INFLUENCE OF GENERALIZED TACTILE CUES ON MOTION SENSATION AND POSTURAL CONTROL

by

GAIL JEANNE STANDISH

S.B., Aeronautics and Astronautics
Massachusetts Institute of Technology
(1985)

Submitted in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE
in
AERONAUTICS AND ASTRONAUTICS
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May, 1990

Signature of Author______________________________

Certified by______________________________
Laurence R. Young
Professor of Aeronautics and Astronautics

Accepted by______________________________
Professor Harold Y. Wachman
Chairman, Department Graduate Committee

INFLUENCE OF GENERALIZED TACTILE CUES ON MOTION SENSATION AND POSTURAL CONTROL

by

GAIL J. STANDISH

Submitted to the Department of Aeronautics and Astronautics
in partial fulfillment of the requirements for the Degree of Master of
Science in Aeronautics and Astronautics

ABSTRACT

Two experiments were conducted in which the influence of generalized tactile cues on the perception of self-motion and postural control were observed. In both experiments a rotating visual field was used to induce circular vection. During half of the runs, subjects' heads were fixed in the center of the field by a biteboard. Subjects indicated their sensation of self-motion through the use of a joystick. In Experiment 1, free swinging pendulums were used to apply tactile cues to the shoulders during some of the runs, and subjects performed all trials in the Sharpened Romberg position. Magnitude of vection and the number of subject imbalance occurrences were recorded. In Experiment 2, the pendulous weights were controlled though a pulley system so that constant pressure was maintained on the shoulders. Various amounts of pressure were applied. Vection magnitude and body sway, as measured at the shoulders, were recorded.

The results from the first experiment showed that the application of generalized tactile cues increased time to onset of vection ($p < .05$) and reduced the number of imbalance occurrences ($p < .05$). Maximum and average vection decreased, but not significantly. In Experiment 2, maximum and average vection decreased significantly during off biteboard runs ($p < .05$), but only trended toward significance on the biteboard. The influence as a tactile cue of the biteboard used in the experiment was greater than that of the shoulder cues. Mental set was also a significant factor in subjects' vection indications. No significant change in magnitude or frequency of body sway was seen as the pressure of the applied cue changed.

Thesis Supervisor: Dr. Laurence R. Young

Title: Professor of Aeronautics and Astronautics

ACKNOWLEDGEMENTS

As with any endeavor of the magnitude of a thesis, there are many people to thank. First and foremost, my thesis advisor, Professor Laurence R. Young. Professor Young taught me the differences between science and engineering, and then showed me how two very disparate disciplines can be so vital to each other. His teaching, and the very nature of the interdisciplinary program offered in the Man-Vehicle Lab, have provided me with a unique education -- one I think will be useful wherever I go.

There are others in the lab who made life a lot easier for me: Mark Shelhamer, who patiently answered even the silliest of questions; Sherry Modestino, who kept me sane and well fed for almost two years; Jim Costello, who can, and does, make anything work; Jock Christie, the man who shared my office and listened to me complain for the last year; Dr. Alan Natapoff, who kept my statistics honest; and all of the other "kids" in the lab that made this such a fun and insane place to be. A very special thanks goes to the "Dome UROP," Shirley Lee. Shirley helped me overcome my fear of smiling Macintoshes, and was integral in helping me complete this research from the original construction of equipment to the last throes of data reduction.

Finally, I would like to thank my husband, Howard. He's never read this document, and probably never will, but he's waited so patiently...

This research was funded by NASA grants NAS9-16523 and NAG2-445

CONTENTS

CHAPTER 1: BACKGROUND

The complexity of the human brain is not something we think about every day . We go about our daily business doing *simple* things -- standing, walking, or perhaps handling an object -- and never realize how complicated each of these activities is. What information is needed to accomplish a task? Which senses do we use? How is the information that is gathered weighted? What movement is required and how is it completed? This thesis involves looking at a specific task, that of maintaining posture and orientation. The study of human perception of spatial orientation based on the signals transduced by the various senses is still a relatively young science in terms of hard data, despite the fact that scientists have been interested since the nineteenth century.

Daily experiences show us which of the senses most obviously affect posture and orientation. Vision is probably the most important of the senses. Walking a straight line, or even standing still with the eyes closed is extremely difficult. The importance of the vestibular system can be seen while watching a child at play, spinning around until he can no longer stand even with his eyes open. Somatosensory cues can also play an important role. One finger touching the wall will stabilize the man in the shower who has his eyes closed to keep the soap out. This section will attempt to treat each of these senses, discussing their utility in maintaining posture and orientation under different conditions, and how they relate to each other.

Perception Based on Multisensory Input

The sensation of motion is probably the key to maintaining posture. An individual standing upright would not need to make any adjustments to maintain that position if all the forces on the body summed to exactly zero. The body would be unaccelerated, and there would be no sensation of motion. Young (1984a) states that "Perceived spatial orientation is closely related to the actual linear and angular motions of the body, and many of the important differences between perception and true motion are explainable on the basis on the dynamic characteristics of the sensors." Visual, vestibular, and somatosensory stimuli can all generate a sensation of motion individually, and each can modify the perception generated by another. The interaction among the senses is particularly interesting, because it is believed that conflict between senses is a primary cause of motion sickness (Oman 1982, Oman et al., 1986).

Motion sensation is also strongly influenced by an individual's mental set. Howard and Templeton (1966) discuss this in terms of constraints. These constraints are dictated by man's typical environment -- what we normally expect to see or feel. For example, most objects we see have a "top" and "bottom," and are defined with horizontal and vertical lines. Oman's work with astronauts in the microgravity environment of Spacelab and in parabolic flight (1988) demonstrated many "visual orientation illusions" wherein subjects often perceived the surface closest to their feet as the "floor" regardless of their true orientation with respect to the aircraft or spacecraft. The constraints provided by gravity had been removed. In our usual environment there are intersensory constraints as well. Howard defines these as "any recurrent combination of a stimulus in one modality with a stimulus in another modality." For example, spinning one's head to the right provides both visual and vestibular stimulation that are thus expected to occur together the next time the same movement takes place. These "perceptual constraints" can actually be quite plastic in nature, as an individual can be retrained to perceive things differently if the environment is altered for a sufficient length of time (Oman et al., 1980, Young et al. 1986a).

Overall, our perception of motion and orientation, using all of the senses as inputs, can be represented schematically. Figure 1.1 (from Young, 1970) diagrams the active spatial orientation process. The following sections will discuss each mode represented in

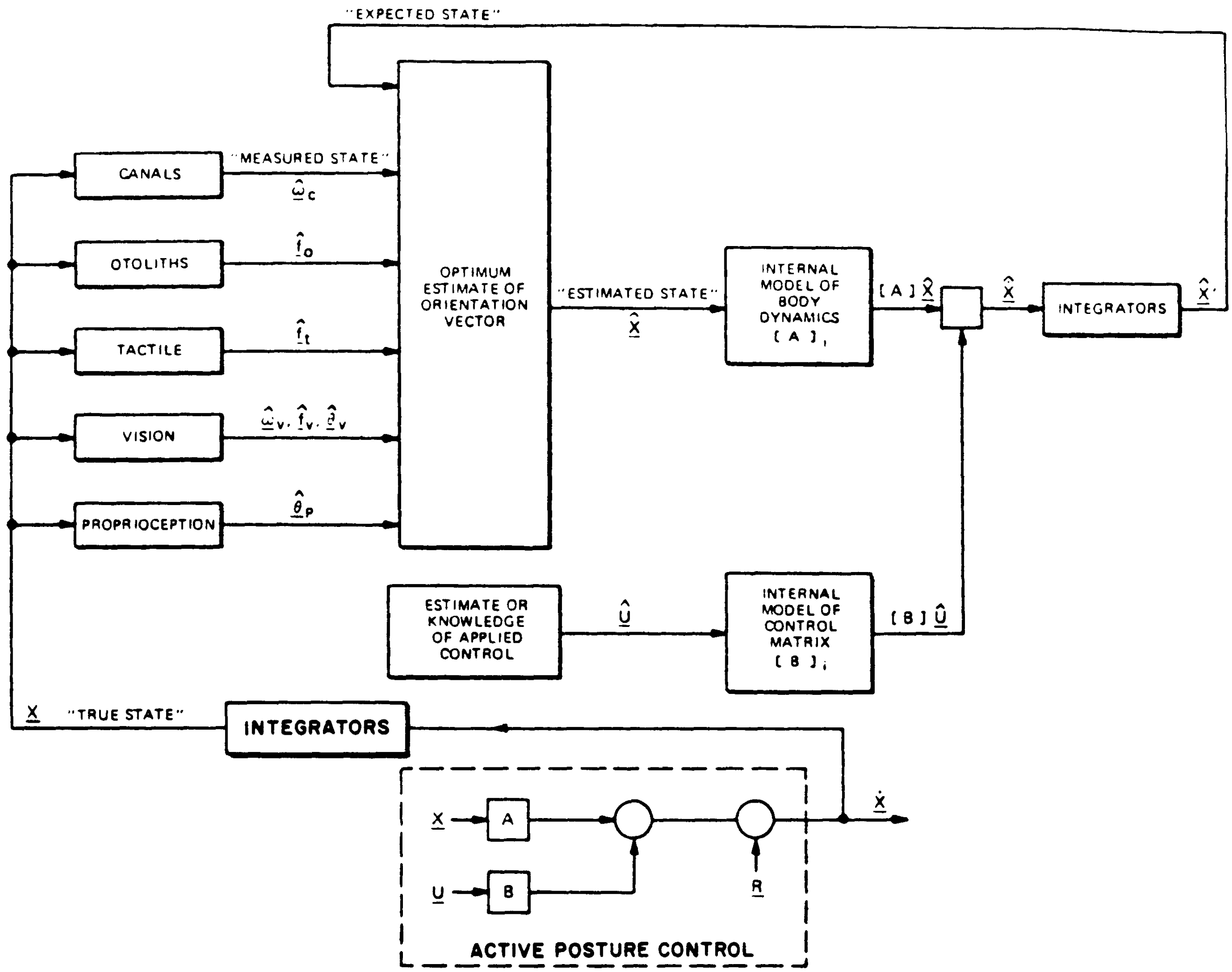


FIG. 1.1. Schematic representation of spatial orientation process. "True state" vector **X**, consisting of linear and angular positions and velocities, is produced by changes resulting from three sources: unforced behavior of body, $\hat{\mathbf{X}}$ processed by A, commanded body changes, commands **U** processed by B, and unmeasured disturbances, **R**. Various sensors are each responsive, especially to one or more components of measured atate. Symbol " ^ " indicates an estimate of the vector; ω, angular velocity, **f**, specific force, gravity minus linear acceleration; θ, angle. Measured state sugnals are combined with "expected state," $\hat{\mathbf{X}}'$, derived from an assumed internal model of the body, in optimum estimator to produce estimate of orientation, $\hat{\mathbf{X}}$. [From Young, 1970]

the model, with the exception of the auditory system, and its influence on orientation and motion perception.

The Vestibular System

Gillingham and Wolfe (1986) state three major functions of the vestibular system in spatial orientation. First, the vestibular system provides the information for "reflexes that serve to stabilize vision when the motion of the head and body would otherwise result in blurring of the retinal image." Second, this systems provides orientation information used in both reflexive and skilled motor activities. Lastly, in the absence of vision, the vestibular system provides perception of motion and position that it accurate as long as the applied stimulus remains within naturally occurring boundaries.

The Semicircular Canals

The semicircular canals are fluid filled toruses that lie in three roughly orthogonal planes. Due to this arrangement, the canals are able to transduce angular accelerations about any axis in space. They act as integrators, and thus for all but stimulus frequencies less than about 0.1 Hz, their output reflects the angular velocity of the head with respect to inertial space (Young, 1984a). The time constant for decay of this velocity signal is about 15 seconds. Thus, a subject spun in the dark, without visual cues to reinforce motion sensation, would no longer feel that he is rotating a few time constants after the stimulation began.

Otolith Organs

The otolith organs are the vestibular system's linear accelerometers. Two "earstones" -- a utricle and saccule on each side of the head -- can between them sense acceleration in all three dimensions. As with all physical accelerometers, linear acceleration and gravity are indistinguishable from one another. Since the otoliths are the principal non-visual determinant of static orientation with respect to gravity, this "blindness" to the difference between the g vector and other linear acceleration can lead to disorientation and sensory conflict. In microgravity the otoliths no longer indicate "down," while visual system and semicircular canal cues remain valid. This is believed to be a primary reason for the development of space motion sickness (Oman 1982, 1986). Spacelab experiments demonstrate the plasticity of the gains of the various signals, as subjects become more visually dependant as they continue functioning in microgravity (Arrot and Young, 1986), and only return to normal interpretation of otolith information after several days back on Earth (Young et al. 1984, 1986a, Arrott and Young, 1986). The brain's interpretation of the meanings of these signals also changes. Parker et al. (1985) tested astronauts' perception of self motion pre- and post-flight using a roll stimulus. Preflight, subjects correctly drew the curved trajectory they had experienced. Postflight, however, they interpreted otolith stimulation due to head tilt or roll as linear acceleration. Parker's "otolith tilt-translation reinterpretation" also returned to normal several days postflight.

Vestibular Reflexes

The main purposes of the vestibular reflexes are to maintain stable retinal image and upright posture. Melvill Jones (1965) describes this as operation of three discreet body platforms: "(1) the eye-in-skull platform, driven by the external eye muscles rotating the eyeball relative to the skull; (2) the skull-on-body platform driven by the neck muscles; and

(3) the body platform, operated by the complex neuromuscular mechanisms responsible for postural control."

Vestibulo-ocular Reflexes

The vestibulo-ocular reflexes serve mainly to stabilize the retinal image. These reflexes can be elicited by semicircular canal or otolith stimulation. With semicircular canal stimulation, as with a rotation of the head in the yaw plane, canal afferents drive the eyes in the direction opposite of head rotation, thus preventing slippage of the image over the retina. This is called compensatory eye motion. The angular deviation of the eye is physically limited, thus the eye must return to its initial position or a new tracking position. This movement, which is extremely rapid and during which we do not perceive motion, is anti-compensatory. During sustained semicircular canal stimulation such as can be achieved with a subject in a rotating chair or with caloric stimulation, a back and forth eye motion, called nystagmus, is seen. The compensatory portion of this ocular motion is the "slow phase" of nystagmus, while the quick anti-compensatory motions are referred to as "quick phase."

Otolith signals can also elicit eye movements. Lateral linear accelerations produce horizontal eye movements, including nystagmus, while vertical accelerations produce vertical eye movements. Like the reflexes of semicircular canal origin, the eye movements produced by linear acceleration tend to keep the visual image stable on the retina.

The ocular torsion reflex is another otolith induced reflex. In this case head tilt around the roll axis causes the eye to rotate about the visual axis in the opposite direction, repositioning the eye in the direction that tends to maintain an upright and stable retinal image, but with a gain of only about 10%.

The Vestibulocollic Reflexes

The vestibulocollic reflexes (VCR) serve to right the head with respect to gravity by use of neck muscles in response to vestibular stimulation. These reflexes are not very well understood in humans, possibly because they are not nearly as effective as the vestibulo-ocular reflexes in stabilizing retinal image (Gillingham and Wolfe, 1986), and because invasive techniques are often necessary to measure the small movements and potentials generated. Guitton et al. (1986) found that in human subjects distracted by mental arithmetic the contribution of the vestibulocollic reflexes to head stability is negligible. VCR contributions to head motion in cats has been studied to a much greater extent, using invasive techniques or decerebrate animals (Wilson et al., 1979, Baker at al., 1985, and Goldberg and Peterson, 1986).

Fukushima et al. (1987) studied the VCR in alert cats making active head motions, observing that the reflex was not suppressed as had been expected. Birds have highly developed vestibulocollic reflexes, perhaps due to the relative immobility of birds' eyes in their heads. Despite the weakness of these reflexes in humans in comparison to other animals, it is apparent that these reflexes are vital in maintaining an upright head position through vestibular influences on the muscles of the neck.

Vestibulo-spinal Reflexes

Vestibulo-spinal reflexes serve to assure the stability of the whole body platform with respect to inertial space. These reflexes mediate the tonic activity of the "antigravity" muscles that allow a human to remain upright with respect to the gravity vector. Other vestibulo-spinal reflexes allow us to catch ourselves when we fall by extending or retracting arms and legs. Gurfinkel et al. (1988) do not believe posture is controlled only at this level of reflex, but that an internal representation, or "body scheme," exists. This model includes the processing of multisensory input at the unconscious level, as well as a conscious perception of the body in space.

The Visual System

As stated earlier, vision is the most important sensory modality used in static orientation and posture control. This is evidenced by the fact that labyrinthine defective subjects have little or no difficulty functioning normally if visual information is available. There are two distinct visual systems, one that controls object recognition, and another that provides lower level spatial orientation (Gillingham and Wolfe, 1986). Though not used in orientation under normal conditions, object recognition can become important in unnatural settings such as microgravity for situational awareness.

Functionally, visual information is processed as focal vision, for object recognition, or ambient vision, for spatial orientation. These pathways have been studied at the cellular level by Hubel and Wiesel in cats and monkeys (1965, 1977). They identified "edge detectors" and "orientation detectors" in these animals, but no comparable data exists for humans.

Focal Vision

Liebowitz and Dichgans (1980) summarize focal vision as being concerned "in general with the question of what. Focal vision involves relatively fine detail (high spatial frequencies) and is correspondingly best represented in the central visual fields." This information is available at the conscious level, letting us identify and thus "name" objects. Its only function in orientation is as related to the perceptual constancies of which Howard spoke. One knows that tree grow "up," can identify the "top" of a tree from previous experience, and can thus have a conscious knowledge of the orientation of the visual field relative to the body. However, this high level method of orientation can and often does break down in situations such as zero gravity, resulting in inversion illusion or total loss of orientation.

Ambient Vision

Ambient vision is also well described by Liebowitz and Dichgans as the mode that "subserves spatial localization and orientation and is generally concerned with the question of 'where'." Ambient vision usually involves stimulation of the peripheral field. Large spatial frequencies, coarse rather than fine detail, are most apparent. Ambient vision is independent of focal vision -- one can be completely focussed on a single object and still detect motion in the peripheral field, or even read signs using focal vision while still maintaining sufficient orientation to drive a car.

Static Orientation

In static orientation, when neither the body nor the visual field is in motion, straight lines and familiar objects play an important role. Fun houses at carnivals often have tilted rooms in which a person finds it very difficult to walk, because the natural reaction to the surroundings is to align one's self with the wall, in this case a destabilizing reaction. The extent to which individuals are dependant on the visual vertical -- called field dependance -- is highly variable (Young, 1984a). Field dependance is often measured using the "rod and frame" test (Witkin and Asch, 1948, Young et al., 1986b). In this test, a subject is seated in a completely darkened room. He is then asked to set a luminous rod to vertical, with a luminous frame as the only visual reference. The frame may be upright with respect to gravity, or it may be tilted by varying amounts clockwise or counter-clockwise. A field dependant subject tends to set the rod to align with the frame, while a field independent subject is less likely to do so. Neal (1926) found that a slight tilt of the head while attempting to set a line to vertical (with or without a frame) did affect the apparent vertical. This supported data from the late 1800s of Aubert (1861) in which A-effect (named for Aubert), underestimation of head tilt, was seen. This underestimation caused subjects to set the line to a position tilted in the opposite direction from the head rotation. Muller (1916) found that the perception of vertical was often displaced opposite to that expected due to the Aubert phenomenon, especially for large head angles. He termed this overestimation of head tilt "E-effect." Which of these effects a subject experiences varies widely, with some subjects experiencing only A-effect, while others experience both depending on the angle of head tilt.

Vection

The main function of ambient vision in orientation is that of providing motion cues. When there is uniform motion of a large part of the visual field a false sensation of motion often occurs. This sensation is referred to as vection (Young, 1984a). Many examples of vection can occur in daily life. For example, the driver of a car that is stopped at a light on a hill may suddenly feel that he is drifting backwards when the car next to him is actually surging forward. If the visual field is made to rotate about an earth horizontal axis a subject will often feel circular vection, in which some or all of the perceived rotation is attributed to self-motion rather that just the spinning of the visual field (Young 1984a, Watt 1989). The onset of vection is not instantaneous, usually having a latency of 2-5 seconds (Young, 1984a).

Saturated vection, when the subject attributes all of the rotation of the visual field to self-motion, may occur at lower angular velocities (< 50 degrees per second), but is easily inhibited. The strength of vection is affected by many factors, and is a primary focus of the research presented in this thesis. Mind set -- knowledge that one cannot be rotating head over heels, vestibular input -- the otolith organs giving proper indications of down if the subject is upright in one-g, and tactile cues such as pressure on the feet all tend to prevent saturated vection. Experiments performed by Young et al. (1984b, 1986b) have investigated many of these inhibitory cues in one gravity and in microgravity. In one-g the otolith cue may be removed by having subjects view the rotating field while lying supine. This tends to increase vection. Upright in one-g subjects tend to feel paradoxical vection -- a feeling that they are rotating, but also maintaining a static tilt angle. Young, Oman, and Dichgans (1975) found that vection in the pitch and roll axes were strongly dependant on head position, and that the perceived static tilt in the pitch axis was not symmetric, being stronger for pitch forward than backward. Howard, Cheung, and Landolt (1987) studied vection in all three axes, finding that forward pitch vection was stronger than backwards, but unlike Young, that illusory backward tilt was stronger than forward tilt. They also found that yaw rotation around a vertical axis was strongest, this being the situation in which physical rotation could actually occur. In Spacelab experiments (Young, 1986b) the use of bungee cords to hold subjects to the floor and thus apply tactile cues to the feet tended to reduce vection, though the small number of subjects available did not allow for significant quantitative findings.

Brandt et al. (1975) studied foreground/background relationships and their effect on vection. Stationary objects in the foreground, particularly the subject's own body, tend to increase vection, while objects in the background interfere with it. Watt (1988, 1989) also noted that roll circular vection was enhanced by the presence of a non-rotation rim in the near peripheral vision. Ohmi et al. (1987) had no stationary objects in their circular vection experiments, but also found that background moving displays tended to induce greater vection.

Optokinetic Nystagmus

Eye movements equivalent to those discussed in the section on the vestibular system can be induced through movement of the visual scene while the subject remains stationary (Howard, 1966). These eye movements, termed optokinetic nystagmus, serve to reduce retinal image slip slightly, as the vestibulo-ocular reflexes do. Thus, a moving scene which produces horizontal vection will also elicit horizontal nystagmus, just as if the subject were being accelerated laterally. The same is true for vertical and rotational motion of the visual scene.

Somatosensory Cues

There are several terms used to describe the non-visual or vestibular sensory systems. Sherrington (1906) was the first to use the term "proprioception." He defined proprioception to include the vestibular afferent system, but the more common usage includes only the visceral, muscular, and joint afferents. Howard, in Human Spatial Orientation (1966), devotes a chapter to this, titling it "kinaesthesis," while others use "somatosensory," this latter term including external tactile stimulation as well.

Three types of information are provided by somatosensory cues. These are muscle length and tension, limb position, and external pressure. Muscle spindles are the source of the afferent signals from the muscles, while Golgi organs provide similar information from the tendons. Together these receptors indicate length and tonus, and are particularly important in the antigravity muscles which allow one to stand and walk, and retain the head in an upright position. Separate joint receptors feed back the information on limb position, allowing controlled movement of the arms and legs. Though the contributions of these senses to orientation are not as profound as those of the visual and vestibular systems, they are nevertheless important. The lack of antigravity muscle use under water or in microgravity no doubt contributes to disorientation and increased dependance on vision.

Little work has been done assessing the use of tactile cues in maintaining orientation. Howard (1966) omits the tactile modality in his book on orientation because "its role in orientation is of minor importance." Tactile cues do, however, play a significant role in maintaining posture, as can be seen in the righting reflexes of labyrinthectomized animals that appear when cues are applied asymmetrically to the feet. In the Spacelab experiments mentioned earlier, subjective comments of the subjects indicated that tactile cues applied to the feet in an environment where normal vestibular cues were absent did decrease visual dependency. Pressure cues have been used with some success in flight simulators where asymmetric cues on the buttocks can be used to help induce roll sensation and simulate the effects of high-g maneuvering in a limited motion cab. Kron et al. (1977, 1978) created a "g-seat" which was padded with several individual inflatable bladders. Thus, variable pressure could be applied to different parts of the back and buttocks. The seat also employed a variable tension lap belt to apply the appropriate tactile cue to the pilot's ventral area during simulated braking or negative g. These types of stimuli greatly improve the fidelity of a simulator, thus helping with pilot orientation.

In summary, spatial orientation is mediated by all of the sensory modalities (audition was left out because it is not a factor in the experimental work contained in this thesis, though it too can provide information on "where" one is). Though visual and vestibular afferents are the primary sources of orientation information, somatosensory cues also play an important role. The experimental work which follows addresses this by looking at the influence of generalized tactile cues on visually induced motion sensation.

CHAPTER 2: EQUIPMENT

The Rotating Dome

The M.I.T. rotating dome is a roughly hemispherical shell. The inner surface of the shell is covered with 1.9 cm diameter colored dots in a random pattern at a density of approximately 800 dots per square meter (Figure 2.1). The choice of size and density was dictated by earlier studies on visual field parameters and their effects on circular vection conducted by Held et al. in 1975. The distances of the visual surfaces range from 34 cm straight ahead to 17-20 cm laterally and vertically from the mean eye position.

The dome motor is controlled by a Z-80 computer running CP/M as an operating system. The controller program used in all the experiments discussed here was written in "C" in 1984 by Mark Shelhamer and is called "DOMKC". The source code appears in Appendix 1. The dome rotates both clockwise and counter-clockwise at three different speeds. Each combination of speed and direction is given a letter designation. Table 2.1 contains these rotation codes along with the direction of rotation, desired speed of rotation, and measured speed of rotation of the dome. The discrepancy between desired and actual values of angular velocity was not noticed until after the first series of experiments was completed. No adjustments were made prior to the second set so that results between the two could be compared. One dome "run" is made up of six trials, including one trial at each condition from A - F. DOMKC uses two different psuedo-random orderings of these trials. Table 2.2 lists these orderings.

Biteboard

An aluminum biteboard holder is attached to the dome frame. Biteboards are custom fitted to each subject using 3M Express HP Vinyl Polysiloxane dental impression

Table 2.1: Dome Rotation Codes

Rotation code	Direction	Desired Velocity (deg/s)	Actual Velocity (deg/s)
A	CW	30	37
B	CW	45	48
C	CW	60	66
D	CCW	30	40
E	CCW	45	49
F	CCW	60	63

Table 2.2: Dome Runs

Run 1	Run 2
A	B
E	D
F	A
B	C
D	E
C	F

compound (see Appendix 2) and an aluminum blank. The compound takes approximately seven minutes to harden. When the completed biteboard is in place and in use, the subject's head is centered with all of his peripheral vision occluded by the dome (figure 2.2).

The biteboard is instrumented with a strain gage bridge such that torque in the roll axis is measured. Thus, a subject holding onto the biteboard and attempting to rotate his head clockwise causes a positive voltage to be generated. The circuit is a second order system with a gain of 5500 g-cm per volt and a long time constant (decay) of 3.2 seconds. The short time constant is negligible when compared to the dynamics of head motion. This signal is sampled by an analog to digital (A/D) converter at a frequency of 100Hz and sent to the Z-80 or a Macintosh IICX with LabView installed for data acquisition. The Z-80 records this signal at 10Hz, while the Macintosh records at 25Hz.

Joystick

A rotary potentiometer with approximately 90 degrees of rotation is used a a joystick for magnitude estimation of vection. The potentiometer is spring loaded to the center or zero position. As with the biteboard, a clockwise indication from the subject causes an increase in voltage, counter-clockwise causes a decrease. During the first series of tests the joystick was mounted on the dome frame where it was manipulated by the subject's right hand. For later experiments it was modified so that the subject could hold it in either hand while using the other hand to rotate the knob.

Application of Tactile Cues

Generalized tactile cues were added to the apparatus for the current study. They were applied to both shoulders of each subject. In the first set of experiments this was

FIGURE 2.2
Subject in the rotating dome. Subject's head could be fixed using a biteboard, or be free to move.

accomplished by placing two free-swinging pendulums in contact with the shoulders. In this case, a subject leaning to the left would feel an increase of weight on the left shoulder, and would lose contact with the weight on the right. The perceived weight varied from about 20 grams to about 200 grams. The weights also tended to "bounce" if the subject's postural adjustments were rapid.

For the later experiments the system shown in Figure 2.3 was constructed. Two pulleys were used with each pendulum to allow the force applied by hanging a weight vertically to be redirected into a lateral cue. In the previous system, the freeswinging pendulums, the lateral force on one shoulder increased as the subject leaned into it (increasing its displacement), and contact on the opposite shoulder was lost altogether. This new pulley system allowed contact to be maintained on both sides of the subject at a constant pressure. Thus, pressure no longer provided any information concerning postural sway. The applied pressure could be altered by changing the amount of weight suspended. The position of the ball at the end of each pendulum could be adjusted up or down to accomodate subjects of different heights, and the pivots of each could be moved left or right to allow for subjects with wide or narrow shoulders. Potentiometers were added to the pivots of the pendulums so that angular displacement could be measured as an indication of the magnitude of the subject's adjustments. Again, clockwise rotation of these potentiometers resulted in a voltage increase.

Data Acquisition

Experiment 1 and all previous tests

For the early tests the data was acquired on the Z-80 computer that was used to control the experiments. Four channels of data were sampled, two at 10 hz (joystick and biteboard) and two at 100 hz (usually used for electro-myographic (EMG) recording, these

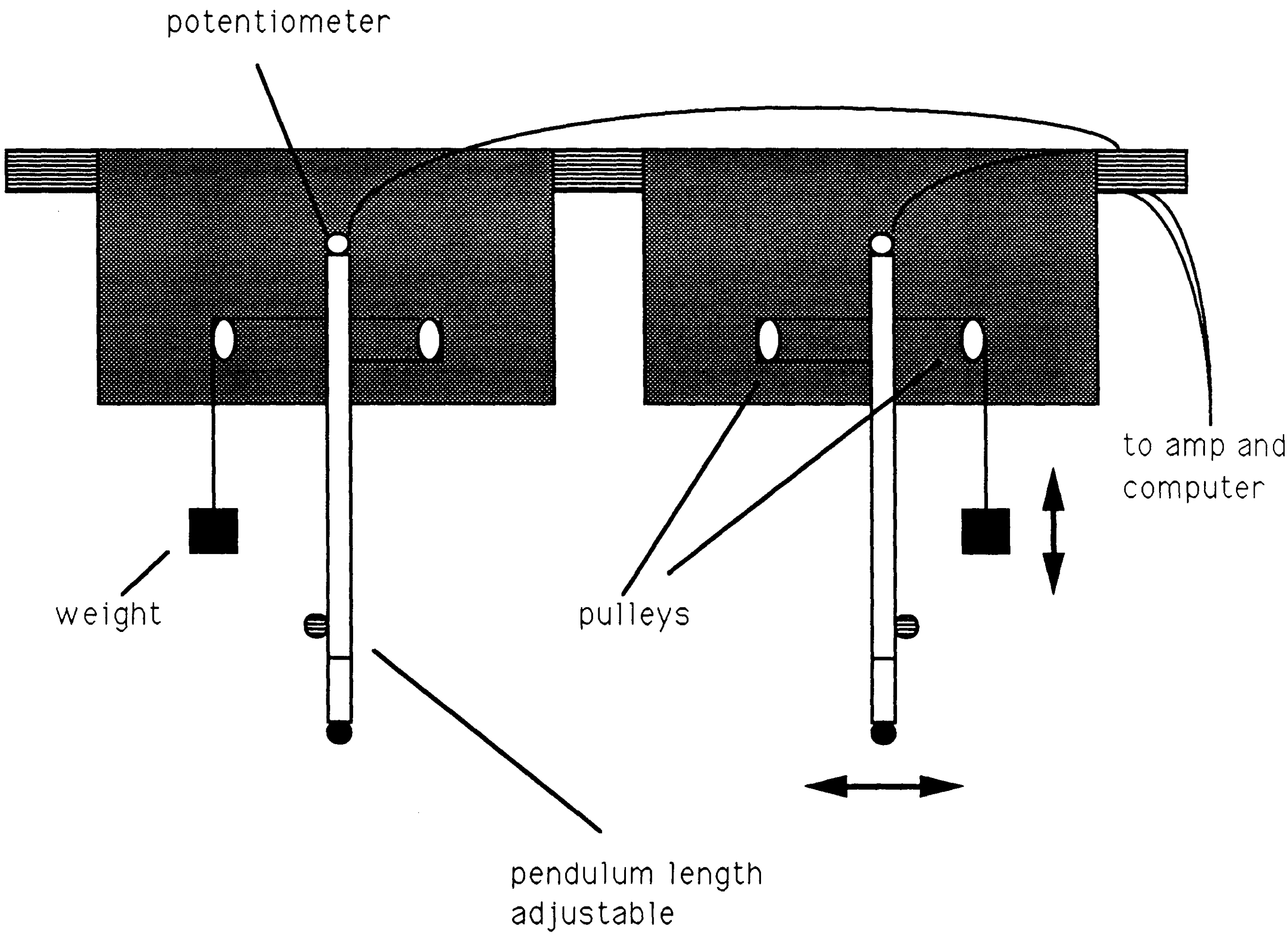


FIGURE 2.3: Pulley system for applying constant force tactile cues to the shoulders. Rotary potentiometers measured changes in voltage as subjects swayed from side to side.

channels were not used in Experiment 1). Two channels could be monitored at any one time by use of an oscilloscope in the dome equipment rack. Trials could be displayed again immediately after a run was completed by using a program called "SHOW2" (also authored in 1984 by Shelhamer, and documented in Appendix 1). The total length of a trial was 40 seconds of sampled data -- two seconds pre-rotation, 33 seconds of rotation, and five seconds post-rotatory.

Experiment 2

Later experiments were performed using a Macintosh IICX running LabView to acquire data. The specific program used for the dome was written in LabView by Nick Groleau. The graphical source code for this program appears in Appendix 3. The real time display panel (figure 2.4) showed three channels of data (joystick and right and left potentiometers) at a sampling rate of 25 hz on each signal. Using this system only the 33 seconds of data generated during dome rotation can be sampled. Upon completion of a trial several parameters were calculated and displayed so that the operator could determine whether or not to save or repeat the trial. The three signals were saved as ASCII flat files in Microsoft Word. The calculated parameters were also saved in a separate Word file. The program automatically sequenced filenames and saved them in folders named by the experimenter.

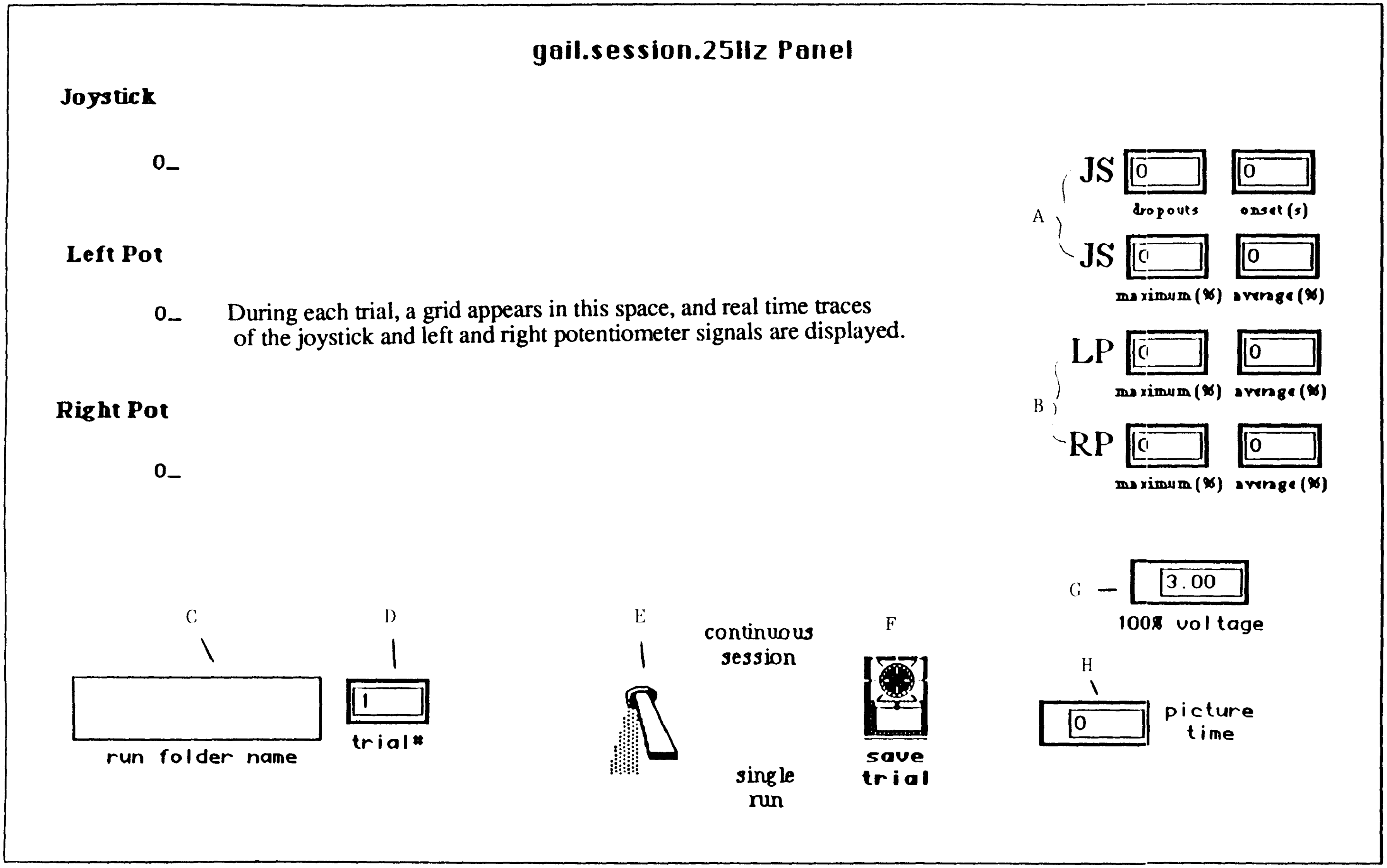


FIGURE 2.4: Experiment 2 Display Panel

A Joystick parameters calculated and displayed at the end of each trial
B Potentiometer (sway) parameters calculated and displayed at the end of each trial
C Name of folder data where data is stored
D Trial number within each run
E Session can be run trial by trial, or as a continuous session by modifying this switch
F This switch allows the operator to choose whether or not to save data
G This number indicates the potentiometer full range voltage
H Modifying "picture time" allows the operator to view the data for a longer before moving on to the next trial

CHAPTER 3: EXPERIMENTAL DESIGN AND METHODS

EXPERIMENT 1

The goals of this set of tests were to determine if the application of tactile cues to the shoulders of a subject during a dome run had any quantifiable effect on the sensation of motion or postural sway, and to see if the pseudo-vestibulocollic reflex could be enhanced enough to be clearly visible. To accomplish this two types of tests were performed with each subject, two runs of six trials each with the biteboard, and two runs without. All of the trials were performed in the Sharpened Romberg position, with one foot placed directly in front of the other, thus reducing the subject's stability in the roll axis. For runs utilizing the biteboard the subjects also used the joystick to estimate the magnitude of vection. They were instructed to deflect the joystick in the direction of their own perceived self-motion regardless of the qualitative nature of that self-motion. If and when the rotating field appeared to be stationary in space, indicating that the subjective feeling of rotation was equal in velocity and opposite in direction to that of the dome, the subject was to indicate "saturated vection" by full deflection of the joystick in the proper direction. Partial vection, more common in the one-g, upright condition in which the tests were conducted, was indicated by a proportional joystick movement. For "paradoxical vection," subjects perceived and indicated a rotation rate but no change in tilt angle. Subjects were given time to practice using the joystick before the actual test runs began to accustom themselves to its limits, and to become self-consistent using it.

Two runs for each subject were performed without the use of the biteboard in order to remove a major tactile cue, conceivably allowing the subjects to develop stronger vection, but also removing the restraint that kept the subject's head stationary and centered within the dome. In this first set of experiments it also prevented the subject from using the joystick to indicate vection. Two types of data were recorded for these tests. The motion of the head, neck, and upper body were recorded by a video camera with a view of the rear of the subject. One of the experimenters also kept track of the number of "imbalance occurrences" or times when the subject had to adjust foot position to remain upright.

Generalized tactile cues were added to a trial by allowing the two weighted pendulums to touch the shoulders of the subject. At the start of the trial the weights were barely touching the subject -- a force of about 20 grams was applied to each shoulder. During a trial this force varied up to a few hundred grams as the subject swayed to the right or left.

Each experiment session consisted of four runs, two with the biteboard and two without. One of each type of run was performed with tactile cues, and the other without. Thus, a total of four runs (24 trials) was completed for each of the subjects tested. The sequence in which the runs were performed was randomized to remove any ordering effect from the data. For each run using the biteboard and joystick, subjective estimation parameters were calculated. The onset latency was defined as the time from the beginning of dome rotation until the first deflection of the joystick by more than 10% of its range for at least one second. The average vection intensity was calculated as the average joystick deflection (relative to full scale) over the 33 seconds of dome rotation (Young, Shelhamer, and Modestino, 1986 and Young and Shelhamer, 1990). The magnitude of the biteboard strain gage signal was consistently too small to be considered more than noise in these experiments. The important parameter in the non-biteboard runs was the number of imbalance occurrences recorded per 240 second run (six trials of 40 seconds each). At the end of each trial, subjects were asked to comment on their feelings of vection and tilt, as well as to mention any outside stimuli that may have contributed to the trial.

Experiment 2

Experiment 2 was designed to be a refinement of the first experiment. The goals here were to determine the effects of varying amounts of constant applied pressure -- perhaps to find a threshold level of pressure that caused a significant effect on vection. In contrast to experiment 1, the tactile cues used in the second experiment offered no extra information to the subject regarding body sway. The pressure on the shoulders was independant of deflection. A second goal was to see if there was any consistent postural response to the rotating dome, and to qualitatively and quantitatively measure any changes in the response due to the addition and varying degrees of generalized tactile cues as well as the effect of the biteboard.

Five different weight conditions were used. Applied cues ranged from 125 grams to 500 grams, spaced at equal intervals, and a "no weight" condition was also included. These stimuli were chosen based on Fechner's Equation for estimation of sensation, modified by the assumption that (delta S)/S is constant (that each subjective just noticeable difference (jnd) has the same relative magnitude, from Krueger, 1989).

$$\ln S = (c/k)\ln(I/I_0)$$

where:

S = perceived sensation
c = scale factor (number of subjective units per jnd)
k = Weber's fraction
I = actual intensity of stimulus
I_0 = absolute threshold

In power form this is:

$$S = aI^{c/k} \quad \text{where} \quad a = (I_o^{-c/k}) \qquad \text{(Stevens, 1957)}$$

Further, from studies by Tegtsoonian in 1971, the observed exponent (c/k) for "heaviness" from magnitude estimation studies is 1.45. "Heaviness" was the closest analog to "pressure" reported in the literature. Using this number as a best estimate, this suggests that one need not double the stimulus to double the sensation the subject feels.

Table 3.1 contains a summary of the test conditions used in Experiment 2. A complete set of experiments using all possible run orderings would have required an unrealistically large number of test subjects. Thus, two psuedo-random orderings within the off biteboard runs were chosen. In these orderings subjects were never presented with a change of stimulus of more than two steps. In other words, a change in weight from 125 grams to 375 grams was allowed (two steps, skipping 250 grams), but a change from 125 grams to 500 grams (three steps) was not. The order of presentation of the set of biteboard or non-biteboard runs also alternated between subjects, as did whether the "weight" or "no weight" condition was presented first during the on biteboard set. Table 3.2 shows all combinations of runs used during experiment 2.

The final protocol took approximately two hours to complete, allowing for short rest periods of a few minutes each between runs.

Table 3.1: Conditions used in Experiment 2

	Tactile Cue (grams)				
	0	125	250	375	500
on biteboard	b0				b500
off biteboard	n0	n125	n250	n375	n500

Table 3.2: Ordering of Conditions

order	A	B	C	D
condition codes	b0	b500	n0	n0
	b500	b0	n125	n250
	n0	n0	n250	n500
	n125	n250	n375	n375
	n250	n500	n500	n125
	n375	n375	b0	b500
	n500	n125	b500	b0

NOTE: For the conditions listed in the above tables, the prefix "b" indicates an on-biteboard run, while "n" indicates an off-biteboard condition. The number following the prefix indicates the amount of the applied tactile cue.

CHAPTER 4: RESULTS

Experiment 1

Experiment 1 was conducted in June of 1989 (Young and Standish, 1989). Nine subjects, four male and five female, participated. These subjects ranged in age from 18 to 55 years, and all performed satisfactorily on the Sharpened Romberg Test for normal vestibular function. For each run using the bite-board and joystick, subjective estimation parameters were calculated. The onset latency was defined as the time from the beginning of dome rotation until the first deflection of the joystick by more than 10% of its range for at least one second. The average vection intensity was calculated as the average joystick deflection (relative to full scale) over the 40 second dome trial. The magnitude of the bite-board strain gage signal was consistently too small to be considered more than noise in these experiments. The important parameter in the non-biteboard runs was the number of imbalance occurrences (steps the subject took to regain balance) recorded per 240 second run (six trials of 40 seconds each). At the end of each trial, subjects were asked to comment on their feelings of vection and tilt, as well as to mention any outside stimuli that may have contributed to the trial.

Subjects' Comments

Six of the nine subjects reported that the light touch of the weights at their shoulders reduced the intensity and/or duration of vection. Subject 1 reported feeling almost no sensation of self rotation at all during these trials. Subject 2 commented that it took much longer to develop vection when the tactile cues were present. Two subjects commented that, with the tactile cues it was "easier to make yourself stop rotating." Subjects 4 and 6 reported little or no difference in the feeling of vection with or without the tactile cues.

Postural Control

To measure the effect of the applied tactile cues on the ability of the subjects to maintain posture, statistical tests on the number of imbalance occurrences were performed. For each subject, each non-bite-board, non-tactile cue run (consisting of six trials) was paired with each tactile run. Each trial was paired by dome condition (direction and angular velocity of the stimulus). The paired t-test was then used for the entire subject pool (total of 54 trials) and for each subject (6 paired trials).

Over the entire data set, the introduction of the tactile cues reduced the number of times that the subject could not maintain the Romberg position by 1.06 occurrences from an average of 1.91 occurrences per 40 second trial ($p < .01$). Only two of the subjects, subjects 1 and 7, had significant within-subject decreases ($p < .05$). Subject 6 did not have any trouble maintaining the position in either condition. Subject 4 showed a slight increase in the number of occurrences when tactile cues were present (n.s.). Figure 4.1 shows the total number of imbalance occurrences for each subject over the entire 240 seconds tested for runs with and without generalized tactile cues.

Vection Indications

To measure the effect of the generalized tactile cues on the sensation of vection, statistical tests on onset latency and average vection were performed. Again, each trial performed without tactile cues was paired with the corresponding trial performed with tactile cues, and the paired t-test was used.

Over all 54 trials, the tactile cues increased the time to onset of vection by 4.4 seconds ($p < .01$) from an average of 4.76 seconds. Subjects 1, 3, and 4 had significant increases from their without to their with tactile cue runs ($p < .05$). Subject 1 did not

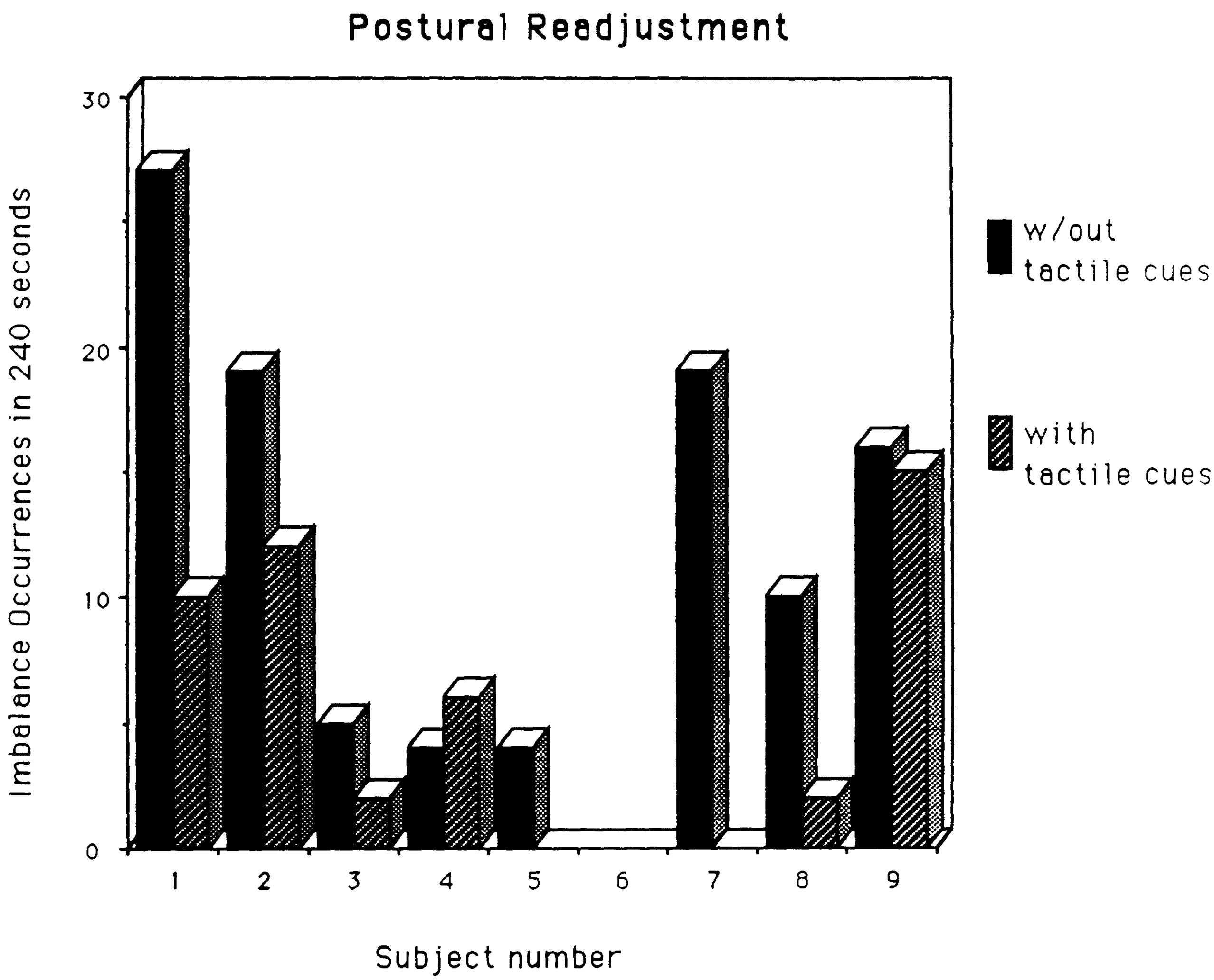


Figure 4.1: Postural Readjustment in Experiment 1

achieve vection at all in five out of six trials performed with tactile cues. Subjects 6 and 7 had slight decreases in onset latency with tactile cues (n.s.). Note that subject 7 was also the subject who found it easy to maintain balance during both conditions, and who commented that there was little or no difference between the two types of runs. Figure 4.2 shows the average onset latency for each subject for runs with and without the tactile cues.

Seven of nine subjects showed a decrease in average vection intensity achieved when tactile cues were present (Figure 4.3), though only one subject showed a decrease of sufficient magnitude to be considered significant ($p < .05$). The increase in average intensity shown by the remaining two subjects was also not significant. The decrease over all 54 trials was 3.48% (n.s.).

Experiment 2

The second set of experiments was conducted during October and November of 1989. Thirteen subjects (numbered Subjects 2 through 14) participated, eight male and five female. Of these subjects, four were non-naive -- all four had extensive experience with the dome, and two had been subjects in Experiment 1. Two of these non-naive subjects were male, and two were female. Table 4.1 contains information on each subject concerning age, height, and weight that was obtained from subject questionnaires prior to testing. All subjects had adequate performance on the Sharpened Romberg test and normal binocular vision.

General Results

This section will focus on comments prevalent among the subjects and the results of visual inspection and statistical analysis of the data across all subjects. Appendix 4 contains the spreadsheet data used for all statistics. This includes calculated values of

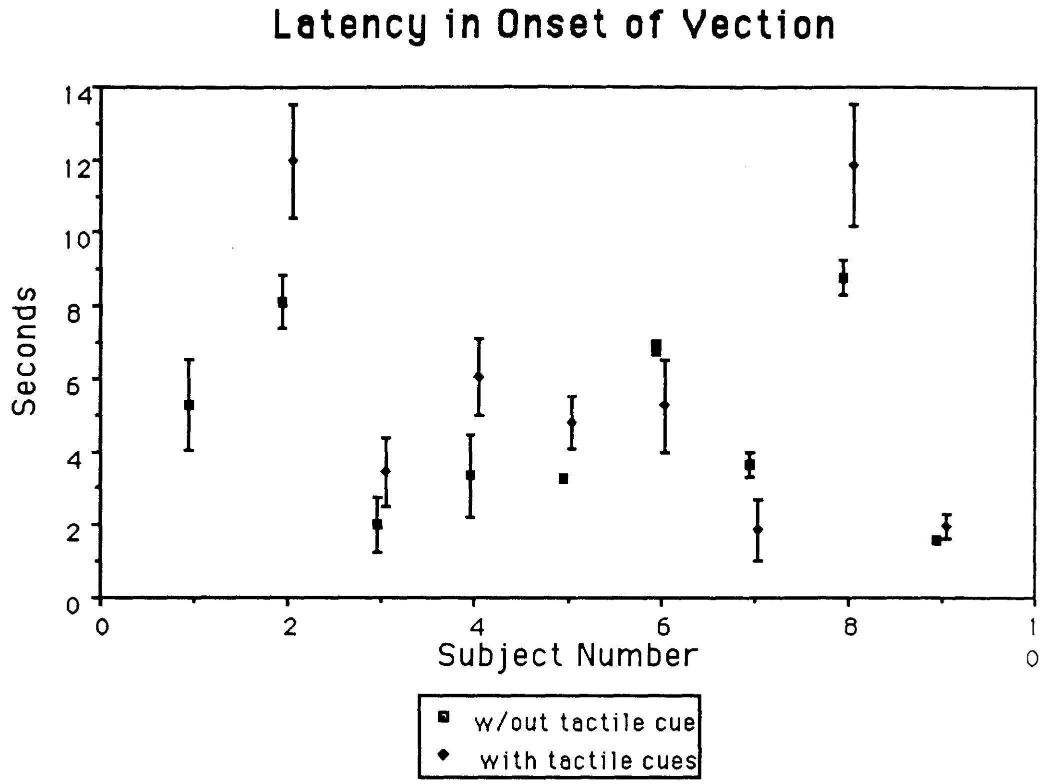


Figure 4.2: Onset Latency for Subjects in Experiment 1
Note: Subject 1 did not achieve vection when tactile cues were applied.

