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Comparison of Five On-Head, Eye-Movement Recording Systems

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16. Abstract

This study compared the relative merits of five eye-movement measuring systems with regard to their applicability for studying drivers' visual behavior. The systems tested were Applied Science Laboratories 210, Applied Science Laboratories 4000 Series, ISCAN Headhunter, NAC Model V, and Ober2. Evaluations were made from laboratory tests on dimensions including accuracy, discomfort (pain and pressure, weight, imbalance, and freedom of movement), view obstruction, safety, and compatibility with the driving task. Consideration was given to the systems' usefulness both for on-road and laboratory use.

Accuracy was evaluated by recording eye-system data output from a subject following a regimented visual tracking task. The ASL 4000 performed best, followed by the ISCAN and the Ober2. Comfort was rated on four parameters by the wearer on a seven-point scale. Overall, the Ober2 rated most comfortable, followed by the ASL 4000. View obstruction was evaluated by mapping the wearer's field of view. Overall, the ISCAN and the ASL 4000 restricted field of view the least. The results from the laboratory tests, as well as from the manufacturers' specifications, are summarized.

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INTRODUCTION

This report describes the second phase of a project regarding human factors and driver eye fixations. In the first phase, the literature describing eye-fixation recording methods and hardware are summarized (Green, 1992). In the current study, five currently-available, on-head eye movement recorders were tested on various measures of four attributes: accuracy, ease of calibration, comfort, and safety. In addition, relevant system specifications are reported. Systems were evaluated mainly for suitability of use in vehicles on public roads, but consideration was also given to use in a laboratory simulator. The systems used in this study were selected based on a few project constraints: all are on-head units; are manufactured within the last 10 years; cost under US$60,000; and are available for rent or use by the authors locally.

Because of the potentially broad audience and its range of research interests, this report does not attempt to provide one overall ranking of the systems tested. Rather, the results are presented feature by feature, so that recording systems may be compared within attributes. For example, a researcher interested in using an eye camera in a laboratory driving simulator may have different requirements for subjects' field of view than a researcher conducting an on-road driving study. The final discussion summarizes each cameras' overall results independently. In this way, readers may focus on features and attributes that are most important to them.

This report should be of interest to researchers who are investigating options for collecting driver eye movements and fixations, or who are considering the purchase of equipment for the study of drivers' eye behavior. This audience will primarily consist of human factors researchers, psychologists, and automotive engineers.

Description of Parameters Evaluated

Accuracy

The accuracy of an eye-movement recording system indicates how distinguishable one eye glance is from another. The acceptable level of accuracy for direction of gaze is dependent upon the experimental question. If the experiment requires distinguishing only between large regions (inside of a vehicle and outside of the vehicle) then only crude accuracy (and consequently, crude calibration) is needed. If the experiment requires distinguishing between glances to small objects close together, then high accuracy and comprehensive calibration are needed.

For this study, a visual tracking task was designed to measure the dynamic accuracy of each eye camera. The output from this task does not reveal accuracy directly, but reveals how the accuracy interacts with the eye-gaze location, when the system is reasonably calibrated. Distortion and inconsistency are common especially at the edges of the functional range of each device. Manufacturers' reported accuracy and resolution are also listed, including compatibility with glasses and contact lenses.

Calibration and ease of use

Constraints on calibration and ease of use are similar for simulated and actual driving. It must be easy to place the unit on the driver's head and to make adjustments on the unit while the subject is sitting in a vehicle.

Ease of calibration was evaluated generally, in this study, based on the amount of time, and number of iterations and procedures that were required to obtain a reasonable calibration. A brief description of the manufacturers' calibration procedures is also included.

Comfort

Subject comfort can significantly impact the outcome of a study. If a headpiece is intolerable or uncomfortable, it will reduce the data collection time for each test session. Subjects may not be motivated to cooperate or even participate if they feel discomfort due to the equipment. In many cases, 30 minutes of use (including calibration time) is a tolerable limit for naive subjects. (Testing on willing colleagues might be withstood longer.) The nature of discomfort associated with wearing the headpieces is fully described, as well as rated for level of acceptance. Some of the identified problem areas, such as imbalance of the headpiece, can be partially corrected by the experimenters.

Safety

When using an on-head, eye-movement recorder for actual driving, the primary concern is the performance of the driver: is the wearer safe to drive with the headpiece? Drivers' field of view can greatly affect driver performance. A restricted field of view is not only unsafe for driving on public roads, but also changes the natural state of driving. Drivers' eye fixation behavior and related head movements will be altered by a reduced field of view. If a sensor or other part of the headpiece is located directly in front of the eyes or face, it will interfere with vision and can be an injury risk in the event of a collision. The field of view of each headpiece was mapped and the areas of blockage, and their associated visual angles, identified.

Subjects' freedom of movement also affects safety. The cables and size of the unit must allow the wearer to turn and move in the full range associated with normal driving conditions. As this study was conducted in a laboratory, freedom of movement was based on wearer appraisal. Excessive on-head unit weight also will also affect drivers' freedom of movement and behavior.

Of course, safety factors differ based on the test location. Safety is not as much of an issue for simulator studies, at least in terms of collision, though a small field of view can unacceptably change fixation behavior. If studies are carefully controlled, limited head movement may be acceptable, but again could affect fixation behavior.

MATERIALS

System Descriptions

All systems tested were infrared based. Two systems (ASL 210 and Ober2) use the relative light reflections from different parts of the eye and eyelid to determine eye position. This method is susceptible to interference from eyelashes and fatigue (which lowers the eyelids). One system (NAC V) uses a single light reflected from the cornea to determine eye position. This method is extremely sensitive to unit movement on the subject's head. The other two systems tested (ASL 4000 and ISCAN) use the relative locations of a light reflected from the cornea and the location of the pupil to determine gaze direction. This two-point calculation is more accurate than single-point, and is less susceptible to slippage of a head-mounted eye camera, or turning of the subjects head, for an off-head eye camera.

Applied Science Laboratories model 210 (ASL 210)

The Applied Science Laboratories model 210 is a modulated infrared based system. A photo emitter with photo detectors on either side is aimed directly at each eye from below, at about 45 degrees (see Figure 1). One set of emitter/detectors measures the difference in reflectivity between the iris and sclera (for horizontal gaze direction), the other set measures the difference in reflectivity between the lower eyelid and the sclera (for vertical gaze direction). The assignment of eyes for vertical and horizontal measurement is determined by the experimenter. The optional scene camera is mounted on a headband on the forehead.

No modifications were done to the device used for this evaluation, although a rear counterweight is recommended to help alleviate neck strain due to forward imbalance.

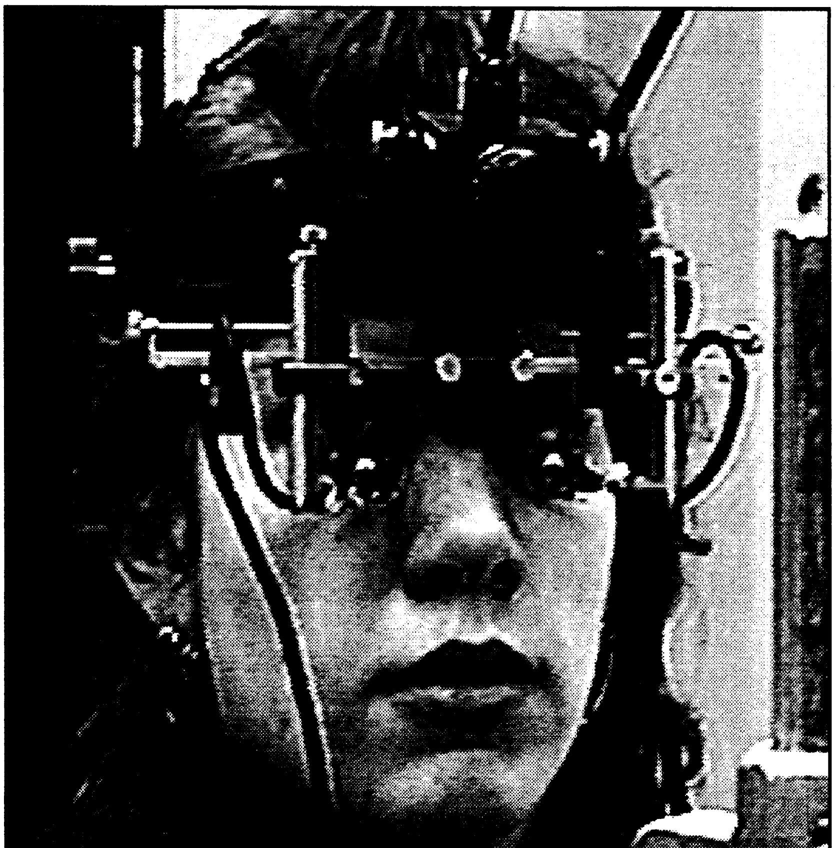

Figure 1. The ASL 210 headset.

Applied Science Laboratories model 4000 (ASL 4000)

The Applied Science Laboratories 4000 series is a near infrared based system. This system, shown in Figure 2, uses a camera and infrared illuminator mounted above the forehead, aimed downward at an infrared coated visor, to obtain an image of the eye with corneal reflection and bright pupil. The system determines the relative positions of the center of the corneal reflection and the bright-pupil image and computes the eye-gaze direction. The optional scene camera is mounted below the visor, avoiding parallax between the computed eye position and the scene. Dark-pupil measurement can be done with an optional optic system.

Figure 2. ASL 4000 with helmet mount and horizontally mounted scene camera.

The device tested had the headband mounting and had a scene camera as shown in Figure 2, except the camera was mounted vertically. The entire eye tracking assembly had been relocated to track the right eye. This was done to prevent the wearer, while driving, from hitting the forward scene camera on the side window. A black cloth head-cover was attached to the top of the visor and the headband to eliminate overhead light. A custom weight was attached to the back of headband to reduce neck strain. To make the device functional in a vehicle for daytime use, custom IR-filter coated plastic was being fabricated for blocking the side-incident light. This configuration had not yet been tested.

ISCAN Headhunter (ISCAN)

The ISCAN is an infrared based system. A camera and infrared light source are mounted above the forehead on a helmet or a headband. The image of the eye is reflected onto the camera lens by a circular, coated piece of glass, mounted at approximately a 45 degree angle, in front of the eye. (See Figure 3.) The system uses a custom algorithm to track the corneal reflection and dark-pupil images, from which it computes the direction of gaze. The optional scene camera mounts beneath the reflective glass and records the forward view as reflected by the front of the glass. The scene camera is mounted horizontally with a prism over the lens to bend the light 90 degrees into the camera.

Figure 3. The ISCAN showing scene camera and reflective glass.

On the device evaluated for comfort and field of view, the forward scene camera mounting had been modified to increase its stability and range of motion. Custom padding is a necessity for fitting the extra large helmet on an average wearer's head. This system, locally available for evaluation, was a six-year-old prototype. The system used for tracking data collection at ISCAN was the latest PC, card-based system. Though the basic function and layout of the head unit is the same for the new system, the components, such as the eye imaging glass and the cameras, have been upgraded.

NAC Eye Mark Recorder model V (NAC V)

The NAC model V system uses two infrared LEDs, mounted below and in front of each of the wearer's eyes, to create a corneal reflection. (See Figure 4.) The images of these reflections for each eye are recorded through a series of mirrors and lenses, by cameras mounted on stalks to each side of the wearer's head. The scene camera is mounted on top of the device, on the wearer's forehead. This system is an old design, from before 1983.

For this experiment, the left camera unit was removed--since we only intended to calibrate the right eye--for increased peripheral field of view, especially needed for driving. Removing half of the device caused an imbalance, which was partially corrected with a counterweight. The original padding was replaced by more extensive custom padding to increase comfort and stability. The wires from the individual head camera units (the right eye camera, the scene camera, and the LED power) were bundled together to allow freer movement, especially head turning.

Figure 4. The NAC model V headpiece.

Permobil Meditech Ober2 (Ober2)

The Permobil Meditech Ober2 is an infrared based system. The head-mounted part of the system is a pair of goggles (see Figure 5). Each eye is surrounded by four arrays of pulsed infrared diodes and detectors, arranged in a square, for determining the horizontal and vertical position of each eye. The system consists of a PC, card-based control board to be installed into a 386 or 486 DOS machine. A small interface box connects the goggles to the board, and provides electrical isolation.

