command networks directing eye movements may receive more information from the vestibularly-derived spatial map than the motor command networks for pointing movements. Alternatively, vestibular input to both systems may be identical but the motor command networks for pointing may not produce as accurate an output as those for eye movements.

Our data provide a measure of an individual's ability to point to a remembered target location using only vestibular cues. These data can be contrasted with similar data derived from subjects whose eye-head coordination and internal spatial map have been perturbed, for example, by wearing minimizing lenses. In addition, these data can be compared to data collected from astronauts exposed to the microgravity environment of space.

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MODELING OF DC SPACECRAFT POWER SYSTEMS

Final Report
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Data Submitted: August 5, 1994

Contract Number: NGT-44-005-803