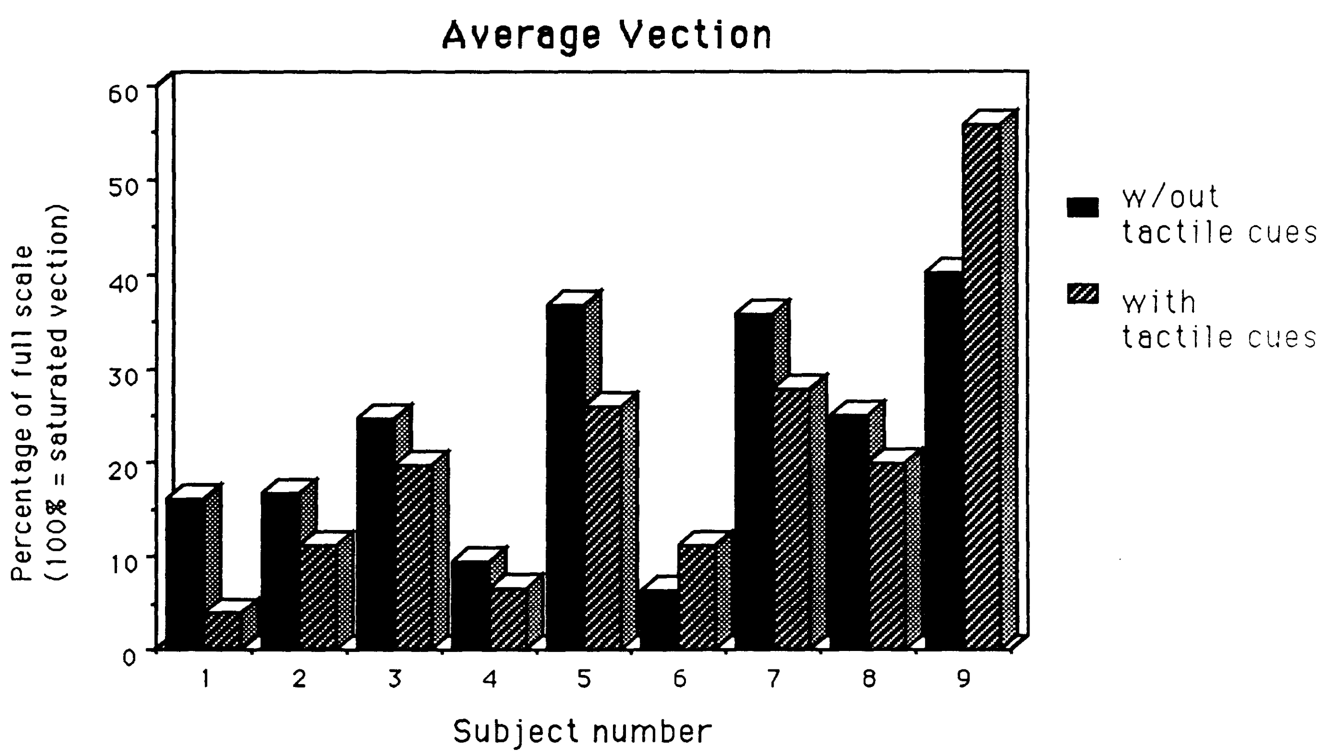


Figure 4.3: Average Vection in Experiment 1

Table 4.1: Subject Data for Experiment 2

Subject	Age	Height	Weight (lbs)	Sex	Naive?
1	23	5'7"	150	M	Y
2	21	5'2"	118	F	Y
3	22	6'	160	M	Y
4	21	5'9"	138	F	Y
5	20	5'	120	F	Y
6	21	5'8"	145	M	Y
7	21	5'7"	175	M	Y
8	48	5'7"	200	F	Y
9	30	5'8"	135	M	N
10	21	5'10"	155	M	Y
11	22	5'6"	125	M	N
12	26	5'8"	175	F	N
13	21	5'10"	210	M	Y
14	20	5'4"	130	F	N

Note: Subjects with a "Y" (for "yes") in the column headed "Naive?" had no previous experience with the rotating dome. Non-naive subjects had past experience with the equipment, as well as knowledge of the results of Experiment 1.

maximum and average vection and left potentiometer indications for each trial listed by subject number, weight condition, and rotation code. The right potentiometer data mirrored that of the left potentiometer but contained more noise, and thus was not analyzed. The bulk of the data for individual subjects appears in Appendix 5, though samples are included below.

Subjects' Comments

Unfortunately, the most prevalent comment among the subjects was that the protocol was very long or fatiguing. Five of the thirteen subjects reported this -- two specifically citing muscle fatigue in the legs and/or neck. Three of the fatigued subjects complained of mild headaches -- one of them (Subject 13) developed other symptoms of motion sickness by the sixth run as well. Subject 13's other symptoms included mild epigastric awareness and sweating.

Five subjects felt little or no vection on the biteboard, or said that they felt a drastic difference between the on biteboard and off biteboard runs. One subject who completed the off biteboard runs as the last part of the protocol complained that he would have scaled his on biteboard magnitude estimates of vection differently if he had had more practice with both types of runs before the actual trials began.

Only two subjects verbally commented that they felt "steadier" or that vection was decreased by the presence of the weights. One also commented that the amount of self-motion didn't seem to change noticeably, but that he was "comforted" by knowing that there was something there -- an indication that he was not tilted to the point of falling.

Posture Data

For each off biteboard trial using shoulder weights (4 runs, 24 trials) the average and maximum values of the pendulum displacement were calculated. These displacement values are reported in A/D units and can be used to compare one trial relative to another for each subject. The A/D values are directly related to the angular displacement of the pendulums and could, through geometric relationships based on the lengths of the pendulums and height of each subject, be converted to absolute right or left displacement of the shoulders. The maximum displacement, about 15 degrees in angle, corresponded to an A/D level of 1024 units, and a range of 6.5 to 8.5 inches of lateral displacement, depending on the pendulum length used and the height of each subject.

Over all trials and for each subject there was no significant change in the maximum or average magnitude of the angular displacement with pendulum pressure. What was of more interest was a visual inspection of the traces generated for each trial. Figure 4.4 shows examples of two position traces plotted directly under the corresponding joystick indications. From all of the traces examined it appears that every subject has an individual postural reaction to the dome, or "strategy" for remaining upright while observing the rotating stimulus. This "strategy" is very consistent within a particular subject, but varies a great deal from one person to another. The consistency within a subject is such that the trace obtained can almost be used as a signature to identify the subject. The appendix containing individual results briefly discusses each subject's postural reaction.

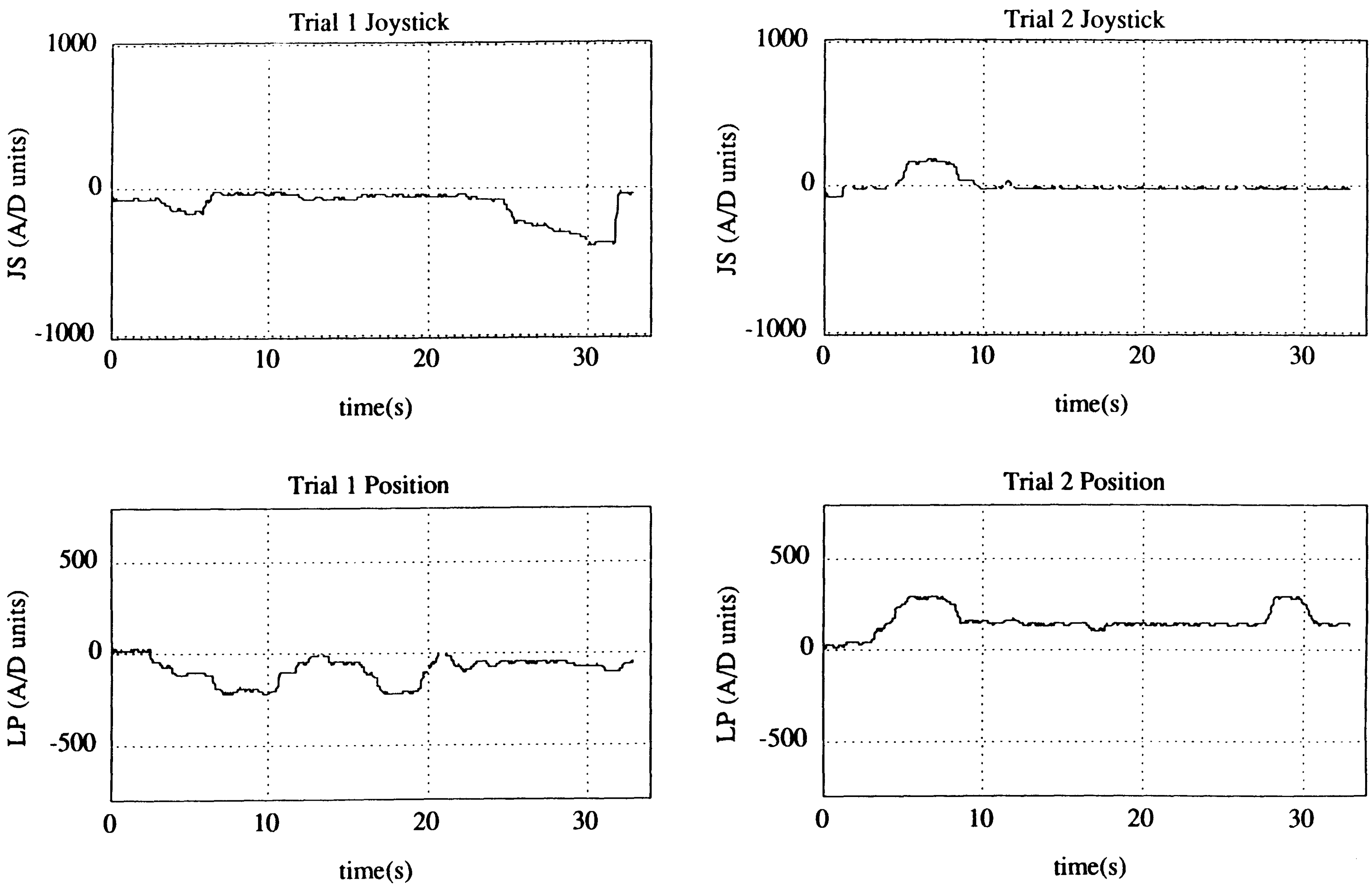


FIGURE 4.4: Sample traces

Subject 2 Joystick and Position Data

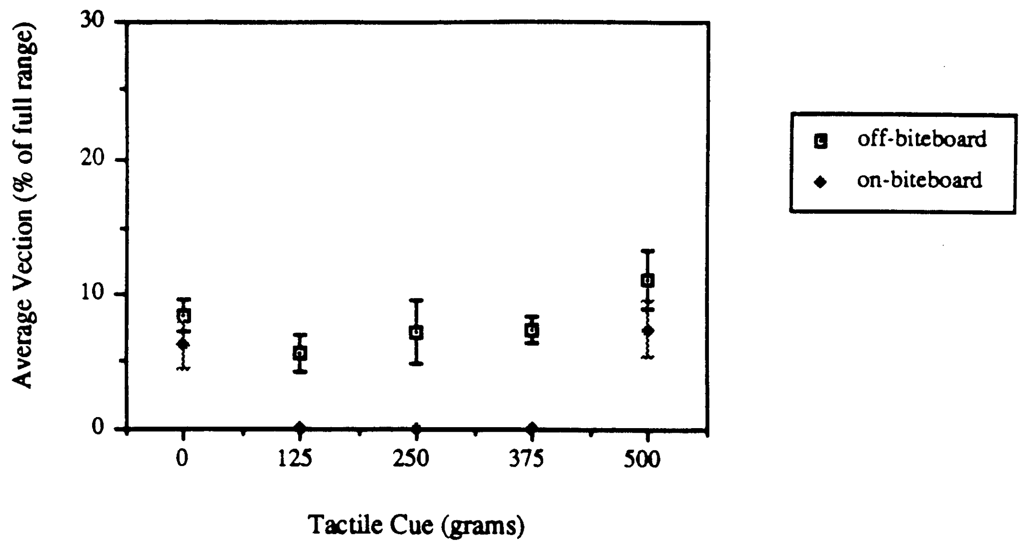
2 of 6 trials, Tactile cue = 125 grams

Vection Indications

As in Experiment 1, maximum vection, average vection, and onset latency were calculated for each trial. Because of a limitation in the acquisition software, onset latency for this set of experiments was defined as the first time the joystick signal exceeded ten percent of full range, but did not include the requirement that the signal remain "high" for a full second. This caused many false onsets to be reported when the system was noisy or the subject was unsure. Noise was a problem -- sometimes up to five percent in the data during about two thirds of the runs. The noise was symmetric, averaging to zero. For these reasons, only maximum and average vection were analyzed, with average vection being the most reliable parameter.

For all runs, plots of maximum and average vection vs. weight were made for each subject. Only a few of the subjects showed a similar trend to that of Subject 1 in the pilot experiments -- a graph to which some curve might be fit. Each of the vection plots is presented in Appendix 5, while examples for one subject can be seen in Figure 4.5. Systat™ was used to perform the statistical test on the maximum and average vection parameters. There was no consistent way to group all of the runs using tactile cues, so in this case t-tests of maximum and average vection for runs without cues vs. runs with the heaviest weights (500 grams) were done for both on and off biteboard runs. These are referred to as n0 vs. n500 (for "no biteboard") and b0 vs. b500 (for "biteboard") t-tests, and are tests that look for a significant change due to the tactile cue. Test for significant changes in the vection parameters between on and off biteboard runs were also performed for both the zero weight and heaviest weight condition. These tests are referred to as b0 vs. n0 (no weight, biteboard vs. no biteboard) and b500 vs. n500 (heaviest weight, biteboard vs. no biteboard). These four tests were done across all thirteen subjects ($n = 78$ trials) and again separately for the nine naive and four non-naive subjects.

Subject 2



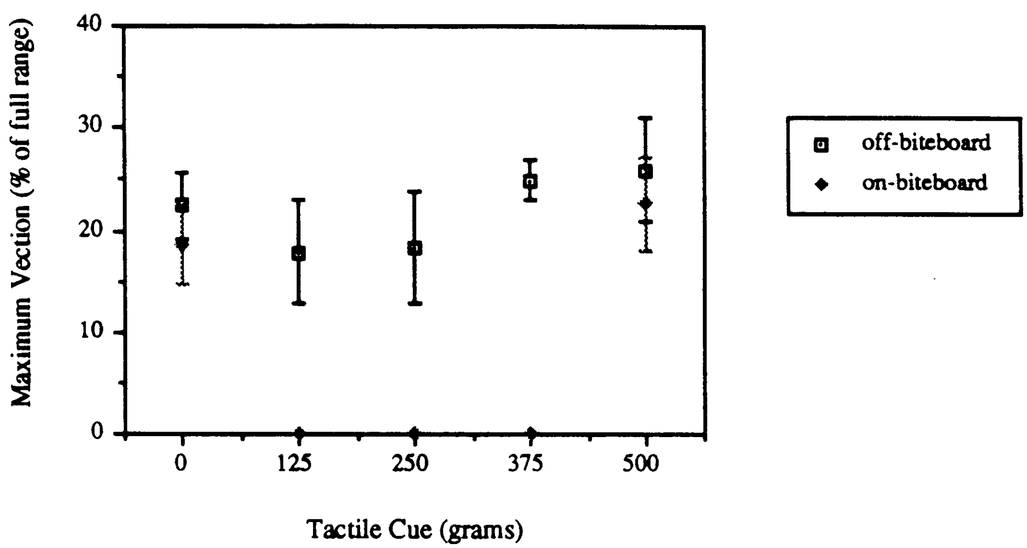


FIGURE 4.5
Plots of Average and Maximum
Vection vs. Applied Tactile Cue

The results for these tests are presented in Table 4.2. In summary, over all subjects the off biteboard no weight vs. weight decrease in vection was highly significant. The change seen in the on biteboard tests was not significant , but was in the correct direction and trending towards significance ($p = .13$ for average vection, $p = .21$ for maximum vection). The test comparing vection achieved with the biteboard vs. that without showed a highly significant decrease in the sensation with the biteboard when no shoulder cues were applied (b0 vs, n) $p < .01$) for both maximum and average vection. The decrease barely missed significance ($p = .053$ for average vection, $p = .064$ for maximum vection) when tactile cues were applied. In all of the comparisons made the small non-naive group had more significant (lower p value) results than the naive group. For the naive group only the b0 vs. n0 test was considered significant ($p < .05$) though all other tests are tending towards significance. The within subject statistics are presented with the other individual results in Appendix 5.

Discussion

The limited results obtained from experiment 1 were much as expected -- the use of tactile cues decreased the sensation of self-motion, though not significantly, increased time to onset of vection, and decreased the number of imbalance occurrences. The analysis of joystick indications in experiment 2 was consistent with this. Off the biteboard the decrease in maximum and average vection was highly significant; on the biteboard the change in these parameters trended toward significance. The decrease in vection with tactile cues was even larger when the no-biteboard vs. biteboard runs were compared. This leads to the conclusion that the biteboard is a stronger tactile cue, and thus has a larger influence in diminishing vection, than the more general shoulder cues. This is also supported by the weight vs. no weight t-tests mentioned previously. When on the biteboard, the shoulder cues have less influence than in off-biteboard trials where they are

Table 4.2

STATISTICAL RESULTS:

P-values for t-tests

Subjects	All		Naive		Non-naive		
n (trials)	78		54		24		
parameter	max vection	ave vection	max vection	ave vection	max vection	ave vection	
b0 < n0	**.000**	**.002**	**.031**	.102	**.000**	**.000**	EFFECT OF BITEBOARD
b500 < n500	.064	.053	.226	.177	**.015**	**.037**	
b0 > b500	.210	.131	.351	.225	.152	.241	EFFECT OF TACTILE CUES
n0 > n500	**.003**	**.011**	.053	.173	**.001**	**.001**	

Note: Entries that appear in bold print indicate significant results the only "extra" orientational cues provided. The strength of this biteboard cue was likely responsible for the absence of 100% saturated vection in spaceflight experiments. Furthermore, in the "within subject" statistics, seven of thirteen subjects showed significant results in biteboard vs. no-biteboard tests, while only five did for weight vs. no weight tests (in each case there was one subject who showed a significant change in the direction opposite to that expected.) In other words, when the head is fixed via the biteboard, this is the overwhelming cue, and a light touch at the shoulders does not have nearly the stabilizing influence it would otherwise have. Table 4.2 summarizes this -- one can see that the t-tests, in order form most to least significant, are b0 vs. n0, n0 vs. n500, b500 vs. n500, and b0 vs. b500.

Table 4.2 also shows how important mind set and familiarity with the test equipment are. When subjects were separated into naive and non-naive groups, the non-naive group clearly showed a higher level of significance on all tests performed despite the fact that the group was smaller. This is a very important consideration. However, the non-naive group still showed overall changes in the parameters to be in the expected directions and trending towards significance. N for this group, nine, was the same as that for experiment 1 in which the results are very similar. A larger non-naive sample in either experiment would probably show significant results in most or all of the tests.

Another interesting result noted in experiment 2 was that individual subject's postural reactions were not influenced by the magnitude of the tactile cue applied. The amount of sway and the frequency of the motion did not change. It was expected from the results obtained in experiment 1 that if the cues influenced vection, then they would also influence postural control. The cues did not affect both measures. This points to the dichotomy present in experiments such as this where elements of psychophysics and of physiology are combined. Consistency in magnitude estimation is difficult, even with subject training, and finding correlations between higher and reflex level functions is difficult at best (Gurfinkel's body scheme (1988) is one "black box" theory to include function at all levels). In these experiments, at the conscious level the generalized tactile cues had a rather dramatic effect, but at a lower level in control of posture this effect was not seen. However, one must remember that no quantitative measures of posture were taken for the zero weight condition, though qualitatively, each subject's reactions appeared the same.

5. The magnitude of the tactile cue over the range tested did not affect the magnitude or frequency of body sway.

Subjects in Experiment 2 showed no significant change in their postural strategy as the amount of the applied weight was changed. Experiment 2 subjects had no trouble maintaining balance, as Experiment 1 subjects did, because they were not in the less stable Sharpened Romberg position.

Recommendations

General

Recommendations for further work can be divided into two categories: those that arise from shortcomings of the present experiments, and those that are suggested by the scientific conclusions of the completed work. In the first category are things such as equipment and instrumentation modifications, as well as changes in the experimental protocol to better control subject variables such as fatigue and mental set. The second category contains recommendations that address other things it might be interesting to know.

For the current experiment:

Measurement of posture:

In Experiment 2, "posture" was measures relative only to shoulder position. The test conductor observed that each subject's strategy for remaining upright was different, including motion in any or all of the following joint areas: ankles, knees, hips/waist, and head/neck. A video or perhaps infra-red sensor system that monitored all of these areas would permit a more detailed look at postural control. Adding lower leg electrodes or the use of a posture platform could also augment the quality of the data.

Training and mental set:

It was obvious from the non-naive subject data that extensive training with the experiment equipment -- how to properly indicate vection -- produced much more consistent results than could be achieved by naive subjects with only a short training period. Ideal subjects would have the extensive training, but would not be aware of the experiment goals, or even versed in the background science. This suggest a protocol that includes several sessions, of which as many as two to four are devoted solely to training. Doing the experiment in several pieces would also make it possible to avoid the fatigue problem encountered due to the one "marathon" session used in Experiment 2.

The tactile cues should be applied in two different ways. One method should not provide a mental image of helping the subject remain upright. For example, pressure could be applied by a harness worn by the subject that moved when the subject moved. The other methods, like the current setup, would suggest that its purpose was to give the subject another clue "which way is up." Using these two methods, an experimenter could obtain better data on the effects of mental set in this experiment.

Future work:

It would be interesting to see this work extended to vection in other axes. Z-axis vection, such as achieved in a rotating drum, would allow an experimenter to study tactile cues separately from otolithic stimulation. Roll vection with the subject supine might also be interesting if a method for reducing the massive body-on-floor cues could be lessened (perhaps by floating the subject on a bed of air or water).

The effects of asymmetrical cues can be studied fairly easily. This experiment would be the tactile equivalent of tilting the subject and testing for effects on self-motion perception.

Of course, microgravity experiments are of great interest. A rotating dome held rigidly in the center of an open area, with a biteboard mechanism that allowed the subject to remain centered in the dome yet rotate freely "head over heels" would allow for many tactile cue experiments, as well as the study of the neck righting reflexes mentioned in Chapter 1. Differences between the effects of localized (bottom of the foot) and generalized cues on vection could be compared in such an environment.

It was surprising to the author how strong an effect on vection a light touch at the shoulders could be. The brain's integration of every piece of information, no matter how seemingly insignificant, into the overall spatial orientation equation is amazing. Its ability to compensate for the loss of a sense, or the addition of a new parameter, is a topic well worth further study in man's natural environment, as well as those such as space, in which he hopes to work.

References

ARROTT, A. P., and L. R. Young. M.I.T./Canadian Vestibular Experiments on the Spacelab-1 Mission: 6. Vestibular Reactions to Lateral Acceleration Following Ten Days of Weightlessness. *Exp. Brain Res.* 64: 347-357, 1986

AUBERT H. Eine Scheinbare Bedeutende Drehung von Objektin bei Neigung des Kopfes nach Rechts oder Links. *Virchows Arch.* 20: 381-393, 1861

BAKER, J., J. Goldberg, and B. Peterson. Spatial and Temporal Response Properties of the Vestibulocollic Reflex in Decerebrate Cats. *Journal of Neurophysiology* Vol. 54 No. 3, 1985

BRANDT, Th., E. R. Wist, and J. Dichgans. Foreground and Background in Dynamic Spatial Orientation. *Percerpt. Psychphys.* 17: 497-503, 1975

FUKUSHIMA, K., K. Takahashi, J. Fukushima, and M. Kato. Lack of Suppression of the Short-Latency Vestibulocollic Reflex during Active Head Movements in Cats. *Brain Behav. Evol.* 30: 200-209, 1987

GILLINGHAM, K. K., and J. W. Wolfe. Spatial Orientation in Flight. *USAF Technical Report USAFSAM-TR-85-31* 1986

GOLDBERG J., and B. W. Peterson. Reflex and Mechanical Contributions to Head Stabilization in Alert Cats. *Journal of Neurophysiology* Vol. 56 No. 3, 1986

GUITTON, D., R. E. Kearney, N. Wereley, and B. W. Peterson. Visual, Vestibular, and Voluntary Contributions to Human Head Stabilization. *Exp. Brain Res.* 64: 59-69, 1986

GURFINKEL, V. S., Yu. S. Levik, K. E. Popov, B. N. Smetanin, and V. Yu. Shilikov. Body Scheme in the Control of Postural Activity. In: Stance and Motion: Facts and Concepts, Gurfinkel et al. ed., Plenum Press, New York, 1988

HELD, R., J. Dichgans, and J. Bauer. Characteristics of Moving Visual Scenes Influencing Spatial Orientation. *Vision Res.* 15: 357-367, 1975

HENN, V., B. Cohen, and L. R. Young. Visual Vestibular Interaction in Motion Perception and the Generation of Nystagmus. *Neurosci. Res. Program Bulletin.* 18: 459-651, 1980

HOWARD, I. P., and W. B. Templeton. Human Spatial Orientation. John Wiley and Sons, London, 1966

HOWARD, I. P. Human Visual Orientation. John Wiley and Sons, New York, 1982

HOWARD, I. P., B. Cheung, and J. Landolt. Influence of Vection Axis and Body Posture on Visually-Induced Self-Rotation and Tilt. From: *AGARD Symposium: Brussels, "Motion Cues in Flight Simulation and Simulator Induced Sickness."* 1987

HOWARD, I. P., M. Ohmi, and W. Simpson. Vection and the Disposition of Competing Moving Displays. From: *AGARD Symposium: Brussels, "Motion Cues in Flight Simulation and Simulator Induced Sickness."* 1987

HUBEL D. H. and T. N. Weisel. Functional Architecture of the Macaque Monkey Visual Cortex. *Proc. Roy. Soc., B.,* 198:1-59, 1977

HUBEL D. H. and T. N. Weisel. Receptive Fields and Functional Architecture in two Nonstriate Visual Areas of the Cat. *J. Neurophysiology* 26: 994-1002, 1965

KRON, G., L. R. Young, and W. Albery. High-G Simulation -- The Tactical Simulator Problem. NTEC Simulation Meeting, 1977

KRON, G., Frank Cardullo, and L. R. Young. Study and Design of High-G Augmentation Devices. *Air Force Report F33615-77-C-0055,* 1978

KRUEGER, L. E. Reconciling Fechner and Stevens: Toward a Unified Psychophysical Law. *Behavioral and Brain Sciences* 12: 251-320, 1989

LIEBOWITZ, H. W. and J. Dichgans. The Ambient Visual System and Spatial Orientation. In: Spatial Orientation in Flight: Current Problems. *AGARD-CP-287. NATO-AGARD, Neuilly-sur Seine, France.* 1980

MAGNUS, R. Some Results of Studies on the Physiology of Posture. *Lancet* Sept. 1926

MELVILL JONES, G. Disturbance of Oculomotor Control in Flight. *Aerospace Med.* 36: 461-465, 1965

MULLER, G. E. Uber das Aubertsche Phanomenon. *Psychol. Physiol. Sinnesorg.* 49: 109-246, 1916

NEAL, E. Visual Localization of the Vertical. *Amer. J. Psychol.* 37: 287-292, 1926

OHMI, M., I. P. Howard, and J. P. Landolt. Circular Vection as a Function of Foreground-Background Relationships. *Perception* Vol. 16, pp. 17-22, 1987

OMAN, C. M. A Heuristic Mathematical Model for the Dynamics of Sensory Conflict and Motion Sickness. *Acta Oto-Laryngol. Suppl.* 392, 1982

OMAN, C. M. The Role of Static Visual Orientation Cues in the Etiology of Space Motion Sickness. *Proceedings of the Symposium on Vestibular Organs and Altered Force Environment*, Houston, Texas, Oct. 1987

OMAN, C. M., B. K. Lichtenberg, K. E. Money, and R. K. McCoy. M.I.T./Canadian Vestibular Experiments on the Spacelab-1 Mission: 4. Space Motion Sickness: Symptoms, Stimuli, and Predictability. *Exp. Brain Res.* 64: 316-334, 1986

OMAN, C. M., O. Bock, and J. K. Huang. Visually Induced Self-motion Sensation Adapts Rapidly to Left-right Vision Reversal. *Science* 209: 706-708, 1980

PARKER, D. E., M. F. Reschke, A. P. Arrott, J. L. Homick, and B. K. Lichtenberg. Otolith Tilt-Translation Reinterpretation Following Prolonged Weightlessness: Implications for Preflight Training. *Aviat. Space Environ. Med.,* 56: 601-606, 1985

SHERRINGTON, C. S. On the Proprio-ceptive System, especially in its Reflex Aspect. *Brain* 29: 467-482, 1906

STEVENS, S. S. On the Psychophysical Law. *Psychological Rev.* 64: 153-81, 1957

WATT, D. G. D., and J. P. Landolt. Effects of Short Term Weightlessness on Roll Circularvection. From: *AGARD Aeromedical Panel, Copenhagen.* 1989

WILSON, V. J., B. W. Peterson, K. Fukushima, N. Hiral, and Y. Uchino. Analysis of Vestibulocollic Reflexes by Sinusiodal Polarization of Vestibular Afferent Fibers. *J. Neurophysiology* Vol. 42, No. 2, 331-346, 1979

WILSON, V. J., and G. Melvill Jones. Mammalian Vestibular Physiology. Plenum Press, New York, 1979

WITKIN, H. A. and S. E. Asch. Studies in Space Orientation IV. Further Experiments on Perception of the Upright with Displaced Visual Fields. *J. Exp. Psychol.* 38: 762-778, 1948

YOUNG, L. R., T. A. Crites, and C. M. Oman. Brief Weightlessness and Tactile Cues Influence Visually Induced Roll. *Adv. Oto-Rhino-Laryng.*, 30: 230-234, 1983

YOUNG, L R., C. M. Oman, and J. M. Dichgans. Influence of Head Orientation on Visually Induced Pitch and Roll Sensation. *Aviat. Space Environ. Med.* 46(3): 264-268, 1975

YOUNG, L. R. and G. J. Standish. Influence of Tactile Cues on Visually Induced Postural Reactions. Presented at: *2nd Symposium on Head Movement Control. "The Head-Neck Sensory-Motor System.."* Fountainbleau, 1989. In Press.

YOUNG, L. R., C. M. Oman, D. G. D. Watt, K. E. Money, B. K. Lichtenberg, R. V. Kenyon, and A. P. Arrott. M.I.T./Canadian Vestibular Experiments on the Spacelab-1 Mission: 1. Sensory Adaptation to Weightlessness and Readaptation to One-g: an Overview. *Exp. Brain Res.* 64: 291-298, 1986a

YOUNG, L. R., M. Shelhamer, and S. Modestino. M.I.T./Canadian Vestibular Experiments on the Spacelab-1 Mission: 2. Visual Vestibular Tilt Interaction in Weightlessness. *Exp. Brain Res.* 64: 299-307, 1986b

YOUNG, L. R. On Visual Vestibular Interaction. In: *Proc. Fifth Symposium on the Role of the Vestibular Organs in Space Exploration.* Washington DC: U. S. Aeronautics and Space Administration, SP-314, p. 205-210, 1970

YOUNG, L. R. Perceptions of the Body in Space: Mechanisms. Reprinted from: *Handbook of Physiology -- The Nervous System III* Ch. 22, Amer. Physiol. Soc., I. Darian-Smith, ed., 1984a

YOUNG, L. R., C. M. Oman, D. G. D. Watt, K. E. Money, and B. K. Lichtenberg. Spatial Orientation in Weightlessness and Readaptation to Earth's Gravity. *Science* Vol. 255, pp. 205-208, 1984b

Appendix 1

C Language Source Code

Code by Mark Shelhamer, 1984

"SHOW2" modified by the author in 1988

```
/*  domkc.c    M. Shelhamer   November 1984     */
/*  Main dome program for MVL dome rack system   */
/*  Controls dome sequencing and data storage.   */

/*  ** Note: if the name of this program is changed, change */
/*        the first strcpy() statement below. */


#include  dahead1.h      /* Define constants and peripheral devices */

#include  bdscio.h       /* Standard BDS C I/O header */

#include  dextrn.c       /* Data array and pointer definitions */


/* ****************************************************** */

main()
{
int npnts1;                     /* points sampled per large array */
#include  dahead2.c             /* A/D and D/A addresses */
char cond,dr;                   /* condition # (0-7), dome run # */
char a_now,n_now;               /* current stimulus codes (letter, relay)
char filnam[13];                /* data file name */
char buff[15],tdate[9],subjct[2],pgm[9];   /* header block data */
char k;

strcpy(pgm,"DOMKC.C");          /* name of this pgm for header */

filnum=0;                       /* data file # in current series */
maknam(filnam);                 /* make data file name */

/* Print pgm info, get user input */
printf("\n** Program DOMKC - MIT rotating dome experiment **\n");
printf("\nCondition codes: A-F, T=data loop, Q=quit, Z=no rotation.\n");
/* Input through buffer to avoid having to store final null byte */
printf("\nEnter 2-character subject code: ");
gets(buff);
subjct[0]=buff[0];
subjct[1]=buff[1];
printf("\nEnter date (dd-mmm-yy): ");
gets(buff);
for(k=0;k<9;k++) tdate[k]=buff[k];
printf("\nSelect Dome Run 1 or 2: ");
scanf("%d",&dr);

calib(DOMAD,DA);                     /* data feed-thru to check signals */

cond=1;                              /* set to first condition */
while(cond<=7)
     {
   select:                           /* select condition */
     printf("\n\n************************************");
     printf("\n\nEnter next condition code (RETURN=%c): ",ASTIM[dr-1][cc
     a_now=toupper(getchar());
```

```
    if(a_now=='T')                      /* T = calibration loop */
         {
         calib(DOMAD,DA);
         continue;
         }
    if(a_now=='Q') exit();              /* Q = quit */
    if(a_now=='\n') a_now=ASTIM[dr-1][cond];        /* RETURN = default */
    n_now=stimcode(a_now);                  /* get corresponding relay code *
    printf("\nPress RETURN to begin condition %c  (%d sec delay).",
                                                    a_now,DELAY1);
    printf("\nEnter any character to change selection.    ");
    if(getchar()!='\n') goto select;  /* sorry, I had to use a goto */


    npnts1=getdat5(DOMAD,DA,n_now);          /* rotate and acquire data
    printf("\n%d seconds sampled.",npnts1/RATE1);


    printf("\nPress RETURN to store data, any other key to reject: ");
    if(getchar()=='\n')      /* store tha data */
         {
         ++filnum;           /* increment file number (EXTERNAL var) */
         maknam(filnam);     /* make current file name */
         writeit(filnam,dr,tdate,subjct,pgm,npnts1,a_now);  /* write fi
         if(a_now!='Z') {if(++cond>7) cond=7;}
         }
                        /* don't increment condition if Z (no rotation)
                        /* condition Z from now on if cond=7 */
    }
}
```

```
/*  DAHEAD1.H  */
/*  Data acquisition system device registers */
/*  For program DOMKC */

#DEFINE    ADBASE     232         /* A/D Base Address */
#DEFINE    ADCSR      (ADBASE+0)  /* A/D Control and Status Register */
#DEFINE    ADICR      (ADBASE+1)  /* A/D Initiate Conversion Register */
#DEFINE    ADLO       (ADBASE+2)  /* A/D Low Data Nibble (4 LSB) */
#DEFINE    ADHI       (ADBASE+3)  /* A/D High Data Byte */
#DEFINE    START      1           /* A/D Initiate Conversion Code (arbitrar

#DEFINE    DABASE     224        /* D/A Base Address */

#DEFINE    CTC3       11         /* Clock Channel 3 Address */
#DEFINE    CNTL       0065       /* Clock Control Word (octal) */
#DEFINE    TIME       39         /* Clock Time Constant (.0025 sec) */

#DEFINE    RELAY      236        /* Relay register */

#DEFINE    TSECONDS    25        /* Total seconds to sample */
#DEFINE    RATE1      400        /* High sample rate (set by TIME above) */
#DEFINE    RATE2      100        /* Low sample rate */

/* These statements define the maximum number of points sampled */
/* for signals sampled at the high and low rates. */
#DEFINE    LARGE      (TSECONDS*RATE1)
#DEFINE    SMALL      (TSECONDS*RATE2)

#DEFINE    NBLOCKS1   ((SMALL+127)/128)  /* disk blocks / JS, BSG, ACCEL a
#DEFINE    NBLOCKS2   ((LARGE+127)/128)  /* disk blocks / EMGR, EMGL array
#DEFINE    SKIP       (RATE1/RATE2)      /* ratio of fast/slow sample rate

/* Total time of rotation is TSECONDS-DELAY1-DELAY2 */
#DEFINE    DELAY1     2          /* Seconds from sampling start to dome sta
#DEFINE    DELAY2     5          /* Seconds from dome stop to sampling stop
```

```
/*
        The BDS C Standard I/O header file --  v1.46    3/4/82

        This file contains global definitions, for use in all C programs
        in PLACE of (yechhh) CONSTANTS. Characteristics of your system s
        as video screen size, interface port numbers and masks, buffered
        allocations, etc., should all be configured just once within thi
        file. Any program which needs them should contain the preprocess
        directive:

                #include "bdscio.h"

        near the beginning.
        Go through and set all this stuff as soon as you get the package
        and most terminal-dependent sample programs should run much bett
*/


/*
        Some console (video) terminal characteristics:
        (pre-configured for H19/Z19/H89/Z89)
*/

#define TWIDTH  80      /* # of columns */
#define TLENGTH 24      /* # of lines   */
#define CLEARS  "\033E" /* String to clear screen on console    */
#define INTOREV "\033p" /* String to switch console into reverse video
#define OUTAREV "\033q" /* String to switch console OUT of reverse video
#define CURSOROFF "\033x5"      /* String to turn cursor off    */
#define CURSORON "\033y5"       /* String to turn cursor on     */
#define ESC     '\033'  /* Standard ASCII 'escape' character    */

/*
        Console serial port characteristics:
*/

#define CSTAT   0355    /* status port  */
#define CDATA   0350    /* data port    */
#define CIMASK  0x01    /* input data ready mask   */
```

```
#define COMASK  0x20    /* output data ready mask  */
#define CAHI    1       /* True if status active high   */
#define CRESET  0       /* True if status port needs to be reset after i
#define CRESETVAL 0     /* If CRESET is true, this is the value to send

/*
        Modem characteristics:
*/

#define MSTAT   0335    /* status port  */
#define MDATA   0330    /* data port    */
#define MIMASK  0x01    /* input data ready mask        */
#define MOMASK  0x20    /* ready to send a character mask       */
#define MAHI    1       /* True if status logic active high  */
#define MRESET  0       /* True if status port needs to be reset */
#define MRESETVAL 0     /* If MRESET true, this is the byte to send */









/*
       General purpose Symbolic constants:
*/

#define BASE 0          /* Base of CP/M system RAM (0 or 0x4200)  */
#define NULL 0
#define EOF -1          /* Physical EOF returned by low level I/O functi
#define ERROR -1        /* General "on error" return value */
#define OK 0            /* General purpose "no error" return value */
#define JBUFSIZE 6      /* Length of setjump/longjump buffer    */
#define CPMEOF 0x1a     /* CP/M End-of-text-file marker (sometimes!)  */
#define SECSIZ 128      /* Sector size for CP/M read/write calls */
#define MAXLINE 135     /* Longest line of input expected from the consc
#define TRUE 1          /* general purpose true truth value     */
#define FALSE 0         /* general purpose false truth value    */

/*
   The NSECTS symbol controls the compilation of the buffered
   I/O routines within STDLIB2.C, allowing each user to set the
   buffer size most convenient for his system, while keeping
   the numbers totally invisible to the C source programs using
   buffered I/O (via the BUFSIZ defined symbol.) For larger
   NSECTS, the disk I/O is faster...but more ram is taken up.
   To change the buffer size allocation, follow these steps:

     1) Alter NSECTS to the desired value here in bdscio.h
     2) Re-compile STDLIB1.C and STDLIB2.C
     3) Use CLIB to combine STDLIB1.CRL and STDLIB2.CRL to make
        a new DEFF.CRL.

   Make sure you use declare all your I/O buffers with the a
   statement such as:
```

```
        char buf_name[BUFSIZ];
*/

#define NSECTS 8        /* Number of sectors to buffer up in ram */

#define BUFSIZ (NSECTS * SECSIZ + 6 )   /* Don't touch this */

struct _buf {                           /* Or this...       */
        int _fd;
        int _nleft;
        char *_nextp;
        char _buff[NSECTS * SECSIZ];
};

#define FILE struct _buf        /* Poor man's "typedef" */

/*
        If you plan to use the high-level storage allocation functions
        from the library ("alloc" and "free") then:

          1) Uncomment (enable) the "ALLOC_ON" definition, and comment o

             "ALLOC_OFF" definition from this file.

          2) Re-compile STDLIB1.C, and use CLIB to transfer "alloc"
             and "free" into the DEFF.CRL library file.

          3) THIS IS IMPORTANT!!! Include the statement:

                _allocp = NULL;    /* initialize allocation pointer */

             somewhere in your "main" function PRIOR to the first use
             of the "alloc" function. DON'T FORGET THIS INITIALIZATION!!

        Remember to include bdscio.h in ALL files of your C program.
*/

#define ALLOC_OFF 1     /* disables storage allocation if uncommented */

                        /* only ONE of these two lines should be uncomme

/*
#define ALLOC_ON 1      /* enables storgage allocation if uncommented */
*/

#ifdef ALLOC_ON                 /* if storage allocation enabled, */

struct _header  {
        struct _header *_ptr;
```

```
        unsigned _size;
 };

struct _header _base;           /* declare this external data to  */
struct _header *_allocp;        /* be used by alloc() and free()  */

#endif
```

```
/*  DEXTRN.C  */
/*  Array definitions for rotating dome files. */
/*  These are external variables, and must be declared */
/*  at the beginning of each file in which they are used */
/*  (before the first function definition). */

char JS[SMALL];          /* joystick array */
char BSG[SMALL];         /* biteboard strain gage array */
char EMGR[LARGE];        /* right EMG array */
char EMGL[LARGE];        /* left EMG array */
char ACCEL[SMALL];       /* accelerometer array */
char *pjs,*pbsg,*pemgr,*pemgl,*paccel;   /* pointers to the above */

char filnum;             /* file number in current series */
```

```
/*  SHOW2  */
/* Play back dome data from DOMKC */

#include  bdscio.h

#include  dahead1.h

#include  dextrn.c

int fd;

main()
{
#include  dahead2.c
unsigned kount;
char qa,i;
int npnts1;

for(;;)
{

npnts1=readit();
if(npnts1==-1) exit();

printf("\nAccelerometer data? ");
scanf("%c",&qa);

if(toupper(qa)=='Y')
     {
     pjs=&ACCEL;
     pbsg=&ACCEL;
     pemgr=&ACCEL;
     pemgl=&ACCEL;
     }
if(toupper(qa)!='Y')
     {
     pjs=&JS;
     pbsg=&BSG;
     pemgr=&EMGR;
     pemgl=&EMGL;
     }

outp(CTC3,CNTL);              /* set clock control */
outp(CTC3,TIME);              /* set time constant */
i=0;

printf("\nPress RETURN to begin playback. ");
getchar();

for(kount=0;kount<npnts1;kount++)
     {
     while(inp(CTC3)!=TIME) {;}
     outp(DA[2],*pemgr++);
     outp(DA[3],*pemgl++);
     if(++i==SKIP)
```

```
          {
          i=0;
          outp(DA[0],*pjs++);
          outp(DA[1],*pbsg++);
          }
     if(kbhit()) {break;}
     }
printf("\n\nDONE\n\n");
}
}

/* ****************************************************** */

readit()
{
int npnts1,nbl;
char i,filnam[13];

choose:
for(i=0;i<13;i++) filnam[i]=0;
printf("\nFile name: ");
gets(filnam);
if(filnam[0]==0) return -1;   /* CR FLAG */

fd=open(filnam,0);
if(fd==-1)
     {
     printf("\nERROR IN FILE OPENING\n");
     goto choose;
     }

npnts1=rdhead();

nbl=read(fd,JS,NBLOCKS1);
if(nbl!=NBLOCKS1) printf("\nERROR IN JS DATA READ\n");

nbl=read(fd,BSG,NBLOCKS1);
if(nbl!=NBLOCKS1) printf("\nERROR IN BSG DATA READ\n");

nbl=read(fd,EMGR,NBLOCKS2);
if(nbl!=NBLOCKS2) printf("\nERROR IN EMGR DATA READ\n");

nbl=read(fd,EMGL,NBLOCKS2);
if(nbl!=NBLOCKS2) printf("\nERROR IN EMGL DATA READ\n");

nbl=read(fd,ACCEL,NBLOCKS1);
if(nbl!=NBLOCKS1) printf("\nERROR IN ACCEL DATA READ\n");


if(close(fd)==-1) printf("\nERROR CLOSING FILE\n");
```

```
return npnts1;
}

/* ****************************************************** */
```

```
rdhead()
{
int npnts1;
char buff[25];
char k,nblh;
#include  dahead2.c
char filnam[15];

struct header {
char hsubjct[2];
char hsessn[4];
char htdate[9];
char htest[10];
char hdescr[20];
int hrate1,hrate2;
char hpgm[9];
int hnbl1,hnbl2;
int hnpnts1;
char hcomm[50];
char hcdx;
char pad[13];              /* must fill file sector (128 bytes) */
};

struct header hd;

/* Output is done through buffer to place final null byte */
/* if needed (needed for puts). */
nblh=read(fd,hd,1);
if(nblh!=1) printf("\nERROR READING HEADER\n");
printf("\nHeader Data\n");
buff[0]=hd.hsubjct[0];
buff[1]=hd.hsubjct[1];
buff[2]=0;
printf("\nSubject Code: ");
puts(buff);
buff[0]=hd.hsessn[0];
buff[1]=hd.hsessn[1];
buff[2]=hd.hsessn[2];
buff[3]=hd.hsessn[3];
buff[4]=0;
printf("\nTest Session: ");
puts(buff);
printf("\nTest Date: ");
for(k=0;k<9;k++) buff[k]=hd.htdate[k];
```

```
buff[9]=0;
puts(buff);
printf("\nTest: ");
puts(hd.htest);
printf("\nData: ");
for(k=0;k<20;k++) buff[k]=hd.hdescr[k];
buff[20]=0;
puts(buff);
printf("\nSampling Rates: %d %d",hd.hrate1,hd.hrate2);
printf("\nAcquisition Pgm: ");
```

```
puts(hd.hpgm);
printf("\nNominal File Sizes: %d %d",hd.hnbl1,hd.hnbl2);
npnts1=hd.hnpnts1;
printf("\nPts / Large Array:  %d",npnts1);
printf("\nTest Condition: %c",hd.hcdx);
printf("\nComments: %s\n",hd.hcomm);
return npnts1;
}
```

Appendix 2

Biteboard Material Information

Biteboard Material Information

Name: Express™ Vinyl Polysiloxane Impression Material System

Manufacturer: 3M Dental Products Division

Type: HP Softer Set Putty, product number 7306H

Handling Information:

Certain gloves will inhibit the setting of putty. Test gloves to confirm proper setting times, wear vinyl gloves or use vinyl overliners. Alternatively, remove gloves and thoroughly wash hands to remove other sources of potential contamination (e.g. hand lotions and glove residues).

Mix equal volumes or weights until uniform and streak-free (approx. 20-30 seconds).

The palms of the hands will generate heat which reduces putty working time. When mixing the putty catalyst and base, knead with your fingertips.

Do not intermix jars of putty from different kits. Base and catalyst combinations must be kept intact to insure proper setting time.

If you don't use the putty within 90 seconds from the start of mixing, discard and remix.

Express putty must be used with a lower viscosity Express vinyl polysiloxane impression material in order to obtain highly detailed impressions.

Express impressions should be stored at dry room temperatures. Do not store in water or excessive humidity.