Nothing was altered on the Ober2 for this experiment; however, wearer comfort would improve if thin padding were added over the plastic edges that rest against the cheeks.

A supplementary video superposition PC card is being planned for this system. This would allow the subject's eye fixations to be recorded onto video. It is not known if the video source would be on- or off-head. If the video source were to be on-head, it would increase the size and weight of the equipment worn by the subject.

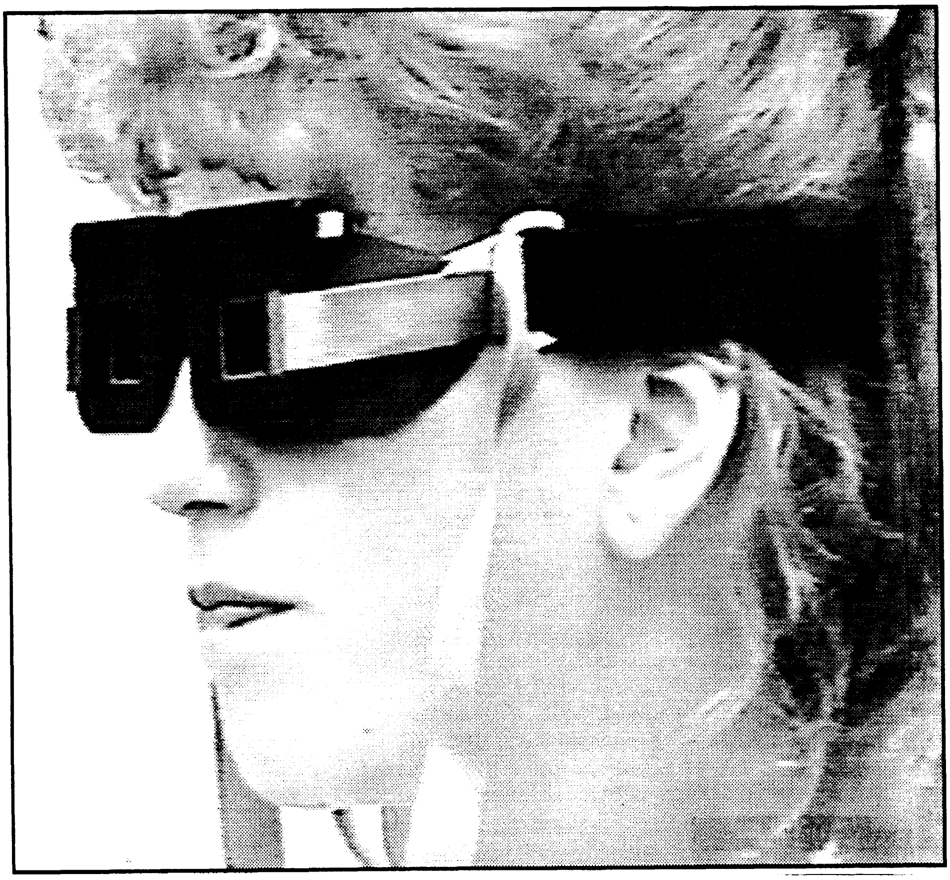

Figure 5. The Ober2 goggles.

Equipment Specifications

The systems described in the above section vary in functional range and accuracy. Table 1 shows the range, precision, and accuracy of each system, as reported in their documentation. Precision refers to the average angular error the system will have in measuring the distance the eye fixation moves from one point to another. Accuracy refers to the average angular error the system will have in identifying a given fixation location in real space. Note that the precision is generally much better than the accuracy. Accuracy is more closely related to calibration than is precision.

The systems tested also vary by maximum sampling rate. The sampling rate for standard NTSC video analysis is 30 Hz, the update rate of video. The values in Table 2 are the maximum sampling rate for numeric data collection. The NAC model V is limited to 30 Hz because the data are communicated to the output unit at the top of each video frame.

Table 1. Range, precision, and accuracy of systems tested.

	Horizontal (degrees)			**Vertical (degrees)**		
	Range	**Precision**	**Accuracy**	**Range**	**Precision**	**Accuracy**
ASL 210	±15	0.25	1	±15	1	2
ASL 4000	50	<0.5	1-2	40	<0.5	1-2
ISCAN	±15	0.5	NA	±15	0.5	NA
NAC Model V	60	0.8-3.2 †	NA	45	0.8-3.2 †	NA
Ober2	±25	0.05	0.5	±20	0.05	1

NA = Not available

† Dependent upon compensation settings

Table 2. Sampling rates of systems tested.

	Maximum Sampling Rate (Hz)
ASL 210	1000
ASL 4000	60
ISCAN	60 (120†)
NAC V	30
Ober2	120, 1200†

†Possible with high speed version.

Table 3 lists the weight of all components worn by the subject, and the weight and size of other equipment used for experimentation. Table 4 lists the cost of all components tested in this experiment. Included here is all equipment (from the eye camera supplier and third-party vendors) required for collection of data in digital form. It should be noted that all prices listed here were in effect at the time of writing this report. They are subject to change at the supplier's or manufacturer's discretion. Prices listed for equipment that would be purchased from other vendors are based on an average of prices listed in current computer magazines.

Table 3. Weight and size of equivalent equipment configurations.

System	Weight of Unit on Head	Other Equipment
ASL 210	Sensors 60 g Headband 220 g Scene camera 170 g Total 450 g	Control unit 3.6 Kg (31 x 28 x 14 cm) Video interface Also requires: Video monitor PC compatible computer with Analog to Digital conversion board.
ASL 4000	Optics 280 g Headband 227 g Total 507 g	Control unit rack (three monitors built-in) 36 Kg (51 x 48 x 46 cm) Video interface
ISCAN	Optics/cameras 160 g Headband 185 g Optional Helmet 455 g Total (Headband) 345 g Total (Helmet) 615 g	Two monitors Video interface Also requires: PC compatible computer for installation of Pupil/Corneal Reflection Tracking and Autocalibration System PC cards
NAC Model V	Head unit 420 g	Controller 2.5 Kg (180 x 70 x 280 mm) Viewfinder 230 g (40 x 53 x 155 mm) Data output unit 10 Kg (300 x 100 x 240 mm) Also requires: PC compatible computer with Analog to Digital conversion board
Ober2	Goggles 80 g	Goggle interface box (15 x 15 x 5 cm) Also requires: PC compatible computer for installation of Ober2 board and Video Eye Superimposed board

Table 4. Pricing for systems tested.

System	Component	Cost (US$)
ASL 210	• Control unit, sensor assembly, PC cards and software for data collection • Headband • Scene camera and cables for headband	7,495 375 3,755 **Total $11,625**
ASL 4000	• 4000SU control unit • HMO-b (bright pupil) optics headband mount *Or, optional:* • HMO-d (dark pupil) optics headband mount • Head-mounted scene camera • 2 video monitors	20,000 11,000 7,000 4,000 600 **Total $35,600** (bright pupil) **Total $31,600** (dark pupil)
ISCAN	• Eye imaging system for headband • *Optional* helmet mounting • Scene imaging system for headband/helmet • RK-426 pupil/corneal tracking (PC card) • RK-520 5 point auto calibration (PC card) • 2 video monitors • *Optional* point-of-regard data acquisition and fixation analysis software (additional $1350)	7,000 575 4,600 13,000 6,800 600 **Total $32,000** (Headband-mounted) **Total $32,575** (Helmet-mounted)
NAC Model V	• Goggle unit with right and left eyemark shooting units • Camera controller with remote unit • Data output unit • Viewfinder *System no longer available for sale.*	 **Total $15,000** *Estimated value* *(no longer for sale)*
Ober2	• Standard goggles, junction Box, fast system card (1200 Hz samples max), and software for PC • Standard goggles, junction Box, basic system card (120 Hz samples max), and software for PC	**Total $17,200** (fast system card) **Total $9,900** (basic system card)

Note: For data collection, all systems require a 486-based PC; the NAC also requires an A/D board. The cost of this equipment was not included in the total prices shown above.

Laboratory Setup

Three of the systems--the ASL 210, NAC V, and Ober2--were evaluated in the laboratory at UMTRI. The other two systems--the ASL 4000 and Headhunter--were available for use in nearby laboratories, but were not able to be brought to the UMTRI laboratory. These two systems also required the assistance of other experts for calibration tests, including the systems' owners, users, and manufacturers. The basic laboratory setup for the NAC V and ASL 210 is shown in Figure 6. The set-up was similar for the Ober2, except that the eye camera control unit was a PC card and software installed in the 486.

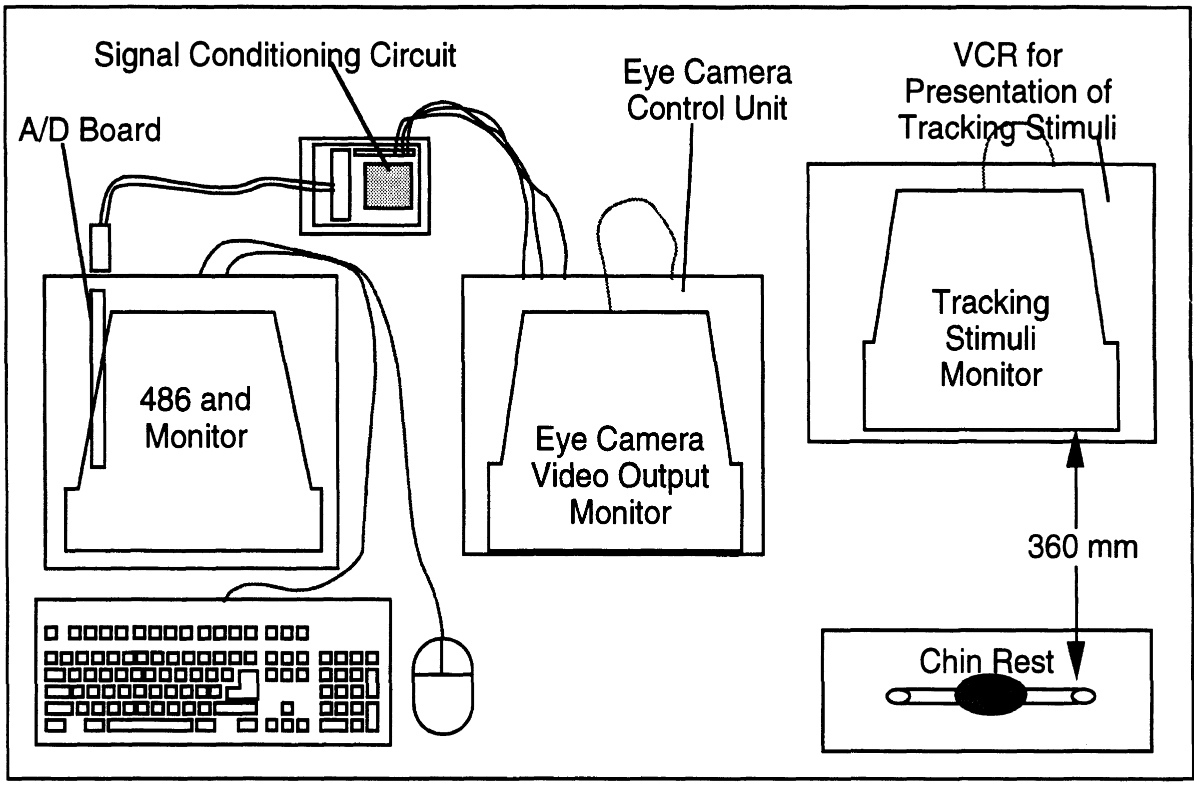

Figure 6. Diagram of the laboratory setup.

The equipment used for this evaluation, not including the eye cameras themselves, is listed below.

- 33 MHz 486 Window/DOS machine with 16 MBytes of RAM, configured by Computer Medic of Ann Arbor
- Mediascan 4A+ TVM Professional Color Monitor, Model MD-14IV+(07)
- Keithley MetraByte DAS 802 A/D Board -- Installed in 486
- DAS Series Standard Software Rev. 1.00
- Panasonic AG-1970 SVHS Video Cassette Recorder (for playing tracking task)
- Panasonic CT-1320M Color Video Monitor (for displaying tracking task)
- Panasonic CT-1383Y Color Video Monitor
- Hitachi VM-H38A Hi8mm Video Camera/Recorder
- Fluke 70 Series II Multimeter

For each session of eye-tracking data collection, the experimenter sat beside the subject at a table (see Figure 7) containing all of the equipment shown in Figure 6. This close proximity made it easy to adjust both the controls of the eye camera and the head-mounted equipment. The calibration sheets were taped to the display where the tracking stimulus was to be presented. The 486 (used for numeric data collection) was also within easy reach of the experimenter.