Timing Information:

Mixing time -- 20-30 seconds
Putty seating time -- < or = 60 seconds
Setting time -- 6 minutes

Material Standards:

Chemical nature:	Vinyl polysiloxane
Category:	A
Maximum compression set:	< 1.0%
Maximum dimensional change:	24hrs: <-.2% 336hrs: <-.3%
Strain in compression:	1% - 5%

Appendix 3

Labview™ Code

Code by Nick Groleau, 1989

INSTRUMENT NAME:

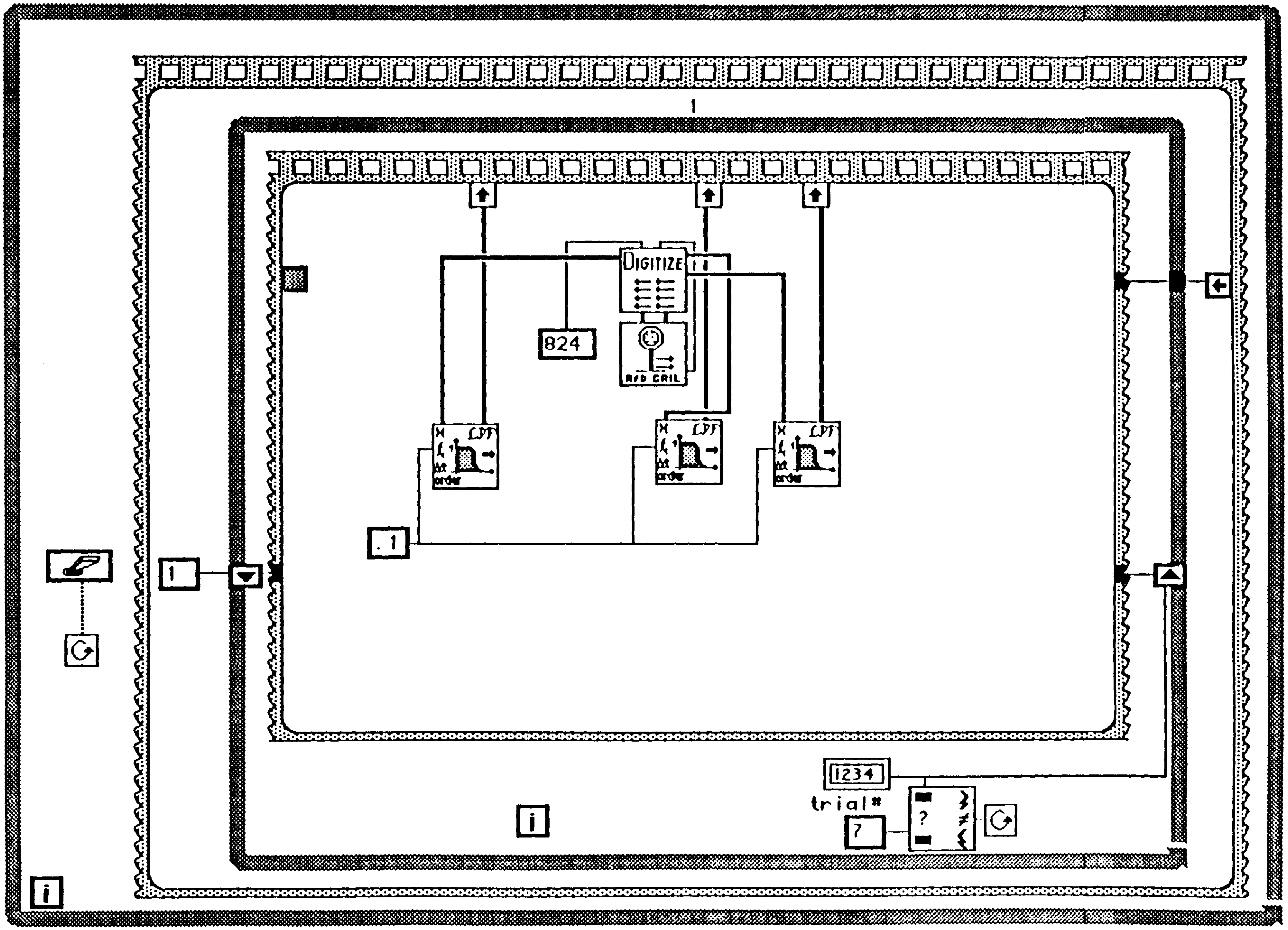
gail.session.25Hz

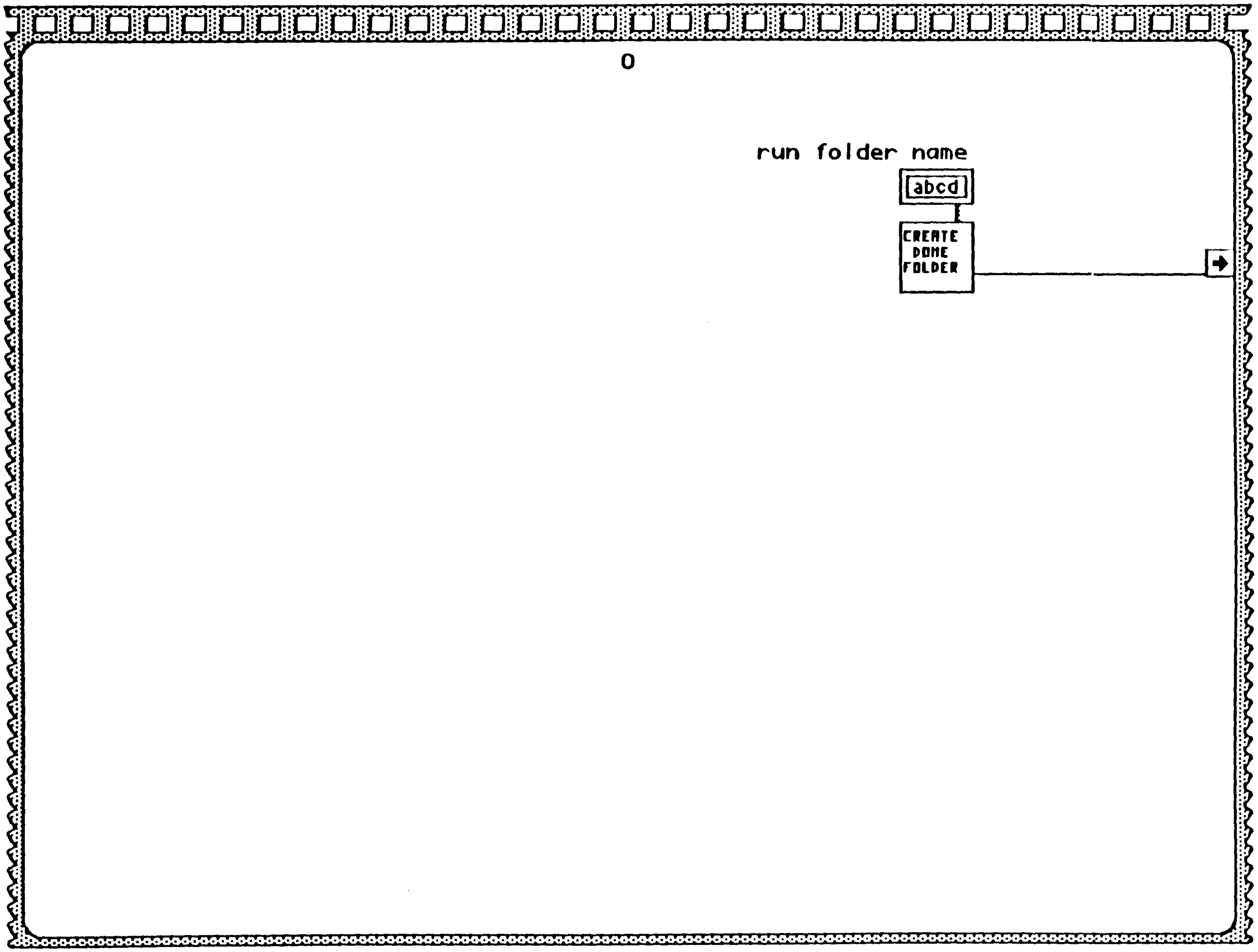
ICON:

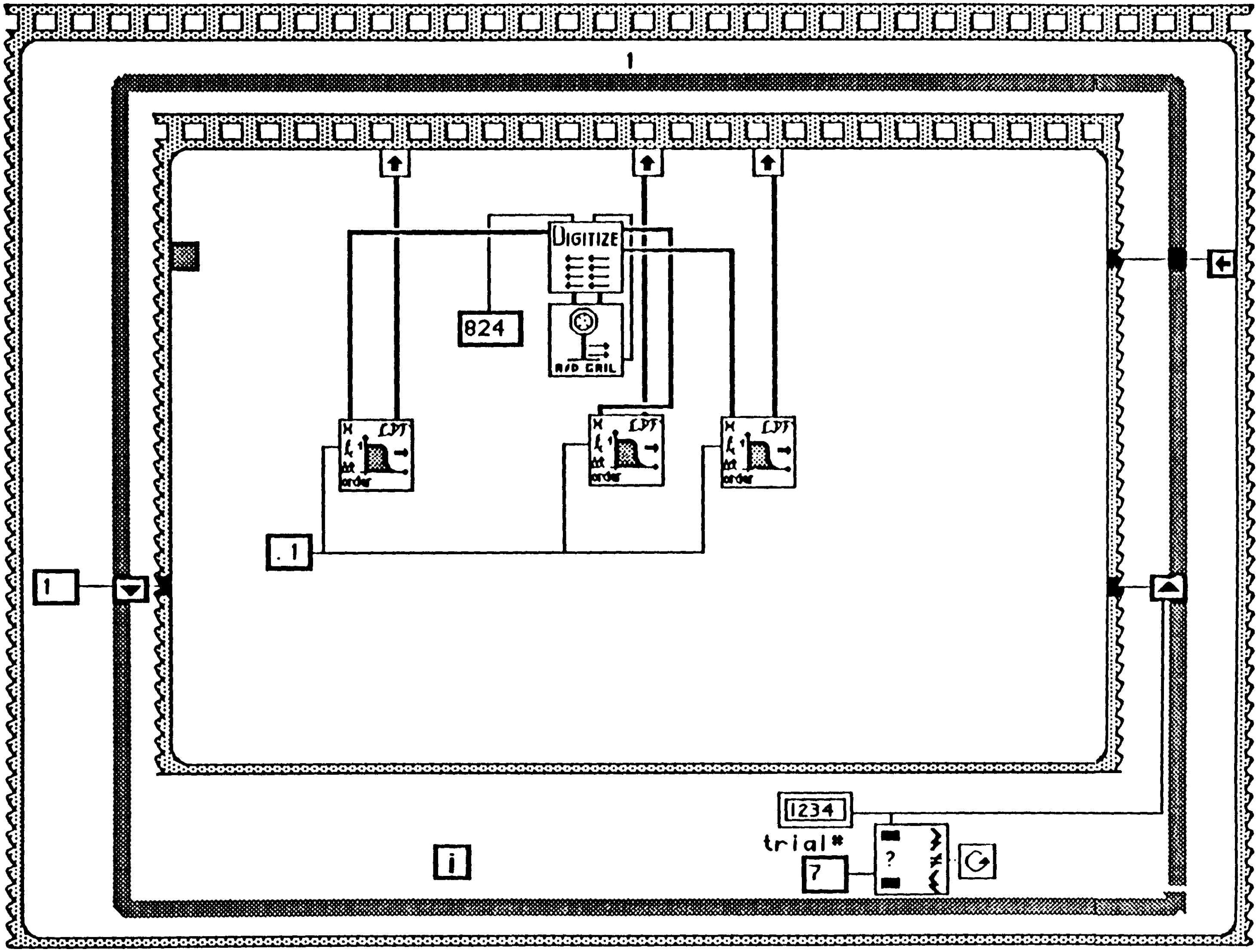
CONNECTOR PANE:

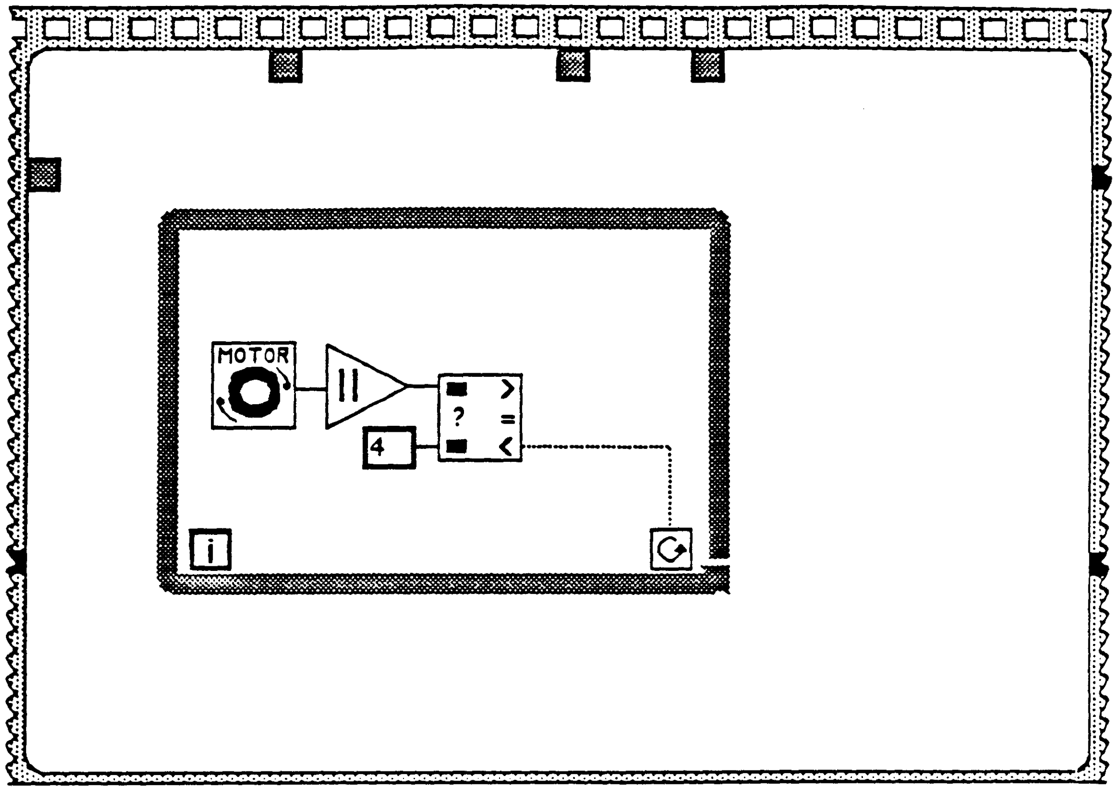
None

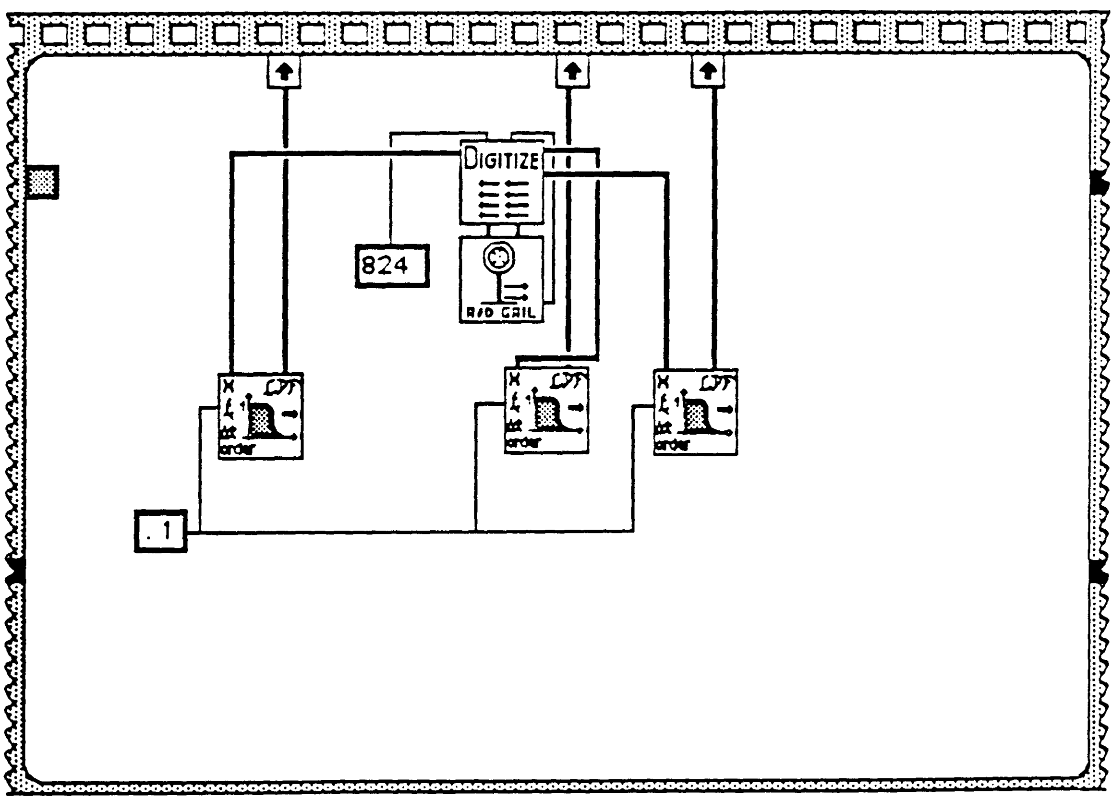
gail.session.25Hz Diagram

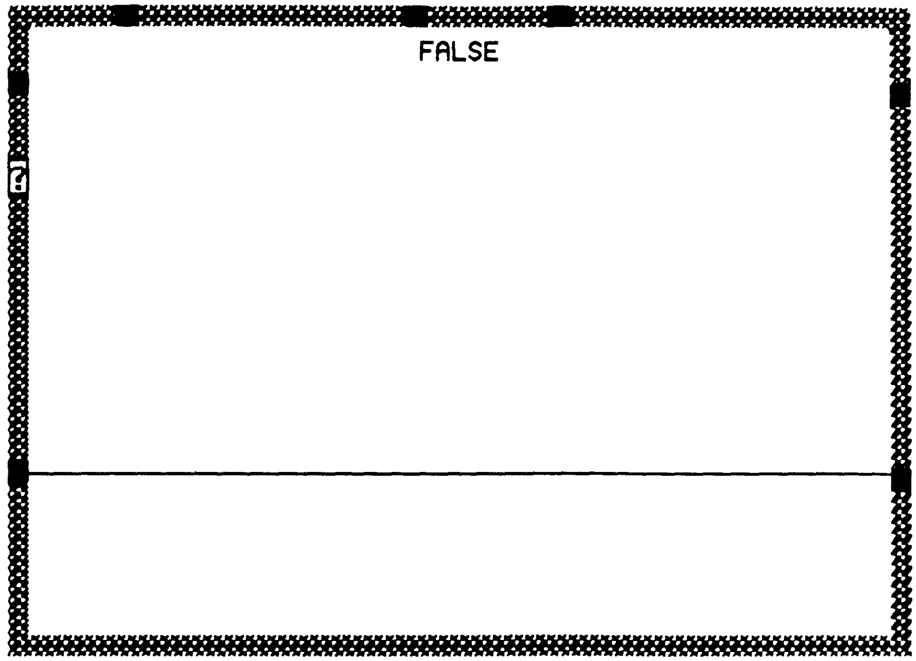


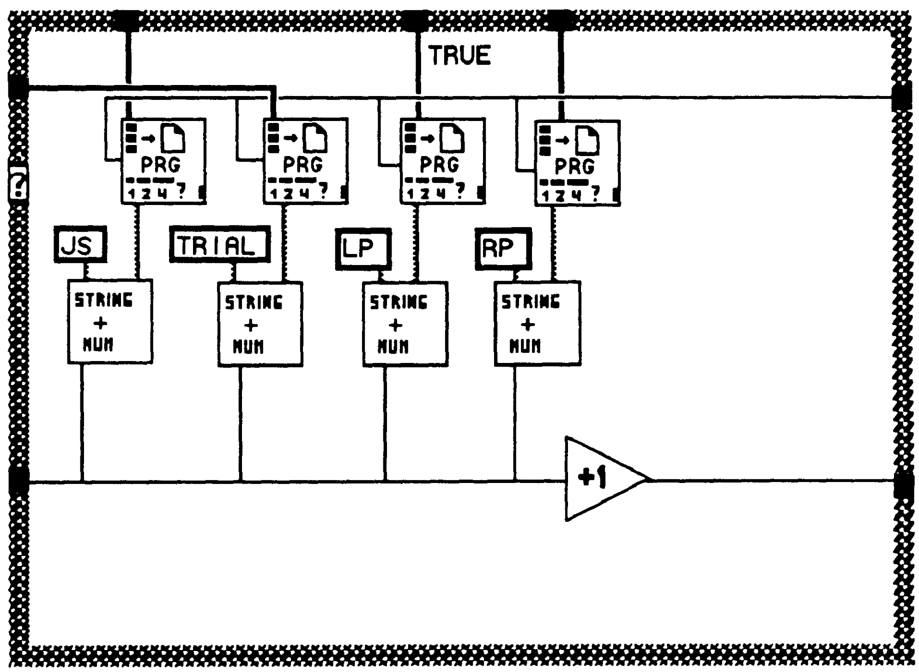

0
run folder name
abcd
CREATE DONE FOLDER

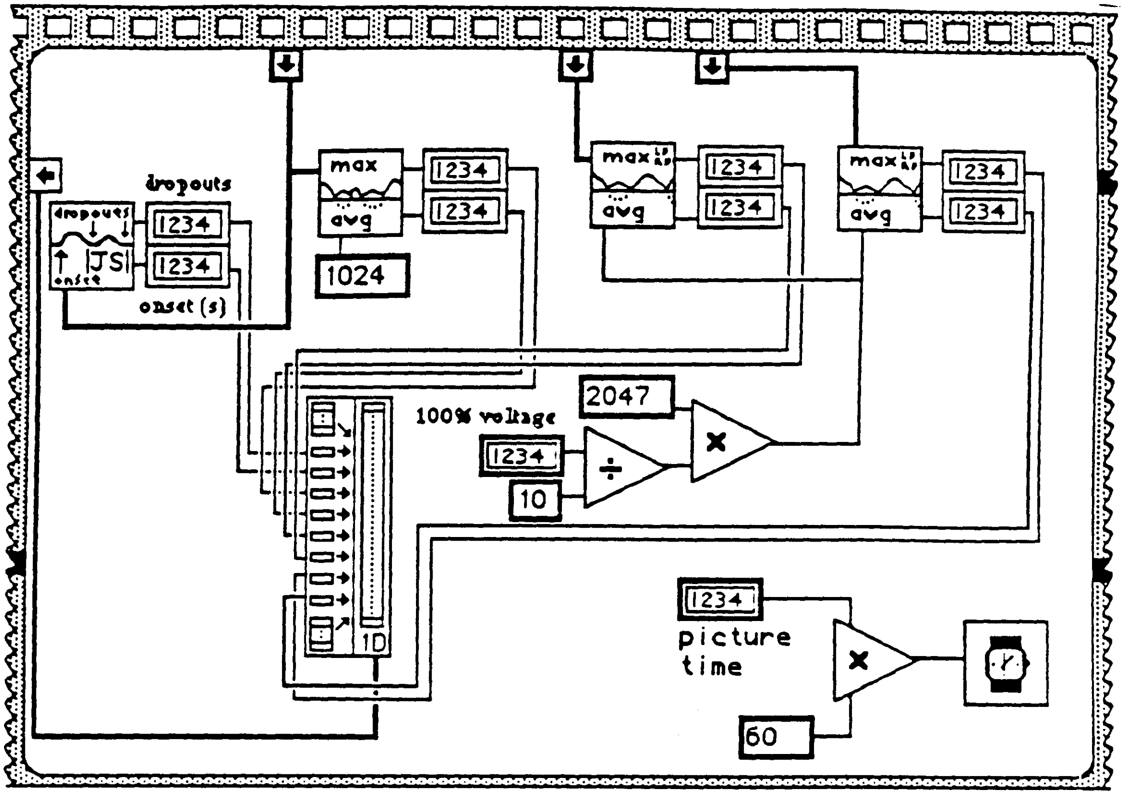

1
DIGITIZE
824
LPF
order
.1
1
1234
trial#
7
i


MOTOR
?
4
i

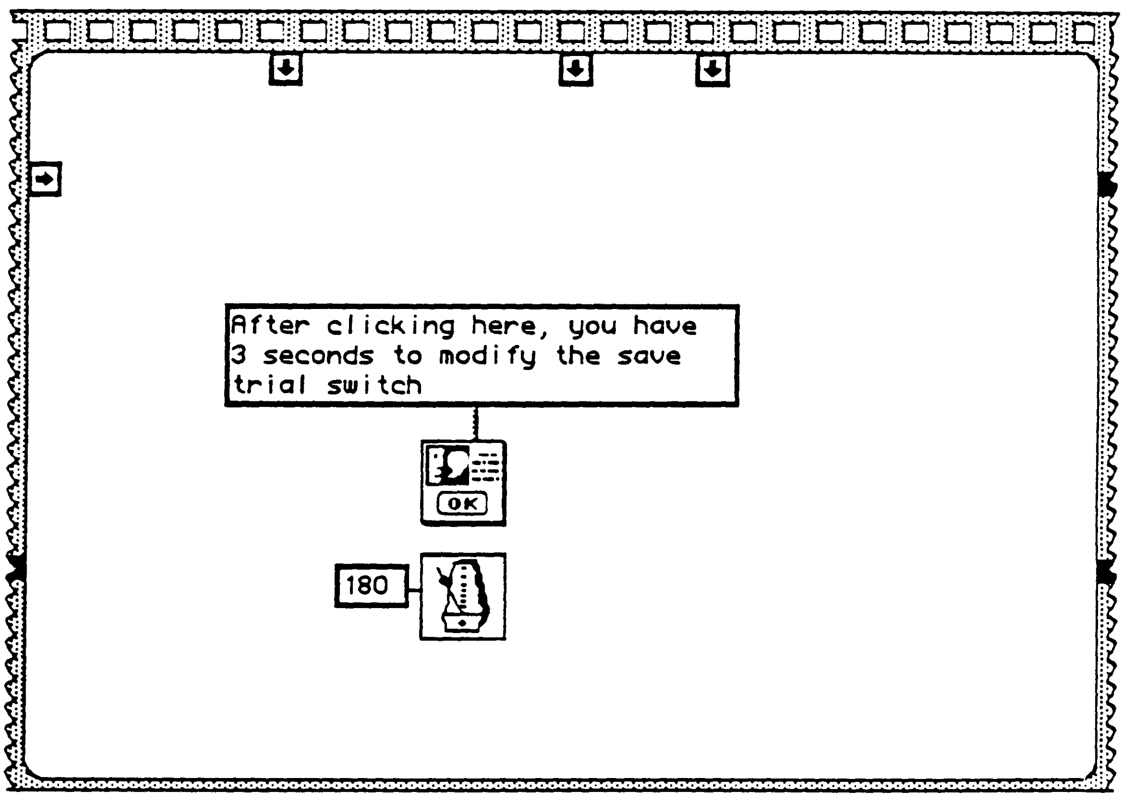

DIGITIZE
824
A/D CHIL
.1


FALSE

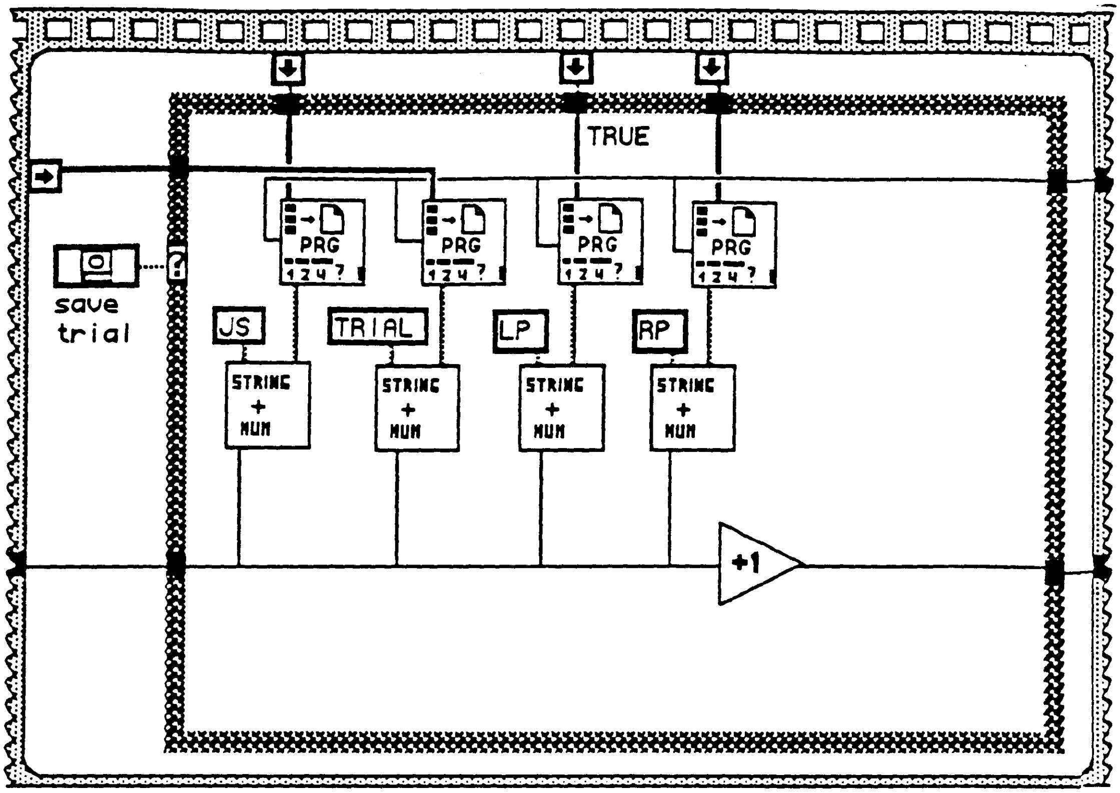

TRUE
PRG
PRG
PRG
PRG
JS
TRIAL
LP
RP
STRING + NUM
STRING + NUM
STRING + NUM
STRING + NUM
+1

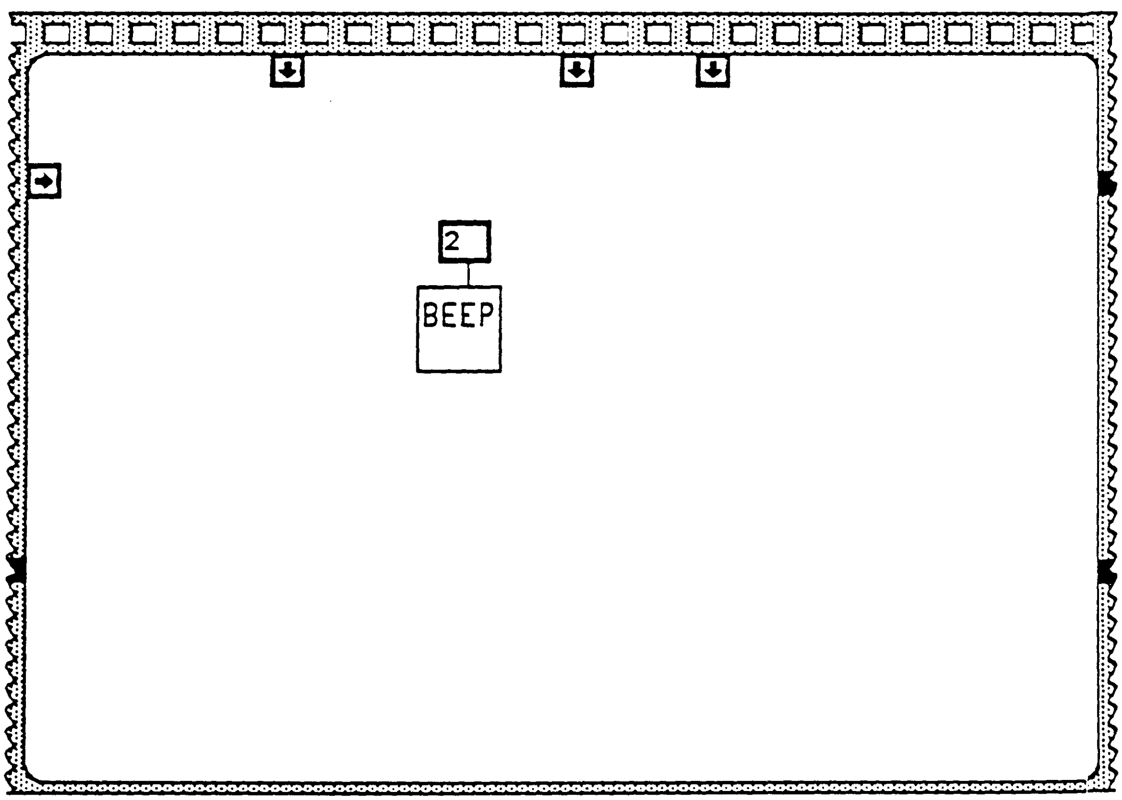


max
avg
1234
1024
dropouts
JS
onset (s)
2047
100% voltage
10
1D
picture
time
60



After clicking here, you have
3 seconds to modify the save
trial switch
OK
180


TRUE
save
trial
PRG
JS
TRIAL
LP
RP
STRING
+
NUM
+1


2
BEEP

Appendix 4

Spreadsheet Data

Joystick/Position Data

	A	B	C	D	E	F	G	H
1	sub	weight	trial	onset (s)	max vec (%)	ave vec (%)	LP max (%)	LP ave (%)
2	2	b0	a	16.12	30.175	9.83	0	0
3	2	b0	e	33	6.273	1.864	0	0
4	2	b0	f	33	7.104	1.536	0	0
5	2	b0	b	6.4	24.027	10.534	0	0
6	2	b0	d	6.28	21.4	9.621	0	0
7	2	b0	c	27.36	21.887	4.046	0	0
8	2	b500	b	4.08	39.364	14.52	0	0
9	2	b500	d	10.24	17.765	5.058	0	0
10	2	b500	a	10.08	30.084	13.331	0	0
11	2	b500	c	33	6.97	3.903	0	0
12	2	b500	e	8.76	19.019	3.216	0	0
13	2	b500	f	8.92	22.915	5.118	0	0
14	2	n0	a	10.88	25.429	10.844	0	0
15	2	n0	e	11.12	18.171	7.123	0	0
16	2	n0	f	9.88	26.759	8.604	0	0
17	2	n0	b	33	8.36	5.032	0	0
18	2	n0	d	10.4	25.43	6.278	0	0
19	2	n0	c	14.08	30.583	12.408	0	0
20	2	n125	a	3.6	37.511	10.084	36.982	14.409
21	2	n125	e	5.04	18.99	2.592	48.361	25.544
22	2	n125	f	33	7.79	6.507	19.069	6.198
23	2	n125	b	16.56	26.967	8.783	39.481	20.57
24	2	n125	d	33	8.073	1.621	42.757	10.554
25	2	n125	c	33	7.862	4.548	5.361	0.03
26	2	n250	b	7.32	38.13	15.782	47.613	19.184
27	2	n250	d	8.16	24.538	7.469	41.042	26.611
28	2	n250	a	8.12	24.306	11.757	65.909	16.764
29	2	n250	c	33	1.805	0.435	57.906	25.507
30	2	n250	e	11.76	15.543	5.132	38.43	26.614
31	2	n250	f	33	5.864	3.093	35.331	26.628
32	2	n375	b	6.92	24.161	8.593	64.598	32.898
33	2	n375	d	25.08	19.448	5.342	65.303	25.996
34	2	n375	a	8.56	29.325	11.374	39.39	9.461
35	2	n375	c	24.4	19.86	5.297	43.027	25.771
36	2	n375	e	24.48	27.895	7.411	44.616	23.405
37	2	n375	f	9.8	29.1	6.766	17.251	2.138
38	2	n500	a	3.6	41.127	19.573	36.906	9.746
39	2	n500	e	6.6	28.321	10.183	57.35	34.348
40	2	n500	f	33	7.064	4.235	27.742	15.46
41	2	n500	b	3.4	16.67	7.273	12.434	3.475
42	2	n500	d	4.56	34.815	13.995	51.233	35.361
43	2	n500	c	9.36	27.909	11.713	19.933	2.605
44	3	b0	a	7.68	44.46	13.83	0	0
45	3	b0	e	7.04	80.755	54.599	0	0
46	3	b0	f	5.32	95.189	33.449	0	0

	A	B	C	D	E	F	G	H
47	3	b0	b	5.68	64.727	44.367	0	0
48	3	b0	d	5.32	97.531	76.265	0	0
49	3	b0	c	5.08	81.016	56.42	0	0
50	3	b500	b	33	8.002	5.283	0	0
51	3	b500	d	13.6	18.913	7.528	0	0
52	3	b500	a	7.64	36.898	10.483	0	0
53	3	b500	c	8.48	11.576	6.353	0	0
54	3	b500	e	5.72	27.627	14.278	0	0
55	3	b500	f	6.16	18.322	9.149	0	0
56	3	n0	b	7.6	30.102	18.97	0	0
57	3	n0	d	3.28	44.651	26.819	0	0
58	3	n0	a	5.68	84.033	53.513	0	0
59	3	n0	c	9.28	31.77	9.154	0	0
60	3	n0	e	6.92	16.267	3.915	0	0
61	3	n0	f	2.92	21.364	8.011	0	0
62	3	n125	a	8.4	16.527	6.926	33.104	25.229
63	3	n125	e	5.24	17.889	3.729	12.483	2.679
64	3	n125	f	29.92	18.134	6.035	24.686	3.1
65	3	n125	b	7.56	23.317	9.154	38.033	22.995
66	3	n125	d	6.2	23.154	8.034	24.854	13.504
67	3	n125	c	12.68	23.459	6.733	29.074	15.04
68	3	n250	b	33	9.663	5.283	13.562	6.095
69	3	n250	d	6.6	18.329	5.948	26.544	13.742
70	3	n250	a	16.28	22.891	9.202	29.491	16.705
71	3	n250	c	33	6.928	5.559	32.69	13.97
72	3	n250	e	10.84	39.745	14.623	25.733	13.664
73	3	n250	f	6.64	28.571	14.006	22.518	11.171
74	3	n375	a	33	7.365	5.593	32.371	13.275
75	3	n375	e	10.56	19.57	10.129	12.602	4.071
76	3	n375	f	6.48	20.174	7.524	10.235	1.028
77	3	n375	b	6.6	34.086	16.796	34.923	25.477
78	3	n375	d	3.64	96.513	35.795	14.643	2.663
79	3	n375	c	6.2	65.565	26.053	33.551	15.975
80	3	n500	b	10.28	21.932	11.699	33.702	18.647
81	3	n500	d	3.12	52.489	24.756	14.28	1.143
82	3	n500	a	5.48	47.77	14.356	24.129	15.341
83	3	n500	c	9.04	29.729	16.288	30.912	20.185
84	3	n500	e	9.52	56.345	18.074	23.696	5.772
85	3	n500	f	6.2	26.451	12.475	9.67	1.161
86	4	b0	a	1.44	49.009	16.243	0	0
87	4	b0	e	0.36	45.742	28.504	0	0
88	4	b0	f	1.8	24.92	15.244	0	0
89	4	b0	b	0.52	45.244	34.506	0	0
90	4	b0	d	1.2	28.391	25.775	0	0
91	4	b0	c	1.36	65.173	50.312	0	0
92	4	b500	b	3.04	80.668	58.854	0	0

	A	B	C	D	E	F	G	H
93	4	b500	d	1.28	56.653	42.432	0	0
94	4	b500	a	0.04	76.613	54.77	0	0
95	4	b500	c	0.88	67.691	38.831	0	0
96	4	b500	e	1	29.046	25.672	0	0
97	4	b500	f	0.52	92.466	64.746	0	0
98	4	n0	a	0.88	98.956	58.419	0	0
99	4	n0	e	1.96	97.779	63.428	0	0
100	4	n0	f	5.16	98.325	47.633	0	0
101	4	n0	b	1.72	98.764	57.85	0	0
102	4	n0	d	1.32	97.239	58.471	0	0
103	4	n0	c	2.28	98.83	63.68	0	0
104	4	n125	a	0.48	58.527	38.266	26.04	1.302
105	4	n125	e	0.44	86.664	56.547	45.991	26.256
106	4	n125	f	1.88	32.67	17.006	30.971	20.189
107	4	n125	b	0.56	57.41	40.854	30.677	3.191
108	4	n125	d	1	40.822	16.134	46.316	27.783
109	4	n125	c	0.52	86.483	50.241	24.792	15.087
110	4	n250	b	2.92	71.546	42.877	39.187	15.961
111	4	n250	d	1.52	97.848	51.572	31.031	11.087
112	4	n250	a	0.96	98.855	61.045	16.906	11.206
113	4	n250	c	2.48	97.813	56.294	21.96	6.622
114	4	n250	e	1.28	98.198	61.351	20.063	5.04
115	4	n250	f	2	98.53	67.754	37.648	18.039
116	4	n375	b	1.08	98.443	50.789	11.263	0.511
117	4	n375	d	1.84	63.55	39.23	28.839	9.622
118	4	n375	a	0.96	98.772	51.213	12.007	2.917
119	4	n375	c	1.32	64.88	41.925	23.849	4.725
120	4	n375	e	1.36	54.346	23.135	30.697	9.066
121	4	n375	f	1.64	64.062	23.937	18.194	2.06
122	4	n500	a	1.16	98.226	74.366	26.576	8.966
123	4	n500	e	1.04	97.73	72.81	21.824	2.516
124	4	n500	f	1.2	98.096	74.108	18.001	1.287
125	4	n500	b	0.52	99.036	80.019	14.914	3.642
126	4	n500	d	1.32	97.402	34.024	25.958	11.165
127	4	n500	c	0.88	83.957	52.168	17.22	0.017
128	5	b0	b	6.2	78.903	36.855	0	0
129	5	b0	d	4.96	59.243	39.102	0	0
130	5	b0	a	4.52	98.763	62.708	0	0
131	5	b0	c	5.52	63.819	43.737	0	0
132	5	b0	e	4.68	86.349	60.522	0	0
133	5	b0	f	5.44	96.839	63.221	0	0
134	5	b500	a	2.8	65.497	38.601	0	0
135	5	b500	e	4.6	32.194	19.34	0	0
136	5	b500	f	5.88	67.285	38.532	0	0
137	5	b500	b	4.84	92.794	66.068	0	0
138	5	b500	d	5.8	30.187	17.084	0	0

	A	B	C	D	E	F	G	H
139	5	b500	c	2.04	95.64	71.638	0	0
140	5	n0	b	6.12	34.98	22.329	0	0
141	5	n0	d	7.28	54.523	32.494	0	0
142	5	n0	a	4.24	33.883	24.099	0	0
143	5	n0	c	7.28	49.58	28.182	0	0
144	5	n0	e	6.04	85.91	48.511	0	0
145	5	n0	f	5.08	56.086	37.012	0	0
146	5	n125	a	10.6	37.097	18.688	61.64	32.424
147	5	n125	e	8.72	36.394	18.069	52.142	22.396
148	5	n125	f	5.96	65.434	42.057	86.689	57.481
149	5	n125	b	4.24	38.311	29.366	62.054	50.592
150	5	n125	d	5.4	67.991	42.512	81.811	56.689
151	5	n125	c	3.76	67.841	47.306	61.459	52.433
152	5	n250	b	5.48	45.524	32.328	72.012	37.118
153	5	n250	d	4.64	66.932	42.731	77.493	39.616
154	5	n250	a	4.36	33.571	24.499	88.951	55.095
155	5	n250	c	4.88	82.383	49.799	93.558	75.005
156	5	n250	e	5.6	75.086	44.92	107.359	74.188
157	5	n250	f	5.96	78.034	42.951	100.45	69.178
158	5	n375	a	7.76	45.026	27.228	56.148	31.669
159	5	n375	e	5.36	56.756	38.153	87.331	70.996
160	5	n375	f	4.44	76.231	52.369	102.984	71.254
161	5	n375	b	3.88	51.556	37.947	81.545	50.073
162	5	n375	d	4.64	55.5	37.162	101.694	74.432
163	5	n375	c	5.16	66.359	39.879	107.626	77.206
164	5	n500	b	4.04	70.035	46.563	122.429	73.779
165	5	n500	d	3.8	69.445	42.278	80.961	53.938
166	5	n500	a	4.8	37.703	26.274	100.78	63.369
167	5	n500	c	4	52.932	32.352	156.706	111.027
168	5	n500	e	4.84	94.351	66.508	79.564	50.43
169	5	n500	f	5.64	82.71	48.024	86.773	50.375
170	6	b0	b	0.92	45.276	39.303	0	0
171	6	b0	d	1	31.143	28.174	0	0
172	6	b0	a	0.88	46.458	28.022	0	0
173	6	b0	c	0.64	36.93	32.721	0	0
174	6	b0	e	1.4	27.157	20.964	0	0
175	6	b0	f	0.28	82.04	49.032	0	0
176	6	b500	a	1.32	53.546	41.847	0	0
177	6	b500	e	33	9.283	3.206	0	0
178	6	b500	f	0.92	27.597	15.168	0	0
179	6	b500	b	0.56	34.5	29.254	0	0
180	6	b500	d	0.92	37.178	15.136	0	0
181	6	b500	c	0.64	54.308	46.856	0	0
182	6	n0	b	1.6	52.422	34.009	0	0
183	6	n0	d	2.92	53.891	47.744	0	0
184	6	n0	a	1	81.461	73.133	0	0

	A	B	C	D	E	F	G	H
185	6	n0	c	1.96	98.445	89.393	0	0
186	6	n0	e	1.2	65.951	42.407	0	0
187	6	n0	f	1.96	97.649	89.416	0	0
188	6	n125	a	2	61.562	53.247	29.191	7.595
189	6	n125	e	2.32	18.609	16.244	23.186	14.909
190	6	n125	f	0.56	47.528	44.526	24.578	10.98
191	6	n125	b	1.08	73.138	59.949	15.129	0.268
192	6	n125	d	1.6	35.065	30.996	54.628	27.392
193	6	n125	c	6.88	54.554	39.276	41.321	29.004
194	6	n250	a	1.68	15.06	65.504	14.539	5.243
195	6	n250	e	2	98.209	85.772	44.097	27.703
196	6	n250	f	0.92	98.018	86.438	46.468	36.484
197	6	n250	b	1.76	86.056	78.134	49.385	6.796
198	6	n250	d	1.88	55.527	45.659	54.54	27.476
199	6	n250	c	0.76	98.674	91.426	68.994	9.413
200	6	n375	a	1.44	77.512	65.078	18.304	5.506
201	6	n375	e	1.32	54.917	46.875	37.202	15.556
202	6	n375	f	2.56	73.796	56.64	40.651	15.482
203	6	n375	b	0.64	67.162	60.999	25.46	3.391
204	6	n375	d	3.4	30.961	26.181	40.738	22.609
205	6	n375	c	0.8	96.512	89.814	23.091	1.186
206	6	n500	b	1.44	55.702	50.519	26.272	2.47
207	6	n500	d	0.6	41.028	27.631	45.992	23.893
208	6	n500	a	0.72	55.843	52.736	25.948	4.232
209	6	n500	c	1.32	85.92	77.433	15.148	1.043
210	6	n500	e	1.12	28.631	25.937	69.396	40.436
211	6	n500	f	1.48	67.497	49.431	69.664	34.414
212	7	b0	a	33	8.816	6.147	0	0
213	7	b0	e	33	7.388	2.277	0	0
214	7	b0	f	33	6.404	1.947	0	0
215	7	b0	b	33	9.808	6.974	0	0
216	7	b0	d	33	7.921	2.006	0	0
217	7	b0	c	33	8.344	5.849	0	0
218	7	b500	b	33	9.403	6.83	0	0
219	7	b500	d	33	7.865	1.921	0	0
220	7	b500	a	33	8.589	6.986	0	0
221	7	b500	c	33	7.122	2.643	0	0
222	7	b500	e	31.56	10.015	5.551	0	0
223	7	b500	f	33	7.205	1.423	0	0
224	7	n0	a	3.88	31.678	24.315	0	0
225	7	n0	e	1.18	54.343	36.155	0	0
226	7	n0	f	3.64	44.659	23.524	0	0
227	7	n0	b	4.04	36.465	26.722	0	0
228	7	n0	d	21.04	17.61	8.493	0	0
229	7	n0	c	2.96	46.378	32.009	0	0
230	7	n125	b	5.72	26.824	19.199	49.709	23.427

	A	B	C	D	E	F	G	H
231	7	n125	d	15.44	17.949	9.857	32.794	6.135
232	7	n125	a	7.96	18.055	12.341	40.739	25.407
233	7	n125	c	6.24	23.453	15.387	65.003	13.583
234	7	n125	e	8.32	17.764	12.815	27.442	8.544
235	7	n125	f	5.08	30.879	20.87	44.941	21.671
236	7	n250	a	7	15.142	10.426	39.52	21.469
237	7	n250	e	9.44	20.456	13.807	44.409	11.607
238	7	n250	f	5.76	19.795	15.247	27.865	0.859
239	7	n250	b	2.2	25.643	17.234	67.979	23.31
240	7	n250	d	33	8.525	1.883	16.899	1.776
241	7	n250	c	1.52	45.003	35.821	68.212	23.896
242	7	n375	b	8.56	34.976	19.706	71.855	35.335
243	7	n375	d	12.8	18.82	10.699	29.709	7.211
244	7	n375	a	5.8	28.967	18.366	63.81	32.857
245	7	n375	c	7.2	13.137	8.246	26.228	17.29
246	7	n375	e	12.08	22.138	11.792	30.078	3.012
247	7	n375	f	8.2	29.344	18.501	35.897	7.413
248	7	n500	a	4.88	23.357	16.154	50.378	22.281
249	7	n500	e	7.08	19.886	11.921	22.896	1.26
250	7	n500	f	11.04	29.157	16.039	23.009	2.211
251	7	n500	b	8.28	29.543	17.462	56.535	33.393
252	7	n500	d	14.44	18.189	7.146	30.952	7.558
253	7	n500	c	3.88	27.988	17.167	83.329	34.315
254	8	b0	a	2.12	99.783	66.567	0	0
255	8	b0	e	3.76	99.836	36.698	0	0
256	8	b0	f	4.6	98.637	18.846	0	0
257	8	b0	b	4.28	98.435	16.249	0	0
258	8	b0	d	6.72	99.06	27.568	0	0
259	8	b0	c	5.08	97.867	47.01	0	0
260	8	b500	b	5.92	97.381	23.1	0	0
261	8	b500	d	8.12	99.178	52.471	0	0
262	8	b500	a	10.88	97.761	15.373	0	0
263	8	b500	c	8.72	97.758	19.495	0	0
264	8	b500	e	6.2	98.809	30.382	0	0
265	8	b500	f	6.76	100.026	26.27	0	0
266	8	n0	a	6.8	97.95	15.88	0	0
267	8	n0	e	4.48	98.25	30.956	0	0
268	8	n0	f	3.12	99.372	28.625	0	0
269	8	n0	b	6.32	98.053	10.285	0	0
270	8	n0	d	9.16	46.851	3.006	0	0
271	8	n0	c	6.16	98.43	10.81	0	0
272	8	n125	a	12.56	95.581	4.417	104.72	28.826
273	8	n125	e	10.92	99.61	8.485	43.453	3.584
274	8	n125	f	33	8.654	4.427	32.905	9.879
275	8	n125	b	33	8.413	2.861	53.565	11.324
276	8	n125	d	13.8	99.685	9.109	39.147	1.589

	A	B	C	D	E	F	G	H
277	8	n125	c	33	7.836	3.106	17.238	4.191
278	8	n250	b	6.44	98.243	13.138	32.155	19.926
279	8	n250	d	12.48	98.179	23.5	29.383	19.85
280	8	n250	a	5.76	97.547	8.55	68.032	4.302
281	8	n250	c	33	3.035	1.035	40.379	8.6
282	8	n250	e	5.28	97.127	6.022	70.058	5.131
283	8	n250	f	6.44	97.797	6.978	41.274	11.057
284	8	n375	b	33	2.049	0.625	26.159	11.094
285	8	n375	d	9.64	97.991	8.466	43.19	14.663
286	8	n375	a	11.72	99.791	10.753	71.147	11.399
287	8	n375	c	33	7.222	4.905	26.757	1.208
288	8	n375	e	8.32	98.7	6.283	24.295	10.84
289	8	n375	f	33	3.268	1.076	44.463	5.538
290	8	n500	a	6.76	96.494	7.832	12.401	2.491
291	8	n500	e	9.8	96.884	3.225	50.711	27.684
292	8	n500	f	33	2.969	0.887	46.529	28.533
293	8	n500	b	33	7.941	5.272	28.98	4.249
294	8	n500	d	33	8.128	5.221	34.854	10.708
295	8	n500	c	33	8.073	5.179	69.303	6.362
296	9	b0	a	6.72	23.48	11.985	0	0
297	9	b0	e	5.36	28.36	16.533	0	0
298	9	b0	f	10.44	48.58	22.879	0	0
299	9	b0	b	1.52	45.419	25.125	0	0
300	9	b0	d	5.04	49.534	26.584	0	0
301	9	b0	c	3.36	23.174	15.389	0	0
302	9	b500	b	4.36	22.721	14.322	0	0
303	9	b500	d	9.96	28.434	13.175	0	0
304	9	b500	a	3.52	35.877	24.472	0	0
305	9	b500	c	3.32	39.619	27.668	0	0
306	9	b500	e	12.08	19.341	9.261	0	0
307	9	b500	f	8.16	22.118	11.354	0	0
308	9	n0	a	2.6	46.856	36.397	0	0
309	9	n0	e	2.36	68.29	48.555	0	0
310	9	n0	f	4.92	44.022	27.543	0	0
311	9	n0	b	2.24	57.222	40.018	0	0
312	9	n0	d	3.36	44.764	28.205	0	0
313	9	n0	c	2.56	54.876	40.305	0	0
314	9	n125	b	4.16	24.765	14.979	13.597	6.316
315	9	n125	d	4.2	27.015	19.278	22.141	14.846
316	9	n125	a	3.36	32.269	20.297	19.026	14.798
317	9	n125	c	4.48	28.071	20.173	19.455	11.981
318	9	n125	e	2.2	43.438	28.347	36.285	23.868
319	9	n125	f	5.32	25.673	15.396	34.617	24.574
320	9	n250	b	1.72	28.424	21.441	8.469	3.431
321	9	n250	d	12	27.125	12.788	12.931	6.895
322	9	n250	a	2.6	24.887	15.653	5.388	0.895

	A	B	C	D	E	F	G	H
323	9	n250	c	3.52	14.89	10.071	11.667	4.016
324	9	n250	e	7.96	29.31	15.689	13.416	1.625
325	9	n250	f	7.08	20.618	12.653	13.326	3.529
326	9	n375	a	2.72	23.023	14.508	14.991	6.445
327	9	n375	e	6.8	29.401	17.09	12.764	0.747
328	9	n375	f	7.36	24.225	13.278	14.144	3.739
329	9	n375	b	3.08	21.243	12.405	10.146	3.744
330	9	n375	d	5.04	39.966	24.002	13.607	3.278
331	9	n375	c	1.64	21.374	12.424	20.006	12.532
332	9	n500	a	2.12	17.355	12.078	7.676	1.782
333	9	n500	e	4.68	19.062	12.484	17.276	7.092
334	9	n500	f	2.36	23.721	8.218	13.3	7.035
335	9	n500	b	3	23.009	12.262	13.493	8.187
336	9	n500	d	9.28	46.907	17.894	21.108	15.136
337	9	n500	c	2.08	25.02	18.221	13.628	8.182
338	10	b0	b	3.24	33.275	21.441	0	0
339	10	b0	d	7.72	12.145	4.491	0	0
340	10	b0	a	1.88	45.144	26.997	0	0
341	10	b0	c	2.32	45.039	33.056	0	0
342	10	b0	e	1.64	26.744	15.424	0	0
343	10	b0	f	2.52	55.176	38.987	0	0
344	10	b500	a	4.32	25.768	17.735	0	0
345	10	b500	e	1.84	21.423	13.174	0	0
346	10	b500	f	3.36	28.083	20.437	0	0
347	10	b500	b	2.64	53.74	37.019	0	0
348	10	b500	d	2.04	20.955	6.063	0	0
349	10	b500	c	1.04	45.222	33.761	0	0
350	10	n0	a	7.16	71.28	41.142	0	0
351	10	n0	e	2.76	52.796	34.225	0	0
352	10	n0	f	4.32	57.113	36.759	0	0
353	10	n0	b	4.08	50.24	32.862	0	0
354	10	n0	d	11.84	22.009	12.871	0	0
355	10	n0	c	0.48	83.378	55.39	0	0
356	10	n125	a	3.48	36.425	24.644	56.159	32.883
357	10	n125	e	1.8	28.261	21.222	45.368	13.457
358	10	n125	f	3.28	57.881	38.978	65.399	25.008
359	10	n125	b	1.92	46.638	36.786	55.615	26.181
360	10	n125	d	4.72	21.778	13.047	51.357	15.383
361	10	n125	c	0.92	64	48.953	55.736	41.303
362	10	n250	b	0.92	50.12	33.337	13.691	0.997
363	10	n250	d	6.72	27.086	16.746	28.521	18.238
364	10	n250	a	3	37.705	24.631	21.817	9.133
365	10	n250	c	0.64	46.318	33.553	93.136	52.746
366	10	n250	e	5.84	32.653	22.109	44.672	29.998
367	10	n250	f	8.56	55.73	29.332	57.732	32.849
368	10	n375	b	2.36	43.11	31.959	29.508	6.833

	A	B	C	D	E	F	G	H
369	10	n375	d	6.6	10.391	3.696	51.972	27.294
370	10	n375	a	2.52	47.687	31.523	41.329	21.876
371	10	n375	c	2.72	70.294	50.854	43.746	26.957
372	10	n375	e	7.4	24.375	12.968	46.102	22.766
373	10	n375	f	4.08	30.654	21.171	92.674	55.393
374	10	n500	a	5.88	47.921	29.61	21.891	1.764
375	10	n500	e	4.04	40.322	24.906	28.895	16.73
376	10	n500	f	5.56	49.683	30.858	75.726	48.607
377	10	n500	b	3.04	53.277	35.624	42.278	11.701
378	10	n500	d	3.76	29.99	21.601	60.18	37.106
379	10	n500	c	3.16	64.275	43.248	89.793	48.012
380	11	b0	a	6.16	38.085	23.026	0	0
381	11	b0	e	5.6	35.136	21.014	0	0
382	11	b0	f	3.08	67.125	32.592	0	0
383	11	b0	b	6.76	15.207	8.625	0	0
384	11	b0	d	4.8	33.505	22.365	0	0
385	11	b0	c	1.44	54.529	38.227	0	0
386	11	b500	b	5.76	42.324	19.583	0	0
387	11	b500	d	11.84	18.286	6.386	0	0
388	11	b500	a	4.52	27.562	15.288	0	0
389	11	b500	c	3.24	90.426	48.968	0	0
390	11	b500	e	7.68	23.352	11.651	0	0
391	11	b500	f	3.32	97.632	59.095	0	0
392	11	n0	a	1.32	71.381	50.562	0	0
393	11	n0	e	2.28	47.033	26.437	0	0
394	11	n0	f	2.4	36.663	23.729	0	0
395	11	n0	b	1.76	65.534	46.674	0	0
396	11	n0	d	2.44	59.991	46.202	0	0
397	11	n0	c	1.08	87.253	58.582	0	0
398	11	n125	a	3.36	70.753	52.991	37.353	25.101
399	11	n125	e	2.84	59.68	40.233	34.528	18.692
400	11	n125	f	4.68	51.199	27.54	21.762	6.283
401	11	n125	b	4.44	64.874	36.165	22.697	11.091
402	11	n125	d	3.08	30.589	19.626	21.373	1.066
403	11	n125	c	1.04	82.409	60.197	43.42	31.987
404	11	n250	b	2.56	70.907	48.354	37.472	20.978
405	11	n250	d	6.72	31.028	17.17	13.516	4.59
406	11	n250	a	3.12	72.221	42.4	13.139	3.096
407	11	n250	c	4.12	73.513	43.981	37.977	18.359
408	11	n250	e	5.2	50.635	22.319	20.714	5.224
409	11	n250	f	4.96	79.586	33.408	20.178	4.463
410	11	n375	b	3.76	71.968	48.068	30.744	15.05
411	11	n375	d	4.52	70.338	28.099	16.889	5.766
412	11	n375	a	4.68	65.364	42.945	16.263	7.184
413	11	n375	c	2	78.853	42.555	16.445	10.044
414	11	n375	e	3.76	81.464	33.368	12.358	5.701

	A	B	C	D	E	F	G	H
415	11	n375	f	6.08	88.88	38.537	15.875	7.46
416	11	n500	b	5.44	60.682	36.733	5.119	0.966
417	11	n500	d	2.36	49.472	26.499	3.53	0.784
418	11	n500	a	5.68	57.513	27.871	15.362	8.584
419	11	n500	c	7.68	51.614	16.623	12.867	6.211
420	11	n500	e	4.96	39.699	17.318	26.004	22.157
421	11	n500	f	2.72	98.231	53.6	19.836	9.811
422	12	b0	a	2.28	52.493	33.736	0	0
423	12	b0	e	2.72	26.051	8.126	0	0
424	12	b0	f	3.04	35.998	24.88	0	0
425	12	b0	b	2	29.281	19.313	0	0
426	12	b0	d	3.64	64.21	39.488	0	0
427	12	b0	c	3	54.016	32.694	0	0
428	12	b500	b	2.24	38.034	15.923	0	0
429	12	b500	d	2.36	49.543	33.953	0	0
430	12	b500	a	3.4	28.507	16.199	0	0
431	12	b500	c	3.36	39.593	23.014	0	0
432	12	b500	e	7.12	48.483	30.758	0	0
433	12	b500	f	4.6	46.179	24.306	0	0
434	12	n0	a	2.32	85.829	60.885	0	0
435	12	n0	e	1.44	68.691	35.579	0	0
436	12	n0	f	1.88	58.342	36.127	0	0
437	12	n0	b	1.76	64.12	38.796	0	0
438	12	n0	d	2.68	28.833	17.122	0	0
439	12	n0	c	3.76	87.425	87.425	0	0
440	12	n125	a	1.92	86.509	68.563	64.967	27.031
441	12	n125	e	2.32	39.392	27.664	60.169	27.494
442	12	n125	f	2.44	88.835	55.594	63.855	35.981
443	12	n125	b	1.24	64.928	38.579	71.927	33.794
444	12	n125	d	1.24	75.608	54.838	63.865	33.628
445	12	n125	c	1.96	98.245	71.811	84.548	37.018
446	12	n250	b	3.28	80.421	57.074	88.261	51.365
447	12	n250	d	1.88	48.734	19.734	67.812	33.511
448	12	n250	a	3.4	55.144	27.034	97.018	41.713
449	12	n250	c	2.16	50.95	35.699	83.579	31.902
450	12	n250	e	2.68	29.067	12.683	58.197	36.361
451	12	n250	f	2.2	28.135	13.434	56.977	28.606
452	12	n375	b	2.52	65.13	29.869	31.167	0.065
453	12	n375	d	2.4	34.363	19.195	49.814	23.138
454	12	n375	a	7.52	57.023	29.498	79.672	26.833
455	12	n375	c	8.08	45.296	21.491	31.187	16.731
456	12	n375	e	3.96	53.477	18.657	38.105	14.065
457	12	n375	f	5.24	34.174	20.465	43.022	12.415
458	12	n500	b	2.24	23.172	15.707	16.671	3.294
459	12	n500	d	2.12	18.75	10.087	31.346	5.472
460	12	n500	a	8.28	56.517	28.731	54.356	5.07

	A	B	C	D	E	F	G	H
461	12	n500	c	3.96	73.42	33.717	85.189	30.976
462	12	n500	e	3.28	52.461	31.128	49.757	24.665
463	12	n500	f	8.24	55.372	31.974	73.288	32.507
464	13	b0	b	5.36	55.445	21.446	0	0
465	13	b0	d	4.84	34.169	11.149	0	0
466	13	b0	a	3.2	38.302	9.205	0	0
467	13	b0	c	8.96	31.191	3.464	0	0
468	13	b0	e	5.8	48.033	16.179	0	0
469	13	b0	f	3.88	48.896	24.121	0	0
470	13	b500	a	2.08	38.094	15.579	0	0
471	13	b500	e	0.16	29.159	12.89	0	0
472	13	b500	f	2	49.488	22.489	0	0
473	13	b500	b	3.24	34.647	5.597	0	0
474	13	b500	d	28.2	37.017	7.342	0	0
475	13	b500	c	4.64	32.018	9.687	0	0
476	13	n0	a	1.72	99.819	43.454	0	0
477	13	n0	e	4.24	74.771	30.891	0	0
478	13	n0	f	3.68	98.125	41.997	0	0
479	13	n0	b	3.16	101.404	28.602	0	0
480	13	n0	d	3.2	98.633	20.127	0	0
481	13	n0	c	1.84	100.404	55.924	0	0
482	13	n125	b	4.12	99.874	33.6	23.745	6.813
483	13	n125	d	5.72	97.987	26.835	32.176	14.114
484	13	n125	a	7.4	100.496	38.598	31.096	17.763
485	13	n125	c	2.28	98.157	27.723	27.2	5.823
486	13	n125	e	11.68	56.317	15.08	33.672	10.307
487	13	n125	f	3.38	78.879	16.551	26.22	10.496
488	13	n250	a	1.92	85.894	34.57	31.809	17.065
489	13	n250	e	3.88	98.381	35.626	26.032	1.49
490	13	n250	f	3	98.104	34.18	24.022	1.229
491	13	n250	b	1.56	95.476	33.952	34.174	21.752
492	13	n250	d	3.24	94.587	23.497	20.041	2.965
493	13	n250	c	0.8	100.857	30.348	49.794	23.125
494	13	n375	b	1.24	100.39	26.277	13.915	0.064
495	13	n375	d	3.64	50.753	13.182	20.629	11.335
496	13	n375	a	1.84	98.787	30.461	13.525	3.773
497	13	n375	c	4.12	100.017	24.487	36.696	11.869
498	13	n375	e	3.36	53.96	13.384	37.62	13.841
499	13	n375	f	2.28	65.029	14.11	21.966	6.036
500	13	n500	a	2.04	66.402	16.594	34.376	11.262
501	13	n500	e	5.24	56.974	17.6	26.574	12.636
502	13	n500	f	0.28	36.996	11.302	25.404	9.414
503	13	n500	b	0.2	86.292	29.403	19.935	7.967
504	13	n500	d	1.08	33.409	15.459	33.982	13.448
505	13	n500	c	1.4	100.337	24.465	40.756	13.527
506	14	b0	a	3.8	38.1	26.194	0	0

	A	B	C	D	E	F	G	H
507	14	b0	e	5.96	18.968	10.28	0	0
508	14	b0	f	2.72	28.49	22.194	0	0
509	14	b0	b	4.12	24.964	20.002	0	0
510	14	b0	d	6.64	19.697	13.819	0	0
511	14	b0	c	2.76	37.518	29.77	0	0
512	14	b500	b	1.56	24.823	18.85	0	0
513	14	b500	d	33	7.759	4.519	0	0
514	14	b500	a	5.88	24.53	18.267	0	0
515	14	b500	c	2.4	33.979	27.396	0	0
516	14	b500	e	31.56	10.068	5.849	0	0
517	14	b500	f	3.92	19.381	15.366	0	0
518	14	n0	b	1.84	74.736	46.241	0	0
519	14	n0	d	9.72	34.235	16.946	0	0
520	14	n0	a	1.56	59.102	40.847	0	0
521	14	n0	c	0.24	58.388	40.488	0	0
522	14	n0	e	5	61.306	32.237	0	0
523	14	n0	f	1.6	62.044	37.745	0	0
524	14	n125	b	2.84	33.596	25.401	60.2	49.388
525	14	n125	d	3.68	28.845	21.211	40.796	24.764
526	14	n125	a	3.6	46.576	37.267	47.948	13.073
527	14	n125	c	1.6	39.669	32.601	42.252	32.788
528	14	n125	e	6.12	21.184	14.305	49.875	20.643
529	14	n125	f	3.84	29.61	18.697	66.377	29.356
530	14	n250	a	3.04	63.906	45.479	51.167	32.749
531	14	n250	e	4.24	39.216	25.335	35.32	19.223
532	14	n250	f	3.44	29.678	22.551	43.761	23.323
533	14	n250	b	2.64	36.062	25.211	61.665	42.829
534	14	n250	d	3	34.472	22.389	44.582	23.161
535	14	n250	c	0.88	43.077	29.928	60.83	23.019
536	14	n375	a	1.8	55.923	36.569	39.084	10.19
537	14	n375	e	3.04	27.463	19.432	45.91	23.894
538	14	n375	f	2.44	26.076	18.664	47.997	23.038
539	14	n375	b	3.32	51.135	34.407	55.527	31.115
540	14	n375	d	4.36	51.854	37.402	41.832	16.637
541	14	n375	c	3.16	47.186	36.448	60.518	38.838
542	14	n500	b	2.84	58.086	45.302	51.243	29.211
543	14	n500	d	3.2	41.934	29.927	38.31	18.402
544	14	n500	a	2.16	50.799	36.046	32.138	21.552
545	14	n500	c	1.96	46.077	34.48	57.019	39.185
546	14	n500	e	4.48	31.691	20.487	37.526	18.974
547	14	n500	f	3.16	34.878	25.175	25.484	4.338

Appendix 5

Individual Results from Experiment 2

INDIVIDUAL RESULTS

For each of the Experiment 2 subjects a paragraph containing his or her comments along with a short description of postural reaction and individual vection parameters will be presented. Plots of maximum and average vection vs. weight and examples at each weight condition of posture data are also included in this appendix.

Subject 2 (naive)

Subject 2 commented that she felt tilted before the onset of vection, and that this was a very strange sensation, because she had no apparent reason to be tilted. Examples of the joystick and position data from this subject (figures A5.1 through A5.4) do show that large positional displacements often don't correlate with large deflections of the joystick. Once Subject 2 was tilted to the side she seldom returned to the zero position during a run. Figure A5.5 contains the plots of average and maximum vection achieved vs. the magnitude of the tactile cue used for both on and off-biteboard runs. A straight line with a slope of zero would be a good fit to the off-biteboard data. Subject 2 actually showed an overall increase in vection between trials at zero weight and those at 500 grams. This difference was very close to zero on all tests performed (t-tests, changes in maximum and average vection b0 vs. b500 and n0 vs. n500) and was not significant in any case. In the comparisons of biteboard vs. non-biteboard runs Subject 2 again showed no significant results, though in these cases the change in vection was in the expected direction -- stronger vection without the biteboard.

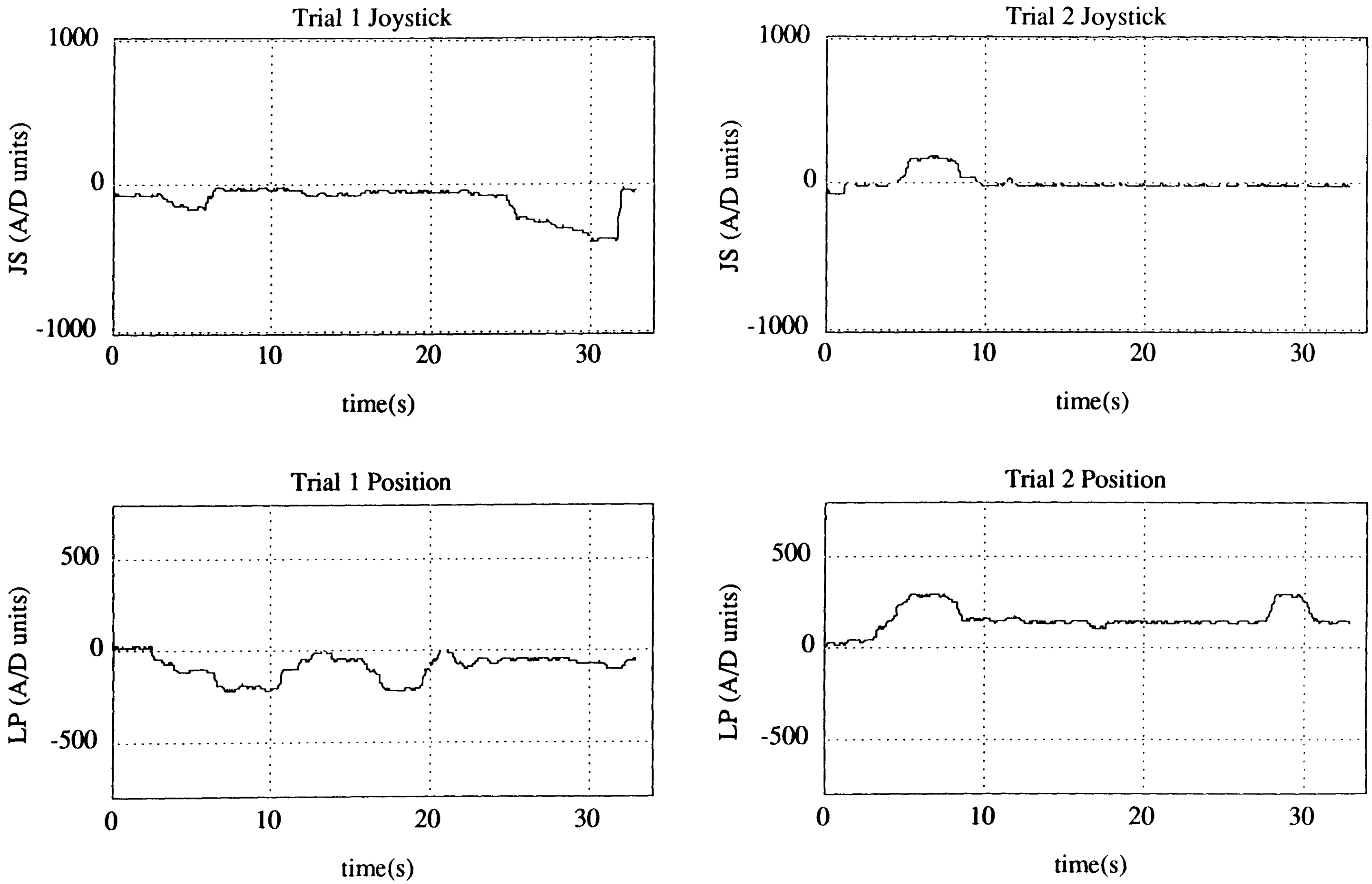


Figure A5.1
Subject 2 Joystick and Position Data
2 of 6 trials, Tactile cue = 125 grams

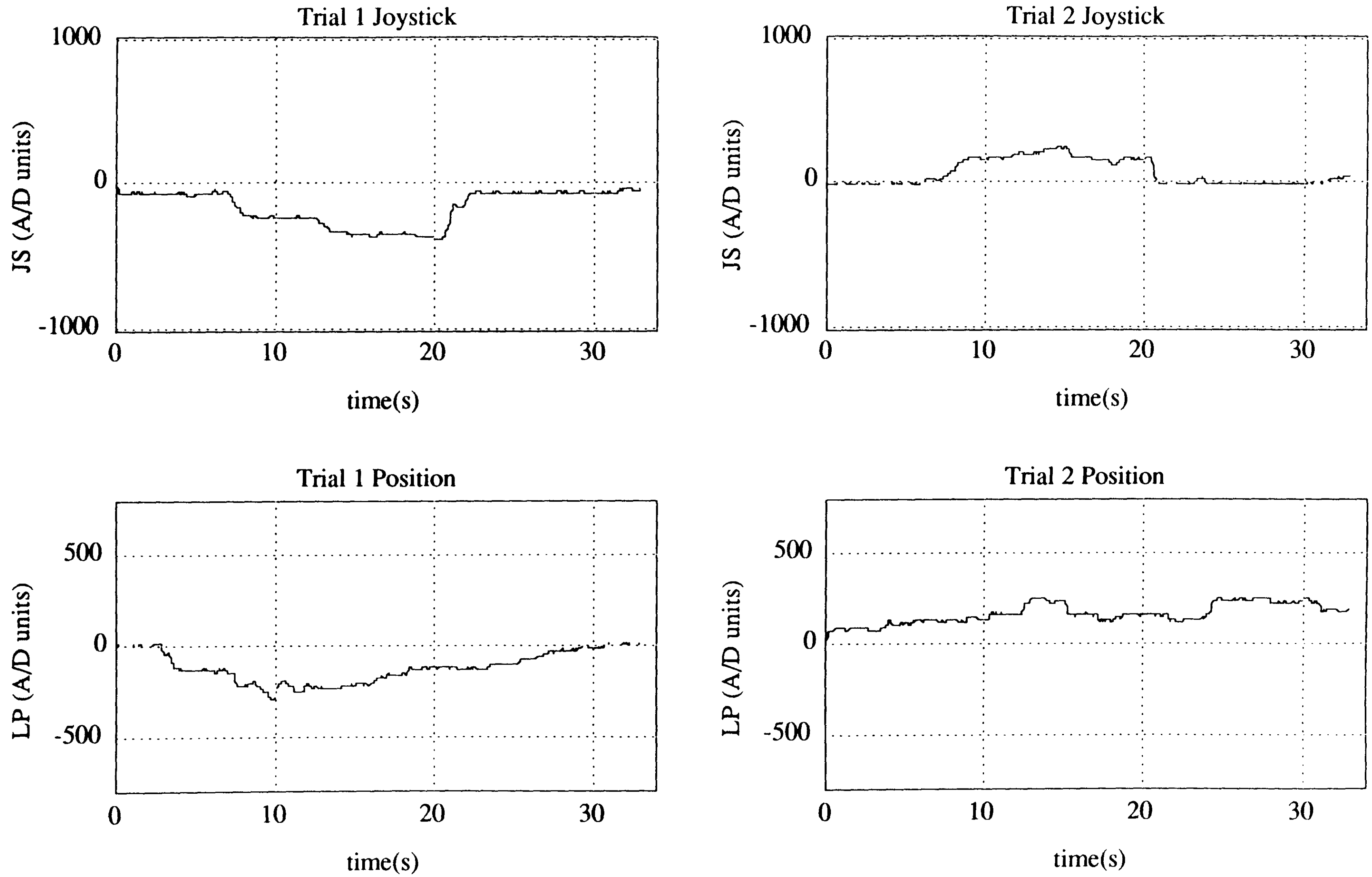


Figure A5.2
Subject 2 Joystick and Position Data
2 of 6 trials, Tactile cue = 250 grams

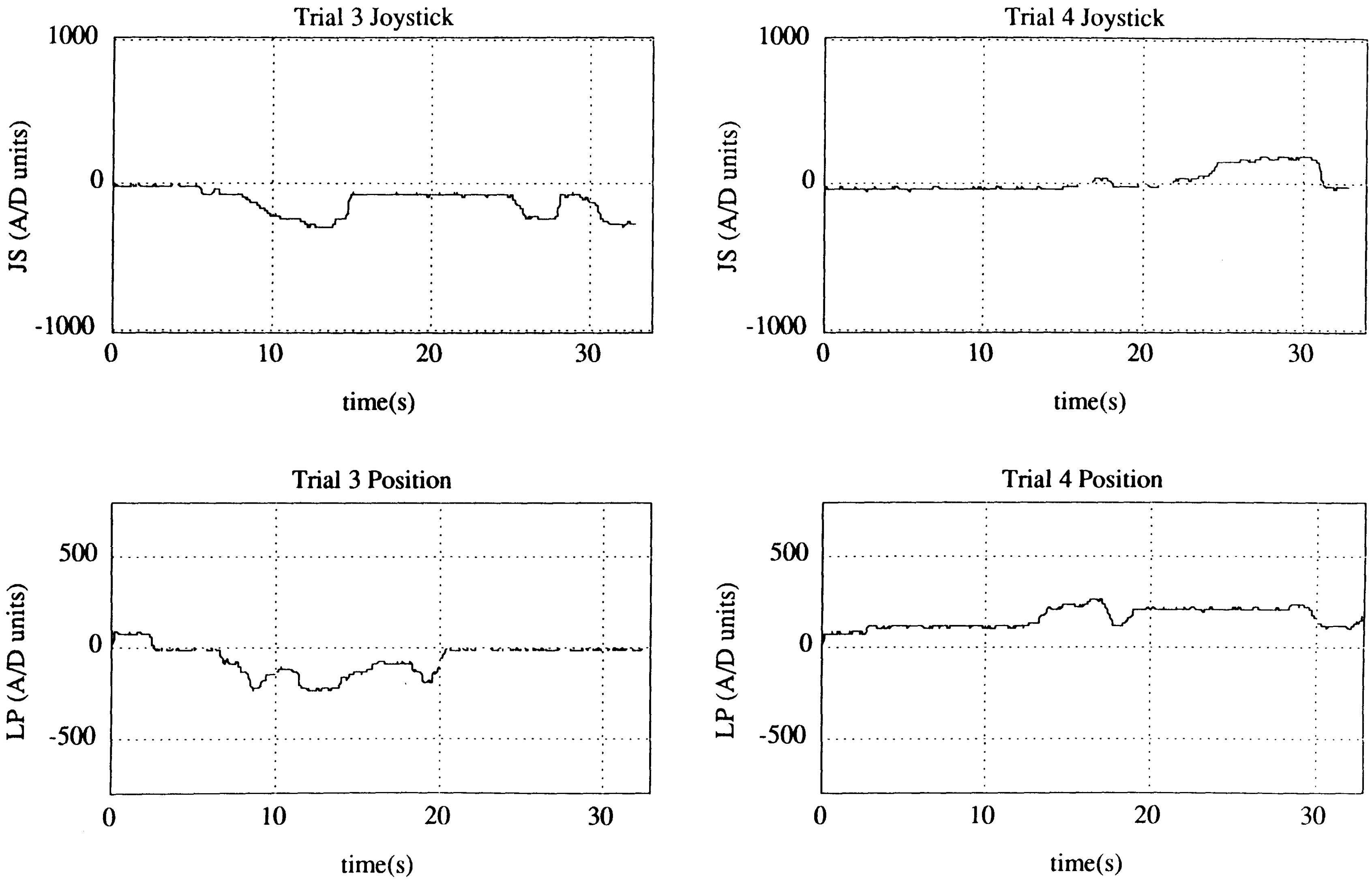


Figure A5.3
Subject 2 Joystick and Position Data
2 of 6 trials, Tactile cue = 375 grams

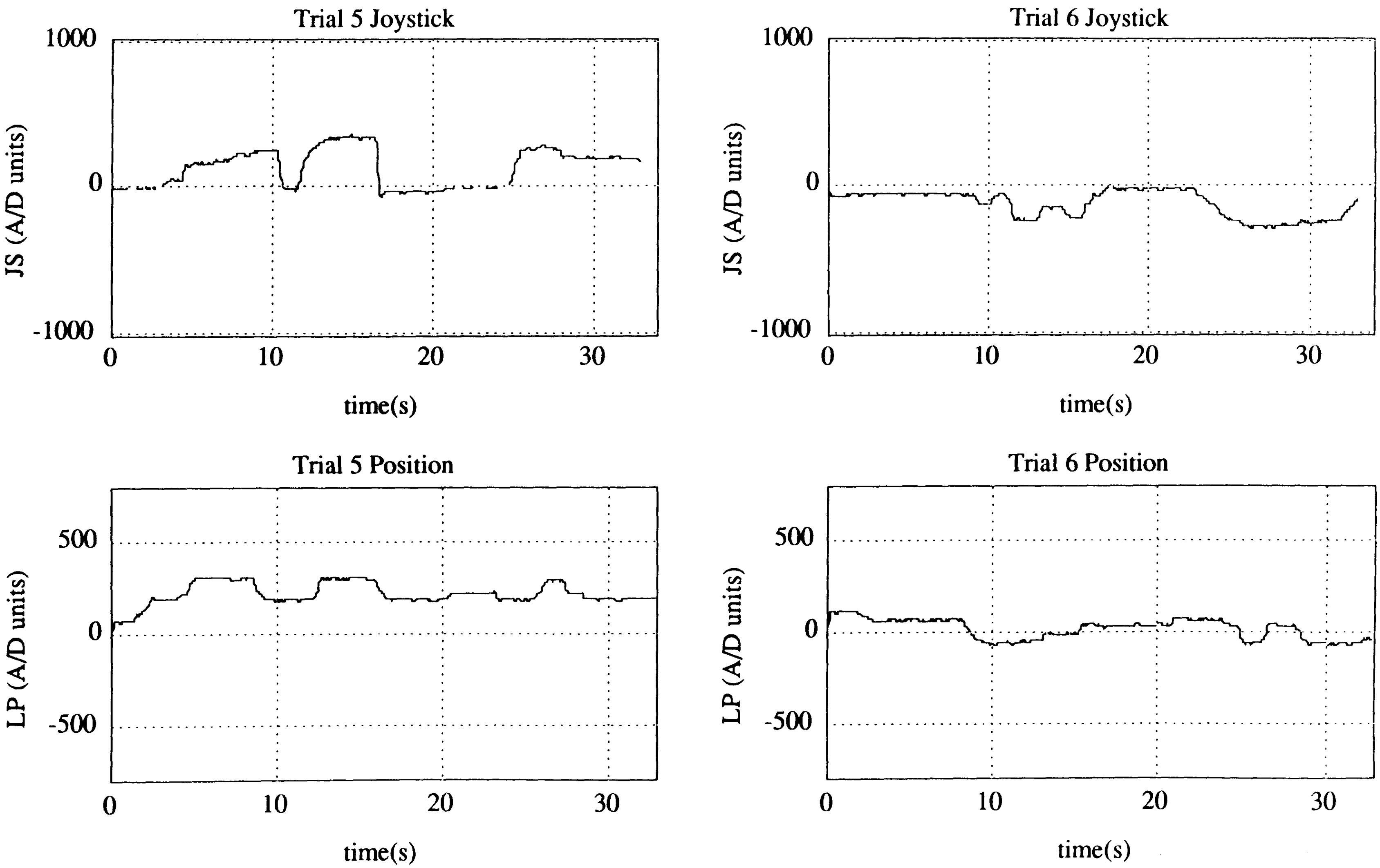
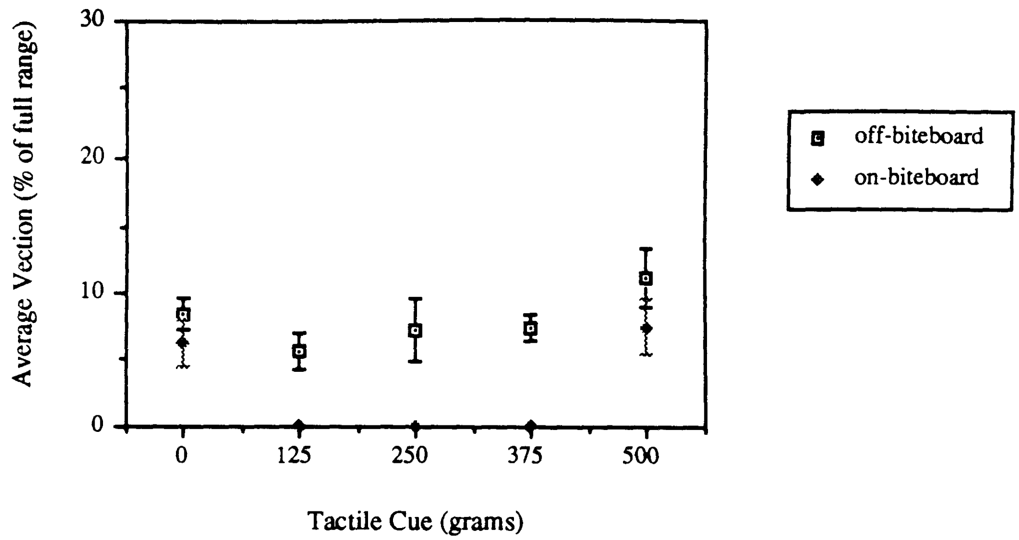


Figure A5.4
Subject 2 Joystick and Position Data
2 of 6 trials, Tactile cue = 500 grams

Subject 2



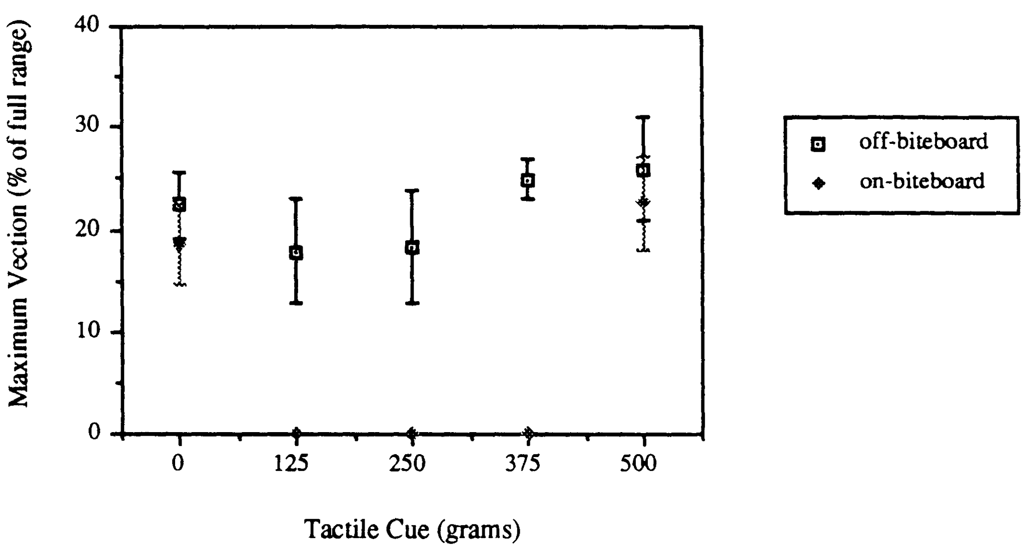


Figure A5.5:
Plots of Average and Maximum
Vection vs. Applied Tactile Cue

Subject 3 (naive)

Subject 3 specifically commented that the strong sensation of motion he felt during the off-biteboard trials would be interrupted by dropouts that occurred when he tilted so far that he was no longer centered in the dome. This subject was "comforted" by the tactile cues, though the magnitude of tilt as measured by the potentiometers did not change with the changing cue magnitude (figures A5.6 through A5.9). This feeling of "comfort" does seem to have affected the subject's vection indications as is seen in figure A5.10. The average vection at zero tactile cue (off-biteboard) is larger than that reported at any of the other conditions. Statistically this change is not significant for the off-biteboard runs, but is highly significant on the biteboard (maximum vection b0 vs. b500, $p = .000$, average vection b0 vs. b500, $p = .002$). Subject 3's vection off of the biteboard was significantly higher than it was on the biteboard when tactile cues were present (maximum and average vection b500 vs. n500, $p < .05$).

Subject 4 (naive)

Subject 4 reported muscle fatigue in the neck and back after the fourth run. This subject had a tendency to sway more one direction than the other (figures A5.11 through A5.14), even tilting opposite the expected direction on a few trials (left tilt was predominant). Figure A5.15, plots of average and maximum vection vs. tactile cue, show scattered points with no apparent trend. Statistically there were no significant results from the off-biteboard runs these plots represent. Subject 4 did show a significant <u>increase</u> in vection when tactile cues were applied during the on-biteboard runs ($p < .05$). This was the only subject to exhibit such behavior. Comparisons of on vs. off-biteboard behavior were more as expected. There was a highly significant increase in vection between the b0

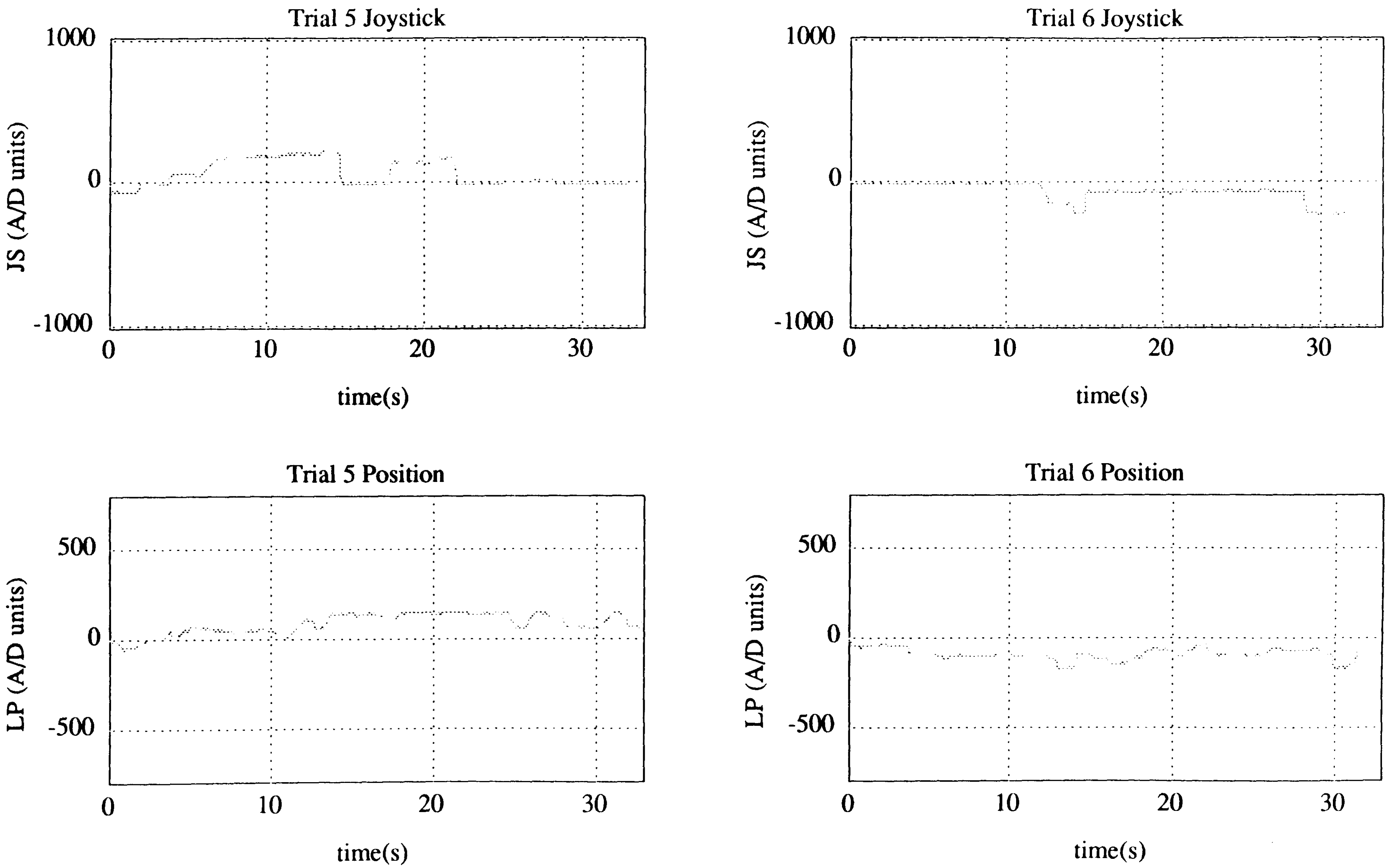


Figure A5.6
Subject 3 Joystick and Position Data
2 of 6 trials, Tactile cue = 125 grams

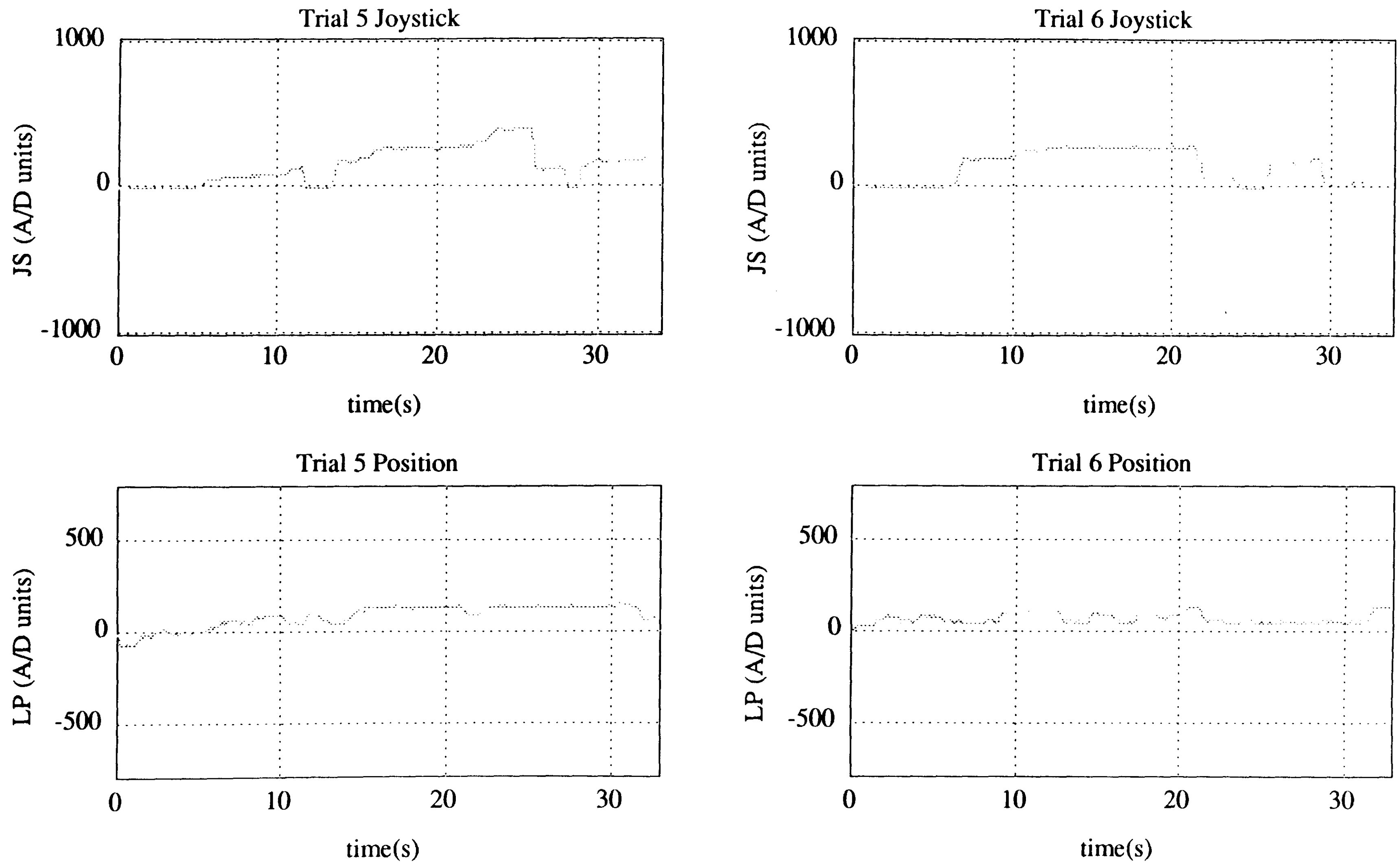


Figure A5.7
Subject 3 Joystick and Position Data
2 of 6 trials, Tactile cue = 250 grams

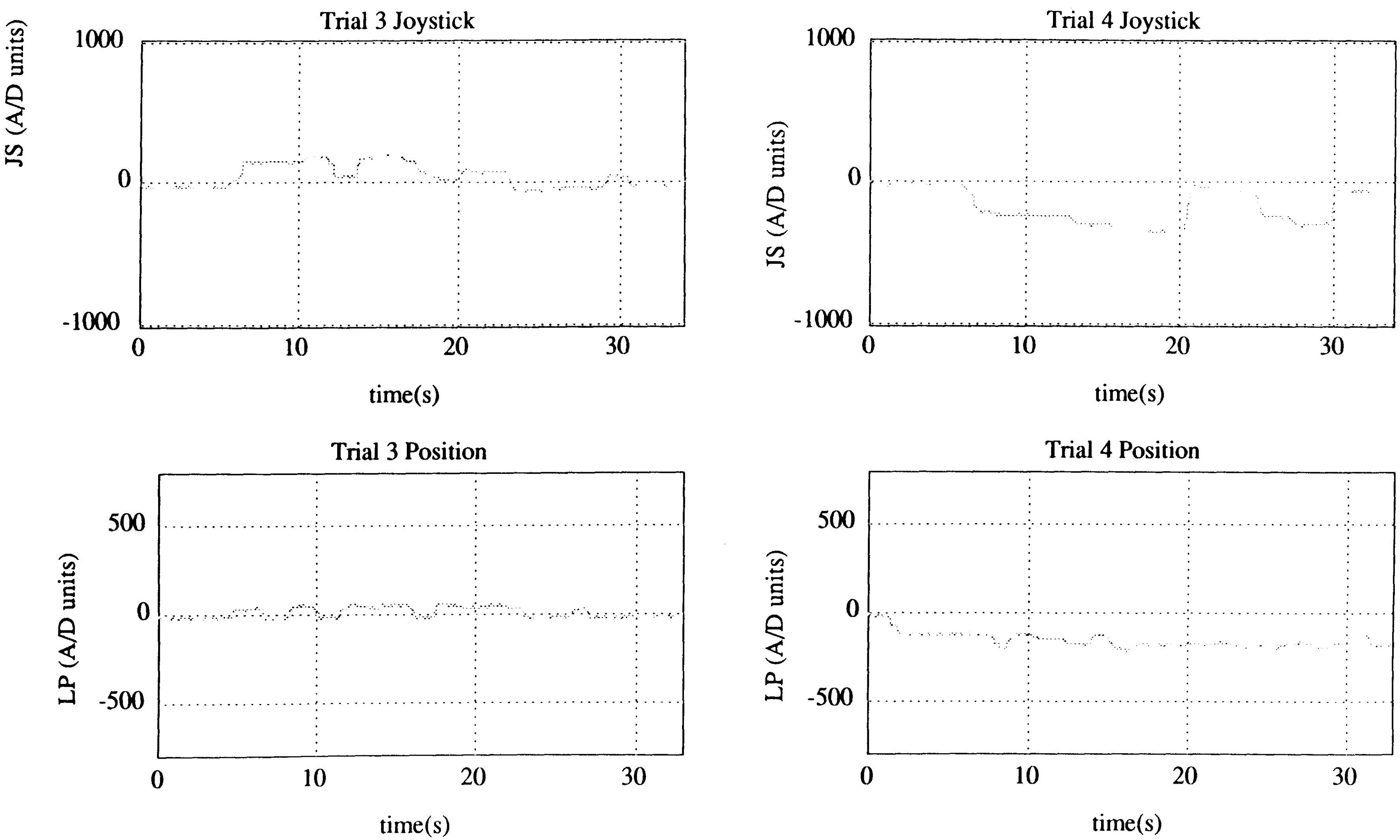


Figure A5.8
Subject 3 Joystick and Position Data
2 of 6 trials, Tactile cue = 375 grams

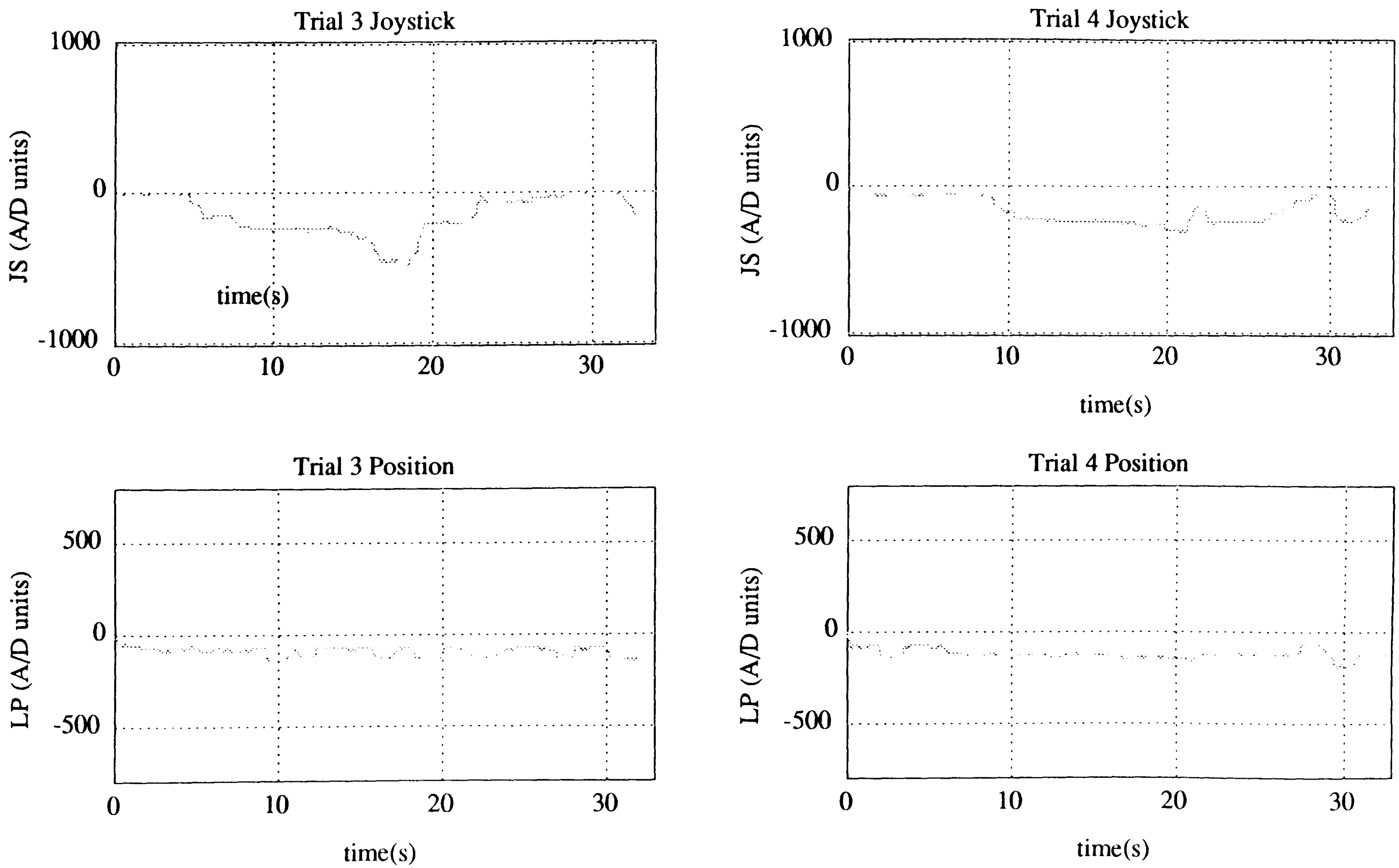
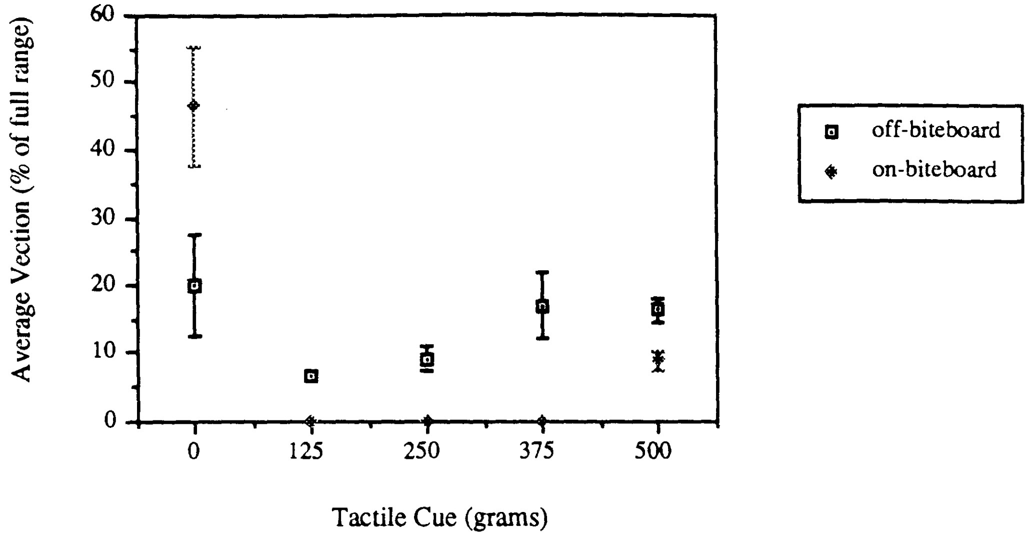