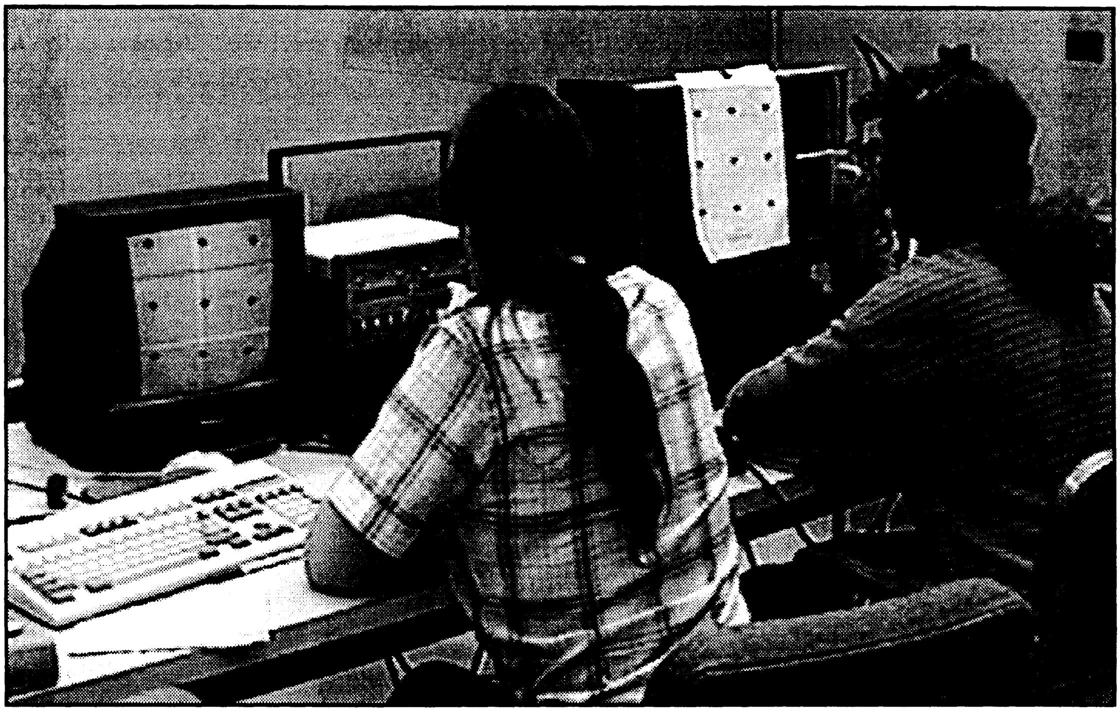

Figure 7. Setup of a typical calibration session at UMTRI.

Test Participants

The authors served as both experimenters and subjects in most tests of this study. Two systems (ASL 4000 and ISCAN) were not tested at UMTRI, and as a result, two other subjects participated in the tracking tasks for these systems. These two systems also required the assistance of other experts (users and manufacturers) for the calibration tests. The other three units (Ober2, NAC V, and ASL 210) were used at UMTRI and all tests were done by the authors. Subjective evaluations and ratings for all five systems were made by the authors.

Access to the systems not leased to UMTRI was limited to a few days. The authors relied upon the assistance of people at those laboratories, and it was not possible to run repeated tests on a large number of subjects. In order to keep testing conditions among systems as comparable as possible, the authors served as subjects and experimenters in as many tests as possible. The authors acknowledge this limitation, and only intend this report to provide insight into the practical problems an experimenter may face when using one of these systems.

TEST METHOD

While there was not one set sequence of tests, as the testing conditions and locations varied, the test protocol did follow a general order. Due to scheduling and rental periods, each system was run through the test protocol thoroughly before moving on to the next system. While the calibration procedure was being learned, the field-of-view testing could be completed with an uncalibrated headpiece. After the calibration procedure was learned, the accuracy tasks were run. Evaluations of headpiece discomfort (pain/pressure, weight, imbalance, and freedom of movement) were done concurrently with field-of-view and accuracy testing. No specific tests were run for subject compatibility, safety, and in-vehicle use, but rather, these issues are discussed based on the other test results and observations.

Calibration Procedure

For systems tested outside of UMTRI, the authors relied upon observation of, and comments from, experts for information regarding calibration. Additional technical information, if needed for explanation of the procedure, was obtained from the eye camera literature provided by the manufacturer. For systems evaluated at UMTRI, the experimenters relied upon the system documentation and practice, to become experts in the calibration procedure.

Field of View

To measure the wearer's field of view and view obstruction, a free-standing enclosure with grid lines was constructed (see Figure 8). The purpose of this was to establish the angular coordinates of the visual boundary and the angular location of other view obstructions caused by the eye camera headpiece.

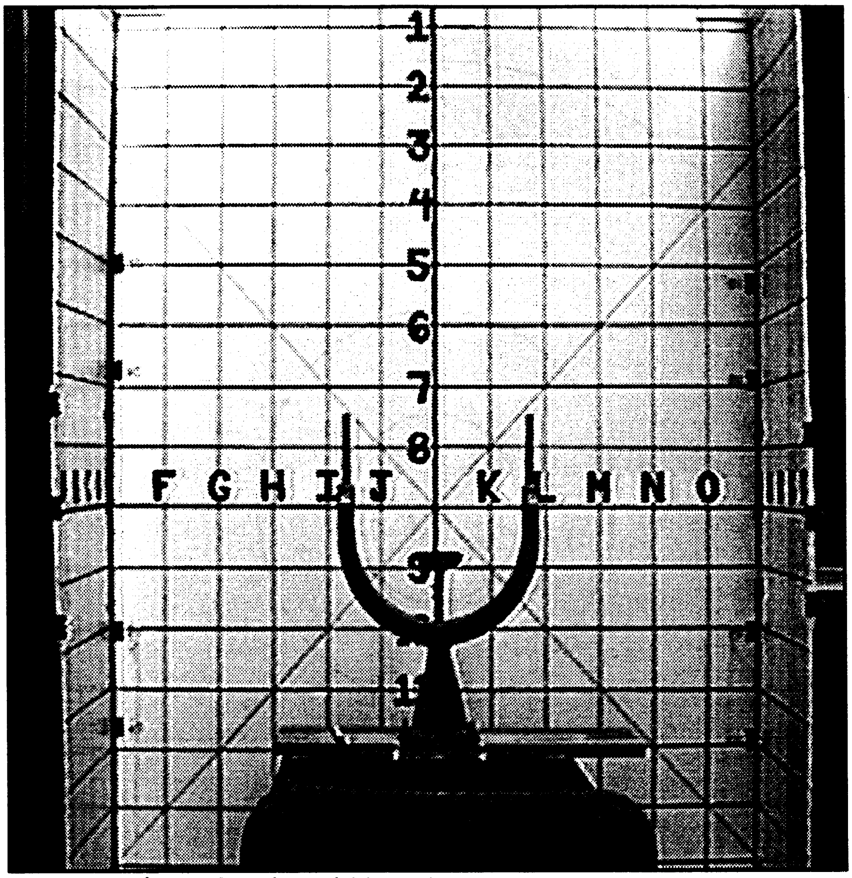

Figure 8. The grid board with chin rest, used for field of view measurement.

To measure wearer's field of view, the eye camera was placed on an experimenter's head. The components of the camera were moved to the position they would be in during data collection, but the system was not calibrated. The chin rest height was set so the subject's eyes were level with coordinate center. The visible field of view was plotted for the areas of the board visible to both eyes. Areas of complete and partial visual obstruction were distinguished. Using a pointer, the wearer traced the boundaries of view obstructions caused by parts of the eye camera. View obstructions caused by facial features were also traced. The experimenter marked the path followed by the pointer on a form which duplicated the grid board. (All forms used in this study are in the Appendix.)

Safety

The level of safety associated with wearing these systems is dependent upon the application. The characteristics of a system safe for use in a laboratory (simulator), are different from those safe for an on-road vehicle driver situation. Safety can be divided into three main concerns: (1) driver field of view; (2) driver freedom of movement; and (3) additional injury risk to the driver in case of an accident. The first two involve not increasing the likelihood that an accident will occur, while the third involves not increasing injury, should an accident occur.

The wearer's field of view determines how many potential accidents or unsafe situations the wearer, as a driver, will detect. It also affects the wearer's scan pattern, forcing her or him to use more head motion to see the mirrors and environment around the vehicle. Freedom of movement interacts with the field of view. Restriction of movement, either by cables, weight, or imbalance, exacerbates the risks resulting from field-of-view reduction. This included not only physical restriction, but subjects' motivation to move their heads based on comfort or annoyance.

Additional injury risk, in the event of an accident, is primarily risk of physical damage caused by the hardware affixed to the subject's head. It is impossible to determine, without testing, if this risk is increased or decreased by the presence of an airbag. There is also the possibility that, post-accident, a subject may need to exit the vehicle unaided. The headgear and/or cables should be easily removable by the subject.

The measurements of field of view, and the experimenters' judgment and experience will be used to evaluate the systems on potential risks.

Discomfort

Subjects identified and evaluated common sources of discomfort from wearing the eye camera headpieces. Subjects indicated the areas on the head where the device was causing discomfort. The subject was given a drawing, depicting a profile and a front view of a head, for marking the discomfort zones. Subjects were also free to make any other comments regarding the comfort of the device.

The subjects also rated the device for four comfort parameters: (1) pain and pressure, (2) weight, (3) imbalance, and (4) freedom of movement. The following scale was used for these ratings:

1	Just noticeable
2	
3	Satisfactory
4	
5	Just acceptable
6	
7	Disturbing
8	
9	Unbearable

Ratings occurred when there was a break between other evaluation tasks. Each system was rated twice. Because some cameras were tested over several test sessions, not all ratings were done during the same session. Copies of all forms are in the Appendix.

Accuracy

Accuracy is a measure of a system's ability to report the correct location of the subject's gaze. For video analysis this means the eye-gaze location marker, added by the eye-camera system to the video image, is located correctly on the target object. For data analysis this means changes in the gaze location are represented precisely by the numerical output. Data output was plotted for each system for a set of four well-defined target paths, in order to provide a representation of each system's accuracy that was comparable, and that captured both elements of accuracy. Unless otherwise indicated, all four plots in each set were from the same session, with the same calibration, and were run in the order of horizontal, vertical, diamond, and diagonal paths. These target paths, shown in Figure 9, were designed to fill the majority of the functional field of the systems tested and to represent different directional movement (horizontal, vertical, and diagonal). These different paths were intended to reveal different kinds of tracking errors.

The viewing distance to the video monitor presenting the tracking tasks was 360 mm, resulting in the tasks filling a vertical visual range of 30.8 degrees and a horizontal visual range of 40.2 degrees. The target was a 3 mm diameter black circle moving in a blue background. Black and blue were used since most eye-gaze location markers are white. It was thought this would facilitate monitoring of the eye-camera system video output. The tracking tasks were programmed in SuperCard and recorded to videotape using a RasterOps 24-STV 24 bit video card and a RasterOps Video Expander II. The videotape was then used for presenting the task to the subjects.

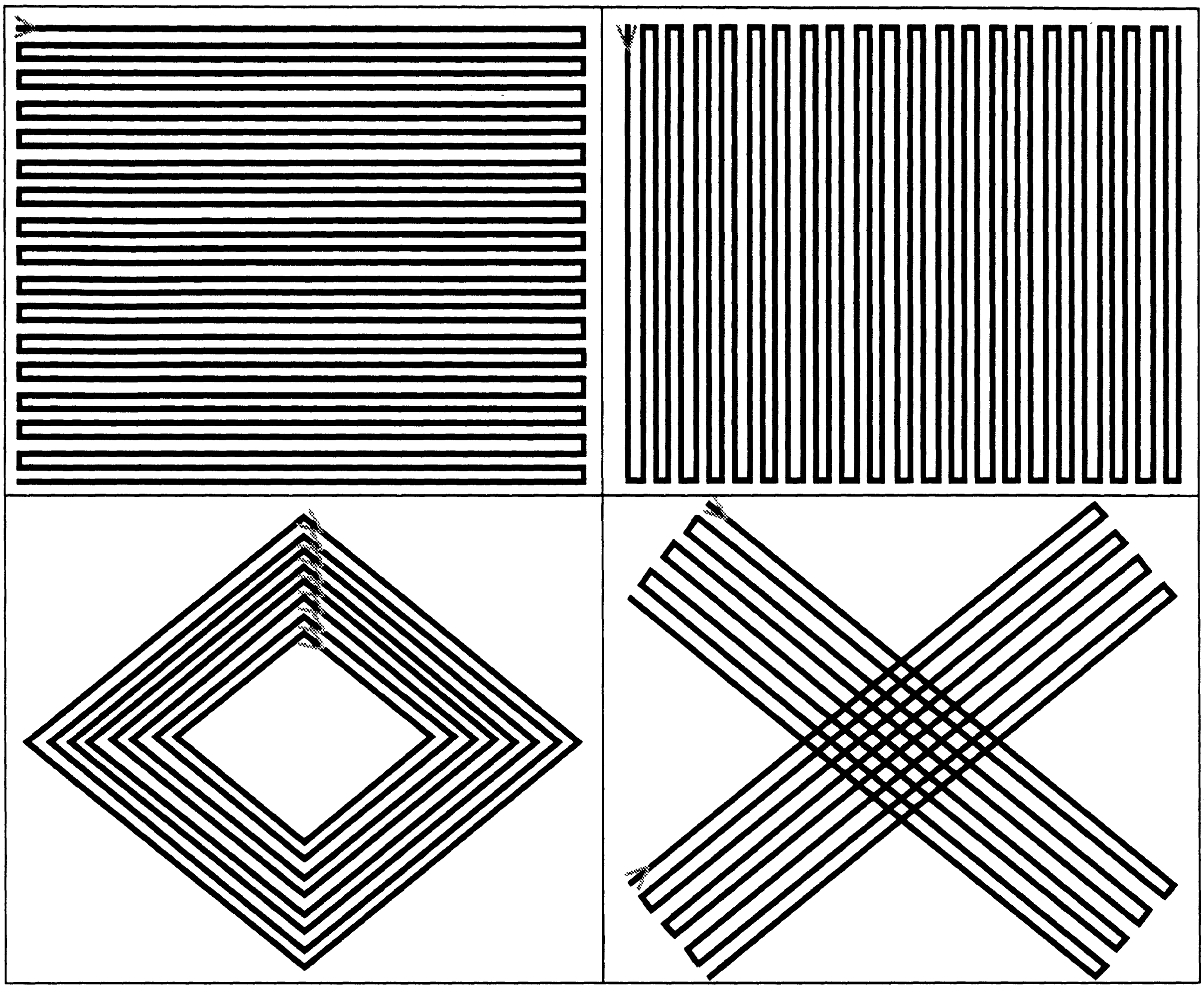

Figure 9. The four paths the target traced in the tracking tasks. (The arrow indicates where the target began each path segment.)

First, coordinate data collection was set up for the system being tested. For some systems this was built in, for others it was necessary to connect the eye-camera system analog outputs to an analog to digital board in the experimental computer. The tracking stimulus videotape was presented on a 13-inch monitor. During test sessions, the subject rested her head in a chin rest mounted at the proper viewing distance. See Figure 10.

The subject was fitted with the eye camera and the system calibrated for targets at the distance of the stimulus monitor screen. The chin rest was used during calibration. The data collection was enabled and the tracking task tape started. Each of the four tracking tasks' data were recorded separately. For most systems, data were collected from two subjects.

Subject Compatibility

Eye camera usefulness can be limited by restrictions on subject type. Limits include incompatibility with some kinds of vision correction, shortened comfortable wear times due to subject age and strength, and limitation on head size for a comfortable fit. Incompatibility with vision correction can be a physical conflict with glasses or calibration problems caused by contacts.

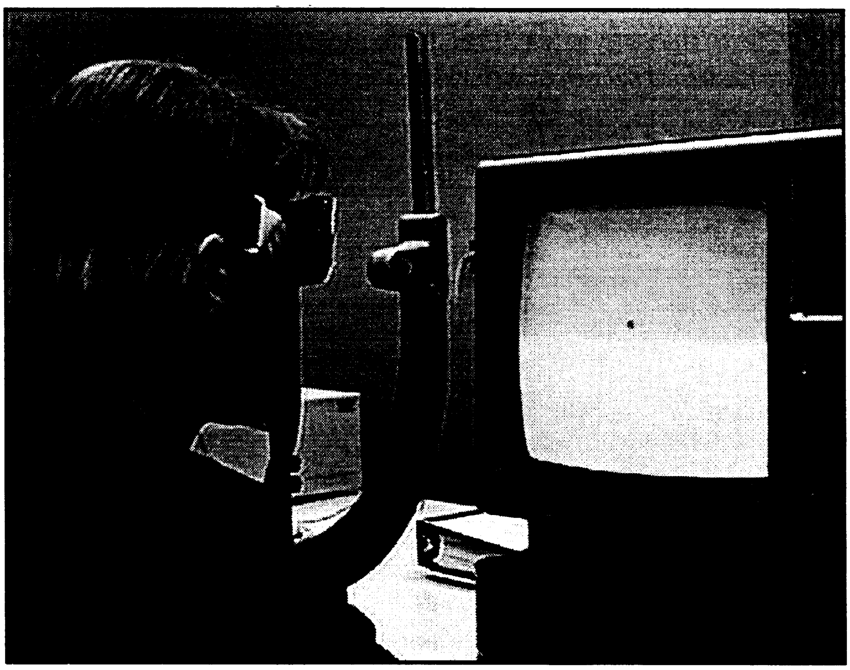

Figure 10. Subject performing the tracking task.

Where reliable information on compatibility with eye glasses and contacts is not provided by the manufacturer, we tested subjects with the type of correction in question. Incompatibility with glasses is sometimes as simple as not being able to fit the eye glasses on with the eye camera.

Other Considerations for In-Vehicle Use

Other factors affect the usefulness and functionality of an eye-camera system if it is to be used on road. Since all of the systems tested here are infrared based, infrared washout due to sunlight is a primary concern. Systems that are well enclosed and have infrared coatings on the exterior transparent surfaces should perform best. The drawback of this configuration, however, can be a severe reduction in the driver's field of view. For systems that track the pupil, the small size of the pupil in bright light can cause tracking difficulties, especially if the system is tracking a bright pupil. Each system's ability to function in a bright infrared environment was determined, either by our own experience, or by the experience of other users.

Another consideration is the size of the eye-camera control boxes and the need for power. If data collection is to be done on road, the equipment must be safely and securely mounted in a vehicle. If the head-mounted equipment is bulky , it may limit the driver height, or may limit where the driver can move his or her head before striking the unit on the headrest or window. The wiring between the headpiece and the control unit must be long enough to be placed around the driver without restricting motion, and rugged enough to withstand the abuse it will inevitably suffer in the vehicle.

RESULTS

The results of the evaluation were based on direct measurement, objective rating, and observation. The calibration procedures described here are based on the descriptions in the documentation, or on observations of experts calibrating a system. The field of view measurement was a direct measurement, in the form of a plot, of the view obstructions imposed on the wearer. The discomfort rating results are presented by system in table form, along with drawings of the areas of discomfort. The plots of the output from the tracking task are also presented by system with additional comments about what they indicate. An overall summary, with tables for comparison across systems, is included at the end of this section.

Calibration Procedure Description and Observations

Each eye camera system's calibration procedure was learned or observed for this evaluation. The calibration procedures are summarized in this section. The procedures are only described in detail enough to allow for comparison of complexity and difficulty. Any additional observations and comments by the experimenters or experts describing difficulties with the procedures are included.

In general, the quality of data output is directly related to the time and effort put into calibration. For systems with manual calibration, output quality is a direct result of the experimenter's experience level with fine tuning the calibration. The experienced experimenter has learned not only the full function of all controls, but has strategies for dealing with anomalies different subjects and environments can produce.

For systems with automatic calibration, more of the responsibility for good output has been put in the hands of the programmers and designers of the system. The experimenter's main influence on the output is installing the device optimally on the subject. Automatic calibration is a time saver, and produces superior accuracy when conditions match those for which the system was designed. However, automatic calibration systems can make it more difficult to troubleshoot what part of the environment or the installation is causing eye tracking to fail. It is possible that learning to use a manually calibrated device involves learning more extensively how conditions interact with the device's functionality.

ASL 210

Eye fixation recording quality of the ASL 210 is primarily affected by the proper orientation of the sensors. It is necessary to adjust the sensor location from the front and side of the wearer's head, while having the subject look up and down, to make certain the alignment is proper through the full range of eye movement. Eyelashes can be a serious disruption.

High precision calibration usually requires repeated adjustment of all controls (see Figure 11). A nine-point fixation sheet is used for calibration (see Figure 12). The size of the calibration sheet depends upon the target area being investigated. The vertical and horizontal zeroing controls are used first to align the fixation with the center point. Then the horizontal and vertical gain adjustments are made. The horizontal adjustment is made while the subject looks at points 4 and 6 repeatedly (verifying occasionally that the center zero has not drifted). If the eyespot moves farther in one direction than the other, and the center point is still aligned, then a linearity adjustment is made. If the eyespot is affected vertically by eye motion in the horizontal, then a crosstalk adjustment is made. The process is repeated for the vertical points 2 and 8.

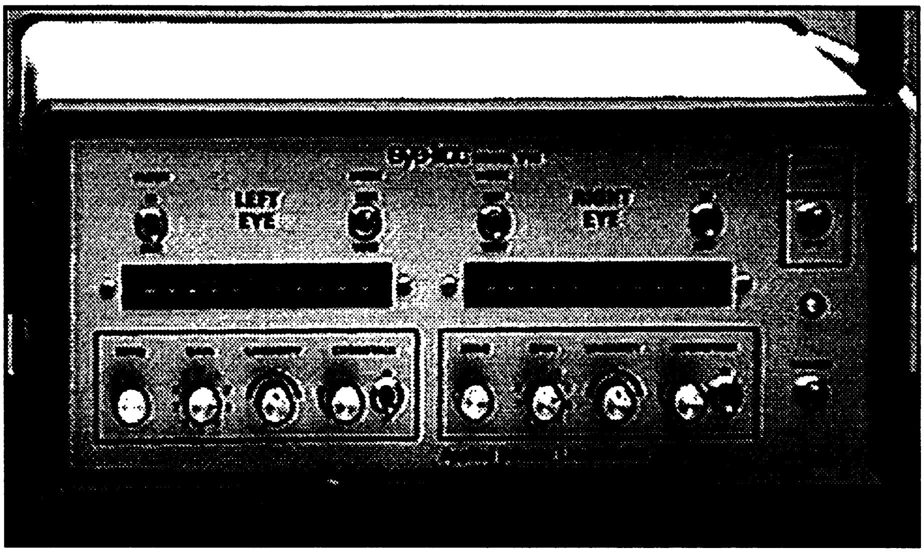

Figure 11. The control box for the ASL 210.

The experimenter then checks the accuracy of the remaining corner points. If the eyespot behaves erratically on one or both of the lower corner fixation points, the experimenters found it was usually due to interference from the eyelashes. Eyelash interference causes a skewing of the eyespot in the lower viewing range. The location of the sensors is changed and calibration adjustments are repeated.

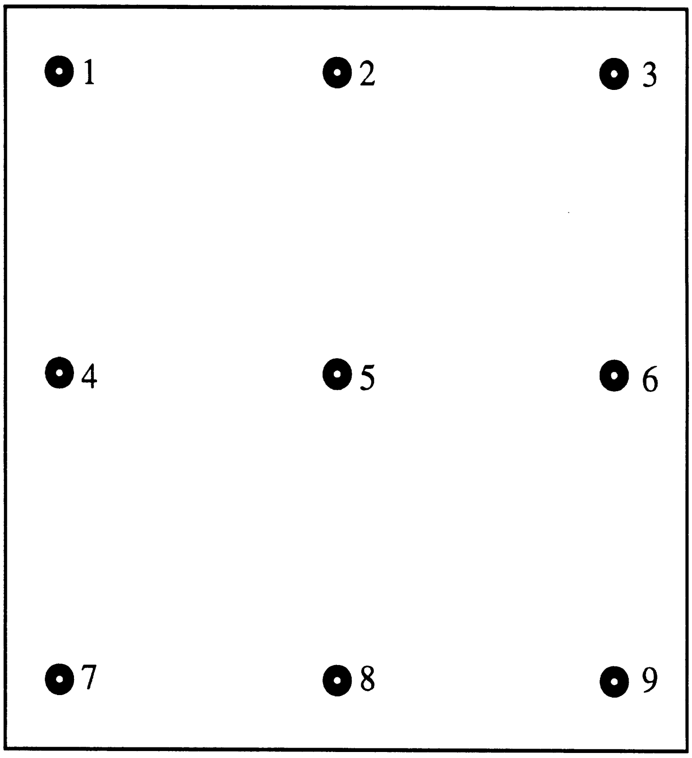

Figure 12. Example nine-point eye calibration sheet.