Figure A5.9

Subject 3 Joystick and Position Data

2 of 6 trials, Tactile cue = 500 grams

Subject 3



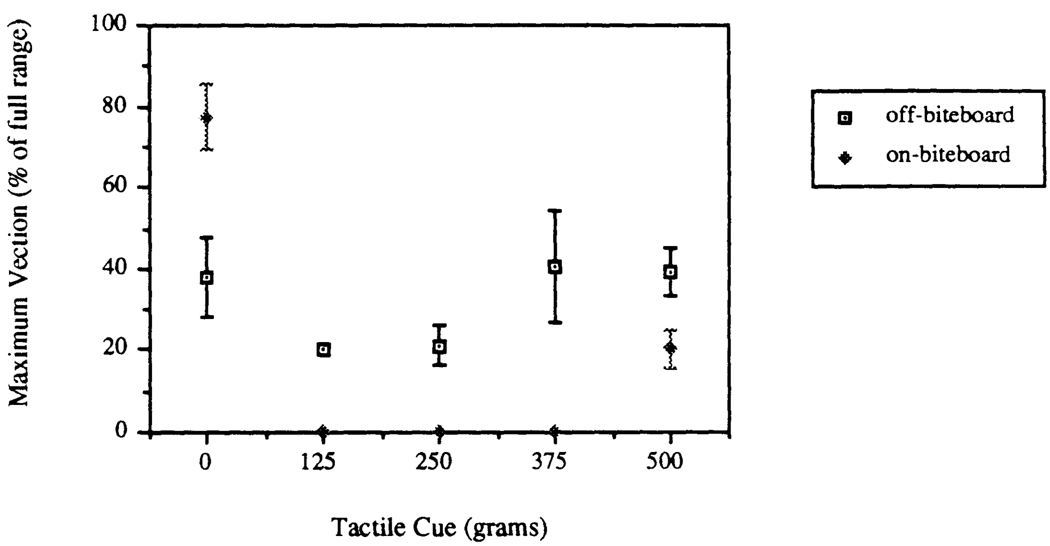


Figure A5.10:
Plots of Average and Maximum
Vection vs. Applied Tactile Cue

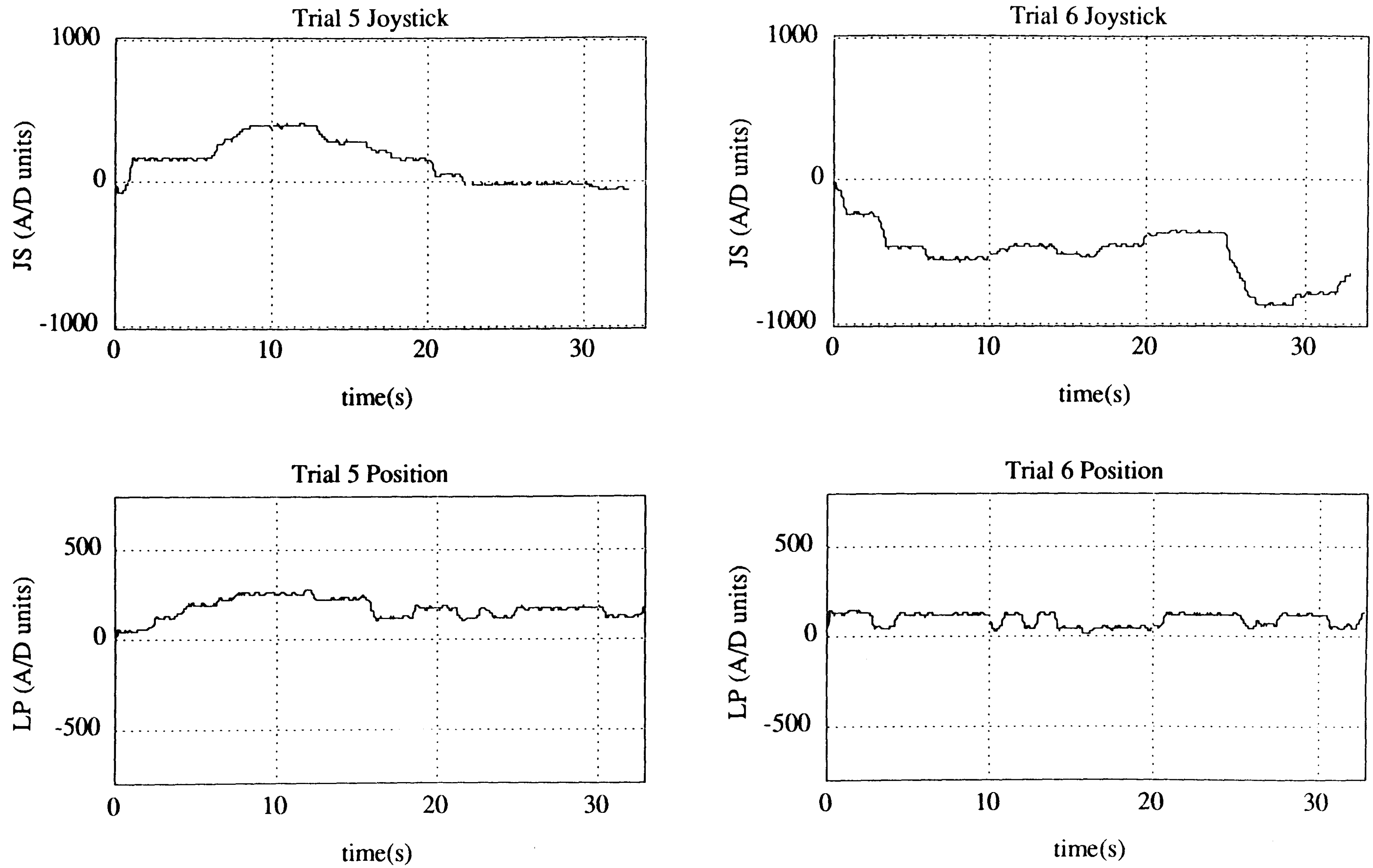


Figure A5.11

Subject 4 Joystick and Position Data

2 of 6 trials, Tactile cue = 125 grams

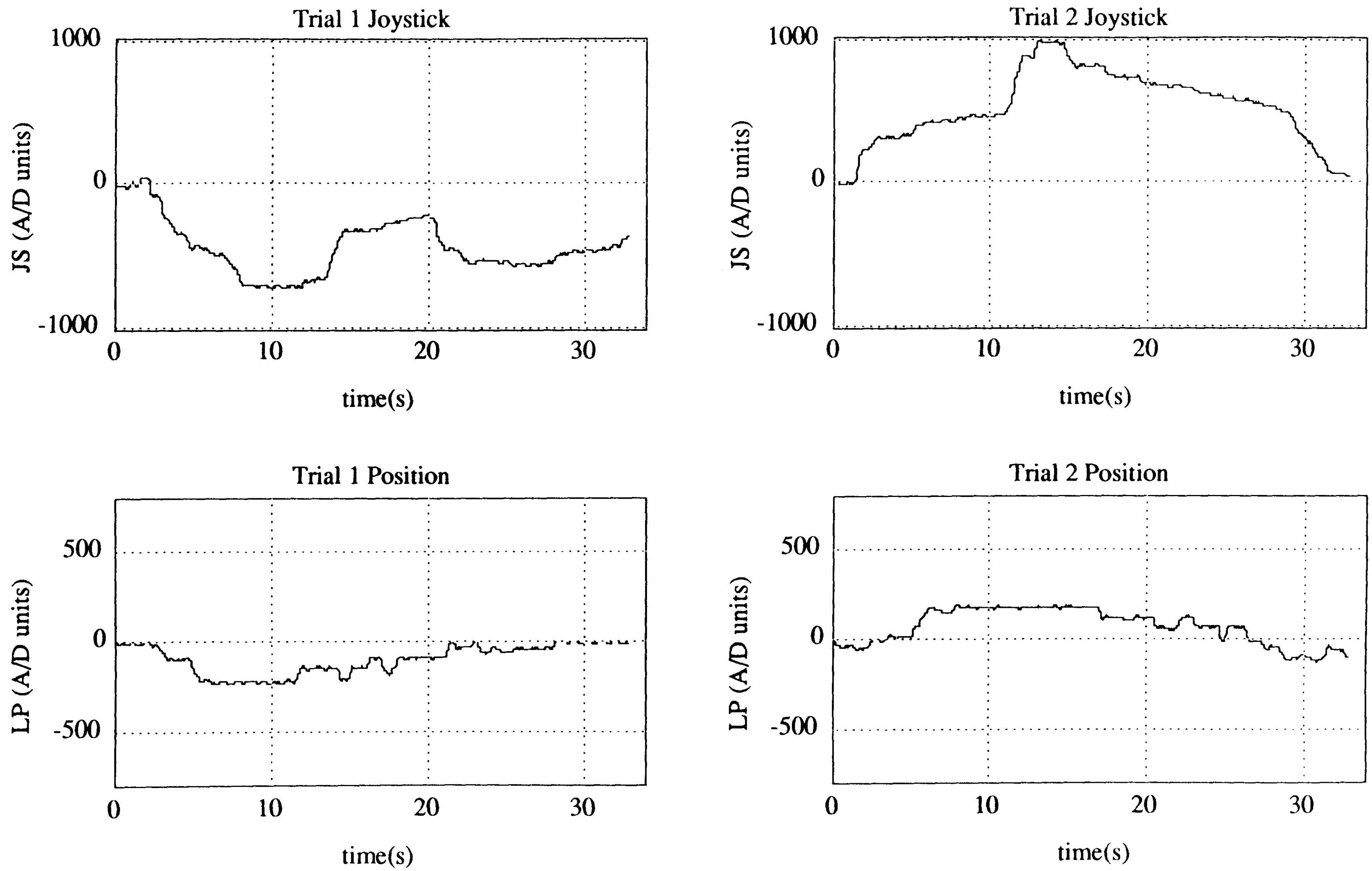


Figure A5.12
Subject 4 Joystick and Position Data
2 of 6 trials, Tactile cue = 250 grams

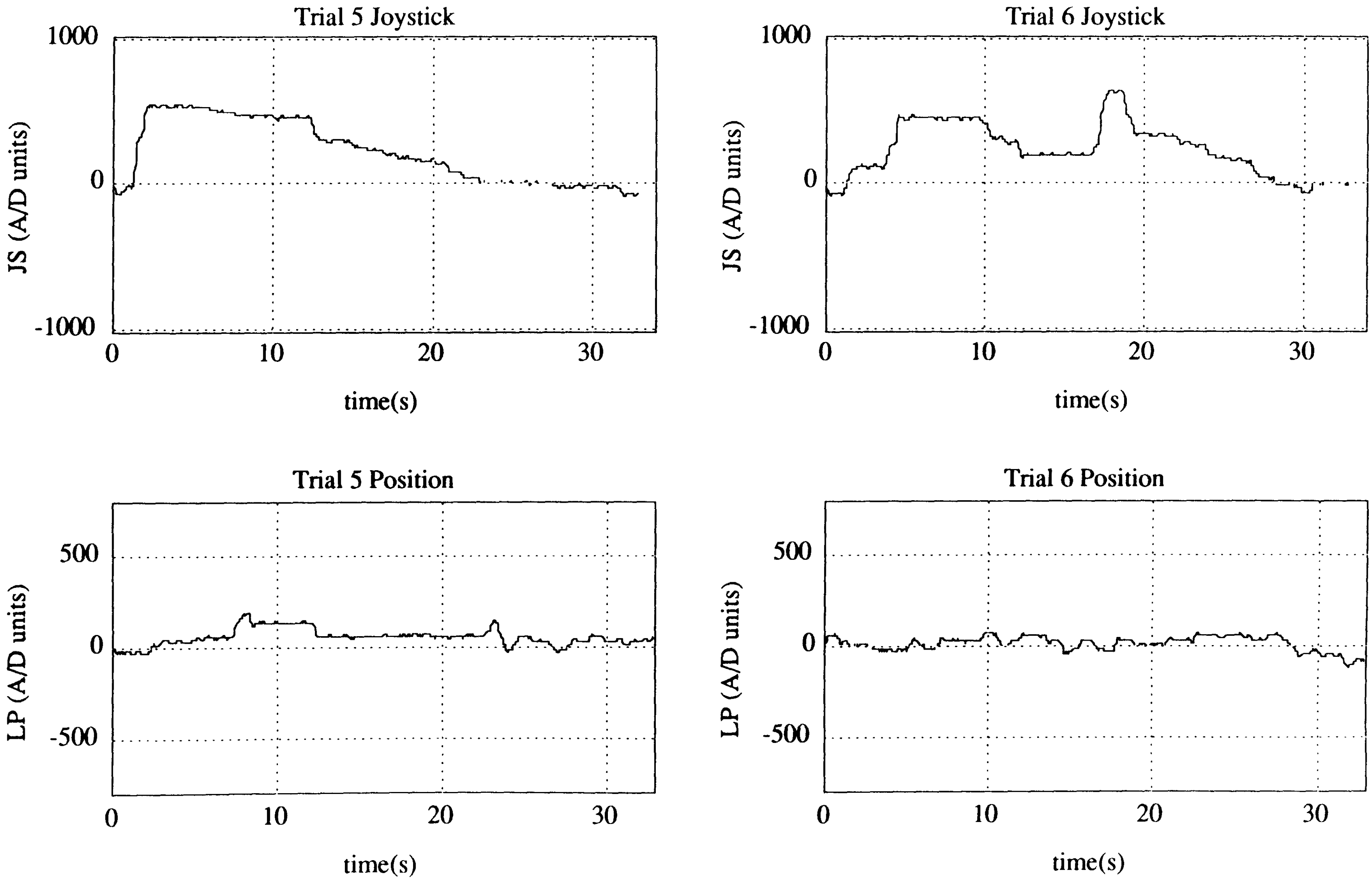


Figure A5.13
Subject 4 Joystick and Position Data
2 of 6 trials, Tactile cue = 375 grams

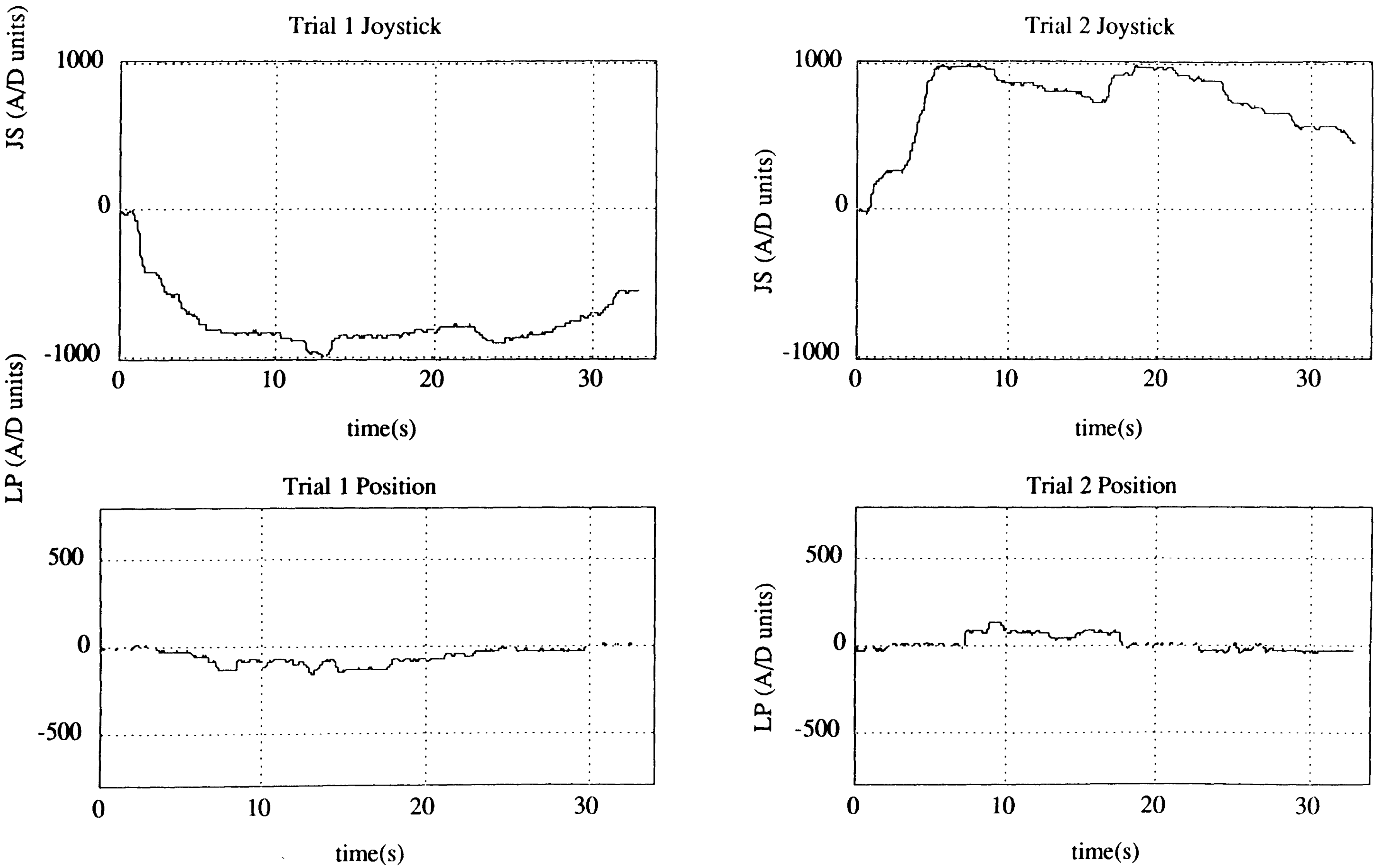
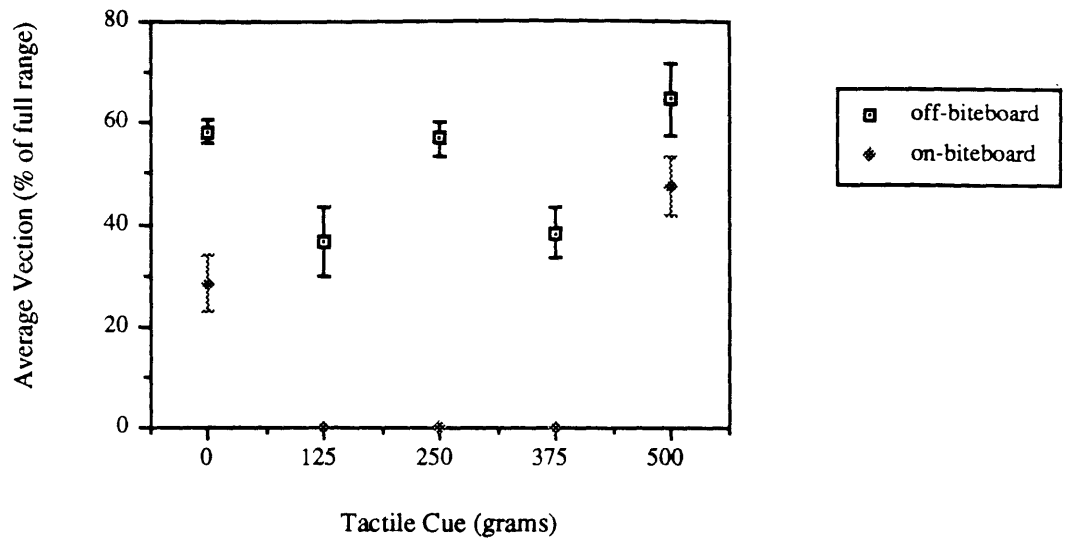


Figure A5.14
Subject 4 Joystick and Position Data
2 of 6 trials, Tactile cue = 500 grams

Subject 4



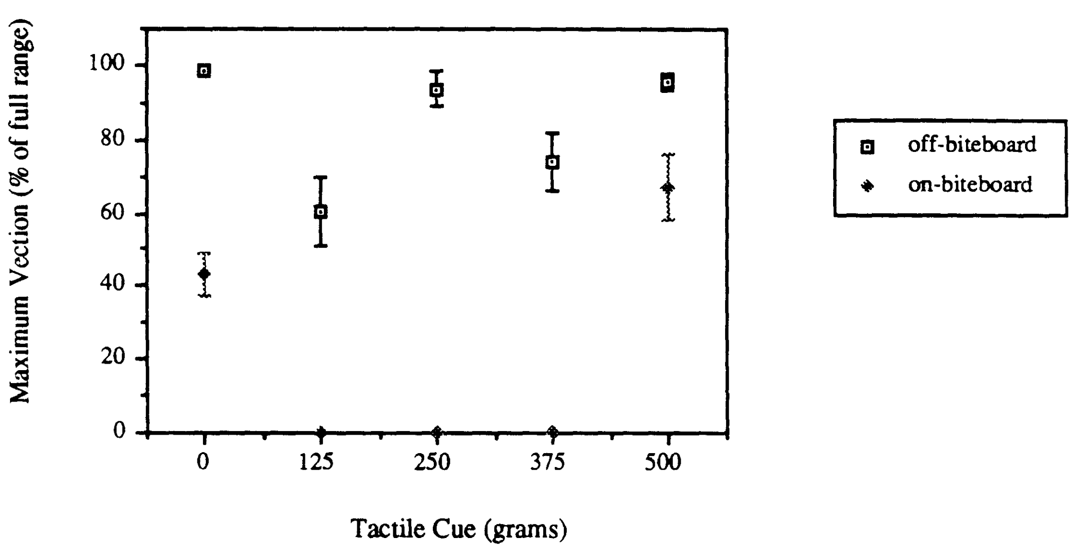


Figure A5.15:
Plots of Average and Maximum
Vection vs. Applied Tactile Cue

and n0 conditions for both maximum and average vection ($p < .01$). This increase was also significant in maximum vection for b500 vs. n500 ($p < .05$), and trending towards significance in the same test on average vection ($p = .099$).

Subject 5 (naive)

Subject 5 did not make any comments about vection or tilt. From figures A5.16 through A5.19 one can see that she would tilt to a fairly large displacement and then remain at a steady tilt angle. It also appears that she may have been indicating tilt rather than vection with the joystick because the vection and position traces appear so similar, though the subject assured the test conductor otherwise when questioned at the end of the test session. Figure A5.20 shows vection vs. applied tactile cue. These graphs and the statistical tests of the weight vs. no weight conditions off-biteboard show no significant change in magnitude of vection. Subject 5 showed a decrease in vection when the biteboard cue was removed, however this change was not significant.

Subject 6 (naive)

This subject commented that he felt steadier during the off-biteboard run with the 500 gram tactile cues (for him this run occurred third in the series of five off-biteboard runs). He, like Subject 3, said that falling off centerline of the dome decreased vection, though this did not occur often. Subject 6's position data (figures A5.21 through A5.24) shows small oscillations close to or about the zero line. The few large displacement indications do not seem to correspond to particular events in the joystick data. Figure A5.25 shows average and maximum vection vs. tactile cue for this subject. The off-biteboard decrease in vection when the 500 gram weights were used was not significant, though trending the that way ($p = .133$). On the biteboard the change was also in the

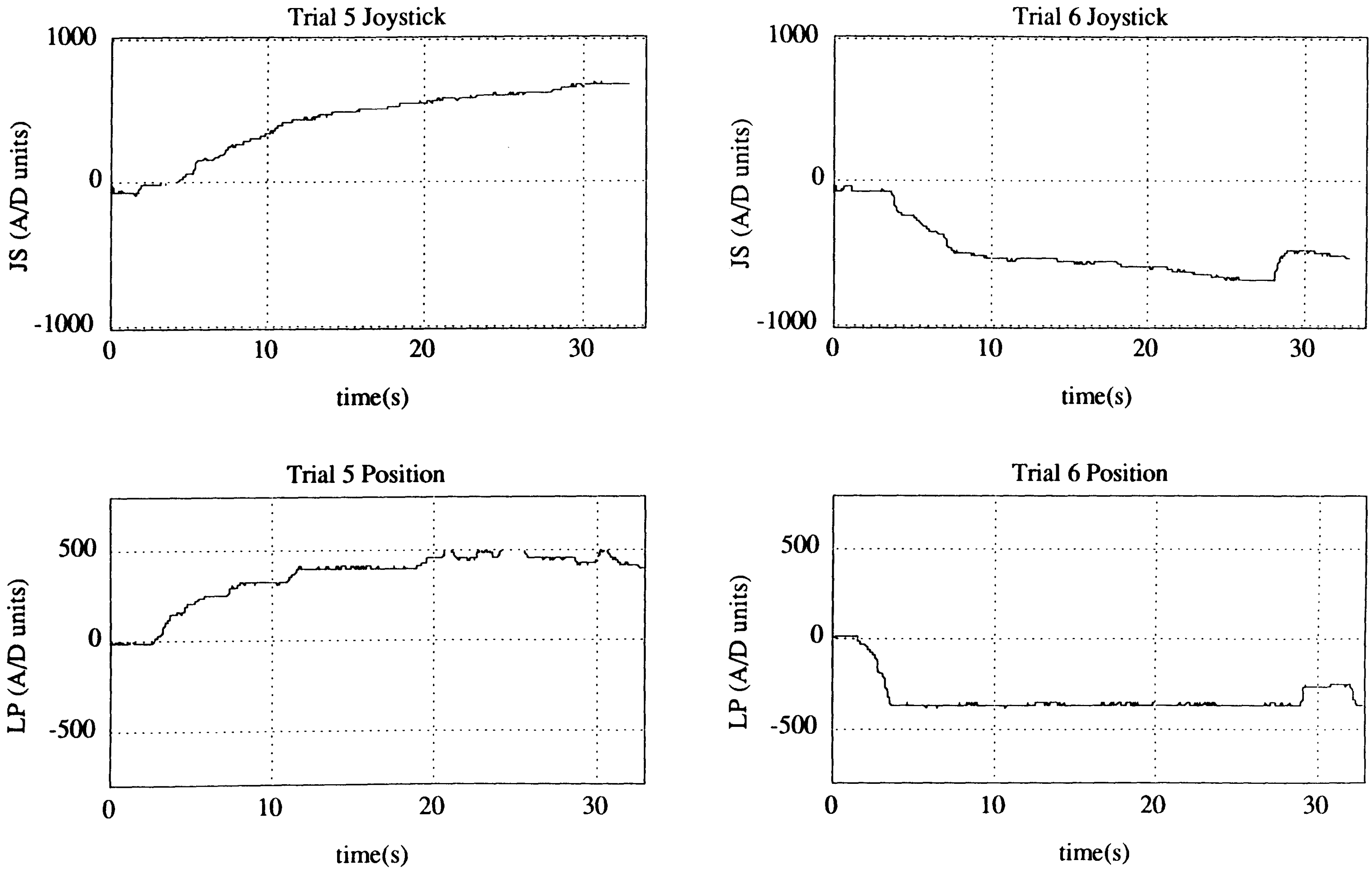


Figure A5.16
Subject 5 Joystick and Position Data
2 of 6 trials, Tactile cue = 125 grams

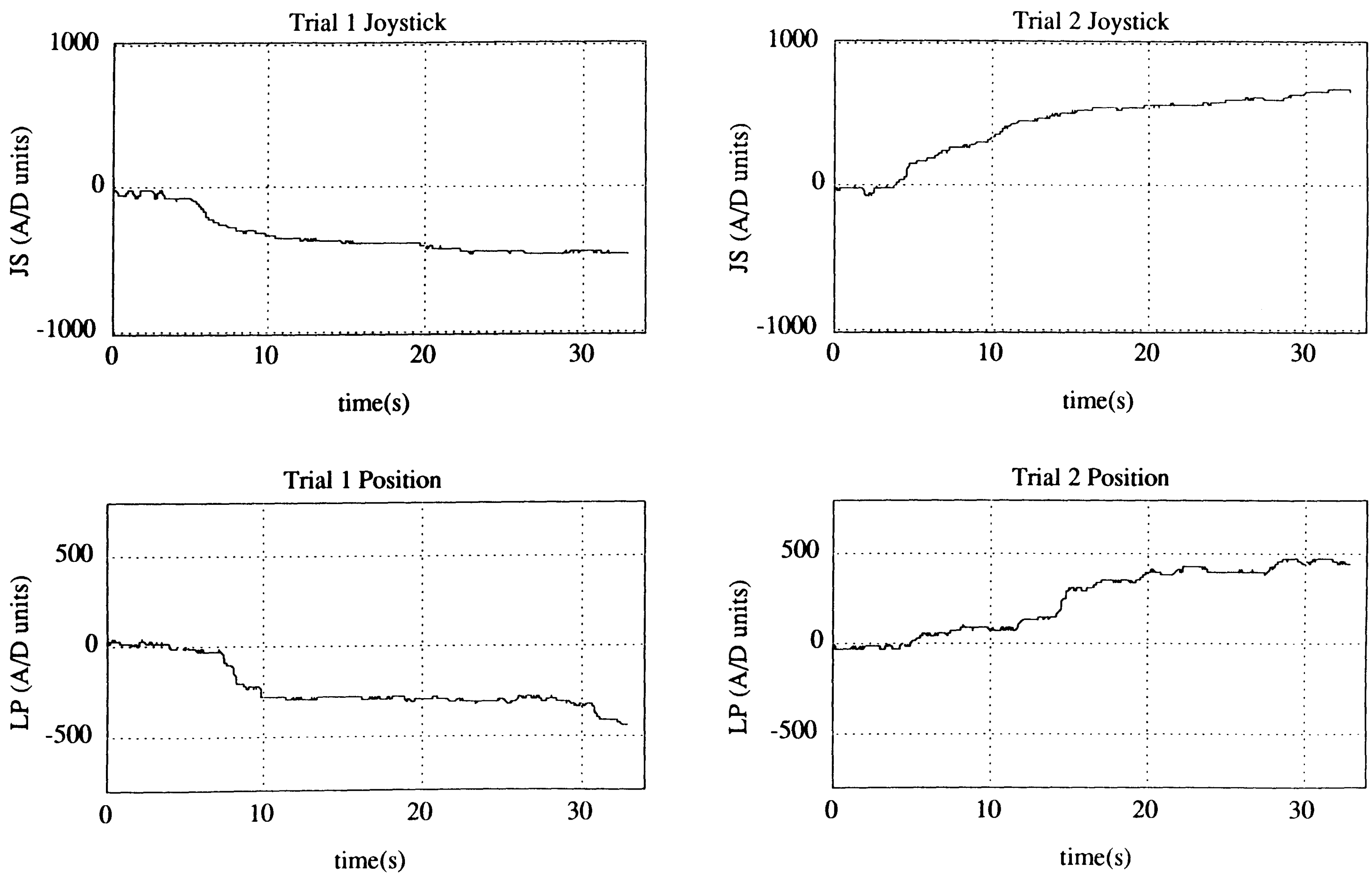


Figure A5.17
Subject 5 Joystick and Position Data
2 of 6 trials, Tactile cue = 250 grams

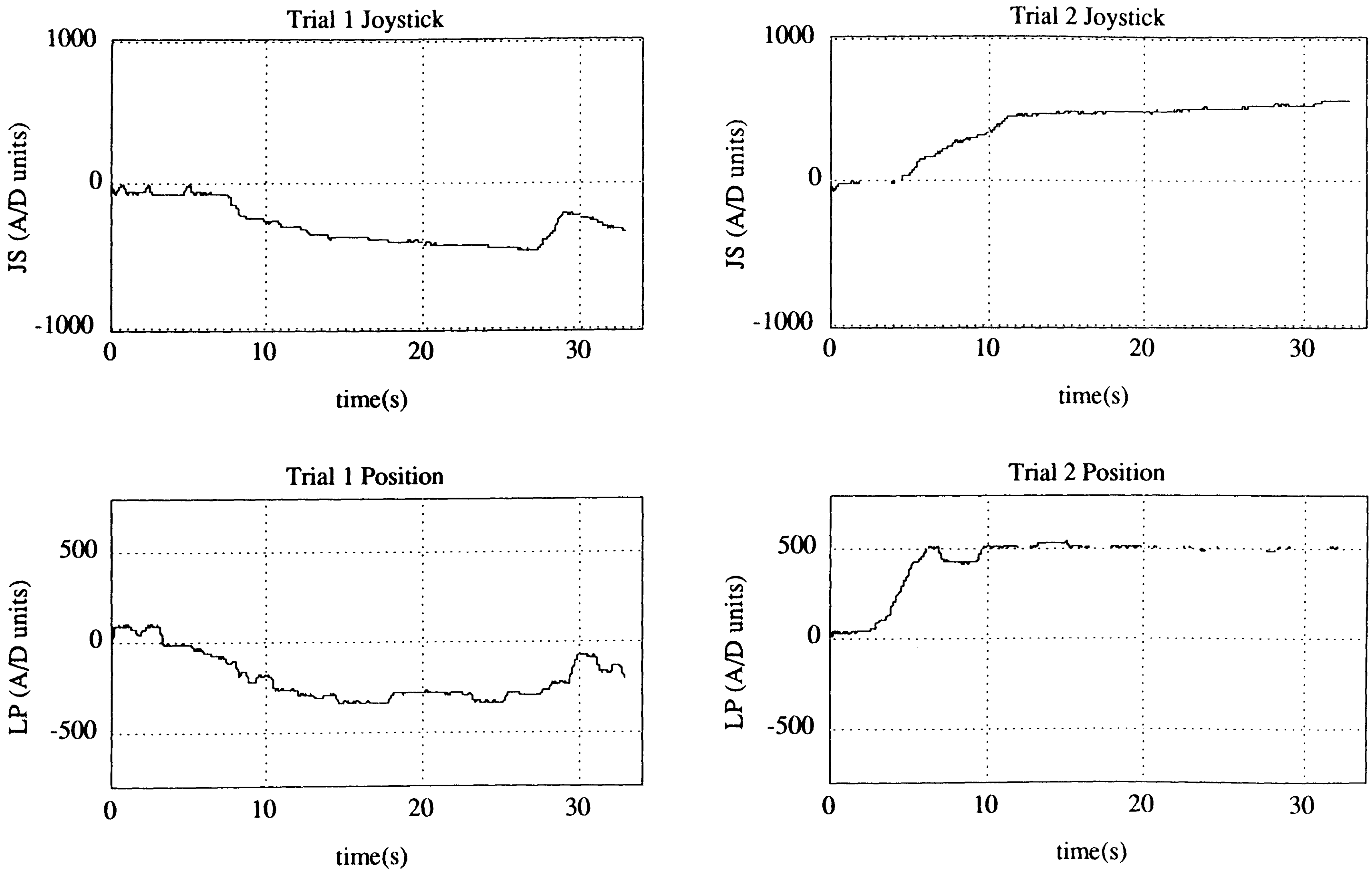


Figure A5.18
Subject 5 Joystick and Position Data
2 of 6 trials, Tactile cue = 375 grams

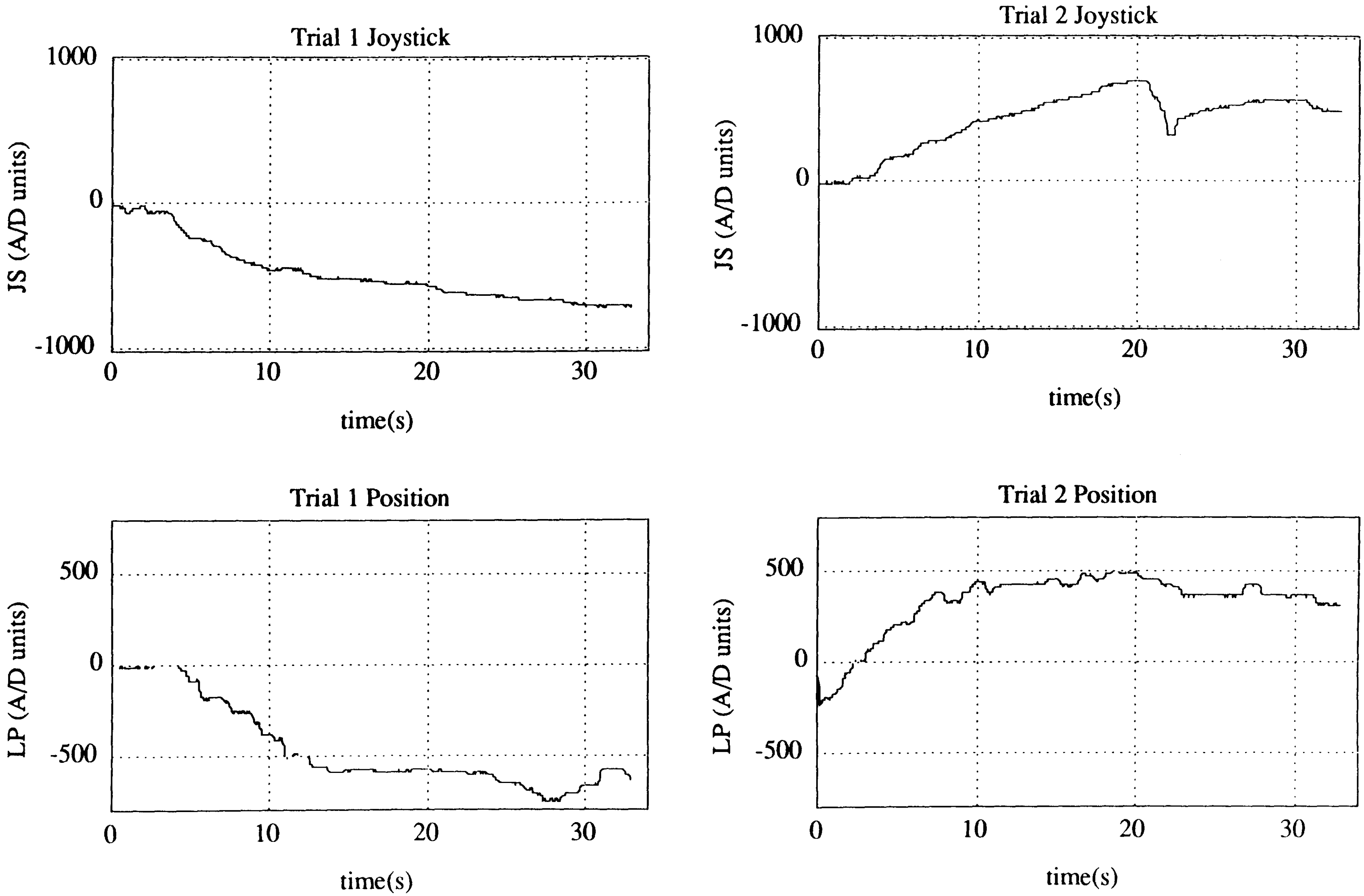
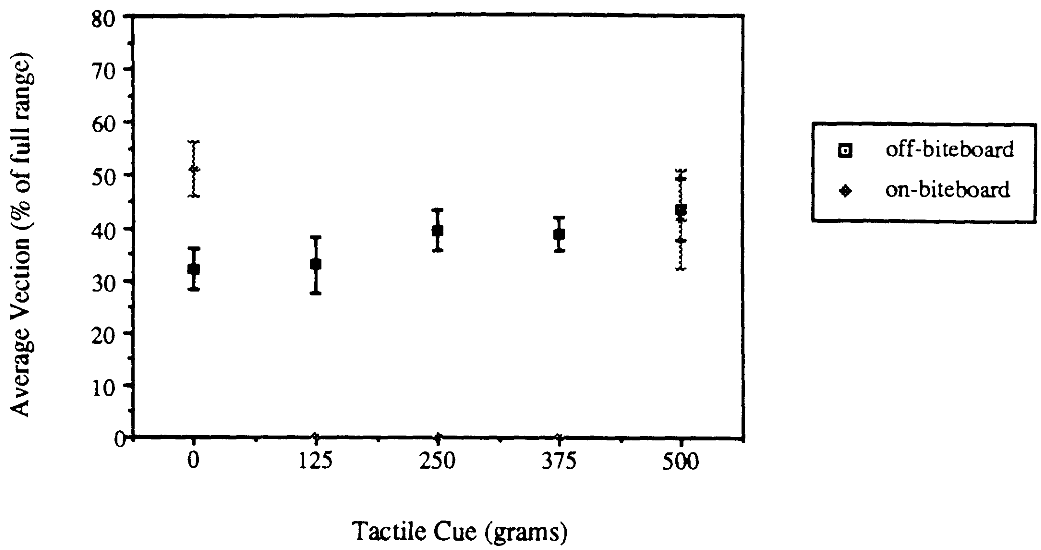


Figure A5.19
Subject 5 Joystick and Position Data
2 of 6 trials, Tactile cue = 500 grams

Subject 5



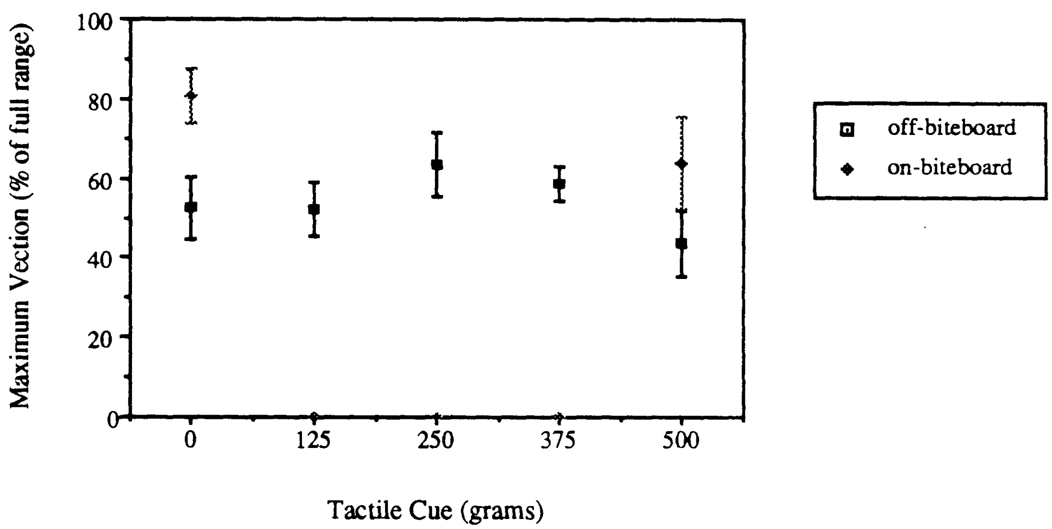


Figure A5.20:
Plots of Average and Maximum
Vection vs. Applied Tactile Cue

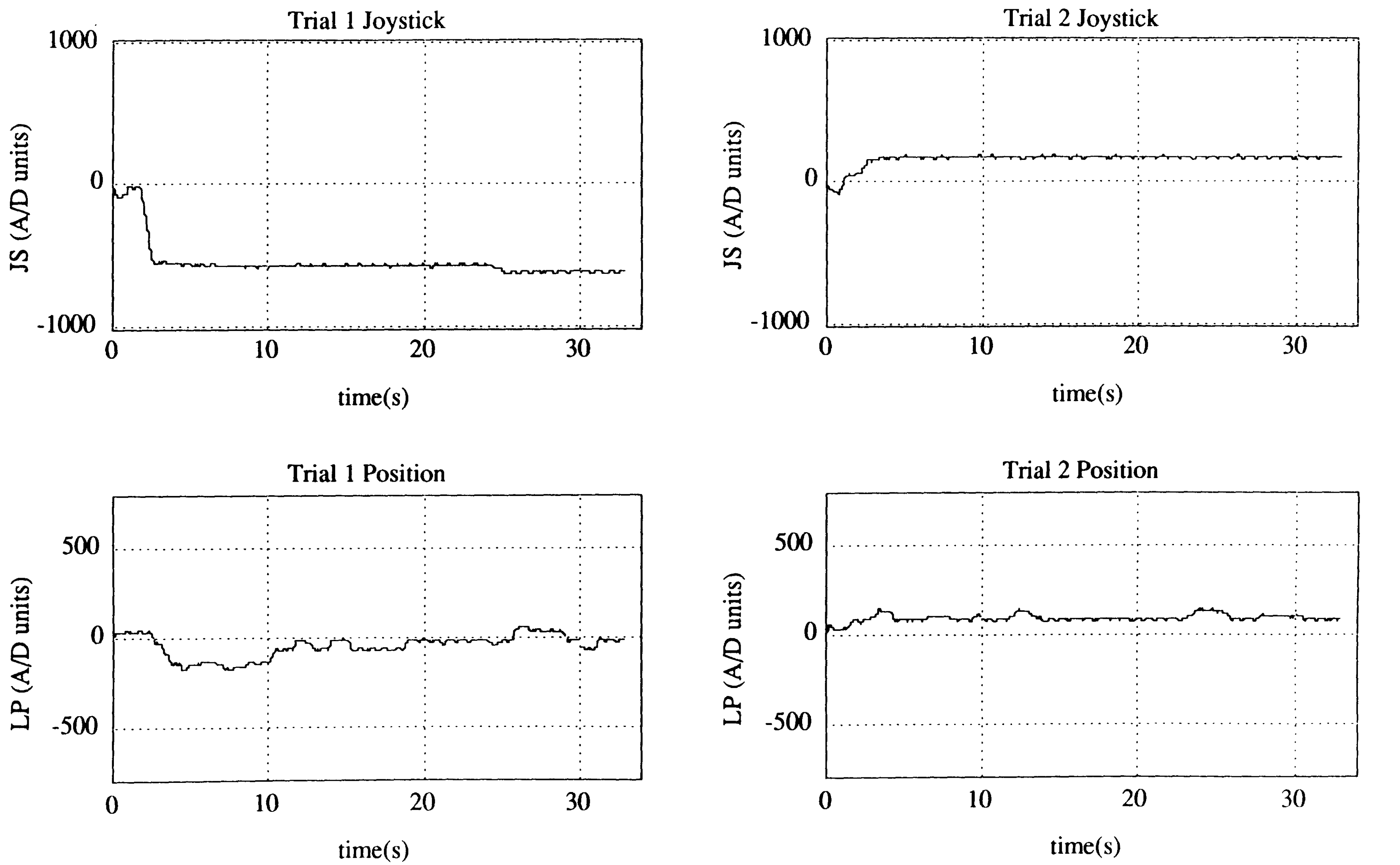


Figure A5.21
Subject 6 Joystick and Position Data
2 of 6 trials, Tactile cue = 125 grams

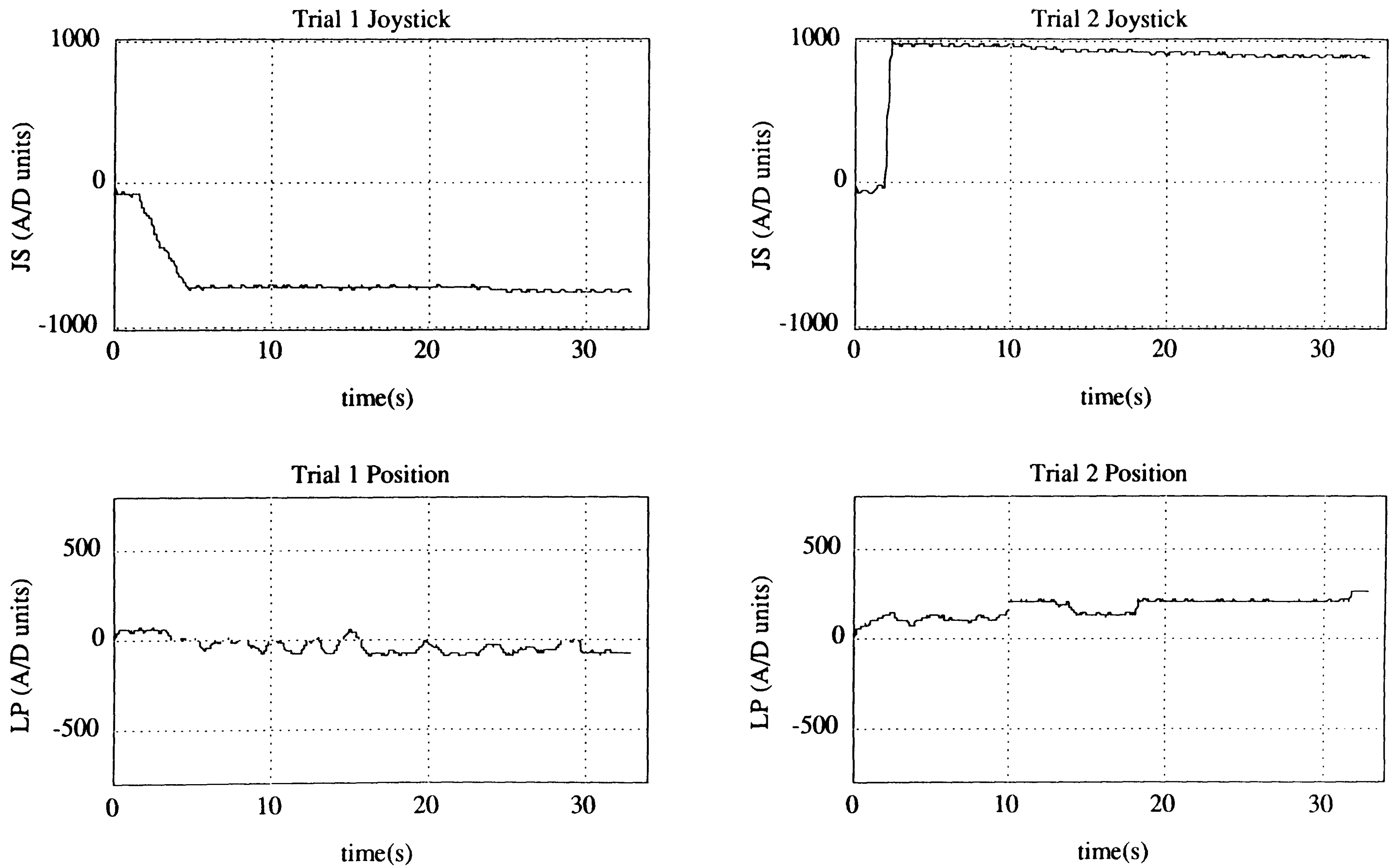


Figure A5.22
Subject 6 Joystick and Position Data
2 of 6 trials, Tactile cue = 250 grams

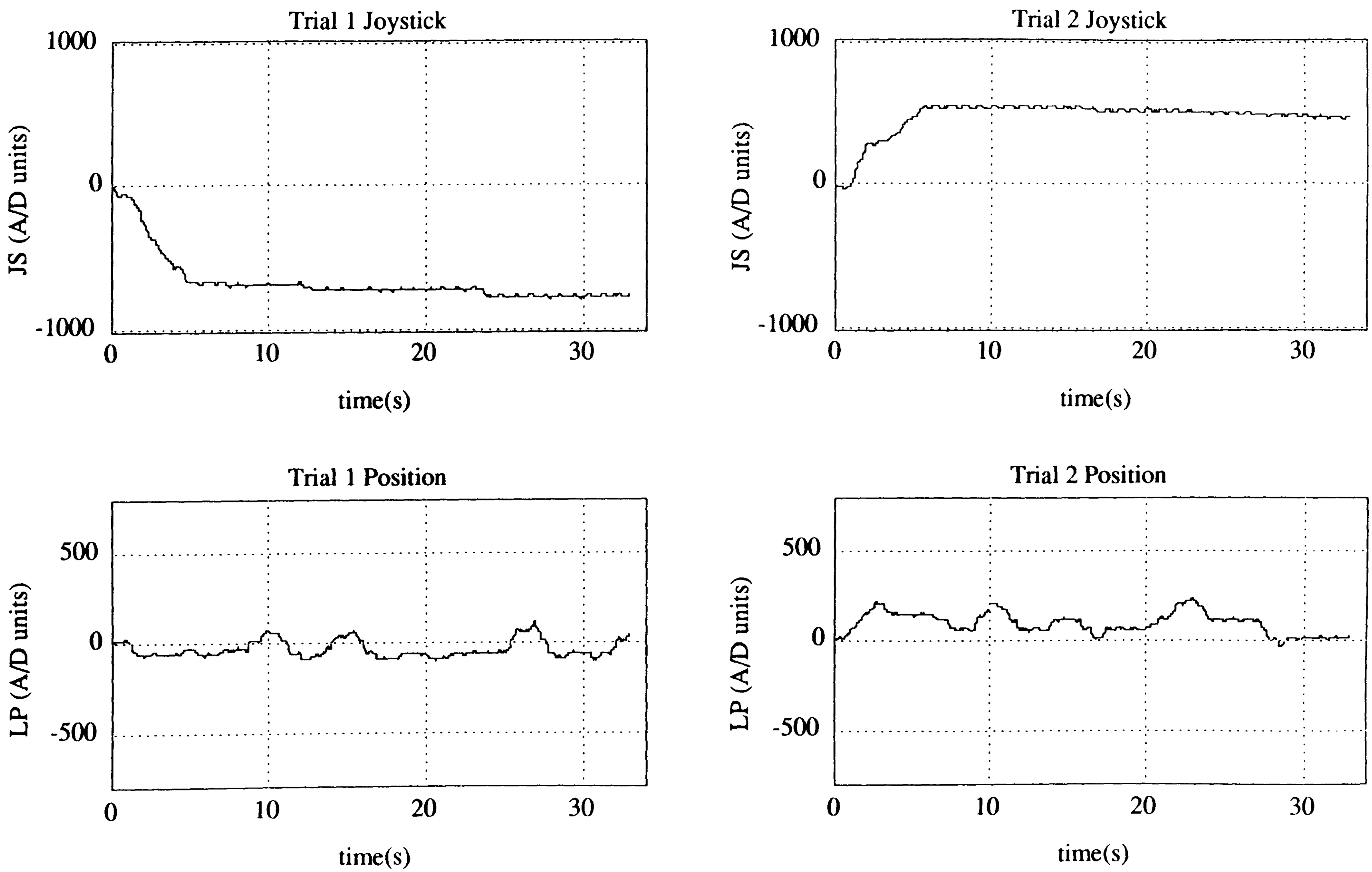


Figure A5.23
Subject 6 Joystick and Position Data
2 of 6 trials, Tactile cue = 375 grams

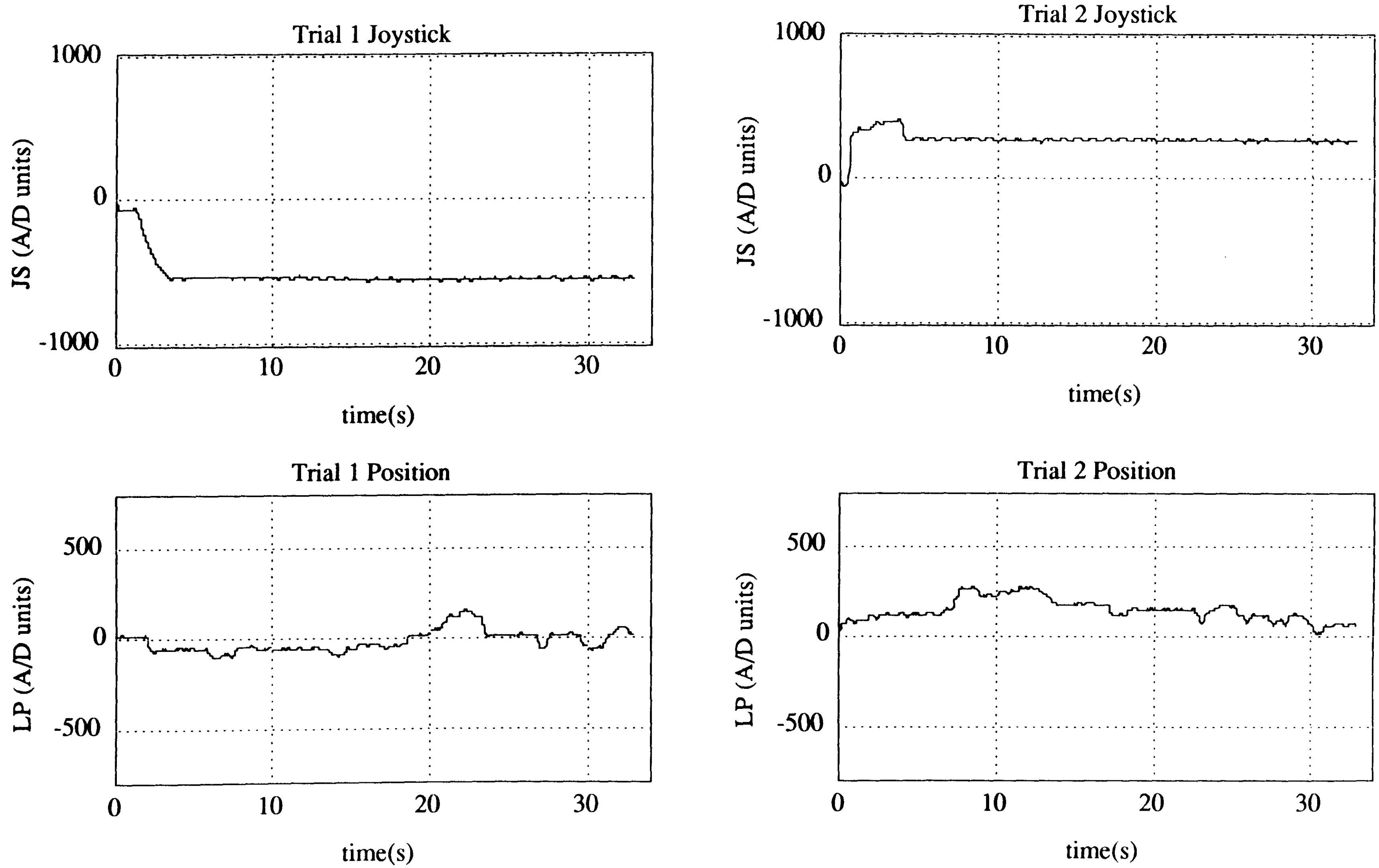
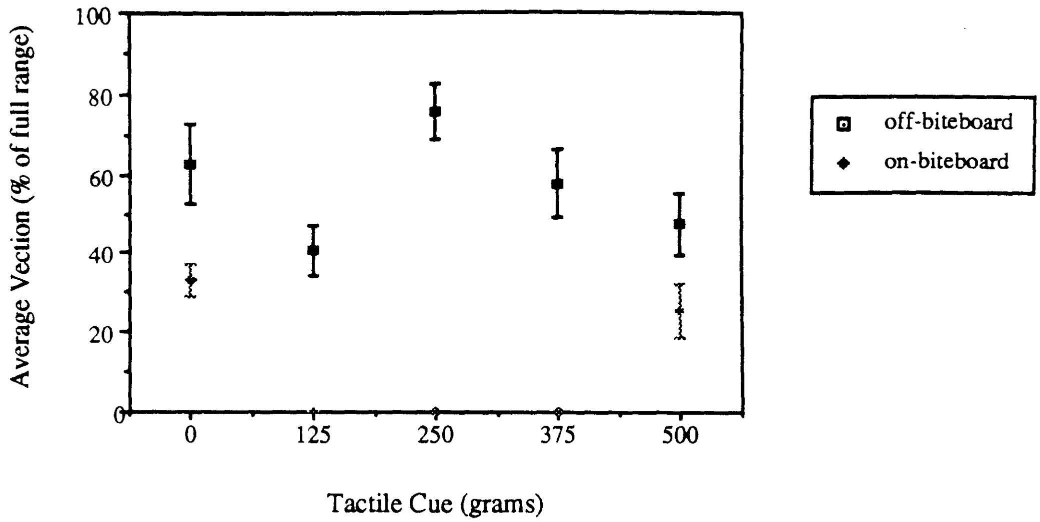


Figure A5.24
Subject 6 Joystick and Position Data
2 of 6 trials, Tactile cue = 500 grams

Subject 6



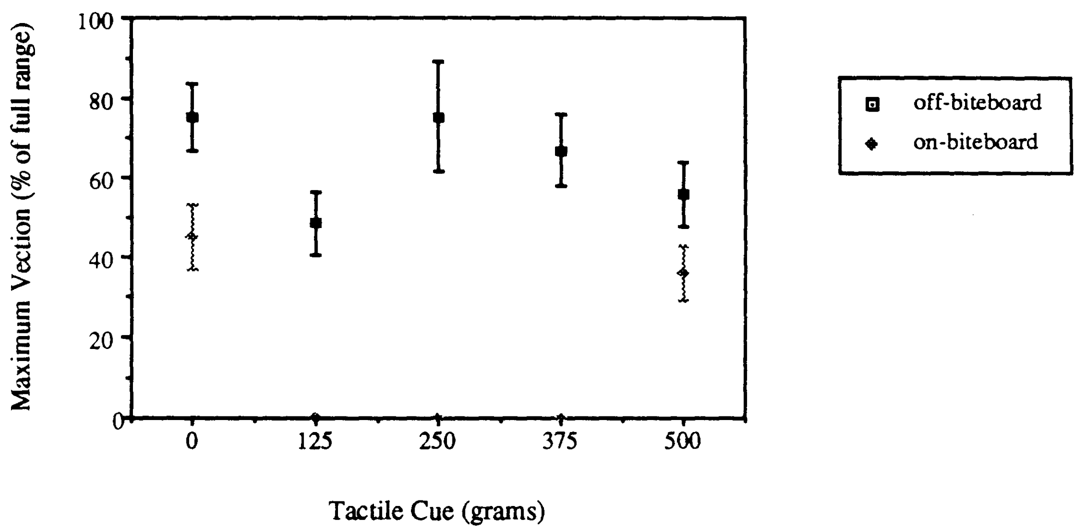


Figure A5.25:
Plots of Average and Maximum
Vection vs. Applied Tactile Cue

correct direction, but was even less significant. The increase in vection that this subject indicated when the biteboard was removed was significant at the zero weight condition (maximum and average vection b0 vs. n0, $p < .05$) and trending toward significance with the 500 gram cues (average vection b500 vs. n500, $p = .06$).