ASL 4000

The 4000 model configuration tested has automatic calibration, run by software on a DOS computer. After the device is placed on the subject, the plastic visor (or window) in front of the eyes is adjusted to give the eye camera a centered view of the subject's eye. The range of motion allowed by the arms holding the window makes this task a little difficult. The forward camera is then adjusted to show the subject's forward view. The arm mount for the camera has a broad range of movement and tilt, which resulted in difficulty obtaining the subject's true forward view. While the camera arm could be locked into position, it was not solid enough to keep it from being bumped out of alignment.

The first step in electronic calibration is done manually. By viewing the control rack video monitor (see Figure 13) showing the system's view of the eye, adjustment is made to optimize recognition of the pupil image and corneal reflection. Computer calibration is done by placing a sheet of nine calibration points, similar to Figure 12, in front of the subject. Using a mouse, the calibration point locations are registered on the computer screen. The subject is then instructed to look at the points in order and each resulting eyespot is entered into the software. The program then makes the necessary compensation to subsequent eye movements to result in the correct eye spot location.

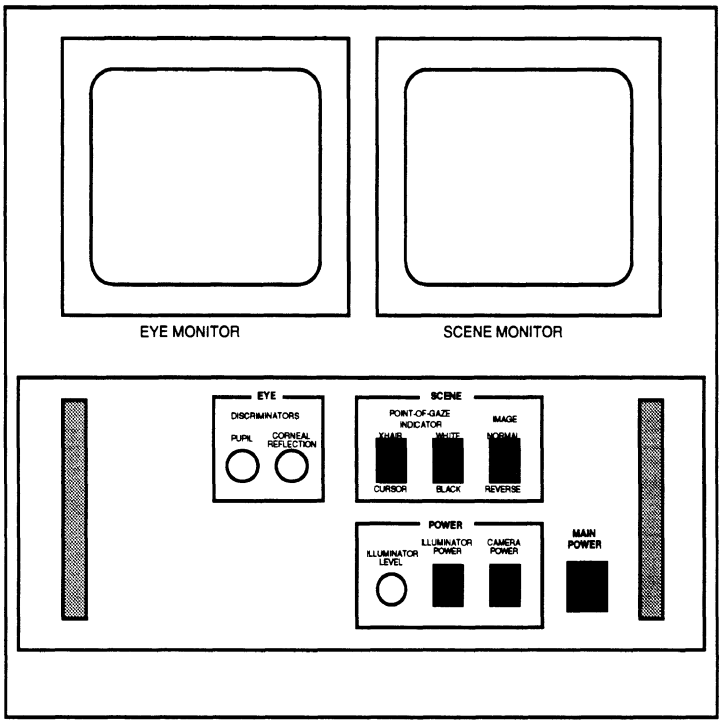

Figure 13. Control panel of the ASL 4000.

To obtain proper function for this experiment, it was necessary to dim the fluorescent lighting to about one-third standard illumination level. It was also necessary to place a black cloth over the subject's head to block the overhead light.

ISCAN

A helmet-mounted ISCAN system was used for the field of view and comfort evaluations. This older model was rack-mounted and is shown in Figure 14. The helmet size was extra large and required foam padding for most subjects. Since the tracking data were not collected on this model, the calibration procedure described below is for the PC card-based model used by ISCAN to collect the data.

The first steps in calibration was to adjust the position of the dichroic mirror so the eye camera mounted on the top front of the helmet recorded a centered view of the eye, and to focus the image of the eye. The threshold for pupil and corneal reflection is then adjusted by the experimenter through software to obtain the best contrast for the system to identify these eye features. It should be verified after adjustment that the system is able to track the eye through the full range of view to be used in the study.

Figure 14. The control panel for the ISCAN.

The experimenter can decide between 5 and 9 point calibration, which is handled completely in software, with the subject looking in turn at select calibration points. Most important during calibration is to watch the eye display to make certain the corneal reflection and pupil are being tracked properly throughout the calibration process. If the system loses tracking on either eye feature, the calibration will be unsuccessful. As with most systems this is most likely to occur at the edges of the functional range.

NAC V

Calibration on the NAC model V system is manual, and requires use of the remote control and the panel on the controller box (see Figures 15 and 16). After the unit has been placed on the subject's head, the experimenter views the subject's eye through the eye camera, adjusting the x and y position knobs and the focus, so the eye is centered and the reflection spot from the LED is clear. The LED angle is adjusted, if necessary, to provide a bright spot on the eye.

The experimenter then switches (using the remote control) to monitor the scene camera and instructs the subject to look in the center of a nine-point calibration chart. The x and y position knobs are adjusted again to center the eye spot. The subject is then instructed to look at a point to one side of center. To get the system to translate the eye spot the correct distance the gain is adjusted, with the remote control, in discrete increments. The indicators for the gain setting are on the control unit. This is repeated for points above and below the center. Linearity is a problem with this device (the eye spot moving farther in one direction than the other for points at equal distance from the center), as is obtaining correct eyespots for the corner fixations. Some quadrants (especially up and away from the nose) are prone to gross error as this condition causes the LED to reflect off of the sclera.

The device is also prone to slippage on the wearer's head, which is highly detrimental to calibration since only one eye feature is used for eye gaze determination. The scene camera does not lock in place vertically, and its movement can dramatically shift the view of the video output.

Ober2

Calibration on this device consists of placing the sensor goggles on the subject's face so the sensors are straight and centered around the eye. Eyelashes can cause interference if the subject allows his or her eyelids to droop. The system is also very sensitive to flickering light sources such as fluorescent lighting. It is possible to decrease this sensitivity by reducing the sampling rate. This allows the device to use spare sampling capacity for light accommodation. Instead of determining the eye location every sample, it can be set, for example, to alternate between sampling the light level of the environment and sampling the eye location. This way it can adapt to lighting changes in real-time. This is effective unless the lighting is cycling rapidly.

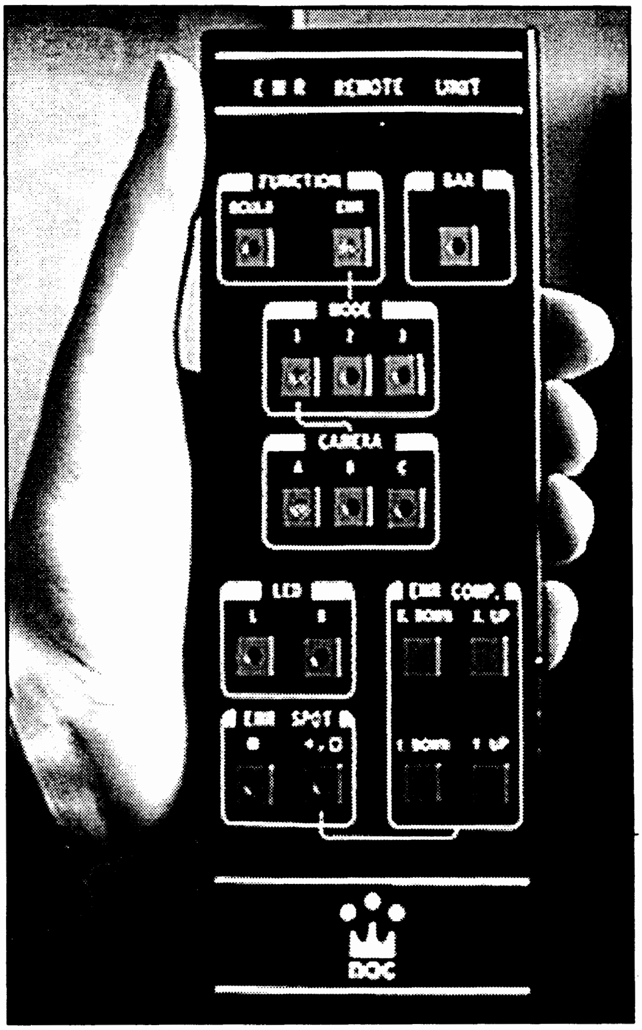

Figure 15. The remote control for the NAC model V.

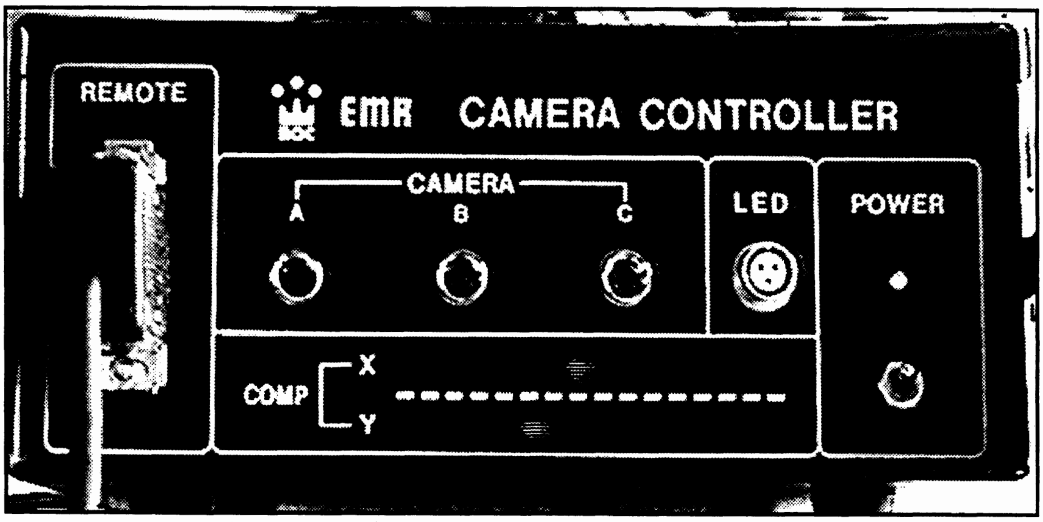

Figure 16. The control box for the NAC model V.

Changes to the sampling rate, visual distance, trial length, and other test conditions are made in the software provided with the system.. The system is intended to be used with stimuli programmed into and displayed by the computer. For the test sessions, a separate monitor presented the tracking stimuli, so a dummy stimulus of text was presented by the Ober2 software. A programmed stimulus had to be loaded into the software to enable data collection.

Field of View

Evaluations were conducted to assess subjects' fields of view while wearing the eye camera headpieces. Areas of complete visual obstruction (such as opaque goggles), partial obstruction (such as small sensors), and other distortions (such as reflections) are identified and labeled. Every system that was tested had some obstruction. This information should be considered if the system being evaluated has areas of blockage where an intended target will be, or if the system will be used for studies of driving on public roads. Subjects may have to turn their head more than usual to view a target (for example, to check a rearview mirror), or may decide not to look at a target because of restriction of movement, or because of the headpiece weight. While the validity of using an on-head eye recorder has not been verified, the less intrusive the system is, the more natural (and valid) the subject's behavior will be.

ASL 210

The field of view area that is blocked by the ASL 210 is caused by the three sensors that are directly in front of each eye. (See Figure 17.) Because one eye is tracked for vertical movement and the other eye for horizontal, it would not be possible to remove one of the sensors to improve vision. The sensors, their mountings, and the forward scene camera, block a significant portion of the direct forward scene, as well as the area above the horizontal center line. The exact positioning of the sensors (and the area they block) will vary slightly for each subjects' calibration configuration.

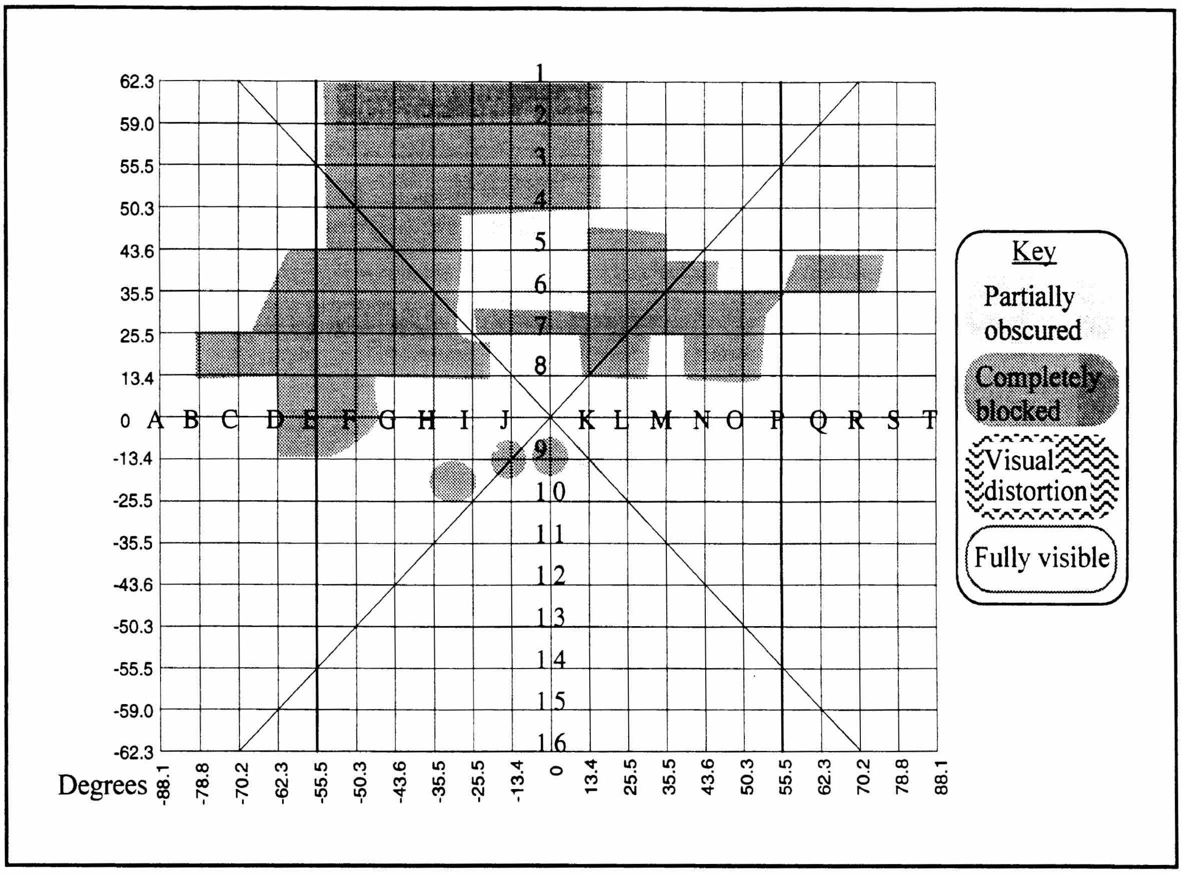

Figure 17. Drivers' field of view while wearing the ASL model 210.

ASL 4000

Sources of visual obstruction from the model 4000 were a seam in the visor, the forward scene camera, and a custom light shield (a black cloth placed over the wearer's head). While the direct forward gaze and peripheral view is unobstructed, the entire area above the horizon is completely blocked. (See figure 18.) The black cloth was used to prevent interference from direct sun light when used in a car, or in a laboratory with fluorescent ceiling lights. This test was with the cloth, as this configuration had been prepared for in-vehicle use of the system. Additionally, a faint distortion appears along a narrow band in the field of view due to a seam in the visor. This ripple, or "double vision" effect, is noticeable when trying to read text that intersects this seam.

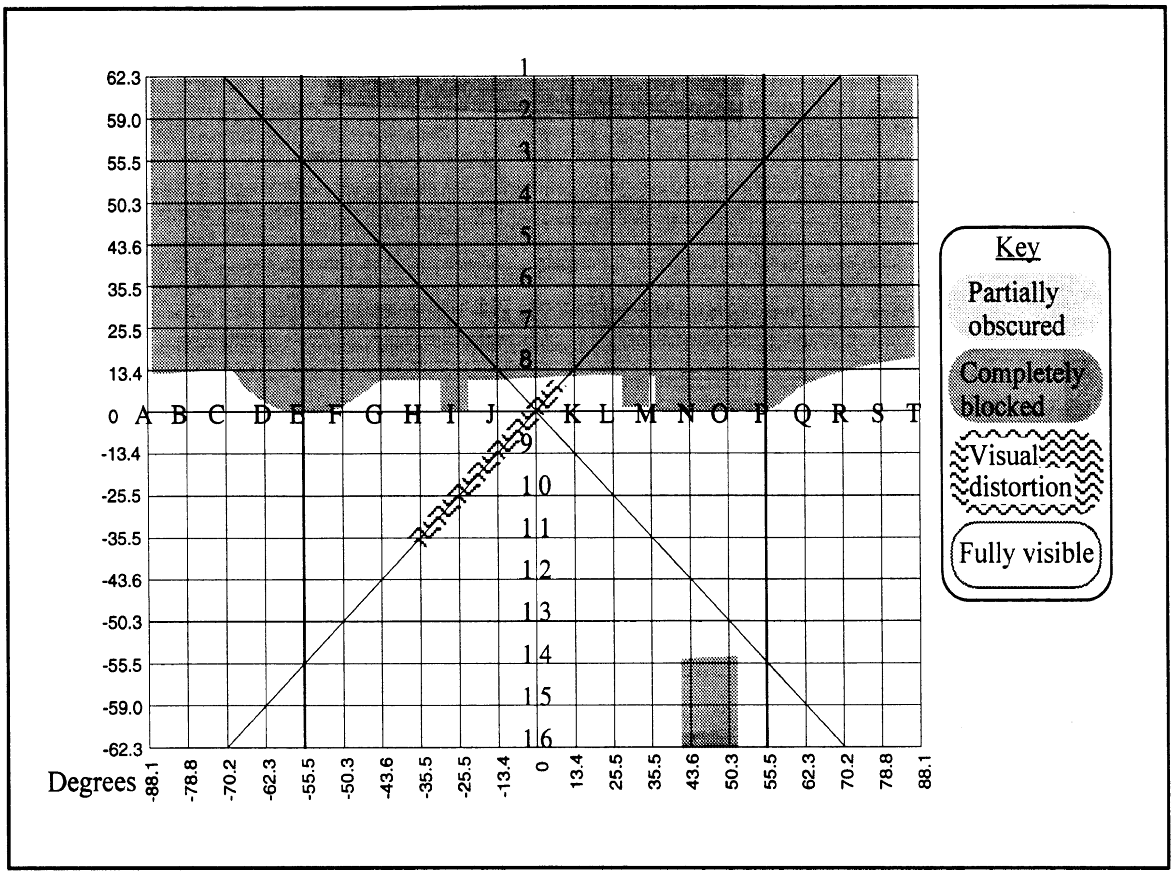

Figure 18. Drivers' field of view while wearing the ASL model 4000.

ISCAN

The unit used for this evaluation is an older helmet-mounted version. This system is now available on a headband or a newer helmet. The newer versions were not available locally for testing. Though the components themselves (the cameras, the reflecting glass) have been upgraded, their basic positioning is the same.

Field of view blockage from the ISCAN tested is caused by the dome protecting the optics attached to the helmet above the forehead, and the reflective glass and its supporting arm. (See Figure 19.) The helmet of the ISCAN extends out enough to block the upper field of view of the wearer. (The helmet used in this test was size Extra Large, and therefore the results would likely be different for other helmet sizes.) In addition, the camera arm and focusing glass extend well into the forward field of view, and into the peripheral field of view on one side. For this test, the system had not been calibrated on the subject; the glass and its supporting arm, therefore, might be positioned slightly lower or more to one side than in an actual test session.

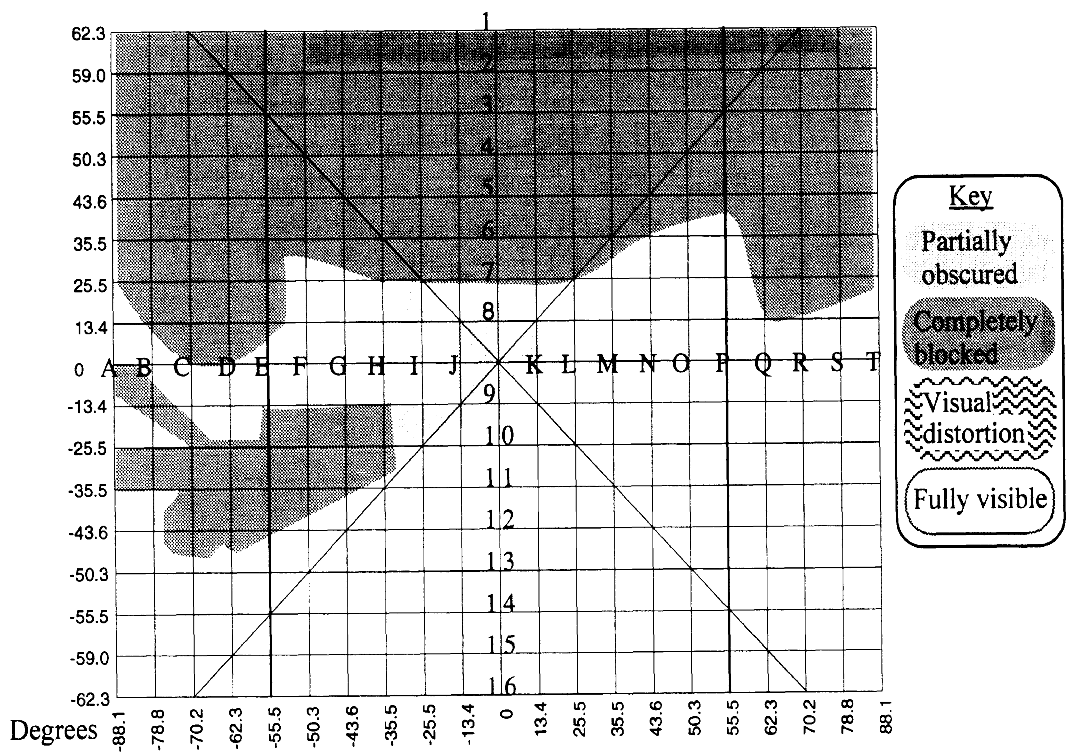

Figure 19. Drivers' field of view while wearing the ISCAN.

NAC V

The goggles that encase the NAC V's sensors are the cause of the visual obstruction when using this system, as shown in Figure 20. The forward line of sight is clear, but tunnel-like. The peripheral area of one side, as well as the upper and lower areas, are completely blocked. The system used in this test had been modified to improve the field of view by removal of the optics for the left eye. This allowed the wearer to see out through the opening normally used by the system to view the left eye. The overall visual obstruction was still substantial.