Subject 7 (naive)

Subject 7 commented that the latency in onset of vection was extremely noticeable, and longer with the heavier tactile cues. He was also the only subject to comment that he felt a difference in the magnitude of vection between clockwise and counter-clockwise rotation of the dome, counter-clockwise being stronger. This did not prove to be significant difference when his joystick indications were analyzed. Figures A5.26 through A5.29 show graphs of joystick and position data for trials at each tactile cue. Figure A5.30 shows the on and off-biteboard vection data for subject 7. The decrease in vection off-biteboard was significant between the zero weight condition and all of the tactile cue runs ($p < .05$). On the biteboard, subject 7 indicated no vection at all, thus the decrease in vection due to the introduction of the biteboard was highly significant ($p = .000$).

Subject 8 (naive)

Subject 8 was the only subject to comment that she actually felt like she was switching directions of rotation. She also felt that the presence of stationary visual cues within her field of view such as the biteboard holder and dome frame increased vection (Watt, 1989, found this result in several subjects). This subject also felt that vection was either "on" or "off", and had trouble quantifying it beyond that. Fatigue was reported by the beginning of the sixth run, and she had a slight headache by the time the protocol was completed. The subject's oscillations around the zero line (figures A5.31 through A5.33, raw data for tactile cue = 250 grams was unreadable) were of large amplitude and low

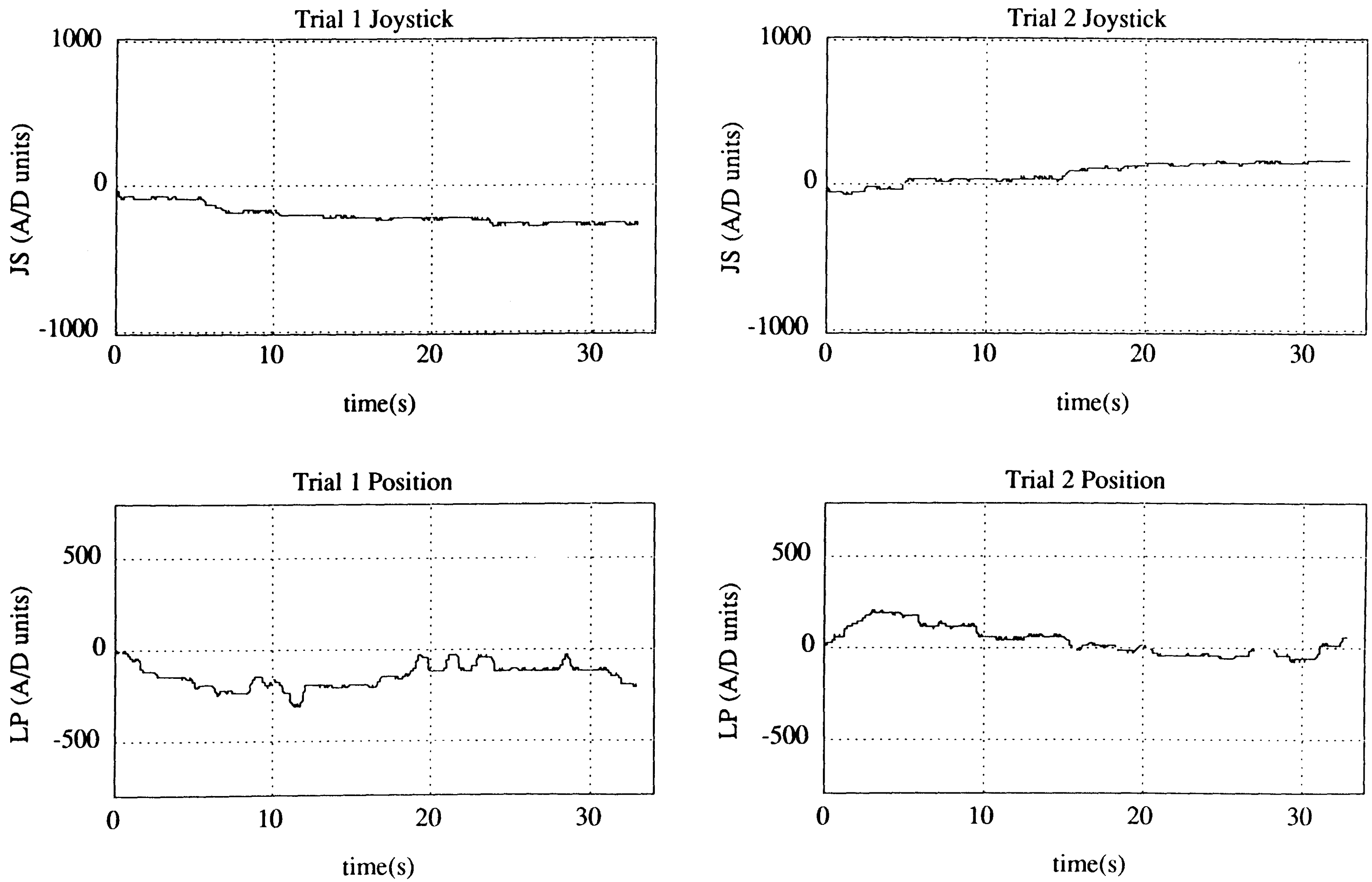


Figure A5.26

Subject 7 Joystick and Position Data

2 of 6 trials, Tactile cue = 125 grams

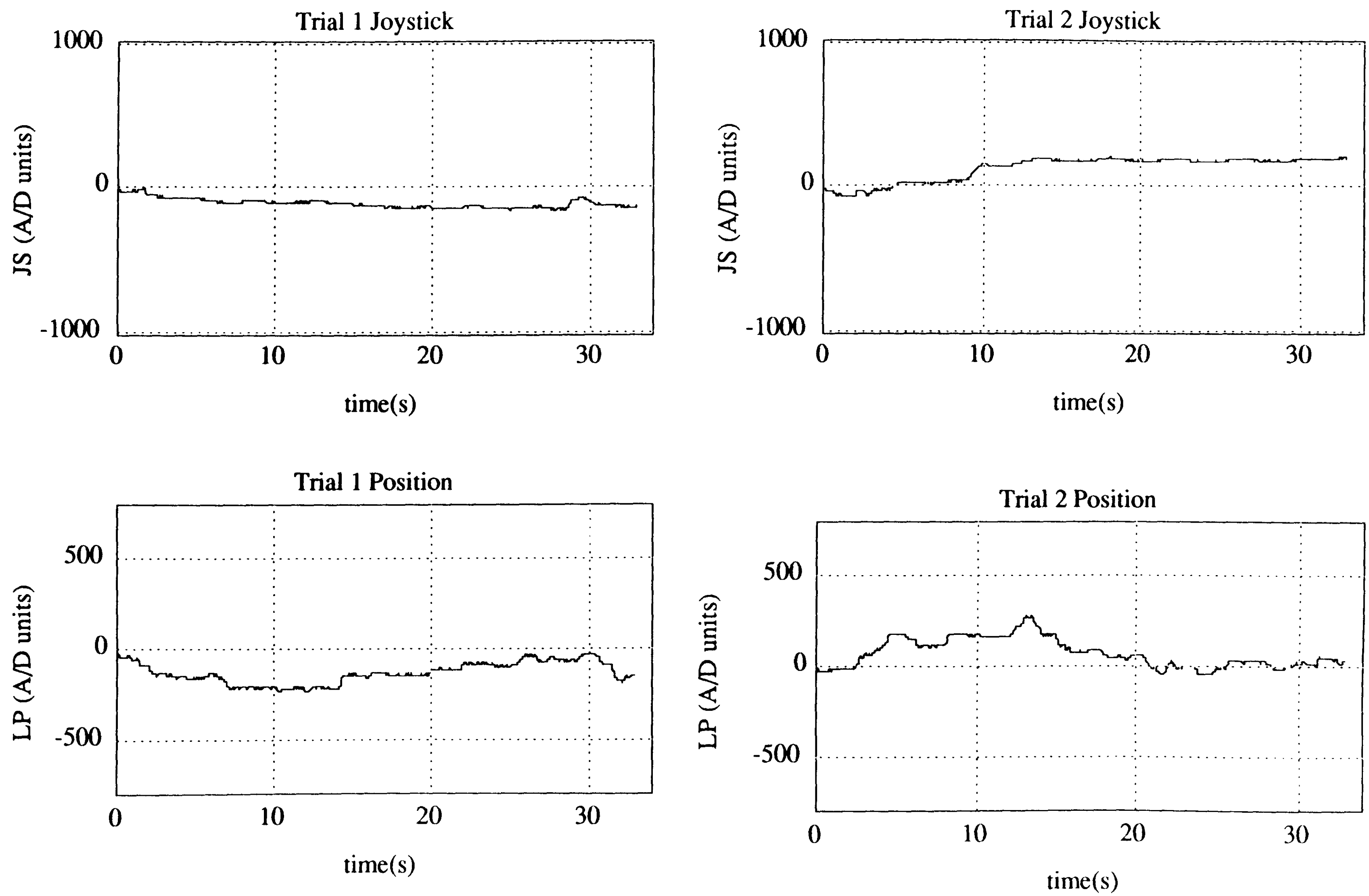


Figure A5.27
Subject 7 Joystick and Position Data
2 of 6 trials, Tactile cue = 250 grams

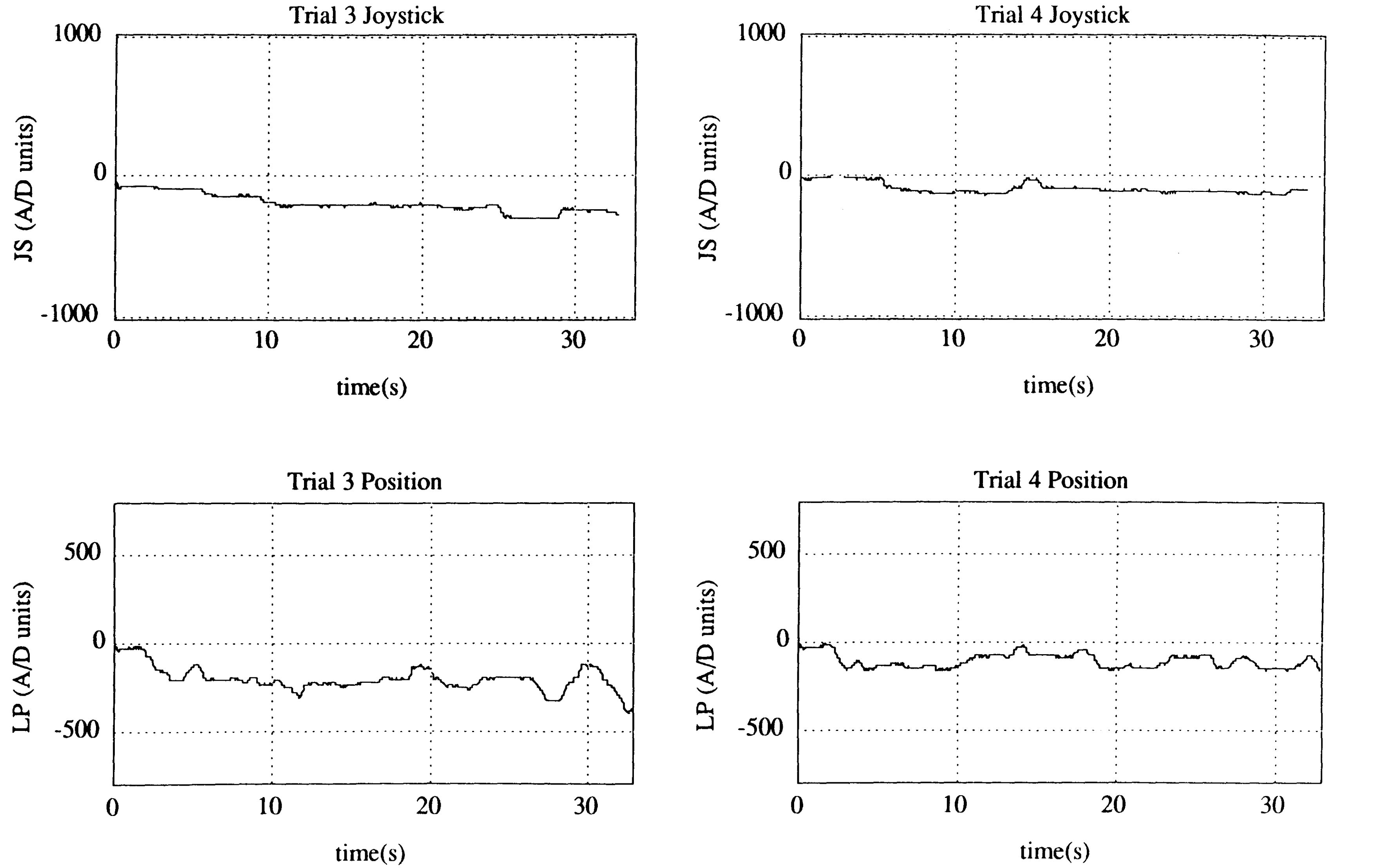


Figure A5.28
Subject 7 Joystick and Position Data
2 of 6 trials, Tactile cue = 375 grams

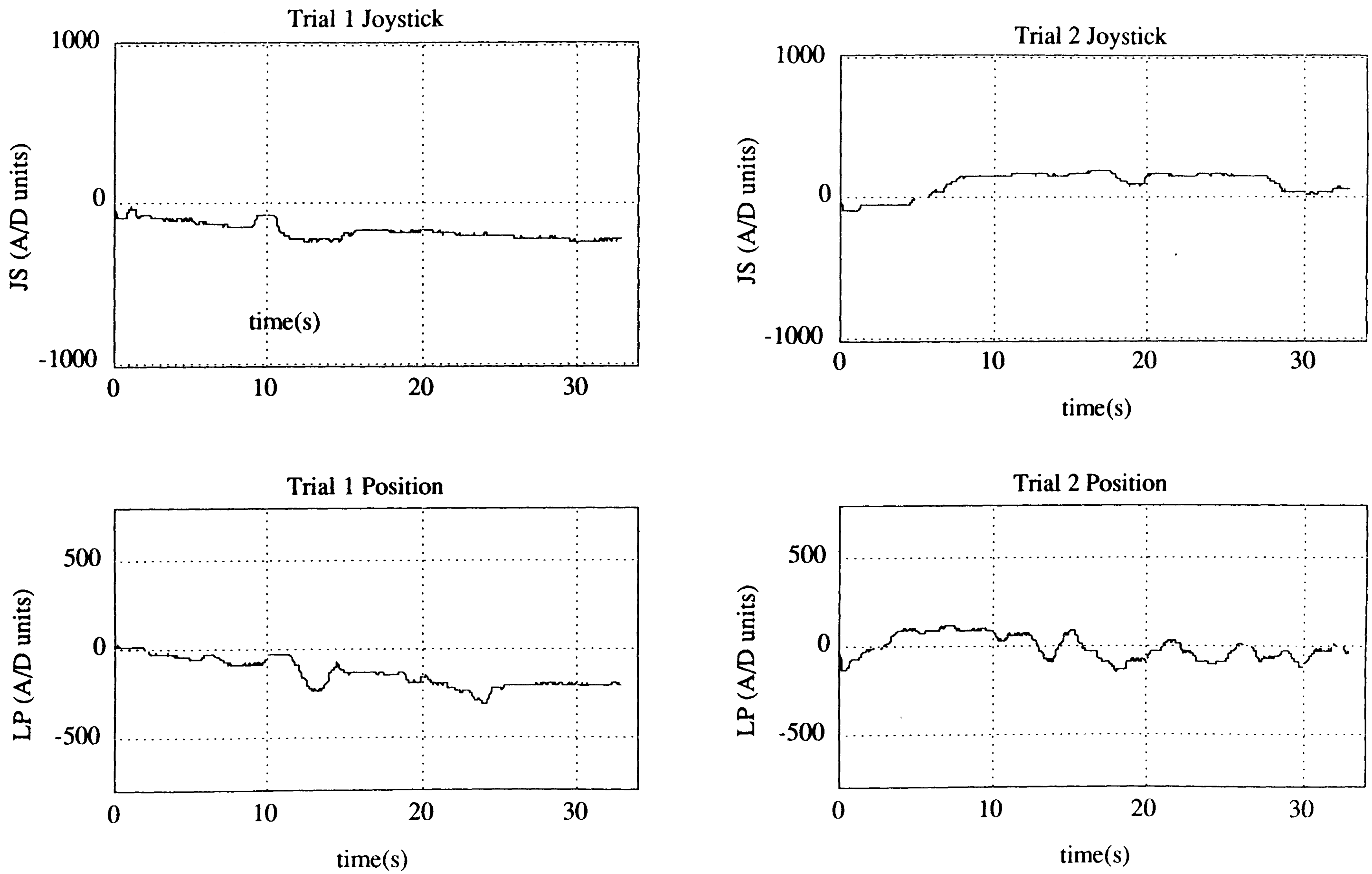
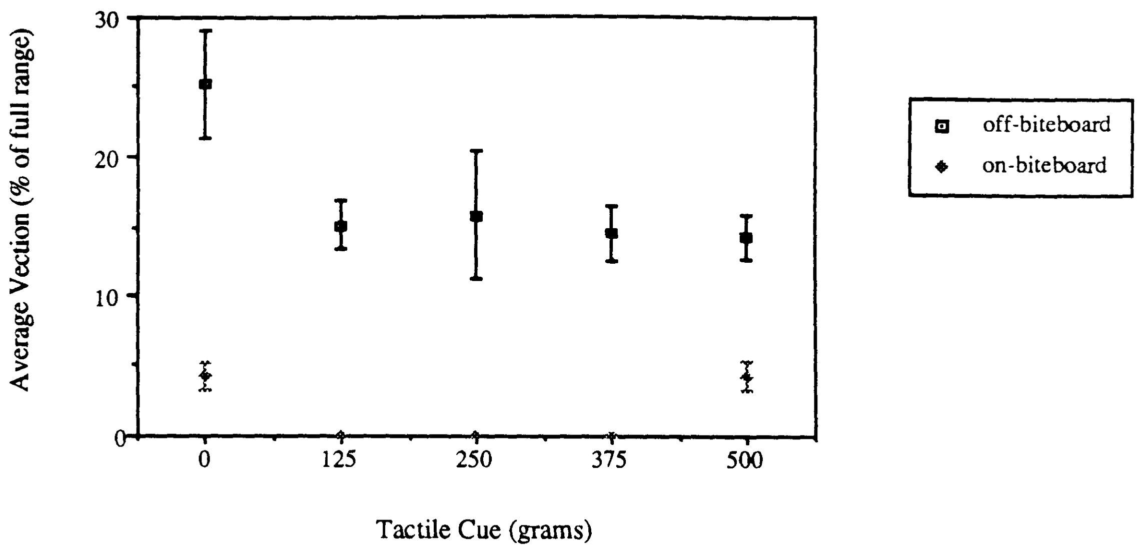


Figure A5.29
Subject 7 Joystick and Position Data
2 of 6 trials, Tactile cue = 500 grams

Subject 7



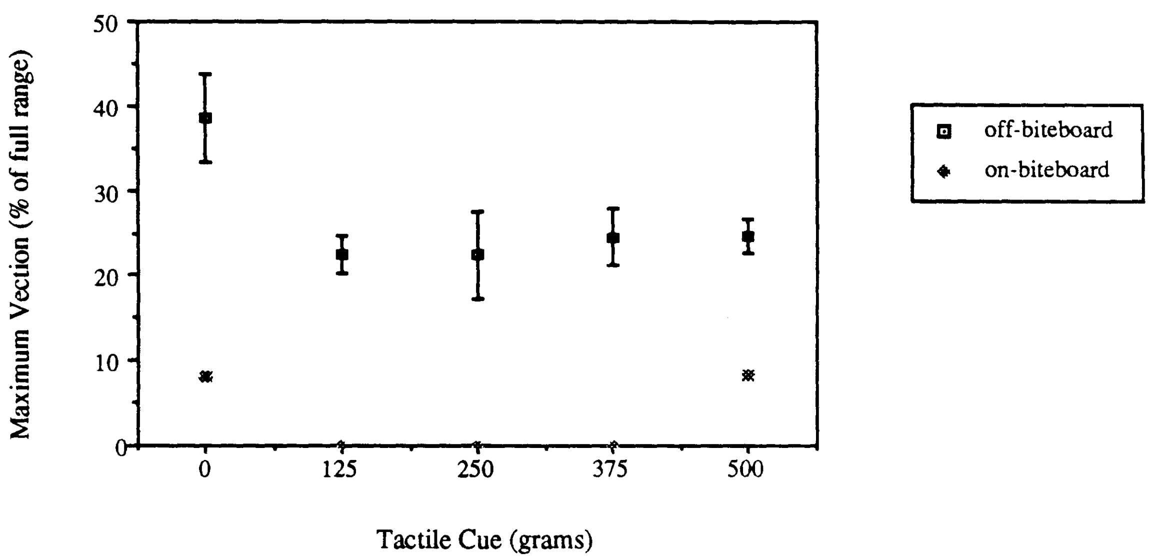


Figure A5.30:
Plots of Average and Maximum
Vection vs. Applied Tactile Cue

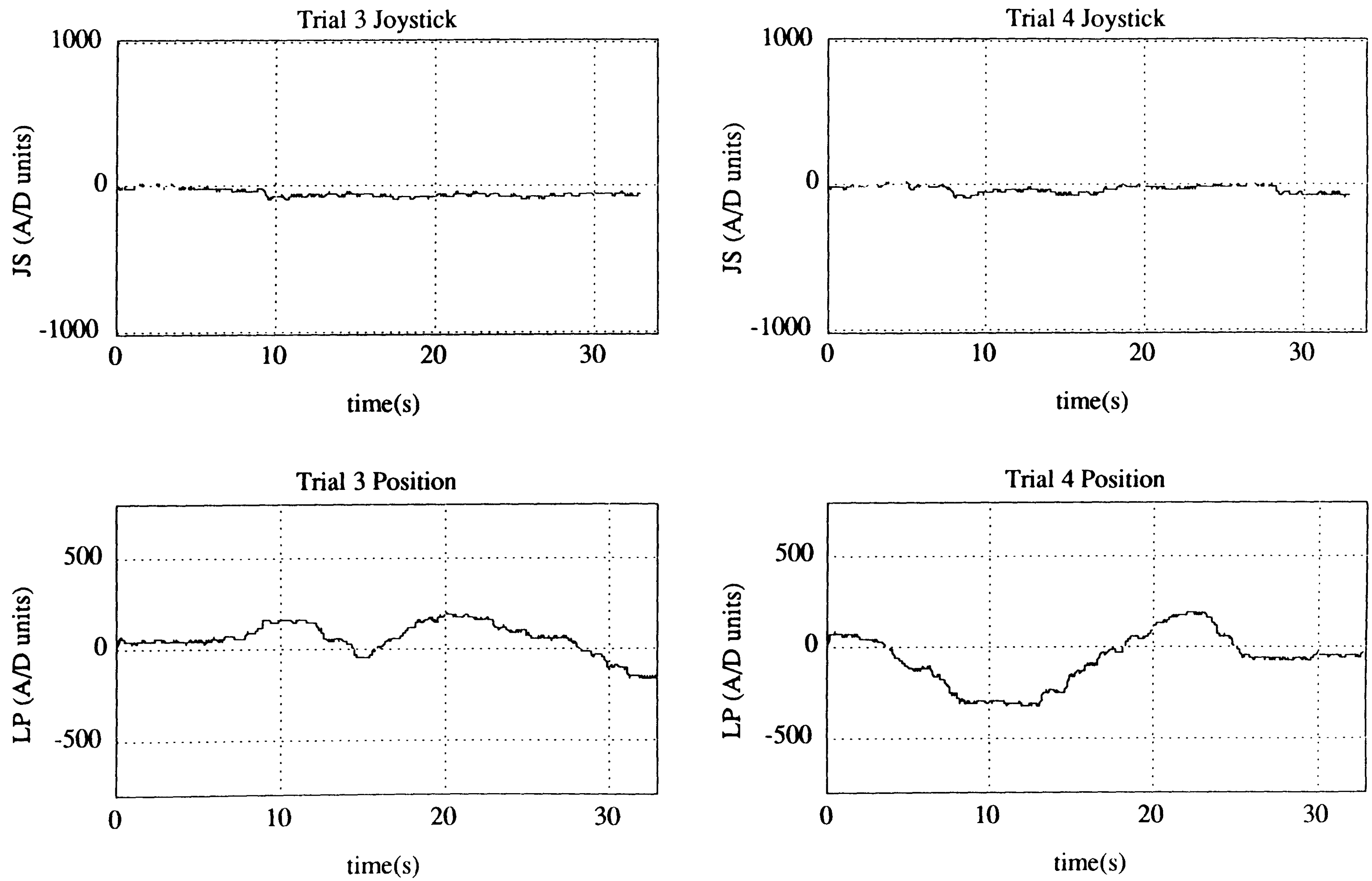


Figure A5.31
Subject 8 Joystick and Position Data
2 of 6 trials, Tactile cue = 125 grams

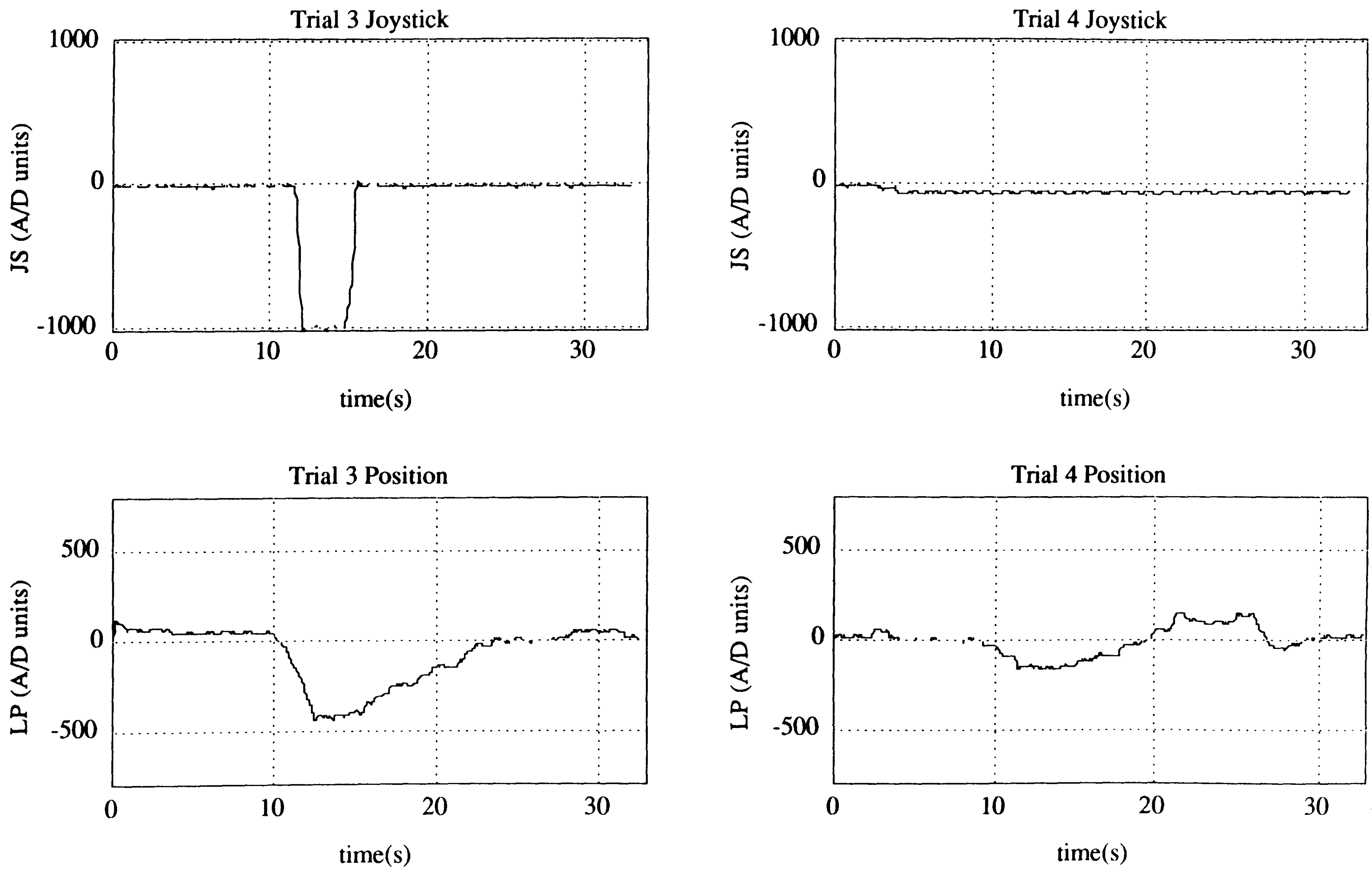


Figure A5.32
Subject 8 Joystick and Position Data
2 of 6 trials, Tactile cue = 375 grams

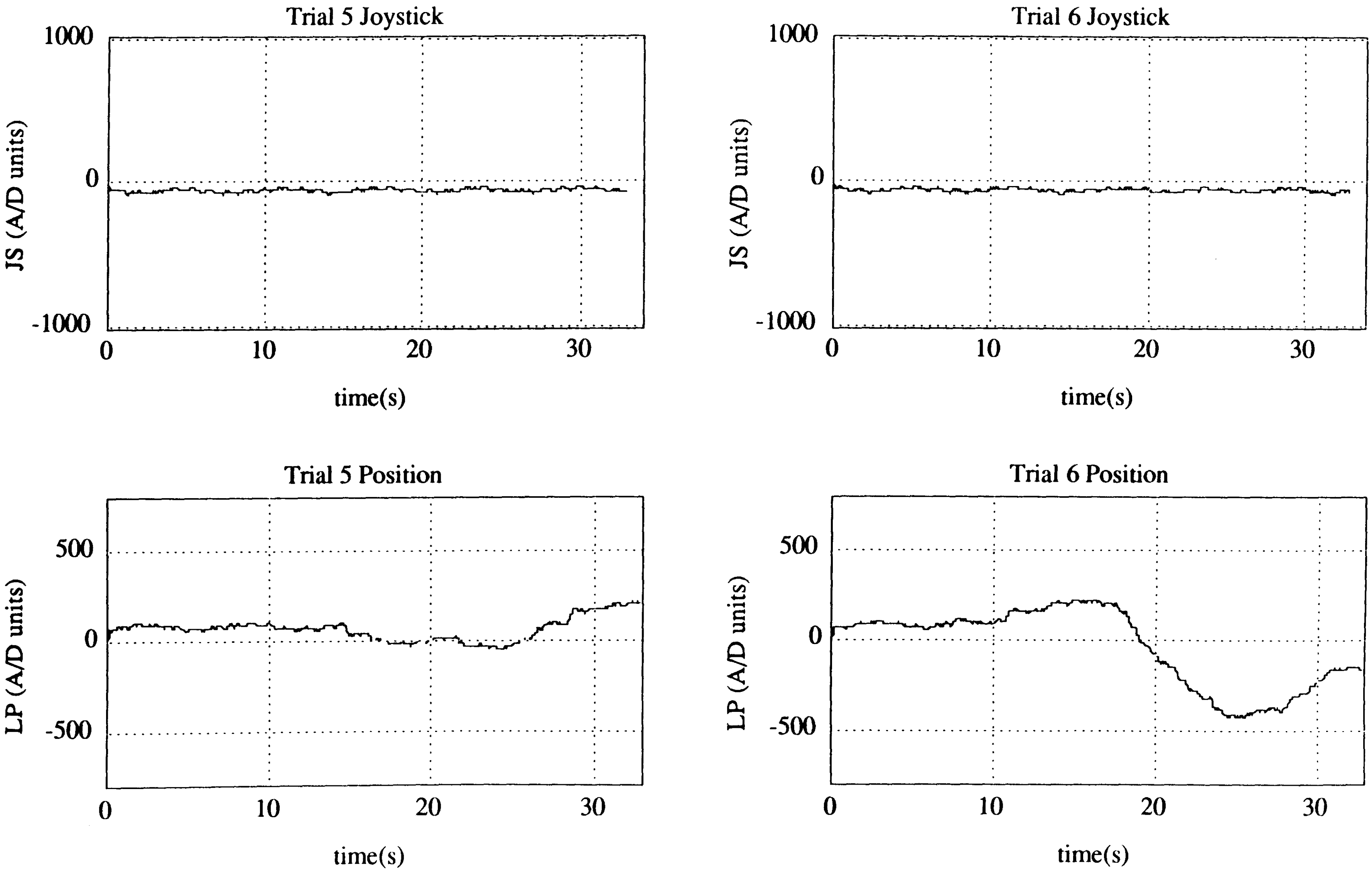


Figure A5.33
Subject 8 Joystick and Position Data
2 of 6 trials, Tactile cue = 500 grams

frequency. The subject's position, left or right of center, does not correlate with the changes in direction of apparent rotation. Figure A5.34 shows magnitude of vection for all runs. The decrease in vection seen between zero weight and 500 grams is significant ($p < .05$). On the biteboard a decrease was seen, but the change is not significant. With the use of tactile cues (b500 vs. n500) this subject had a significant decrease in vection ($p < .05$) when the biteboard was removed. She was the only subject to exhibit this particular trend.

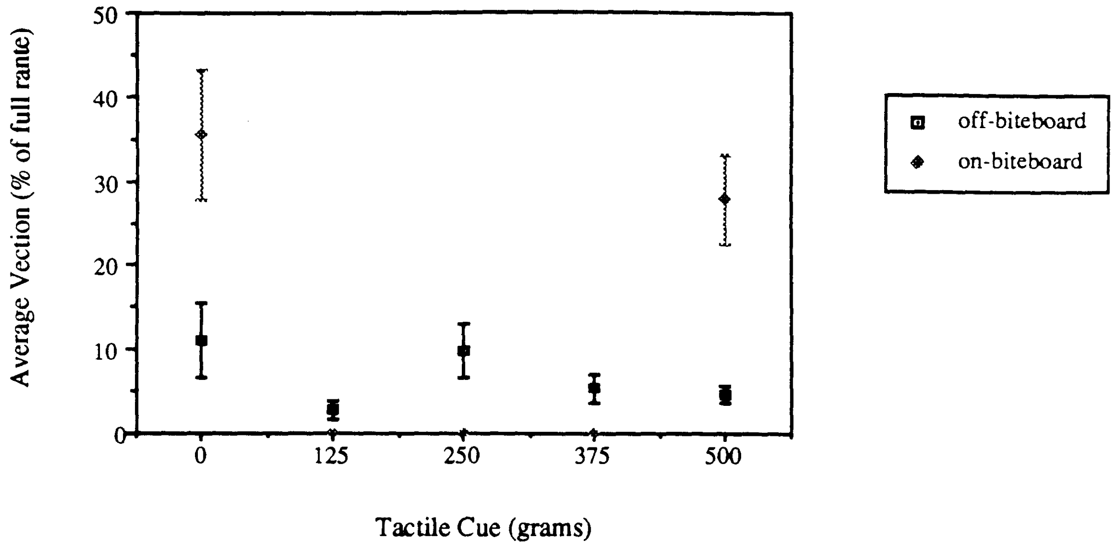
Subject 9 (non-naive)

Subject 9, the first non-naive subject, commented only that the protocol was long. His position and joystick indications (figures A5.35 through A5.38) show very little tilt despite large changes in the magnitude of self-motion. This subject stood very stiffly, and appeared to have more head motion than overall body sway. Figure A5.39 shows a drastic difference between the no weight condition and all other conditions when off the biteboard. This change was highly significant ($p < .01$) for both average and maximum vection. On the biteboard this effect was not significant, though again the change was in the expected direction. The increase in vection between on and off biteboard was significant ($p < .05$) for both maximum and average vection when no tactile cues were applied, but not significant at the 500 gram condition.

Subject 10 (non-naive)

This subject commented that the test session was very long. He also noted that off of the biteboard he occasionally felt full head-over-heels rotation, similar to what he had felt in supine dome trials completed on a previous occasion. This feeling of full 360 degree rotation was not noted on any of the on-biteboard trials. Figures A5.40 through A5.43 show that this subject had a lot of fairly large amplitude oscillations in position. The

Subject 8



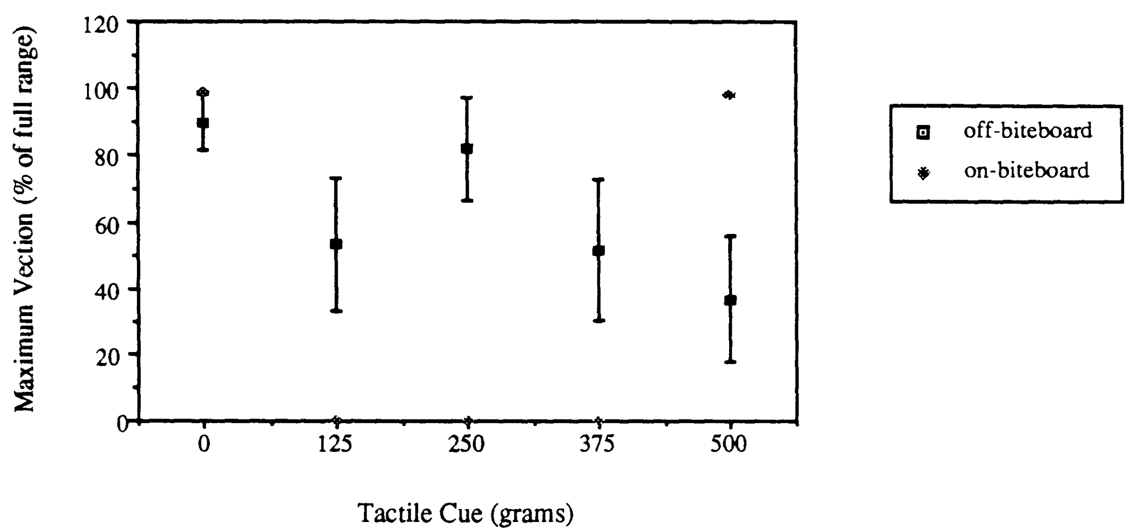


Figure A5.34:
Plots of Average and Maximum
Vection vs. Applied Tactile Cue

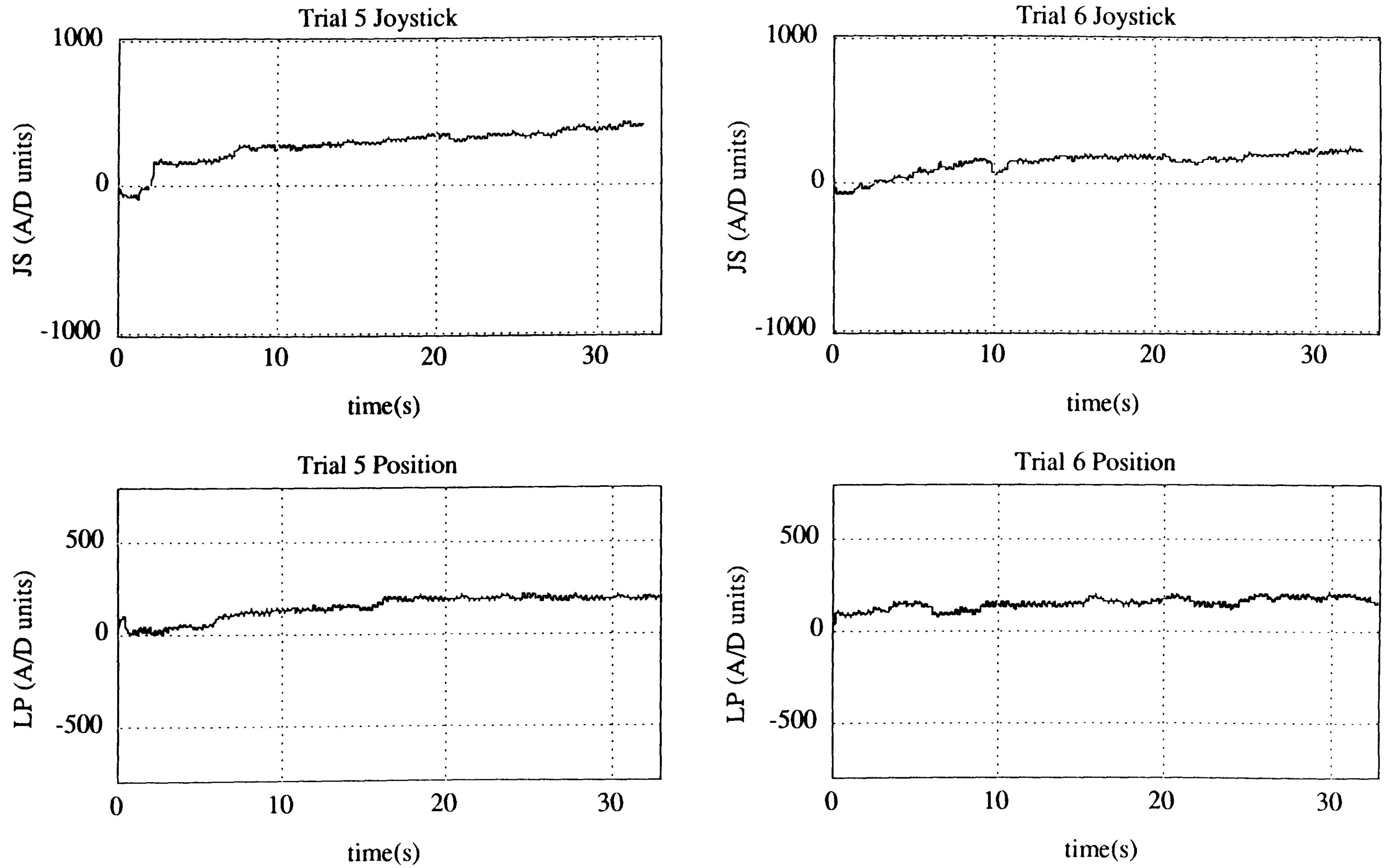
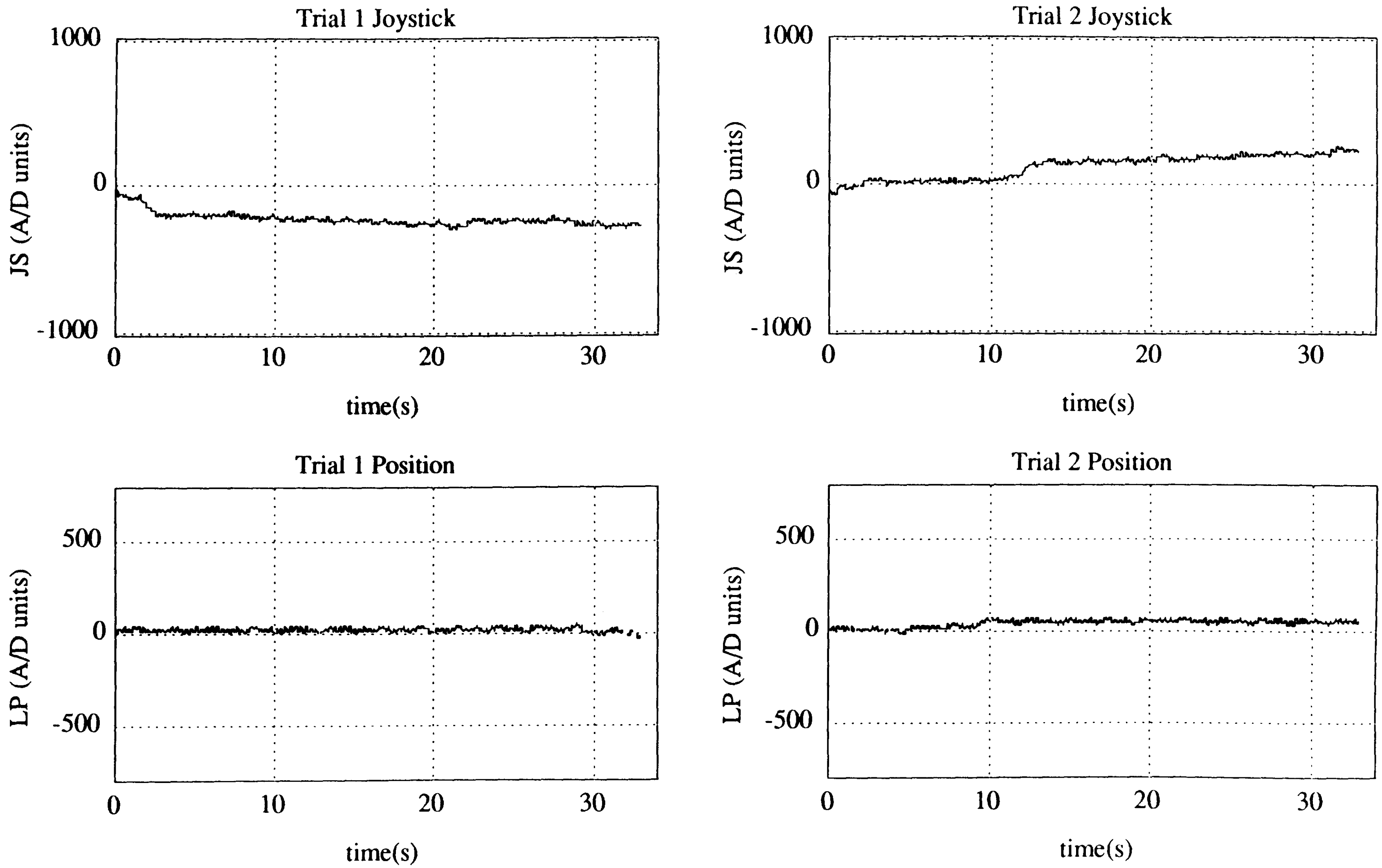


Figure A5.35
Subject 9 Joystick and Position Data
2 of 6 trials, Tactile cue = 125 grams



Fgure A5.36
Subject 9 Joystick and Position Data
2 of 6 trials, Tactile cue = 250 grams

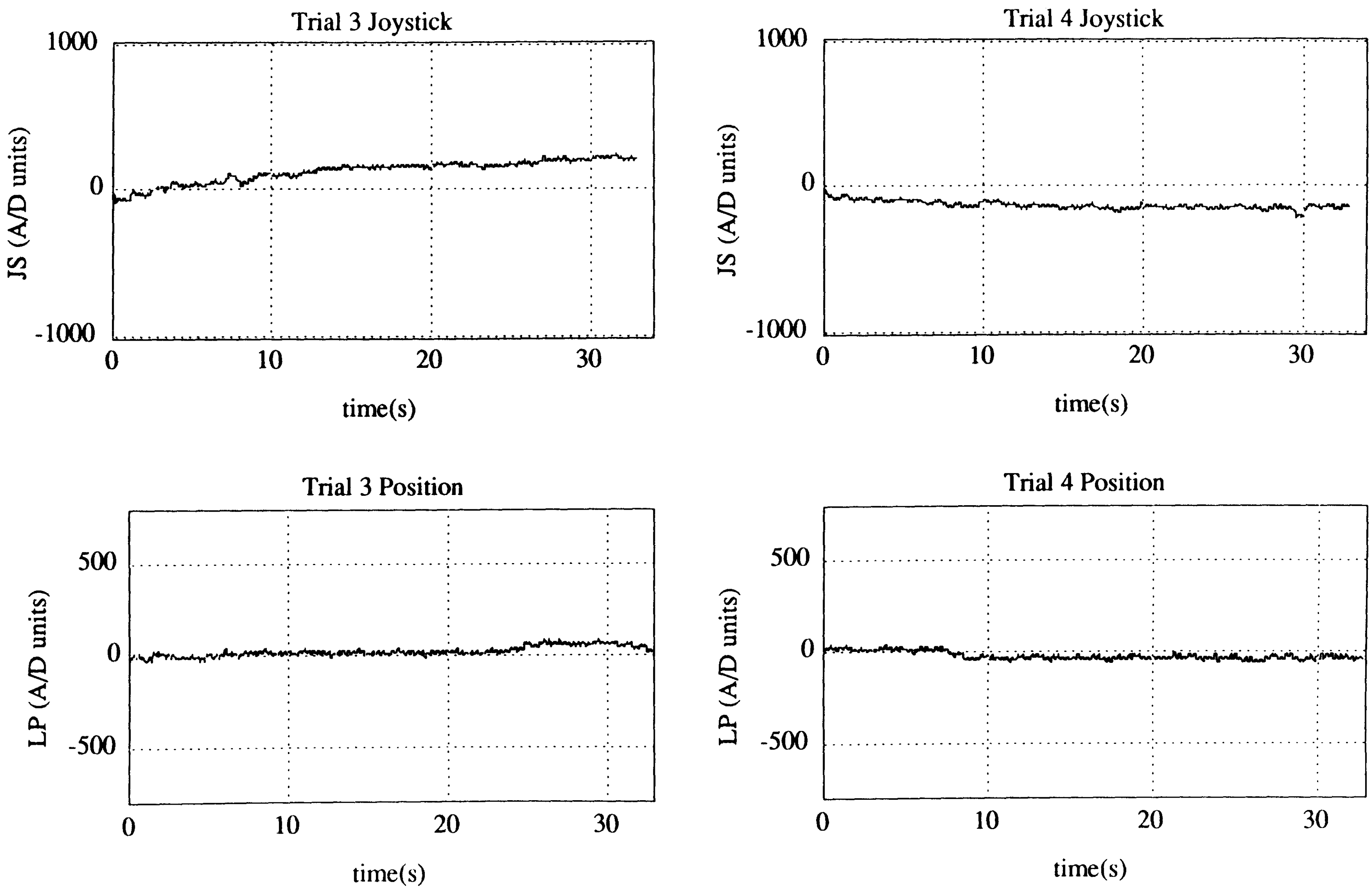


Figure A5.37
Subject 9 Joystick and Position Data
2 of 6 trials, Tactile cue = 375 grams