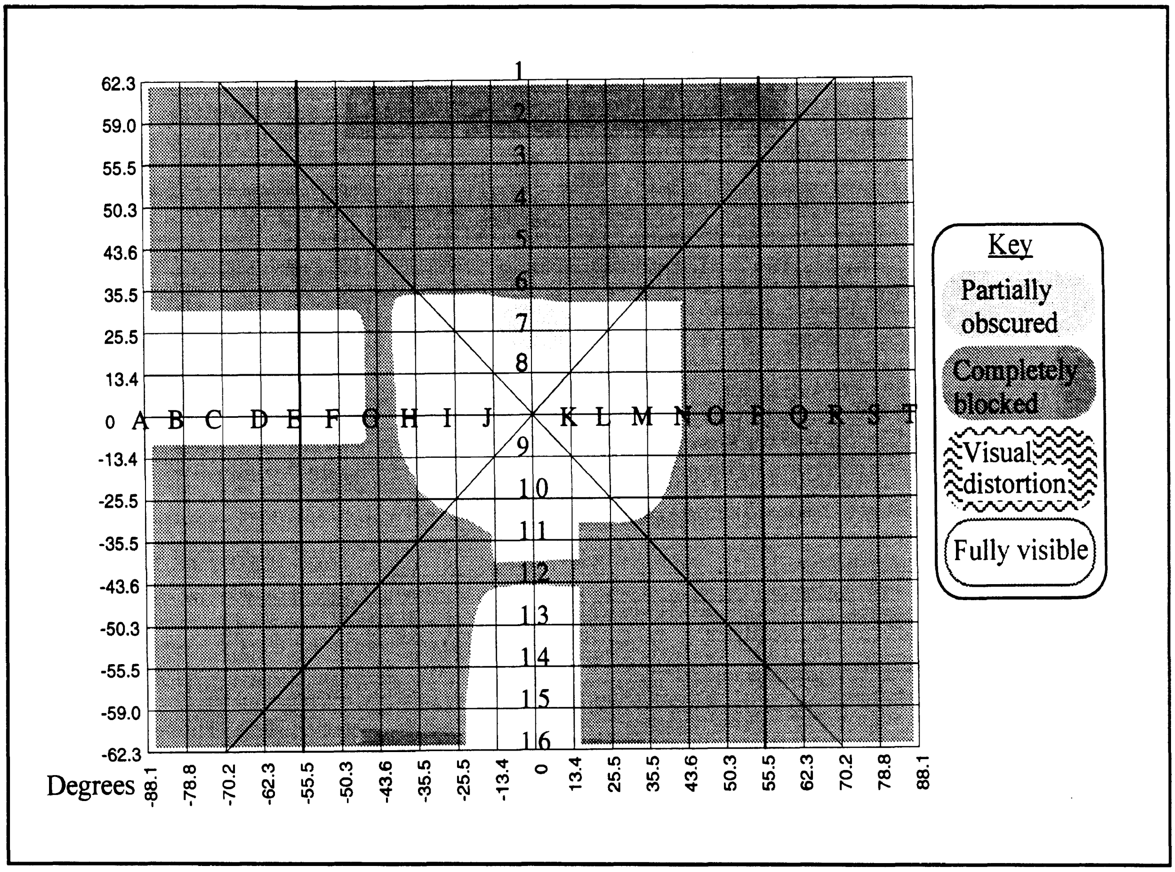

Figure 20. Drivers' field of view while wearing the NAC V.

Ober2

Visual obstruction caused by wearing the Ober2 is due to the goggle frames. The small square shape is necessary due to the sensor array design of the unit, and the sides are sealed to reduce interference from changes in the light environment. As shown in Figure 21, the effect is tunnel vision. The subject looks through a rectangular opening about the size of a 35mm film slide. All peripheral, upper, and lower field of view is eliminated.

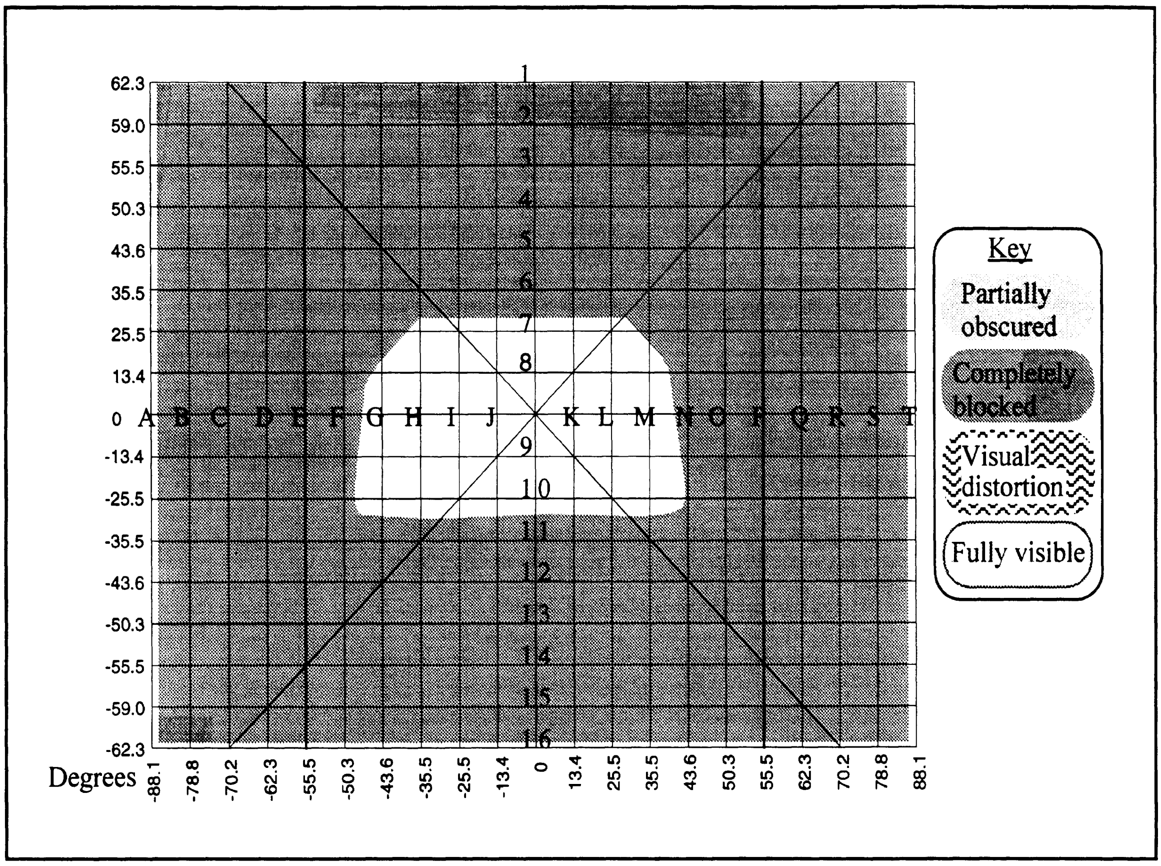

Figure 21. Drivers' field of view while wearing the Ober2.

Discomfort

Two subjects (the authors) assessed the five systems for areas where the headpiece caused discomfort. Drawings of problem areas indicate the type of discomfort, such as pain caused by direct contact with part of the head piece, neck muscle strain from weight, imbalance or restriction of movement, and regions of pressure from the headband or mountings. No time intervals are indicated, as each camera's drawings are composites of all drawings made over all test sessions. Test sessions ranged in length from 5 to 40 minutes.

Whereas the ratings indicate the level of discomfort for various parameters, the discomfort zone drawings describe the type and location of discomfort experienced by wearers. The five cameras were rated for discomfort on four dimensions: pain and pressure, weight, imbalance, and freedom of movement. A scale of 1 to 9 was used, where 1 was "just noticeable" and 9 was "unbearable." Ratings of discomfort were taken within three time intervals, with two ratings per system. Ratings for each system were not necessarily taken within the same test session.

Pain and pressure ratings were based on the severity of head, face, or neck discomfort that subjects felt while wearing an eye-camera headpiece. Subjects rated discomfort from the overall weight, based on the level of discomfort to the head, face, or neck. The level of head, face, and neck discomfort that was caused by the imbalance of the eye-camera headpieces was also rated for all systems. Imbalance may be perceived from side to side, front to back, or both. Freedom of movement restriction was evaluated for how much the subjects felt they could move their head without upsetting the stability of the headpiece. This factor included limitations that physically restrict movement, such as short cables, the perceived fragility of the unit, and the possibility of the headpiece striking the subject or vehicle interior.

ASL 210

As shown in Figure 22, sources of discomfort with the ASL 210 include pressure and weight imbalance. A band of pressure and a spot of slight pain result from the tight fit of the headband needed for stability. In addition, because of the forehead-mounting of the scene camera, there is forward imbalance of the unit. Because of the forward bias, the headband must be fitted fairly tightly, causing a "halo" of pressure around the forehead and downward pressure along the eyebrows. Table 5 shows the ratings of discomfort from wearing the ASL 210.

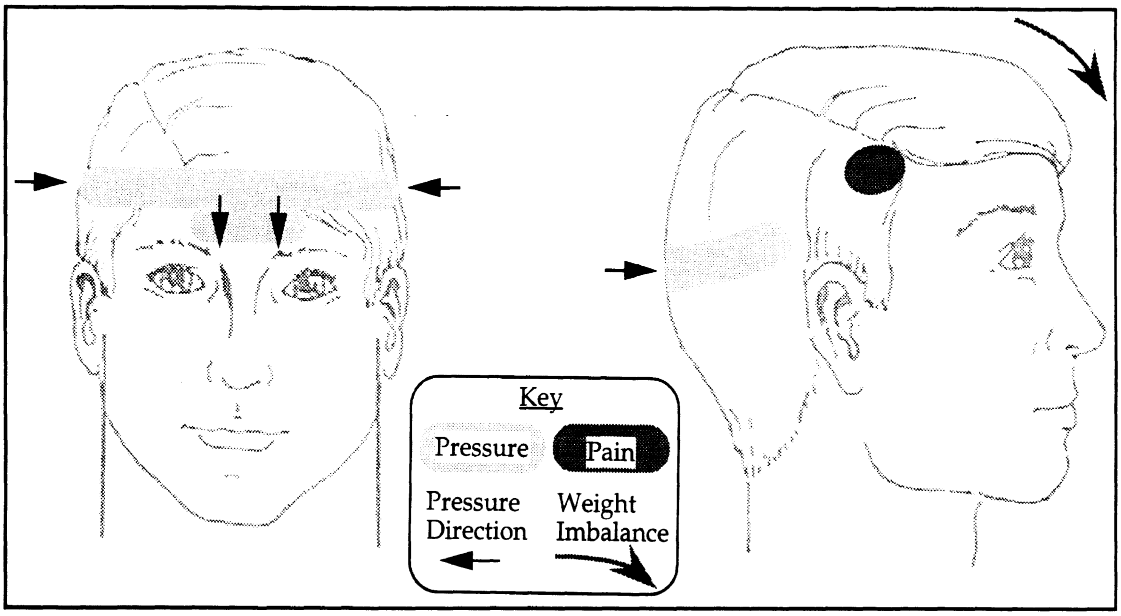

Figure 22. Illustration of discomfort from wearing the ASL 210 headpiece.

Table 5. Discomfort ratings for the ASL 210.

Rating Scale:
1 Just noticeable
↓
9 Unbearable

	ASL 210 Discomfort Ratings			
Time Elapsed (min.)	**Pain and pressure**	**Weight**	**Imbalance**	**Freedom of movement**
0 to 15				
16 to 25	4	4	5	4
26 to 35	7	5	4	3

The most significant pain and pressure problem with the model 210 is caused by the headband. Most of the pressure is against the forehead. The "halo" strap on the headband must be very tight around the subject's head in order to stabilize the unit. Part of this problem is due to the imbalance caused by the forward scene camera. In order to prevent the whole unit from slipping forward, the head strap is adjusted as tightly as possible. The forward imbalance can also result in downward pressure on the eyebrows. The discomfort from the weight of the model 210, evaluated up to 35 minutes, was at the acceptable level. The scene camera on the front of the model 210 headband causes the headpiece to be front-heavy. The discomfort resulting from this imbalance was felt to be acceptable, up to the end of the evaluation period (35 minutes). The reduction in discomfort rating after 25 minutes may be due to the wearer becoming accustomed to the imbalance. Freedom of movement of the model 210 was within acceptable levels for the 35 minute test session. The main restriction on movement was perceived to be the cabling and the weight imbalance.

ASL 4000

Discomfort caused by wearing the ASL model 4000 results from the fit of the headband and equipment imbalance. Figure 23 portrays the problem areas of the 4000's head unit. As there are two sensors, one mounted above the forehead and one mounted on an arm next to the lower cheek, there is imbalance toward both the front and side. This, in turn, requires the headband to be fitted tightly, applying uncomfortable pressure around the head. The overall imbalance results in slight neck strain, while the forward imbalance, in particular, causes downward pressure along the eyebrows. (While testing this model, a custom weight was added to the back head strap, noticeably reducing neck strain.) The discomfort ratings received by the ASL 4000 are shown in Table 6.