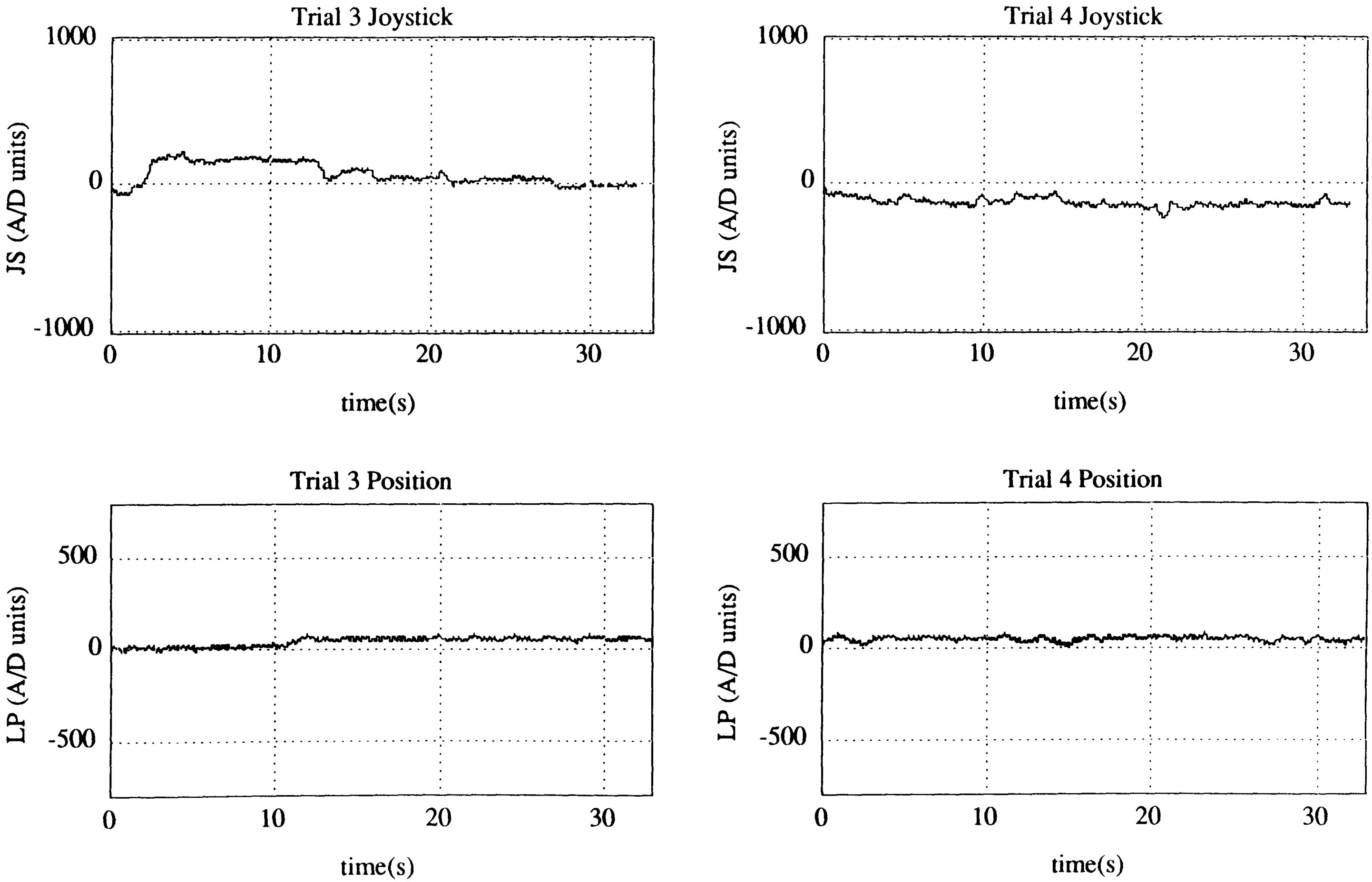
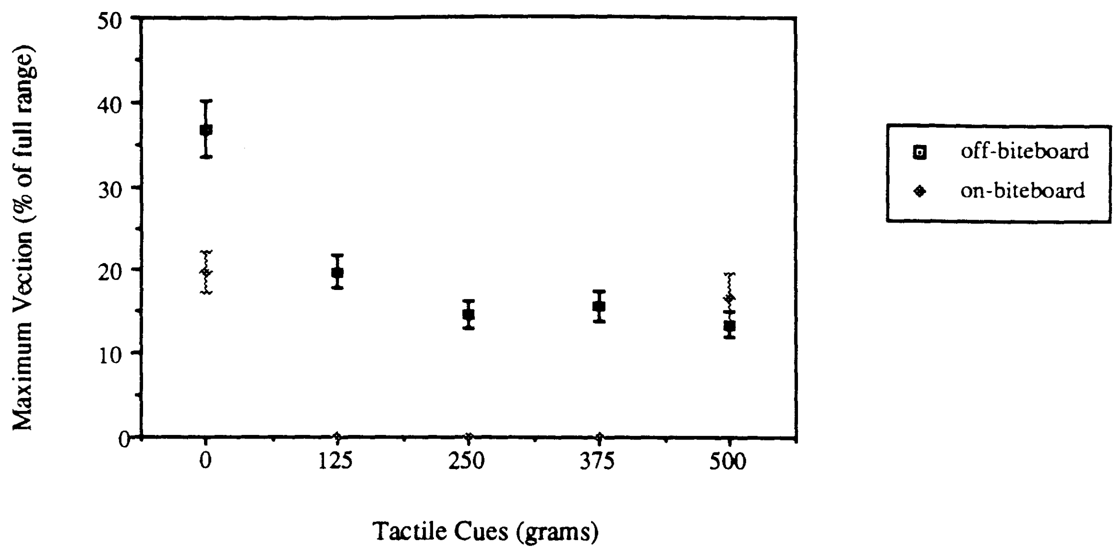


Figure A5.38
Subject 9 Joystick and Position Data
2 of 6 trials, Tactile cue = 500 grams

Subject 9



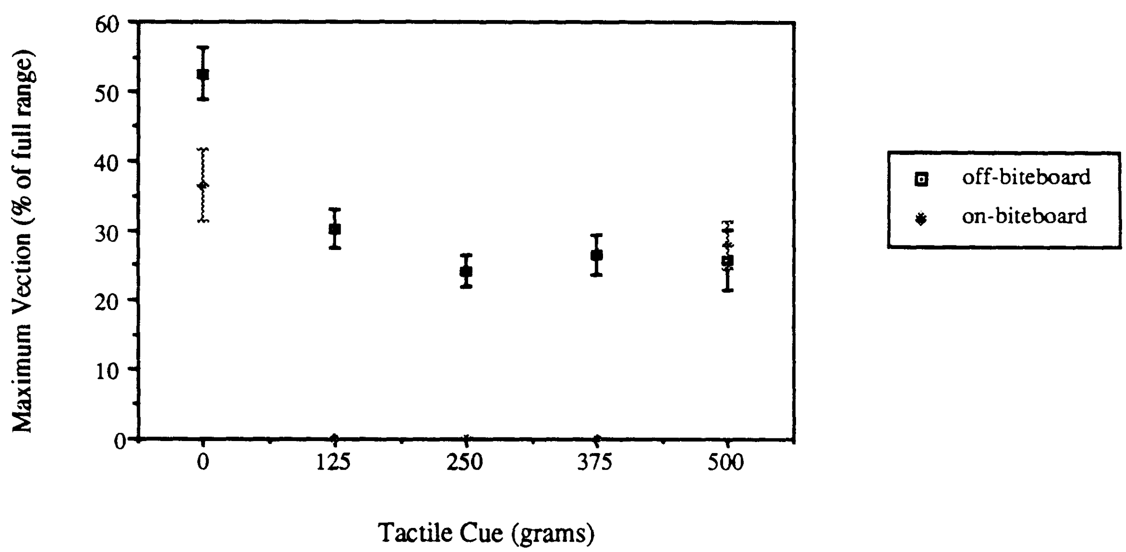


Figure A5.39:
Plots of Average and Maximum
Vection vs. Applied Tactile Cue

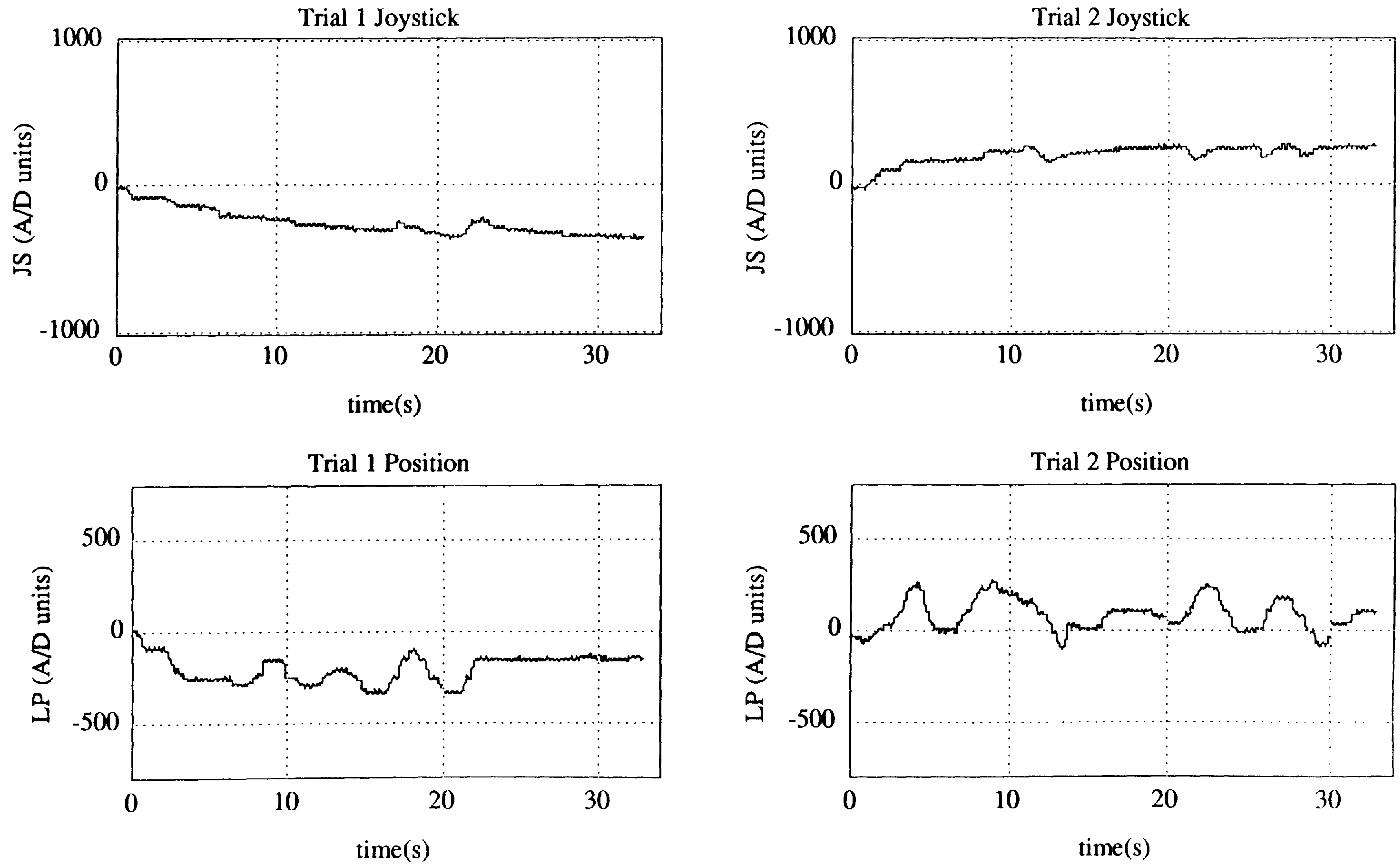


Figure A5.40
Subject 10 Joystick and Position Data
2 of 6 trials, Tactile cue = 125 grams

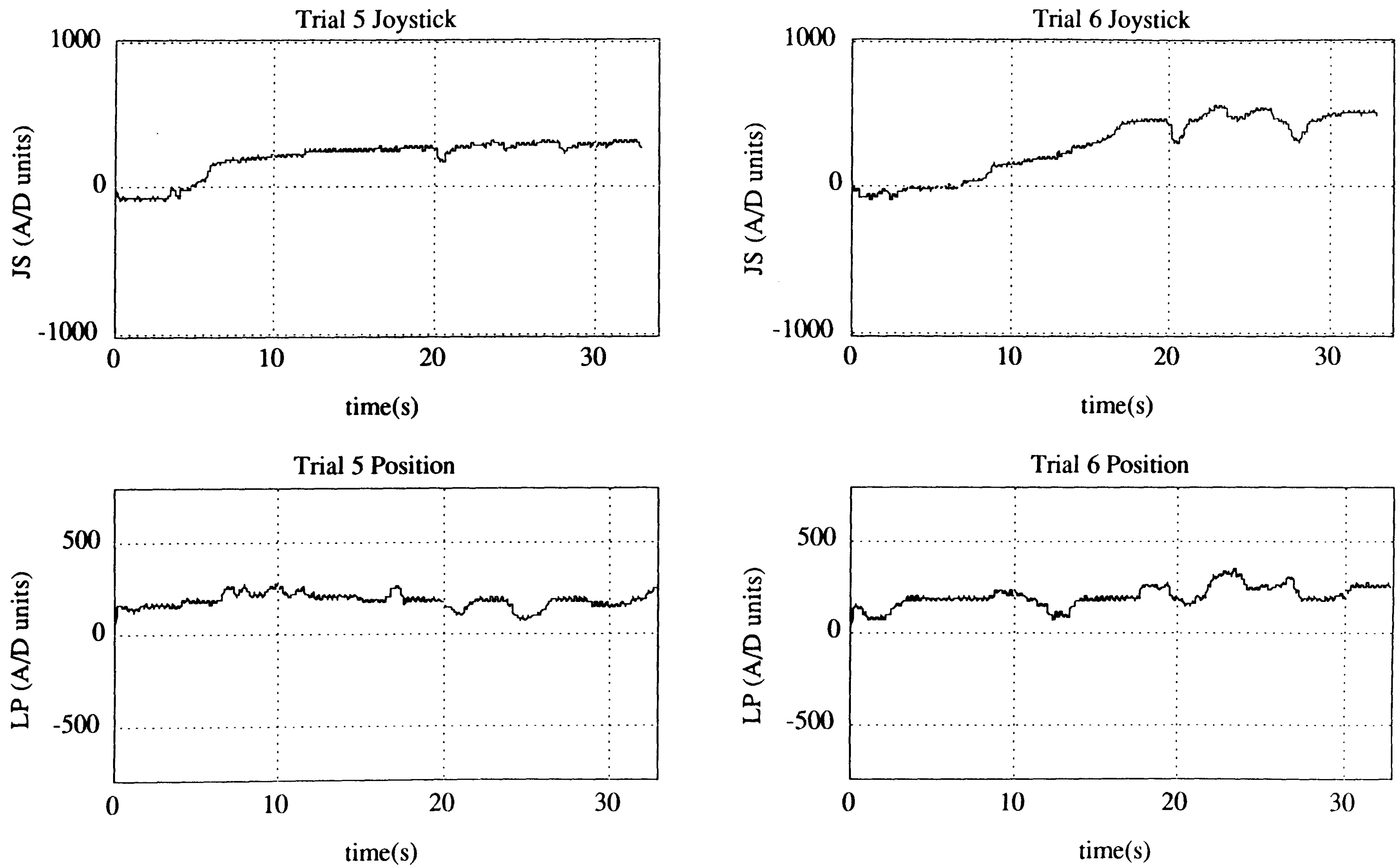


Figure A5.41
Subject 10 Joystick and Position Data
2 of 6 trials, Tactile cue = 250 grams

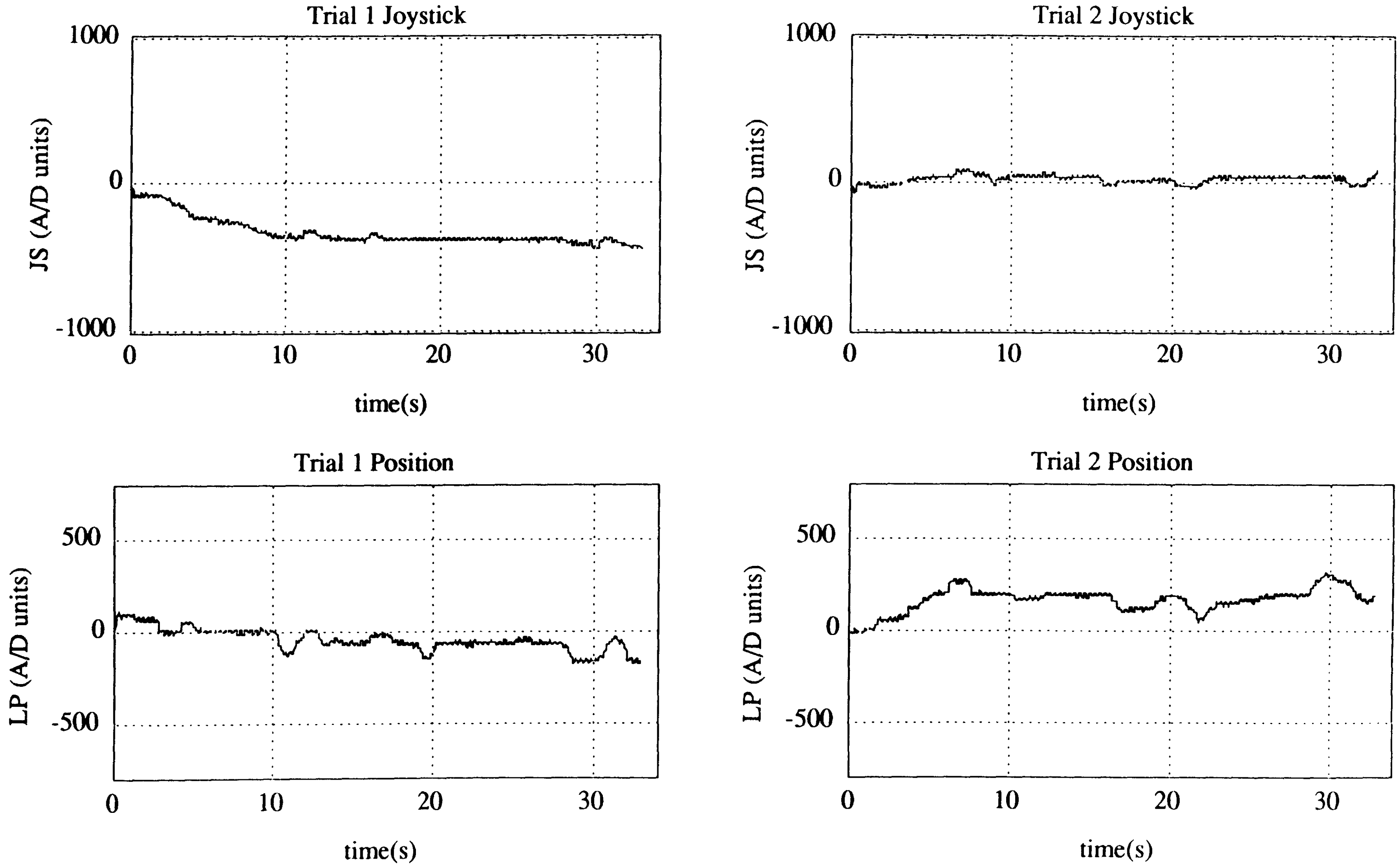


Figure A5.42
Subject 10 Joystick and Position Data
2 of 6 trials, Tactile cue = 375 grams

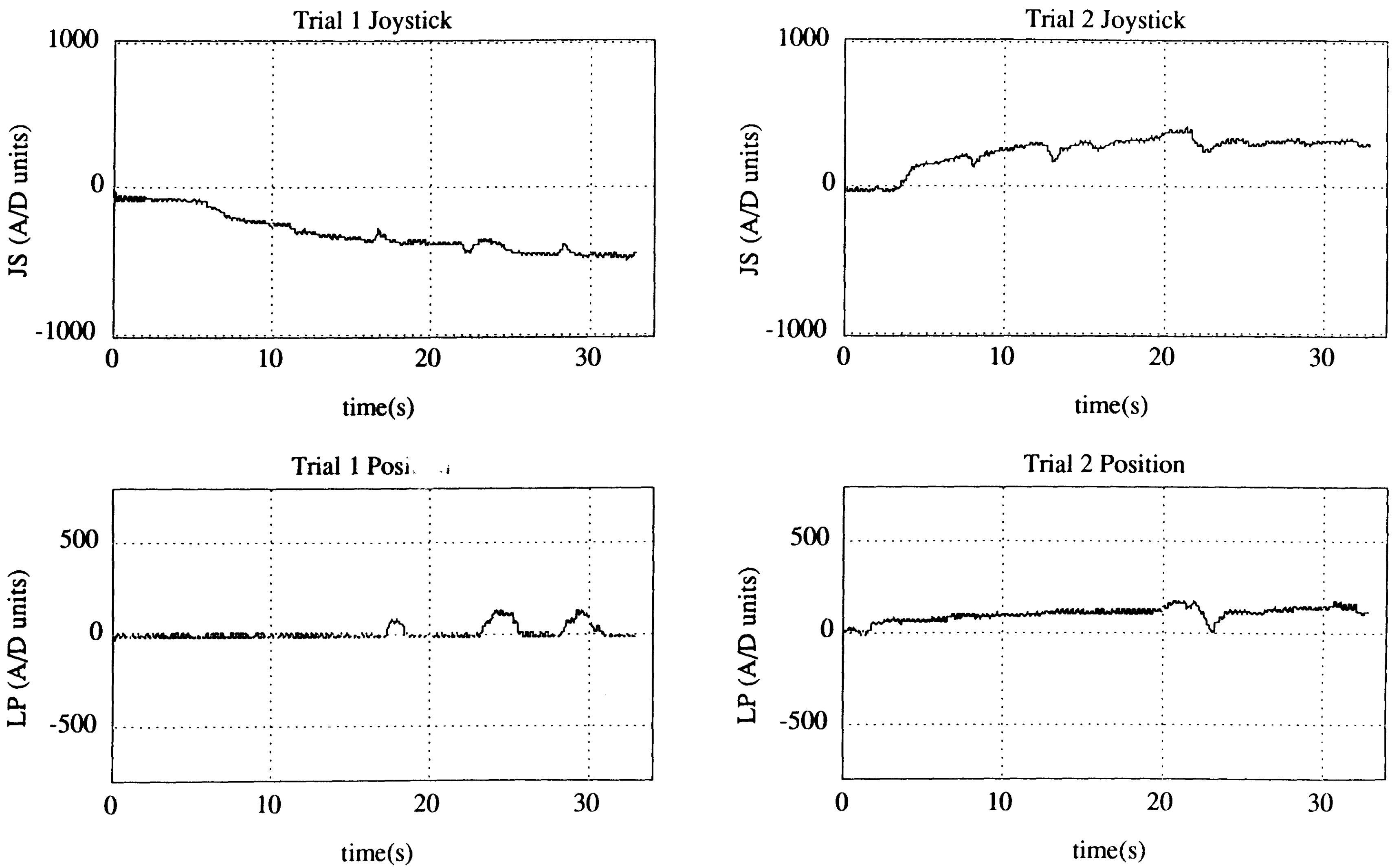


Figure A5.43
Subject 10 Joystick and Position Data
2 of 6 trials, Tactile cue = 500 grams

vection indications look similar enough that it appears as though the subject may have been indicating tilt, with a lag of about a second, rather than vection. Figure A5.44 shows that, off of the biteboard, subject 10 felt more vection (or possibly tilt) at the zero weight condition than at any other, however this change was not significant. The on-biteboard change, again in the expected direction, was also not significant. The increase in vection that this subject felt when the biteboard was removed was trending towards significance for both the zero weight and 500 gram runs (b0 vs. n0, $p = .09$, and b500 vs. n500, $p = .067$).

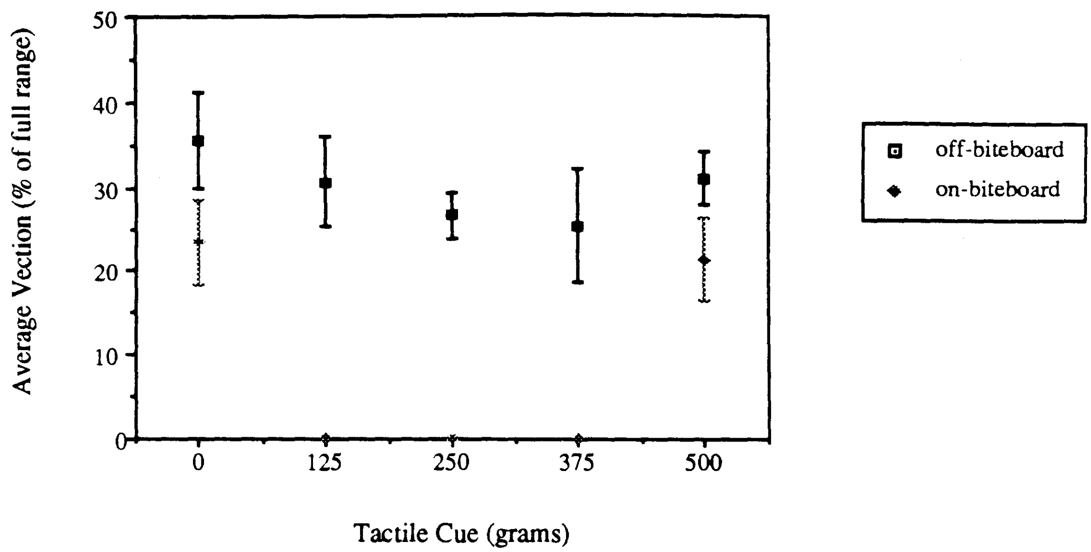
Subject 11 (naive)

Subject 11 was one of the two subjects that verbally reported that the generalized tactile cues decreased the sensation of self-motion. He noted this during the off biteboard run with a tactile cue of 375 grams. Position and joystick indications for this subject show a fairly large amount of body tilt with some high frequency oscillation (figures A5.45 through A5.48). Though subject 11 reported feeling less vection with the weights his joystick indications do not confirm this quantitatively (see figure A5.49). The only statistically significant result this subject demonstrated was an increase in average vection between biteboard and no-biteboard runs without tactile cues (b0 vs. n0, $p < .05$). This same test performed on the values for maximum vection showed a trend toward significance ($p = .074$).

Subject 12 (non-naive)

This subject felt that the onset of tilt and vection were coincident, and expressed concern that she might be indicating large changes in vection when she felt large changes in posture. The comment about the onsets of both sensation being at the same time is

Subject 10



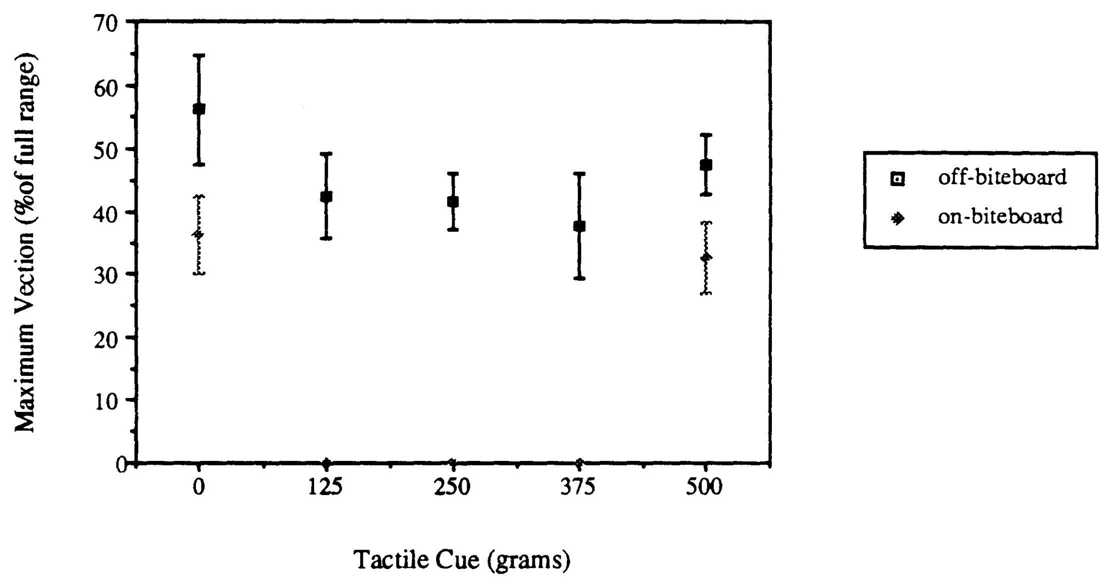


Figure A5.44:
Plots of Average and Maximum
Vection vs. Applied Tactile Cue

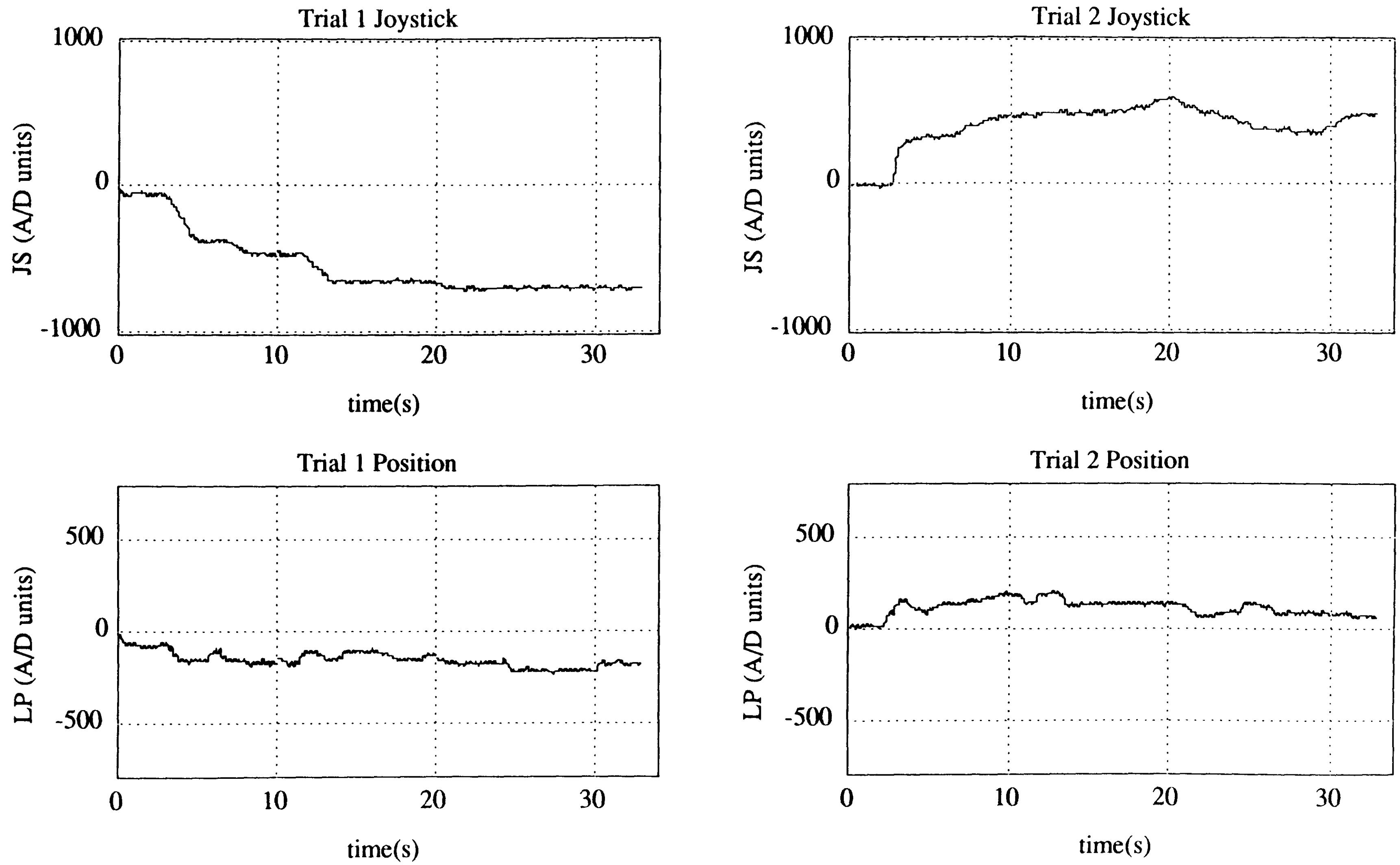


Figure A5.45
Subject 11 Joystick and Position Data
2 of 6 trials, Tactile cue = 125 grams

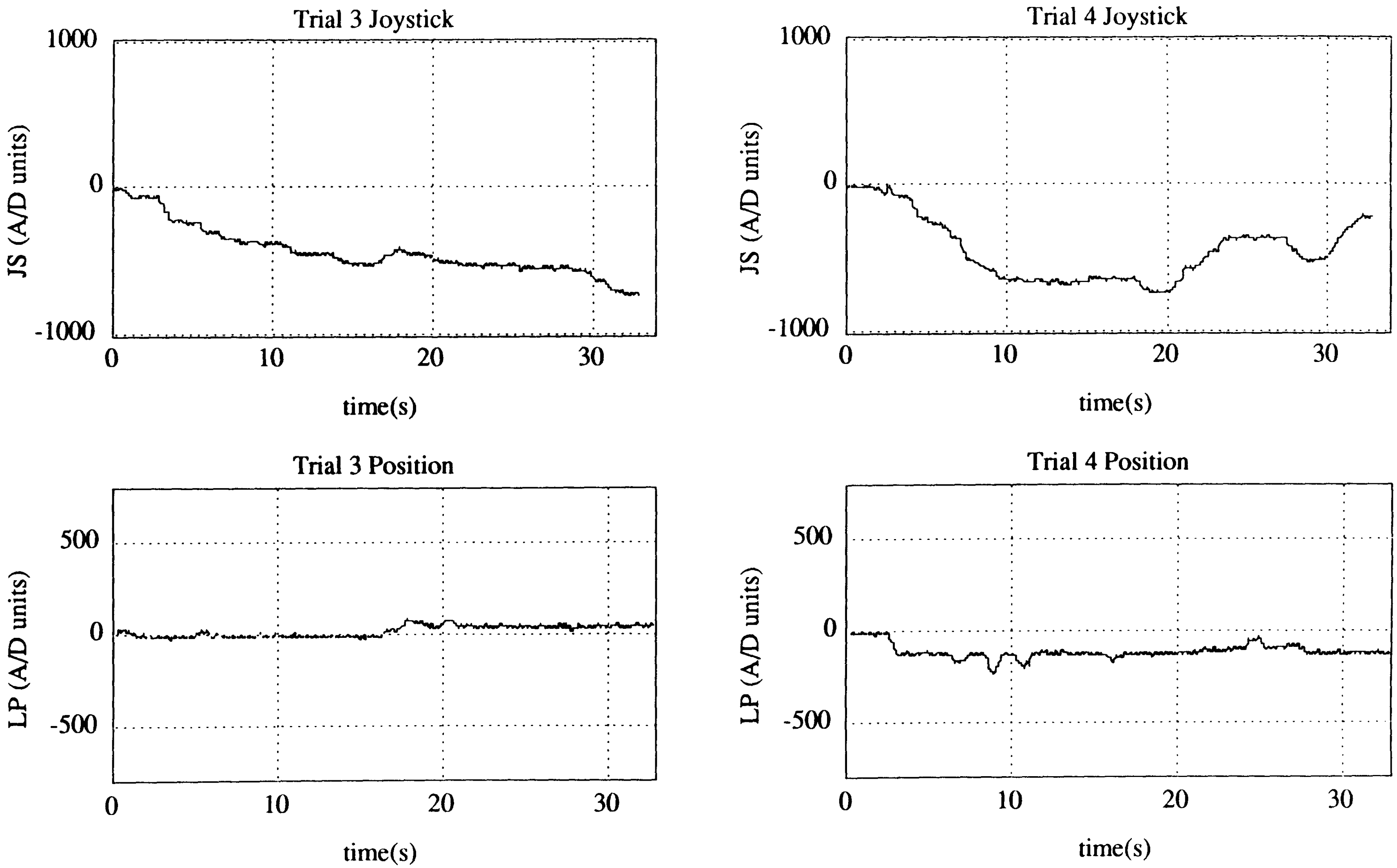


Figure A5.46
Subject 11 Joystick and Position Data
2 of 6 trials, Tactile cue = 250 grams

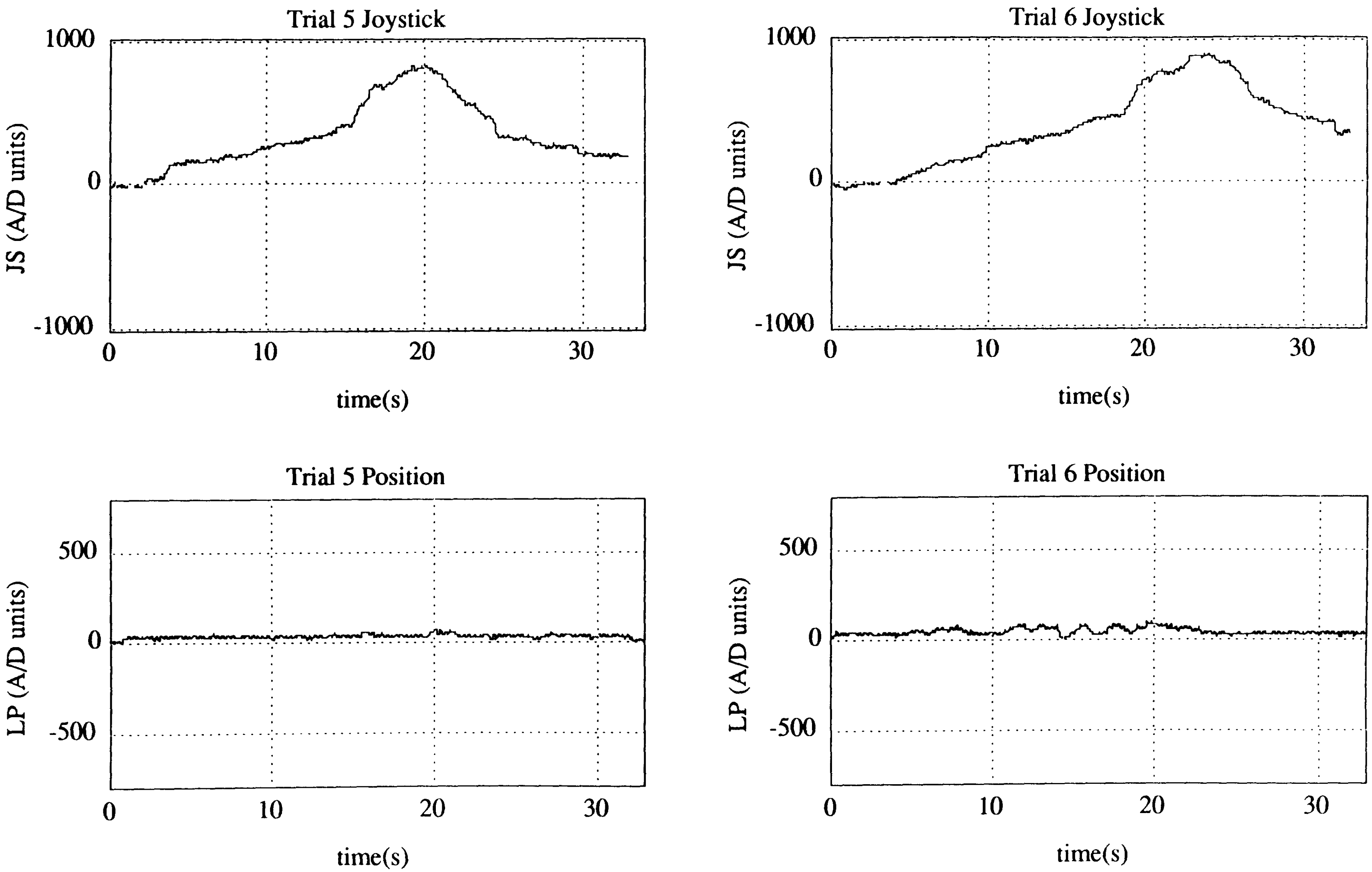


Figure A5.47
Subject 11 Joystick and Position Data
2 of 6 trials, Tactile cue = 375 grams

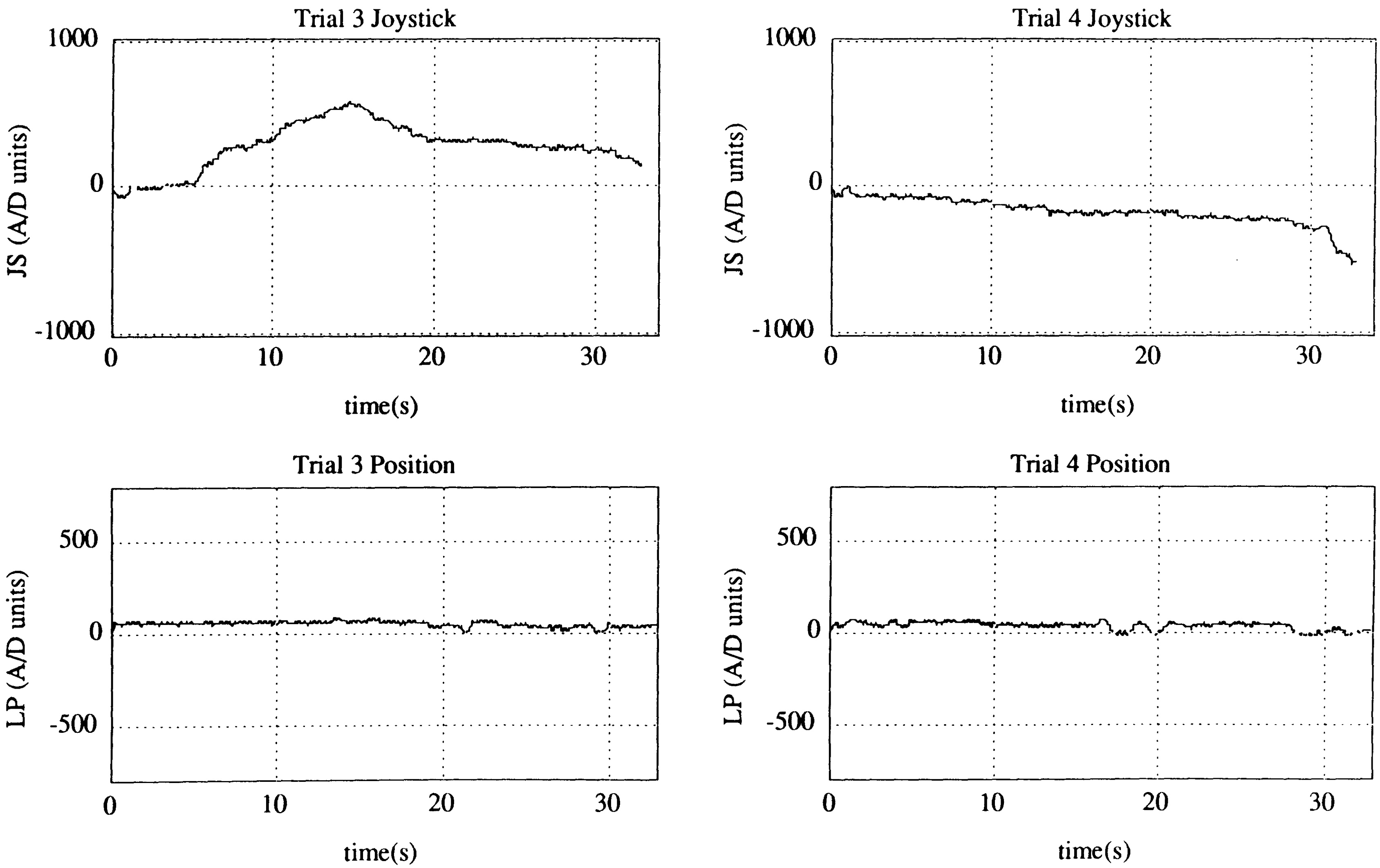
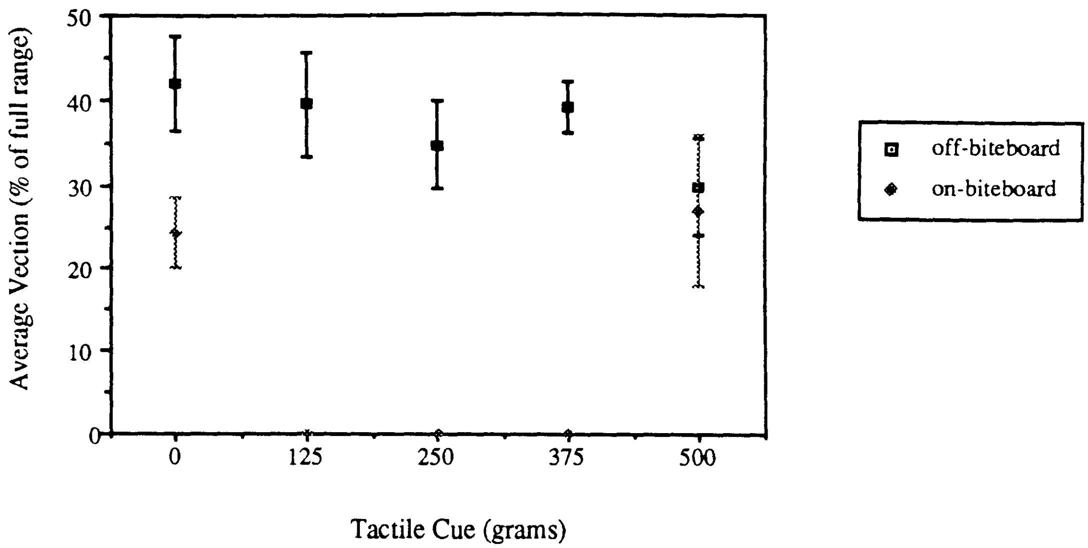


Figure A5.48
Subject 11 Joystick and Position Data
2 of 6 trials, Tactile cue = 500 grams

Subject 11



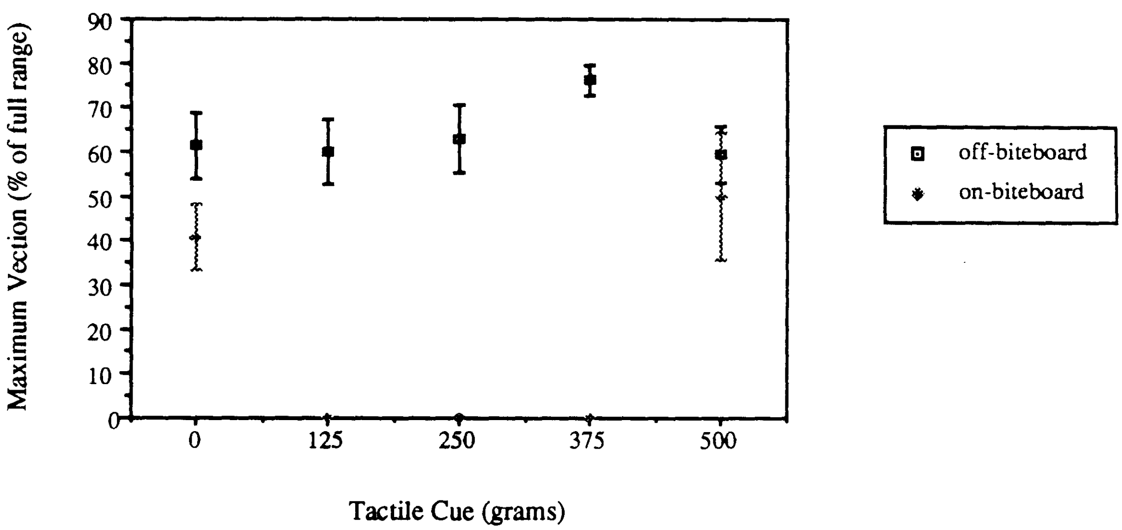


Figure A5.49:
Plots of Average and Maximum
Vection vs. Applied Tactile Cue

reinforced by the graphs in figures A5.50 through A5.53. Figure A5.54, graphs of average and maximum vection, show that this subject felt stronger vection at zero and 125 grams than at 250, 375, or 500 grams for the off-biteboard runs. For the t-test done between the zero and 500 gram conditions (off the biteboard), the change was in the expected direction and trending towards significance (average vection n0 vs. n500, $p = .084$, maximum vection, $p = .156$). The biteboard vs. no biteboard tests showed a trend towards significance with no cues applied (average vection, $p = .107$, maximum vection, $p = .070$) but were not at all significant when tactile cues were applied.

Subject 13 (naive)

Subject 13 complained of several symptoms of motion sickness. His first symptoms, headache and fatigue, began after the fifth run. During the final two runs he also developed slight epigastric awareness and sweating. During the last few runs the test conductor noted increased muscle contractions in the lower legs as well. The data recorded for this subject was very noisy, but plots of position and joystick over time are presented (figures A5.55 through A5.58), and show no apparent correlation between the two signals. Figure A5.59 contains plots of average and maximum vection vs. applied cue for both the on and off-biteboard runs, showing the zero condition vection to be greatest. This result is significant at the $p < .05$ level for the zero to 500 gram comparison (n0 vs. n500). On the biteboard this subject showed a change in vection in the expected direction , but it was not significant. The influence of the biteboard was highly significant, reducing vection in trials with and without the additional tactile cues (b0 vs. n0 and b500 vs. n500, $p < .05$).

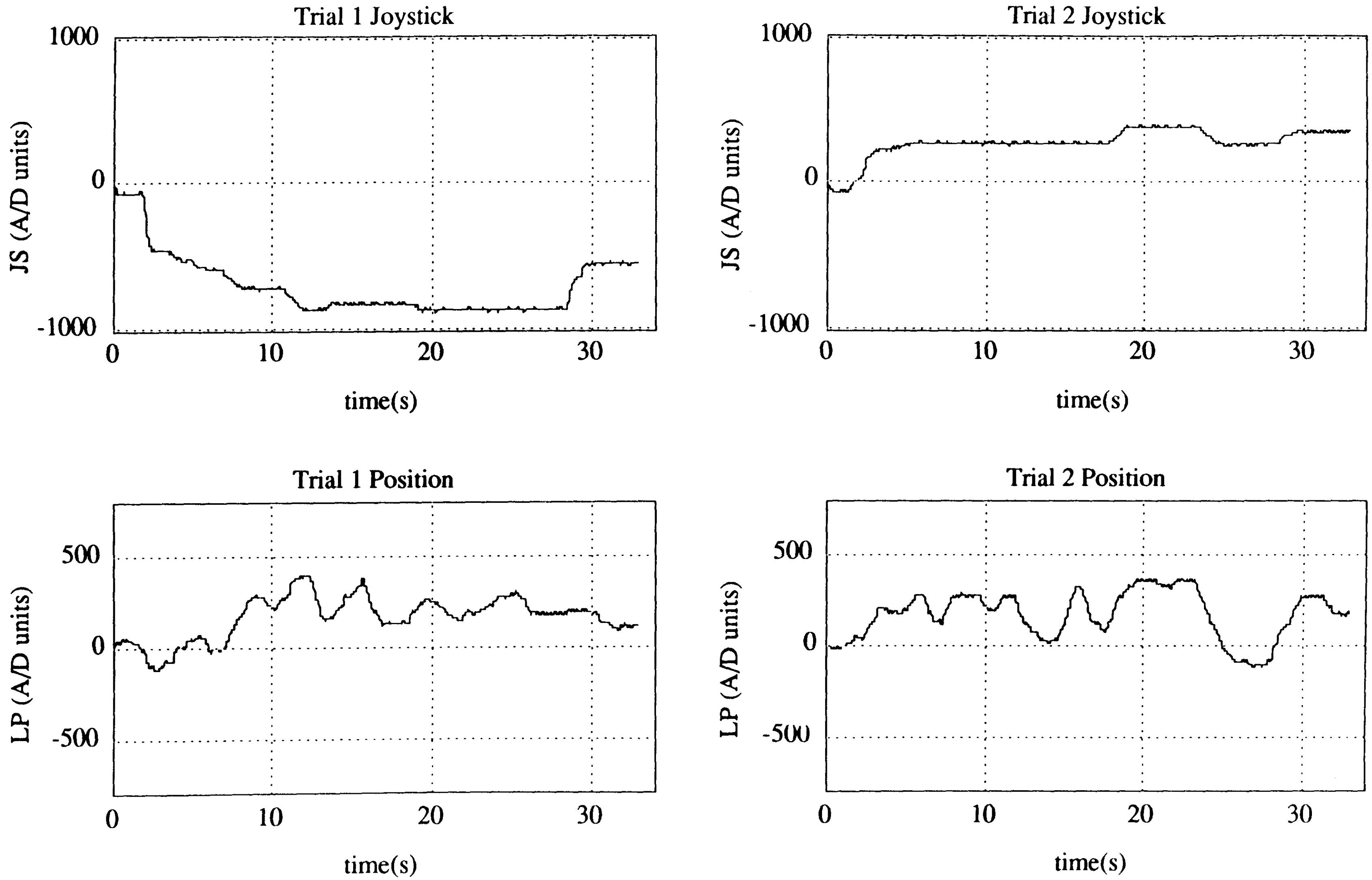


Figure A5.50
Subject 12 Joystick and Position Data
2 of 6 trials, Tactile cue = 125 grams

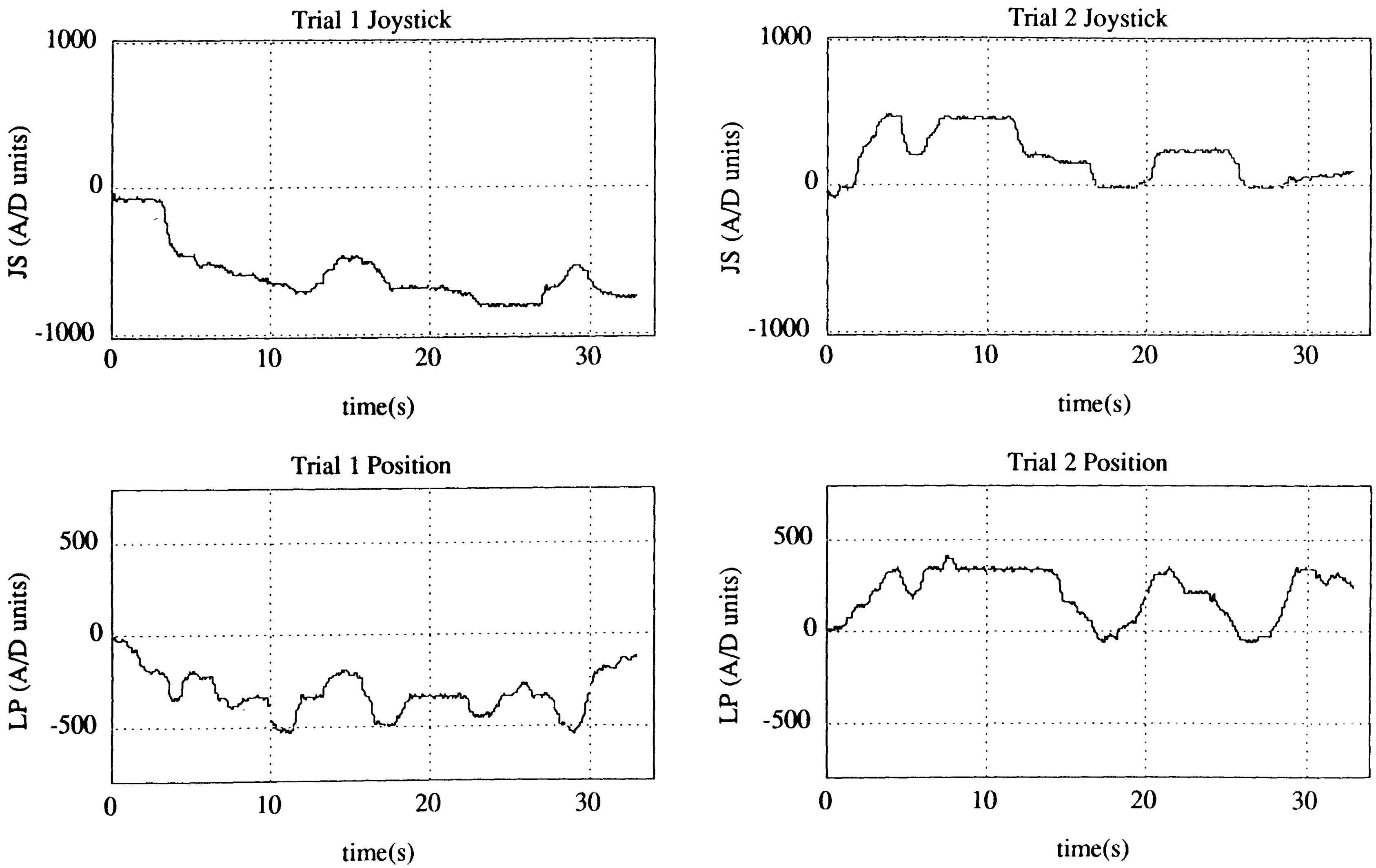


Figure A5.51
Subject 12 Joystick and Position Data
2 of 6 trials, Tactile cue = 250 grams

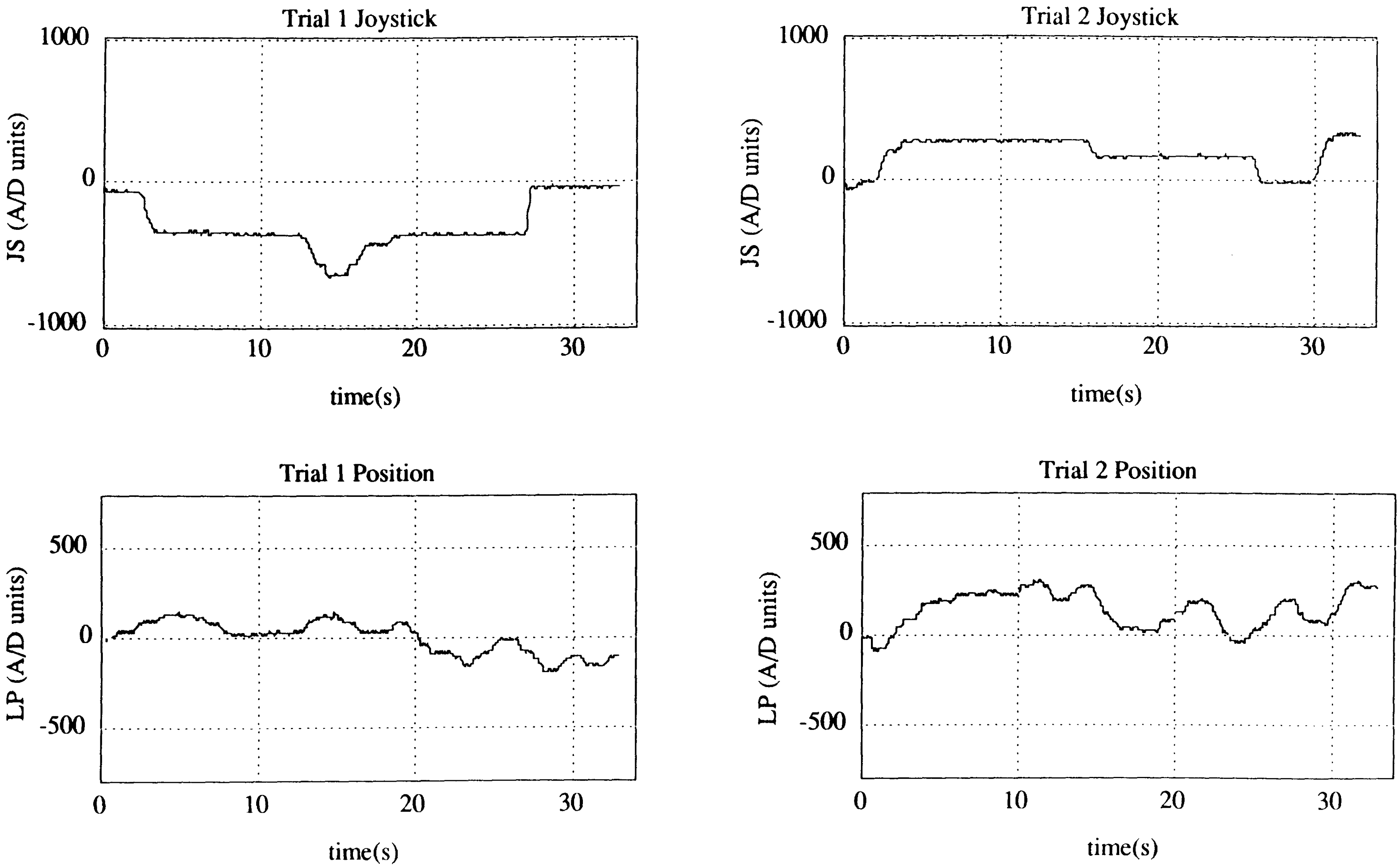


Figure A5.52
Subject 12 Joystick and Position Data
2 of 6 trials, Tactile cue = 375 grams

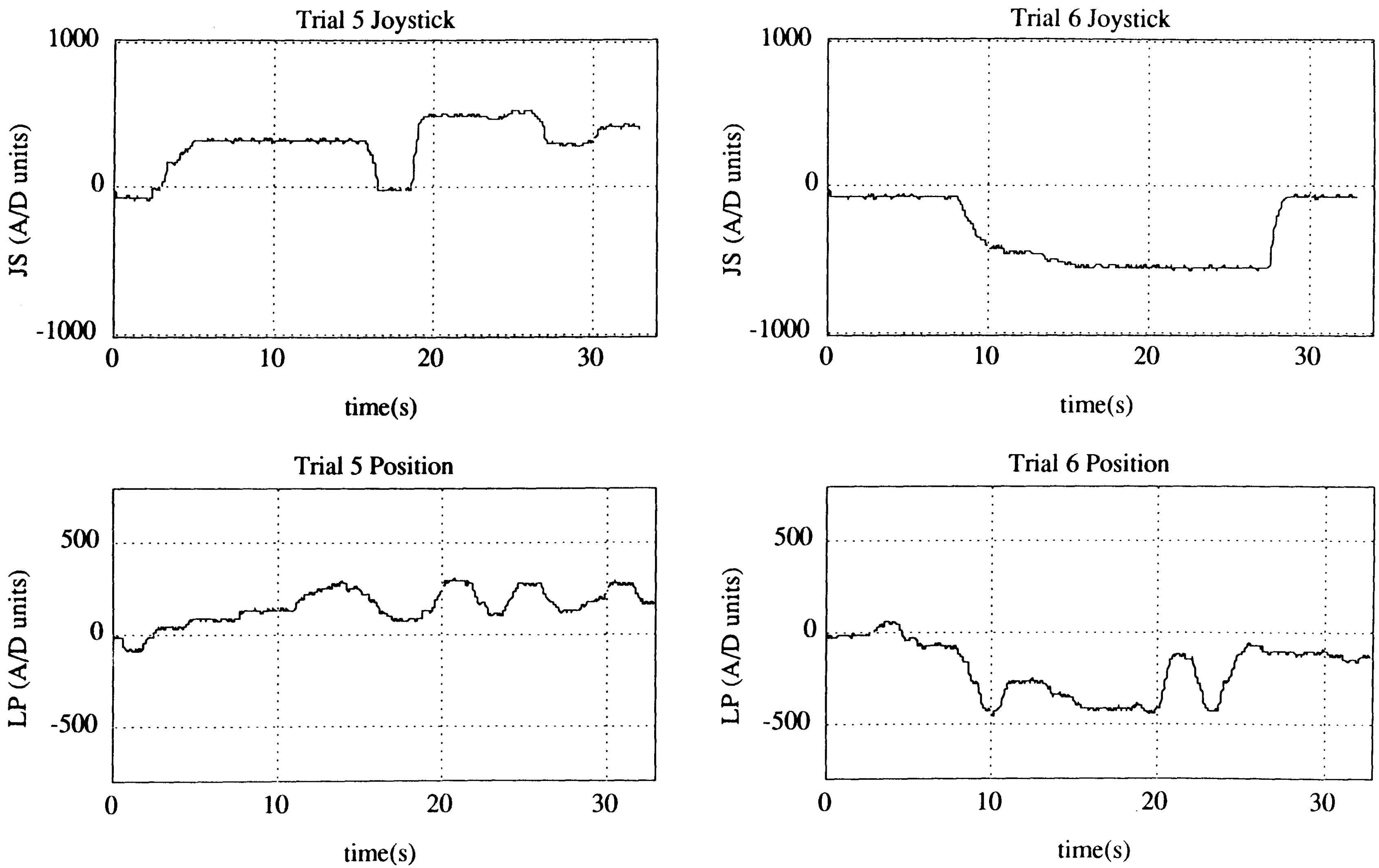
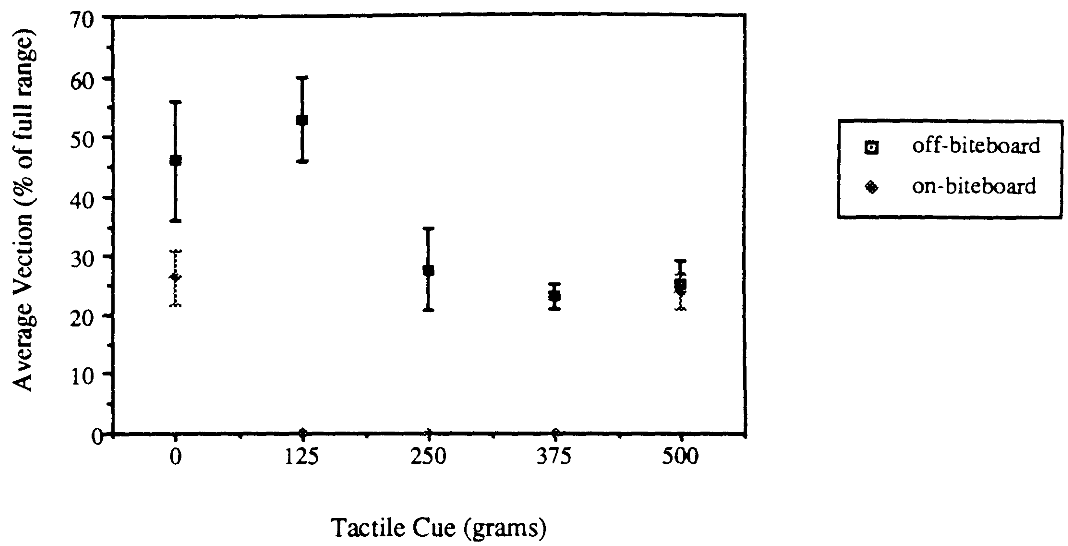


Figure A5.53
Subject 12 Joystick and Position Data
2 of 6 trials, Tactile cue = 500 grams

Subject 12



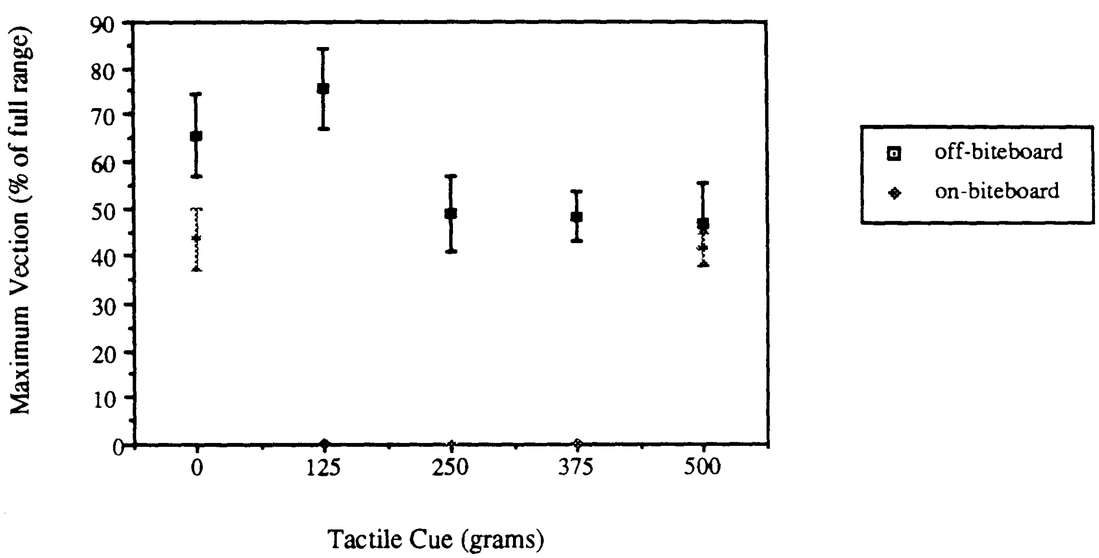


Figure A5.54:
Plots of Average and Maximum
Vection vs. Applied Tactile Cue

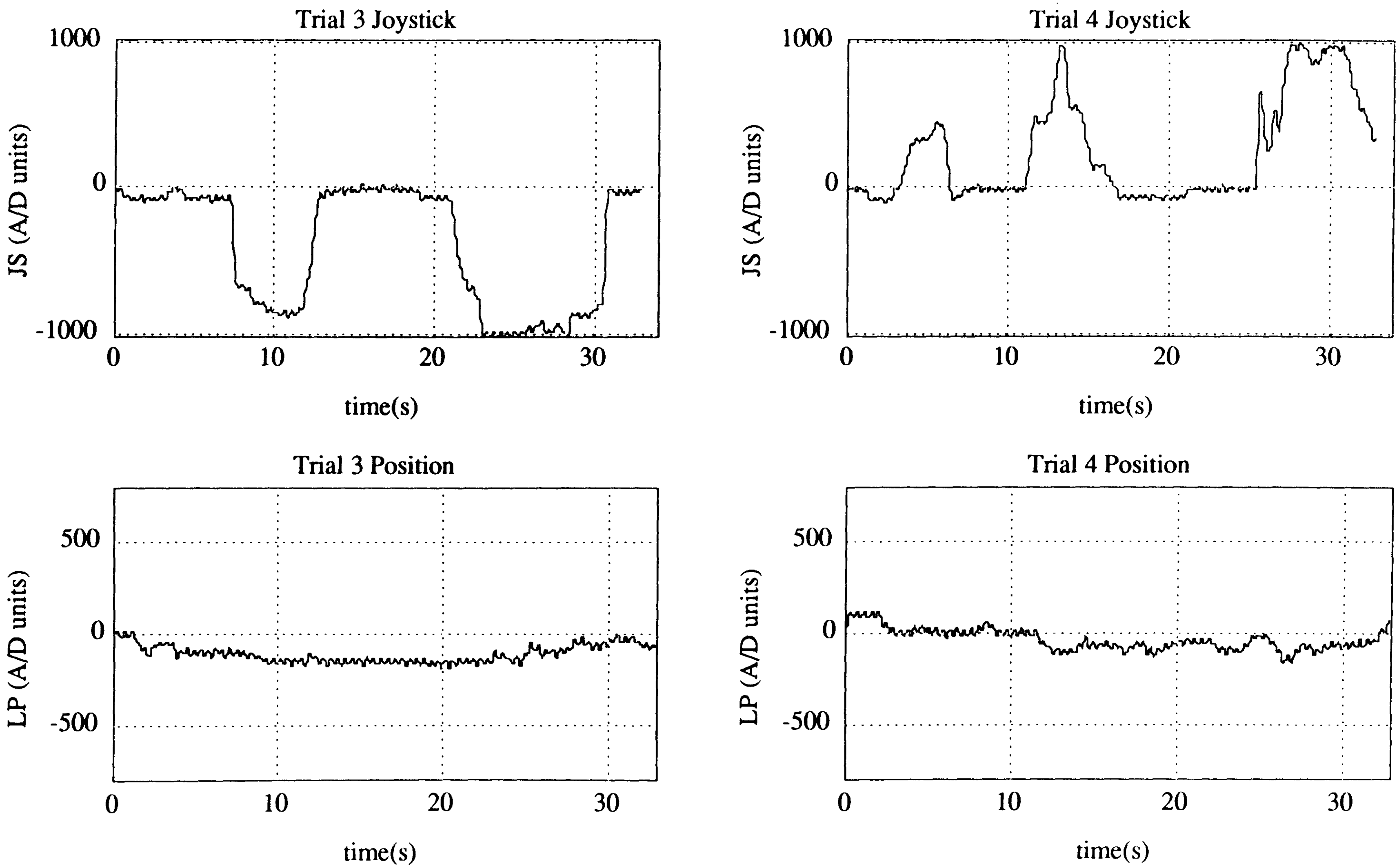


Figure A5.55
Subject 13 Joystick and Position Data
2 of 6 trials, Tactile cue = 125 grams

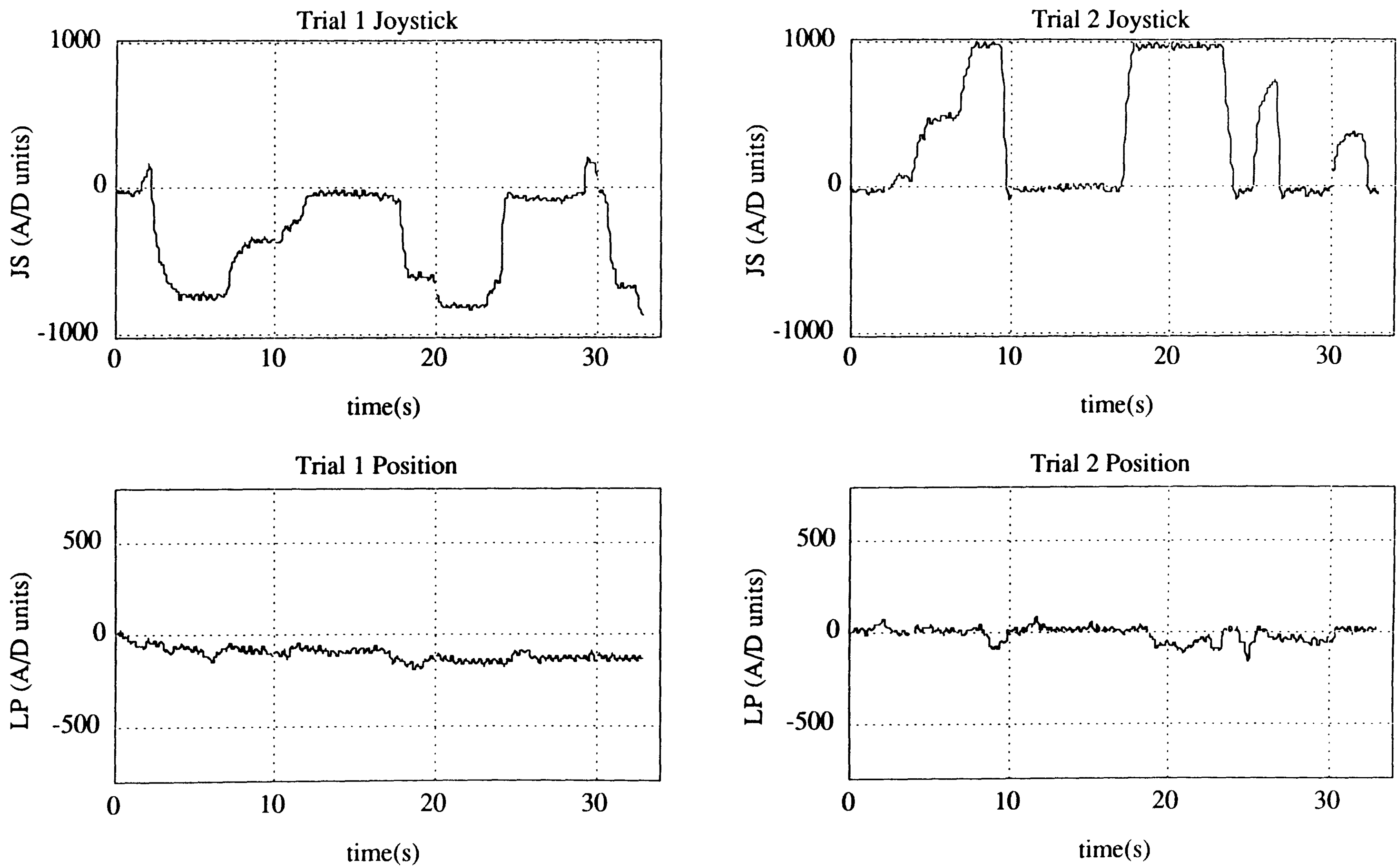


Figure A5.56
Subject 13 Joystick and Position Data
2 of 6 trials, Tactile cue = 250 grams

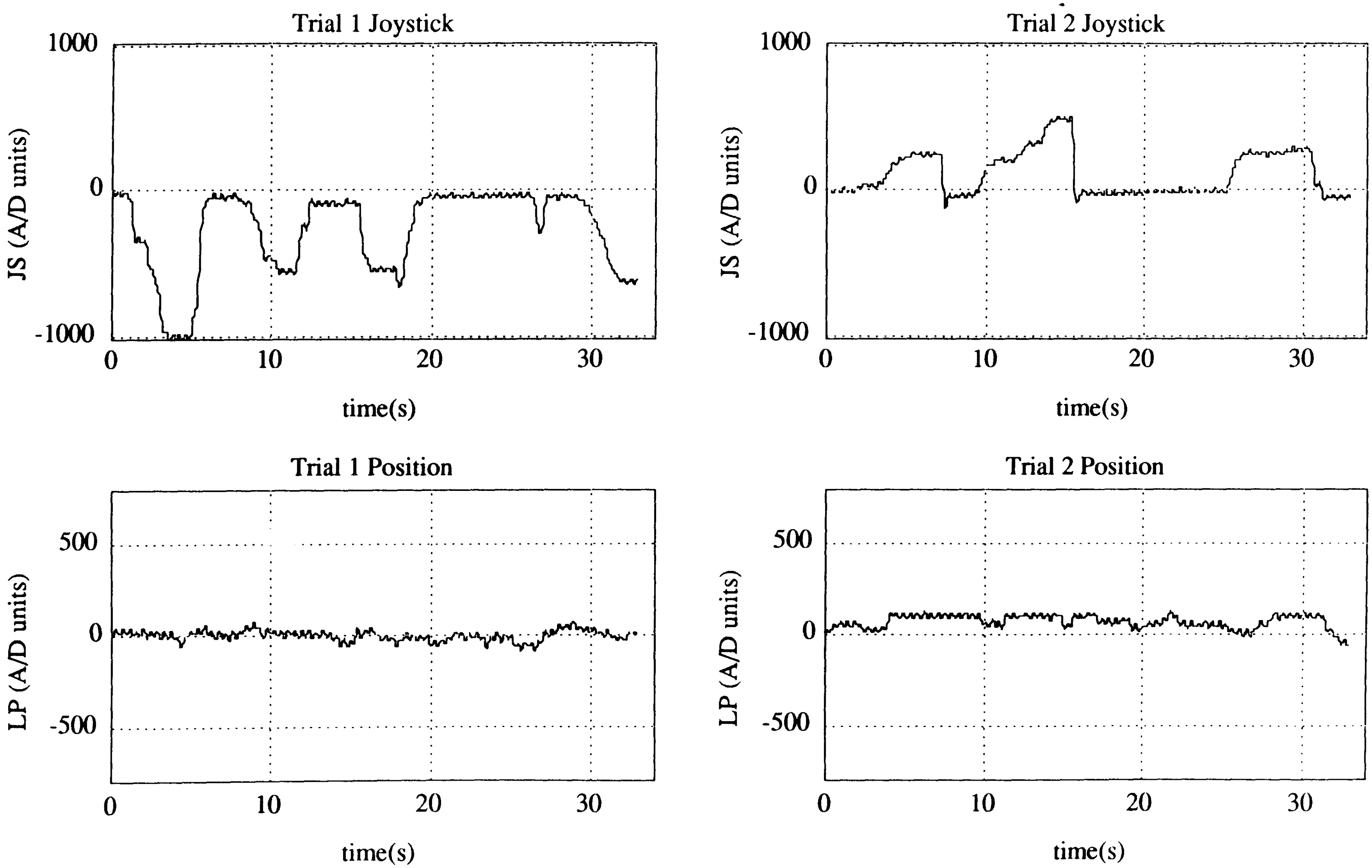


Figure A5.57
Subject 13 Joystick and Position Data
2 of 6 trials, Tactile cue = 375 grams

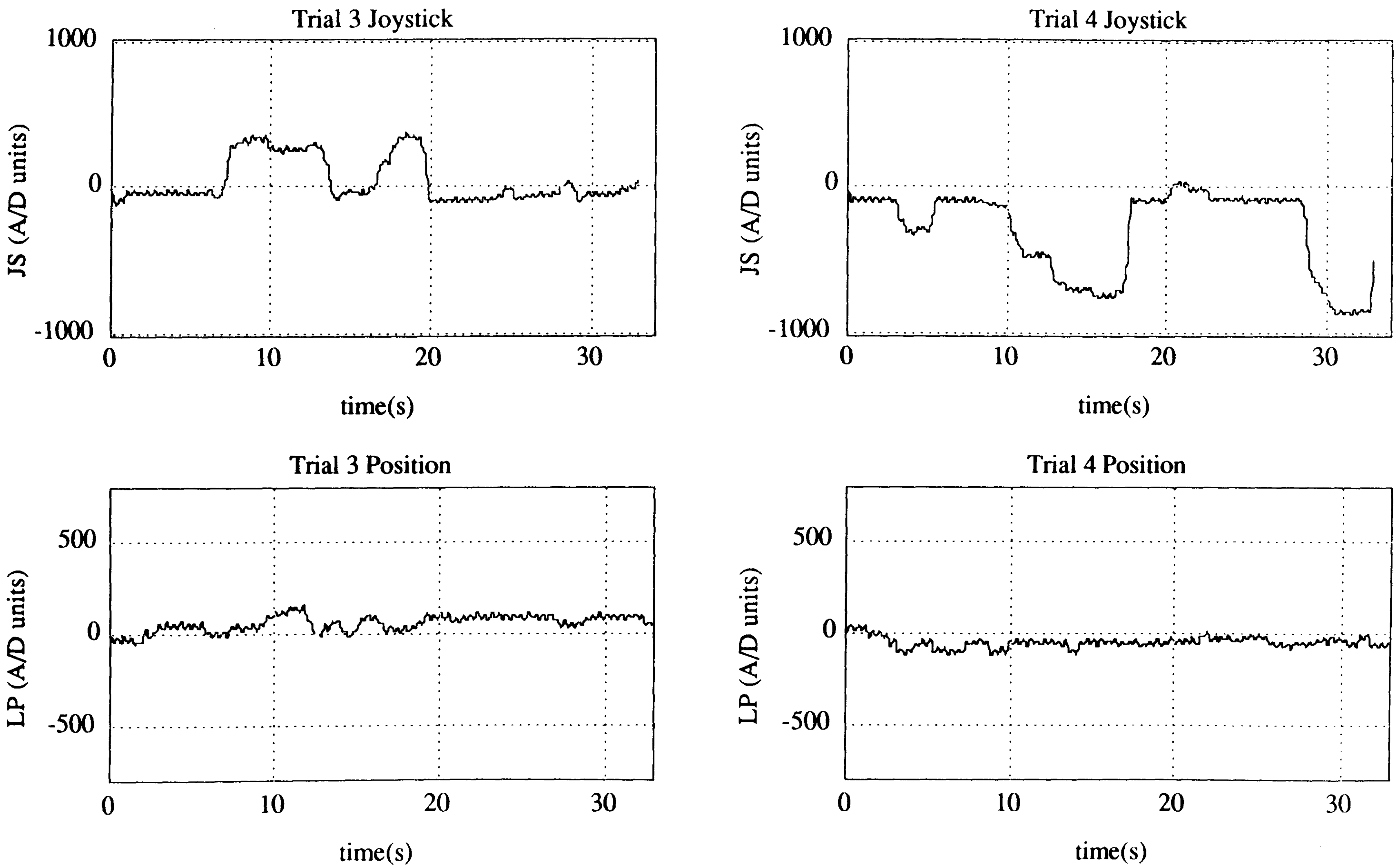
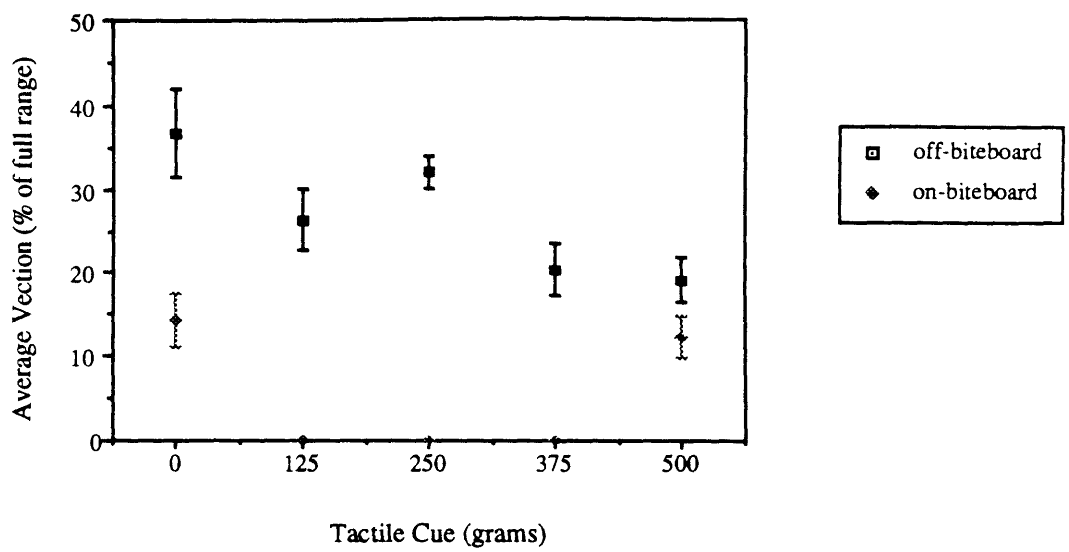


Figure A5.58
Subject 13 Joystick and Position Data
2 of 6 trials, Tactile cue = 500 grams

Subject 13



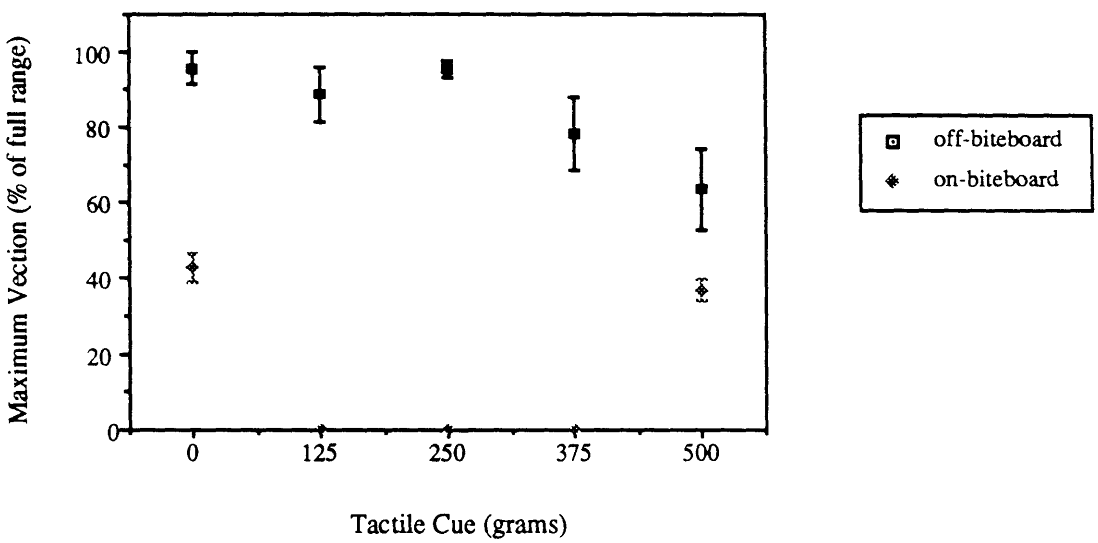


Figure A5.59:
Plots of Average and Maximum
Vection vs. Applied Tactile Cue

Subject 14 (non-naive)

The last subject tested made no specific comments during the test session. The joystick and position signals look very similar (figures A5.60 through A5.63) indicating that even this non-naive subject may have been using the joystick to indicate perceived tilt. Figure A5.64, average and maximum vection vs. tactile cue for all runs shows that the zero weight condition, as expected, has the largest value of estimated vection. This was not, however, a significant result. The tests of biteboard vs. non-biteboard runs do show a high degree of significance ($p < .01$) for average and maximum vection both with and without the shoulder cues applied.

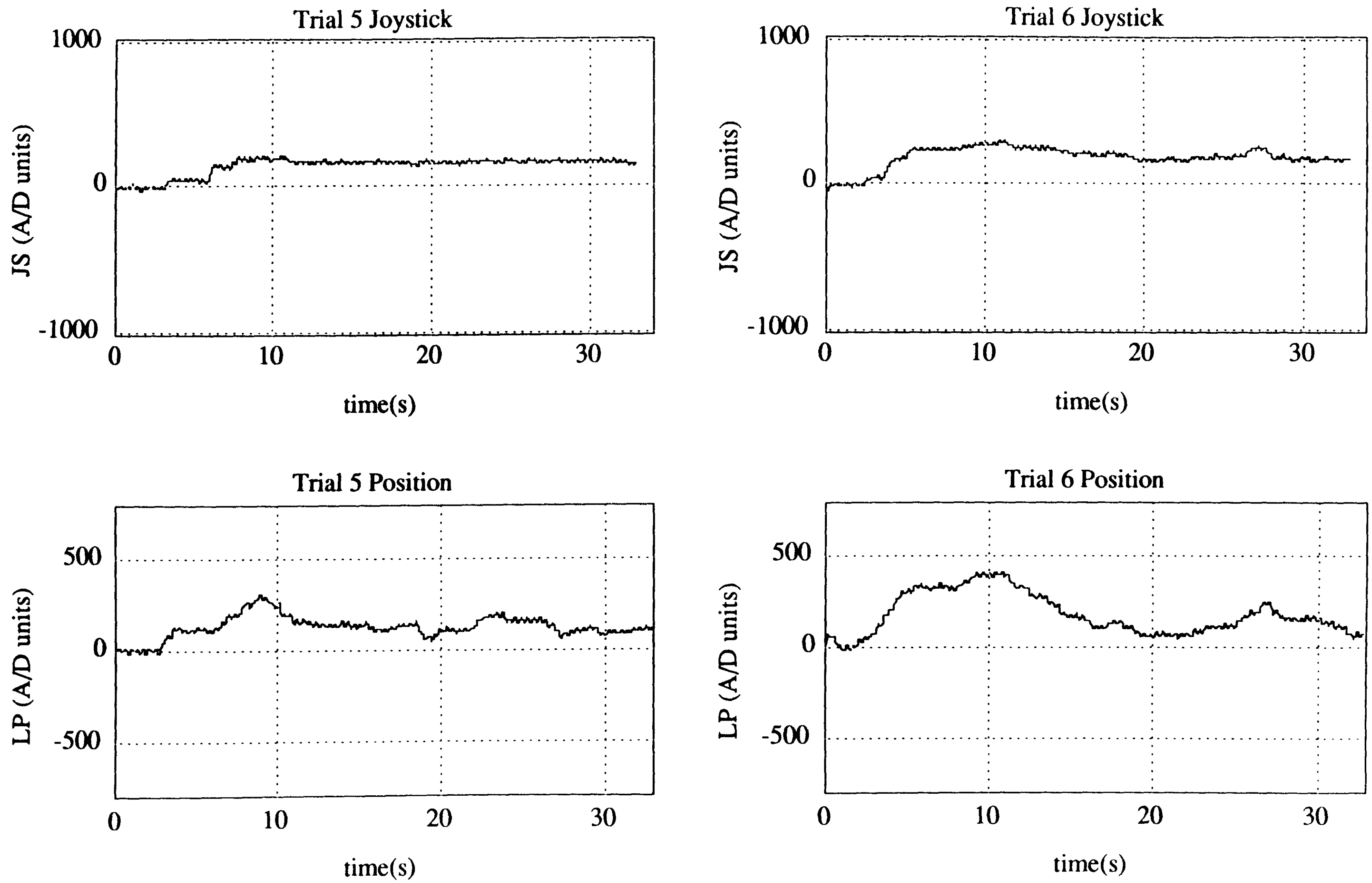


Figure A5.60
Subject 14 Joystick and Position Data
2 of 6 trials, Tactile cue = 125 grams

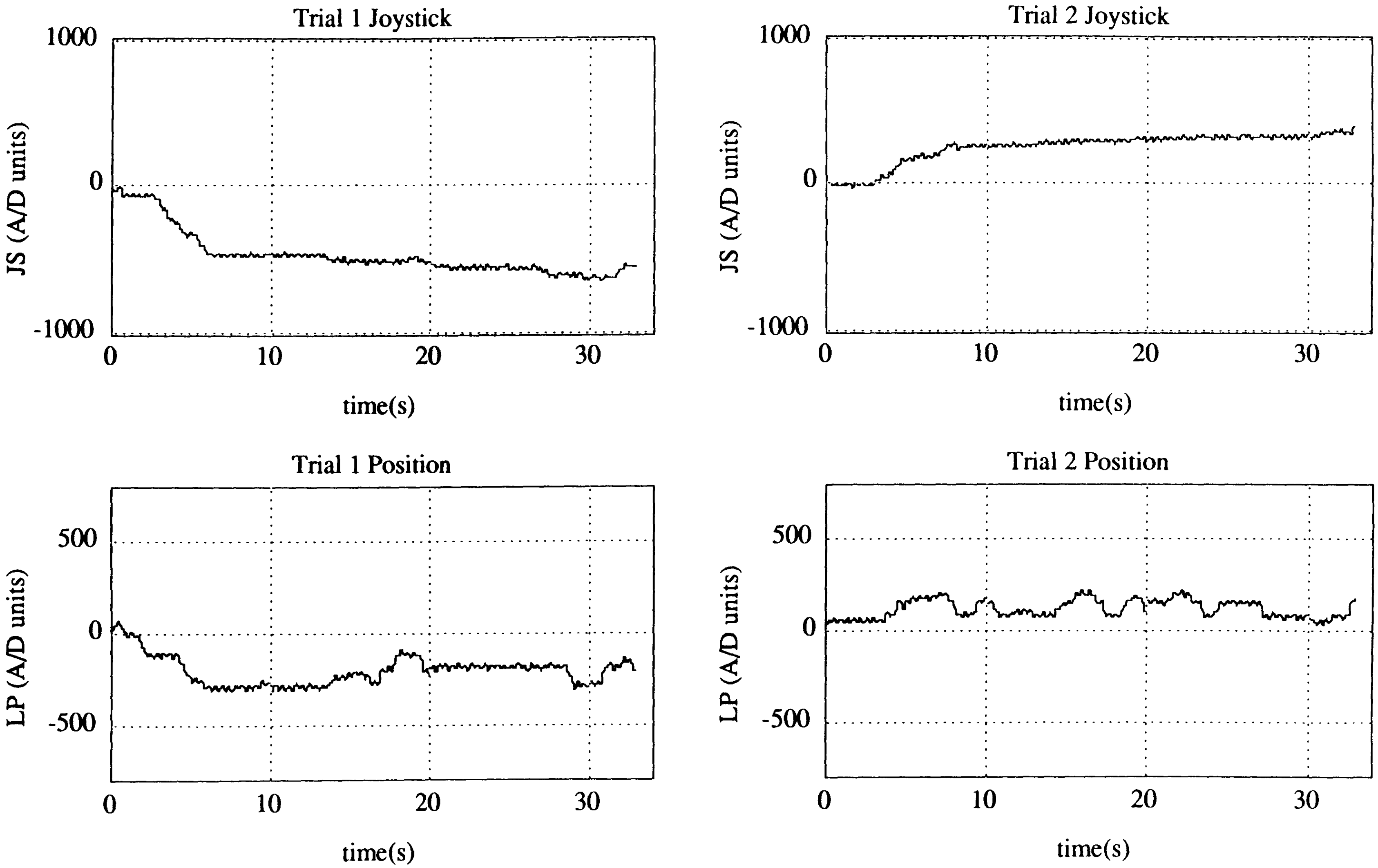


Figure A5.61
Subject 14 Joystick and Position Data
2 of 6 trials, Tactile cue = 250 grams

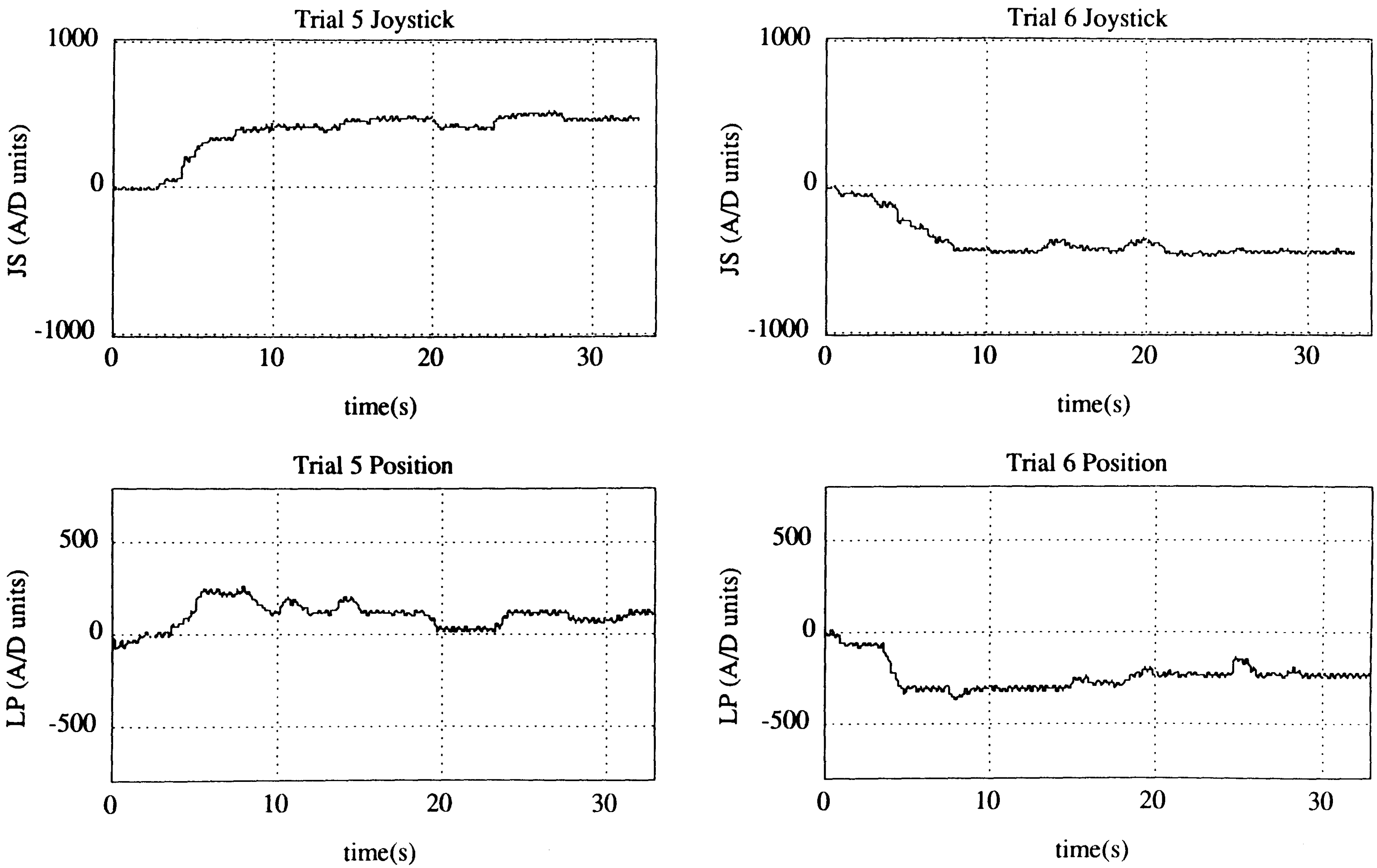


Figure A5.62
Subject 14 Joystick and Position Data
2 of 6 trials, Tactile cue = 375 grams

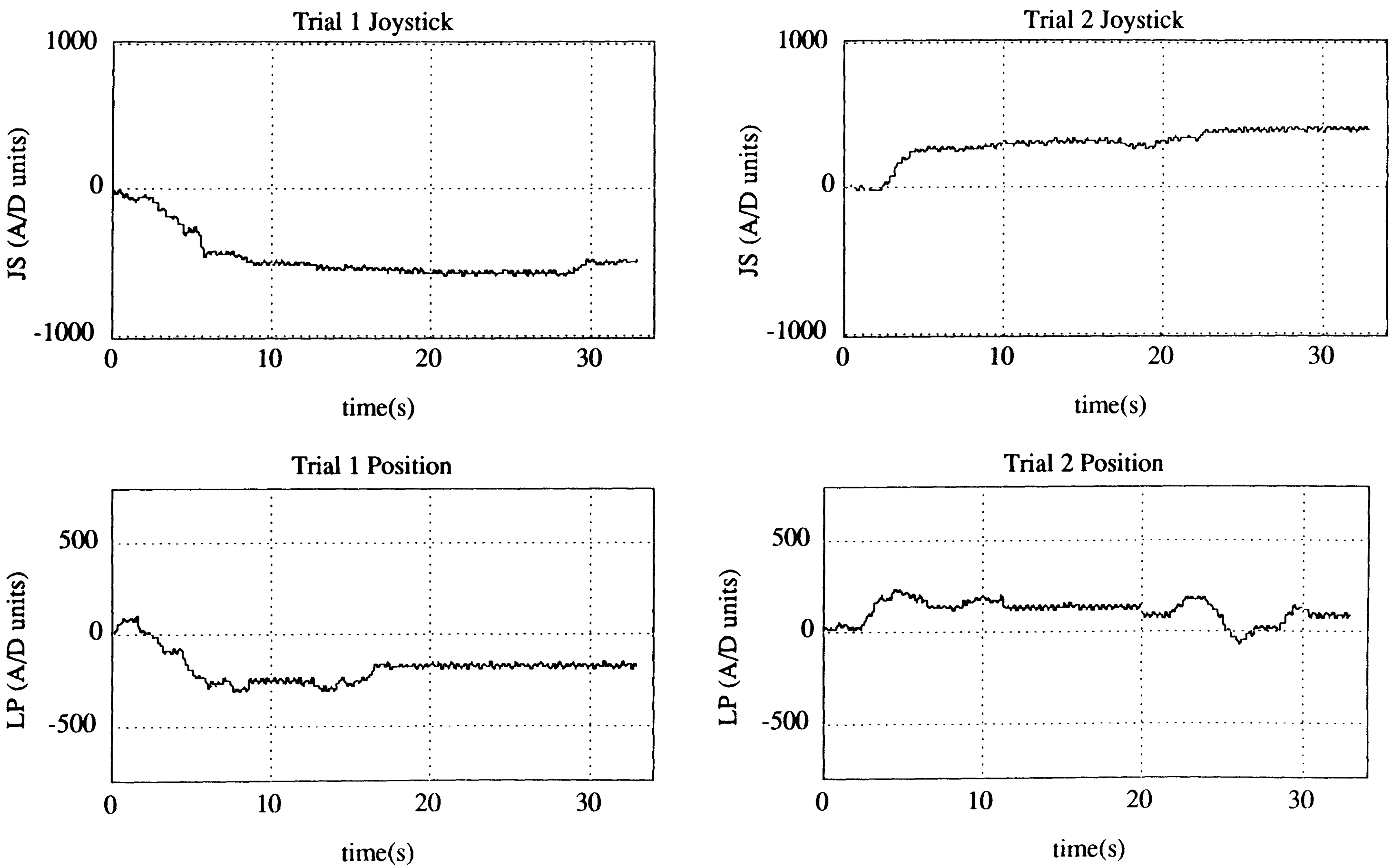
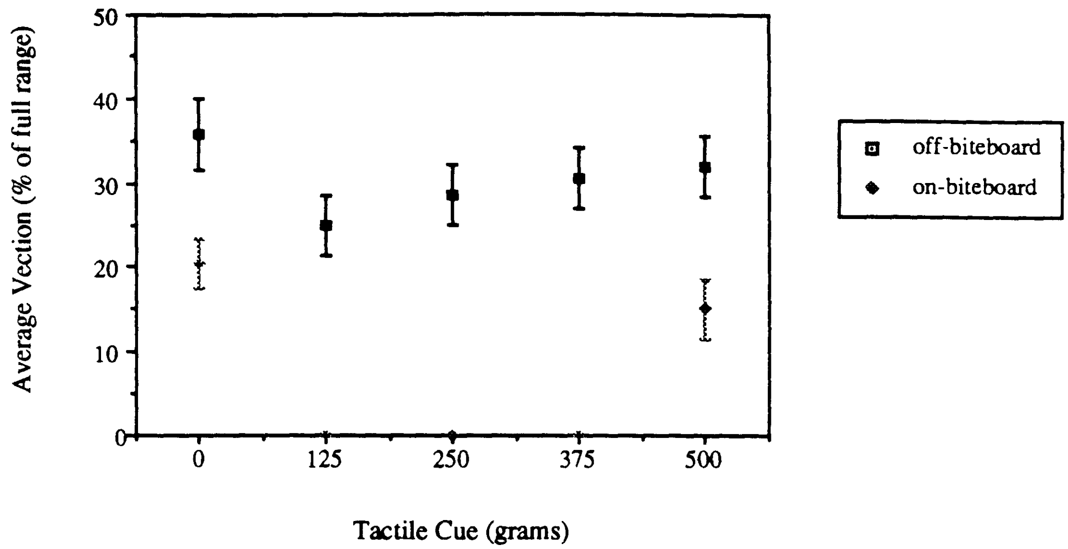


Figure A5.63
Subject 14 Joystick and Position Data
2 of 6 trials, Tactile cue = 500 grams

Subject 14



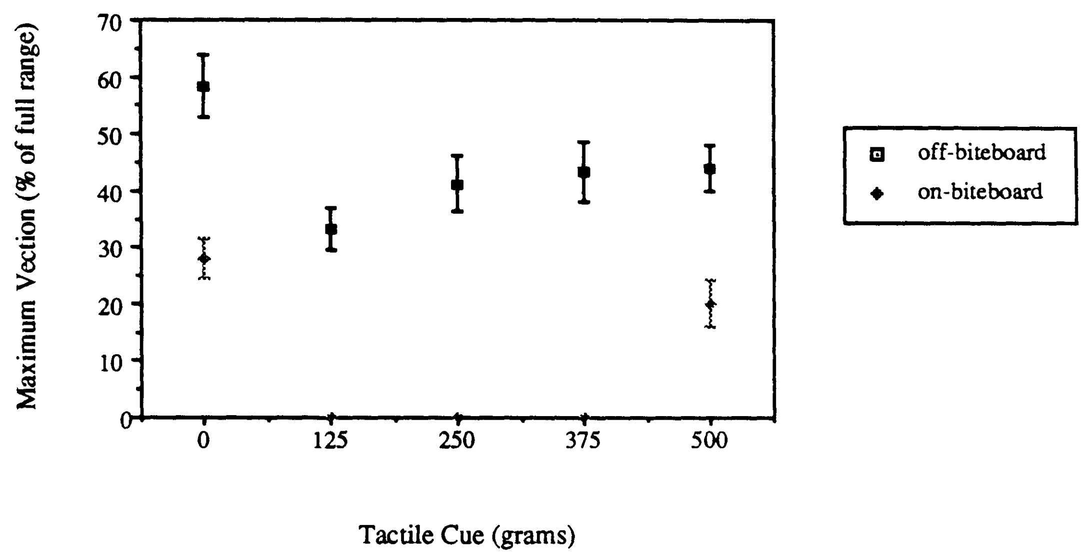


Figure A5.64:
Plots of Average and Maximum
Vection vs. Applied Tactile Cue