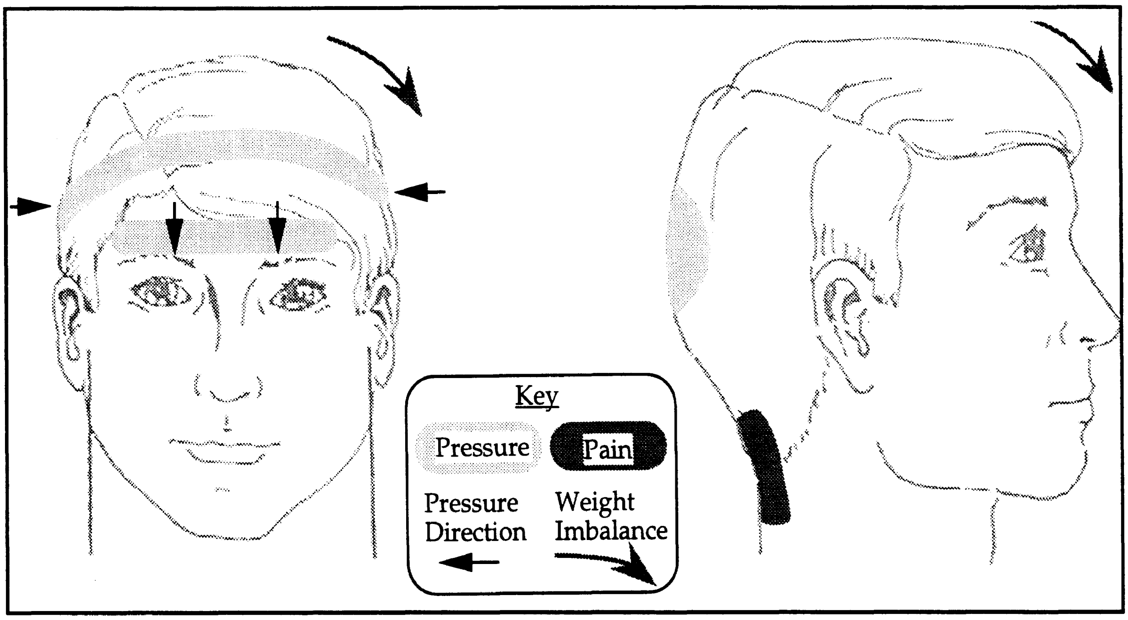

Figure 23. Illustration of discomfort from wearing the ASL 4000 headpiece.

Table 6. Discomfort ratings for the ASL 4000.

Rating Scale:
1 Just noticeable
↓
9 Unbearable

Time Elapsed (min.)	ASL 4000 Discomfort Ratings: Pain and pressure	Weight	Imbalance	Freedom of movement
0 to 15				
16 to 25	2	4	4	4
26 to 35	5	6	4	5

The main source of pressure caused by the model 4000's head unit is against the forehead. The head unit needs to be worn fairly tightly to prevent slippage. Pressure is also felt pushing down on the eyebrows. Some strain along the back of the neck can occur due to the associated problem of forward imbalance (caused by the scene camera and sensor units). Neck strain was reduced when a counter weight was added to the head strap adjustment on the back of the head. The model 4000's ratings for discomfort caused by weight was acceptable up to 25 minutes. When evaluated beyond that time, however, the discomfort was beyond acceptable. The imbalance of the model 4000, caused by the scene camera mounted over the forehead, results in a front-heavy headpiece. The discomfort due to this imbalance was still rated as acceptable. When a custom counter-weight was added to the back of the headpiece, the imbalance was not as noticeable. Even though the overall weight increased, the perceived discomfort decreased. With the model 4000, freedom of movement was rated as acceptable. The side-mounted camera caused some restriction of movement as it was possible for it to contact the subject's shoulder. The weight and concern over upsetting the visor may also have contributed to restricted movement.

ISCAN

Figure 24 describes the areas of discomfort associated with wearing the ISCAN. Discomfort resulting from wearing the ISCAN helmet was due to its overall weight, imbalance, and its method of being fit to the wearer. As this system is incorporated into a pilot's helmet, the overall weight of the unit is substantial, causing noticeable pressure on the neck and the top of the head. The neck also must compensate for the unit's sideways imbalance. Without additional padding added to the inside of the helmet, the chin strap is the only means of fitting the helmet on the head. The edge of the chin strap, coupled with its tight adjustment, was uncomfortable. Ratings of discomfort are shown in Table 7.

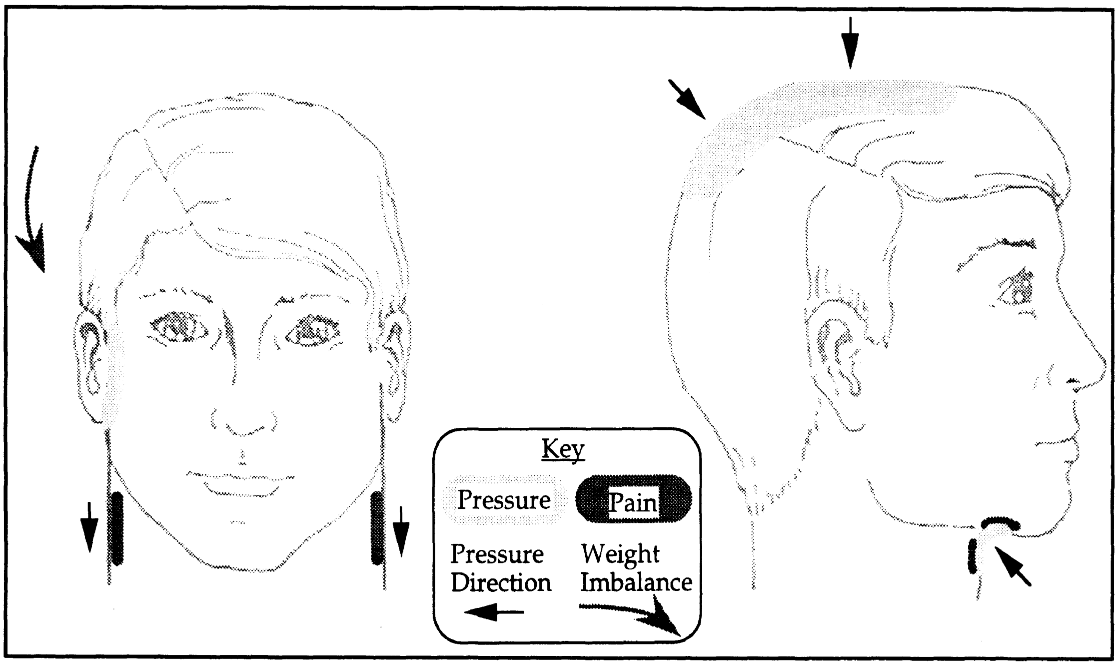

Figure 24. Illustration of discomfort from wearing the ISCAN headpiece.

Table 7. Discomfort ratings for ISCAN.

Rating Scale:	Time Elapsed (min.)	ISCAN Discomfort Ratings: Pain and pressure	Weight	Imbalance	Freedom of movement
1 Just noticeable	0 to 15	5	7	7	6
↓	16 to 25				
9 Unbearable	26 to 35	6	7	8	6

It should be noted that the helmet-mounted unit tested here was an older, heavier version than is now available. Also this unit had been modified by the owners with components that may have been heavier than the original.

Pressure from the ISCAN's headpiece is associated with the helmet and chin strap. While the helmet helps to disperse the weight of the whole unit, there is still pressure concentrated on top of the head. In order to stabilize the unit, the chin strap must be adjusted tightly, and, as there is no padding along the edge of the strap, some discomfort is felt there also. Related to overall weight, neck strain ("compression") was also reported. Lateral neck strain can also be felt, due to imbalance caused by weight of the scene camera mounting. Discomfort from the weight of the ISCAN headpiece was unacceptable even for less than 15 minutes of use. The ISCAN is laterally imbalanced, as the scene camera is mounted on a relatively heavy arm on the side of the helmet. This imbalance was perceived to be more uncomfortable than the longitudinal (front-to-back) imbalance of the other cameras. The ISCAN's imbalance, along with its weight, caused these relatively higher ratings of discomfort. The rating of freedom of movement while wearing the ISCAN was beyond the acceptable level. The tight chin strap made it uncomfortable for subjects to turn their heads. Also, the helmet's weight and imbalance make it difficult to move the head.

NAC V

The majority of the discomfort from the NAC V is related to the front goggles, both in terms of pressure and imbalance. Figure 25 depicts the areas of discomfort associated with the NAC V. Because the top two head straps are not separately adjustable for length, the back head strap must be tightened to prevent the headpiece from slipping. Pressure is thus felt along the forehead and cheekbones, despite some extra padding inside the tested unit. The goggle nose opening may not fit all wearers comfortably, resulting in the side of the nose contacting the hard plastic corner of the goggles. The forward scene camera, mounted above the forehead, causes the headpiece to be front heavy and puts strain on the rear of the neck. The ratings of discomfort for the NAC V are shown in Table 8.

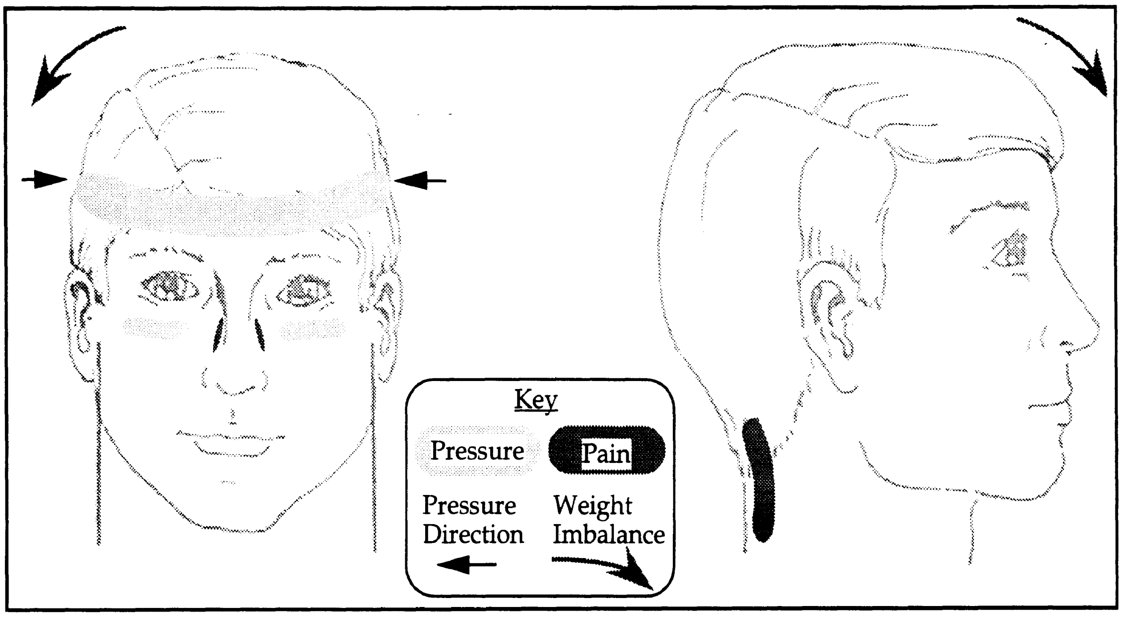

Figure 25. Illustration of discomfort from wearing the NAC V headpiece.

Table 8. Discomfort ratings for NAC V.

Rating Scale:	Time Elapsed (min.)	NAC V Discomfort Ratings			
		Pain and pressure	Weight	Imbalance	Freedom of movement
1 Just noticeable	0 to 15	3	5	5	6
↓	16 to 25	7	6	6	6
9 Unbearable	26 to 35				

Discomfort from wearing the NAC V is caused by the tight adjustment of the headpiece. Two of the head straps are not individually adjustable for length and, therefore, depending on the subject's head size and shape, do not always fit the head to support the headpiece. As a result, the back adjustable head strap must be pulled tighter to prevent slipping of the headpiece. This in turn causes pressure where the unit contacts the face (on the forehead and cheekbones). The NAC V headpiece's weight is acceptable up to 15 minutes. Beyond that length of use, the weight becomes unacceptable. If the NAC V were to be used in a vehicle the left eye sensor would probably be removed to provide a safer field of view for the driver. This would not affect data collection, as data were collected in the tracking task only from the right eye. The discomfort resulting from this imbalance was acceptable up to 15 minutes only. The side sensor-housings that extend off of the NAC's headpiece restrict the subject's freedom of movement. Not only do the plastic casings protrude, but various cables from the different cameras and sensors make it difficult to turn the head without worrying about snagging a cable and thereby pulling the headpiece with it. It was perceived to be the most precarious in this respect.

Ober2

Discomfort that results from wearing the Ober2, as shown in Figure 26, is associated with the contact of the goggles to the face. The rubber edges of the goggles that serve to position the sensors and prevent excess light from interfering, press into the area around the eye. Because the plastic grips the skin of the face, the goggles do not need to be tight to avoid slippage, unlike most headpieces. Ratings for discomfort are shown in Table 9.

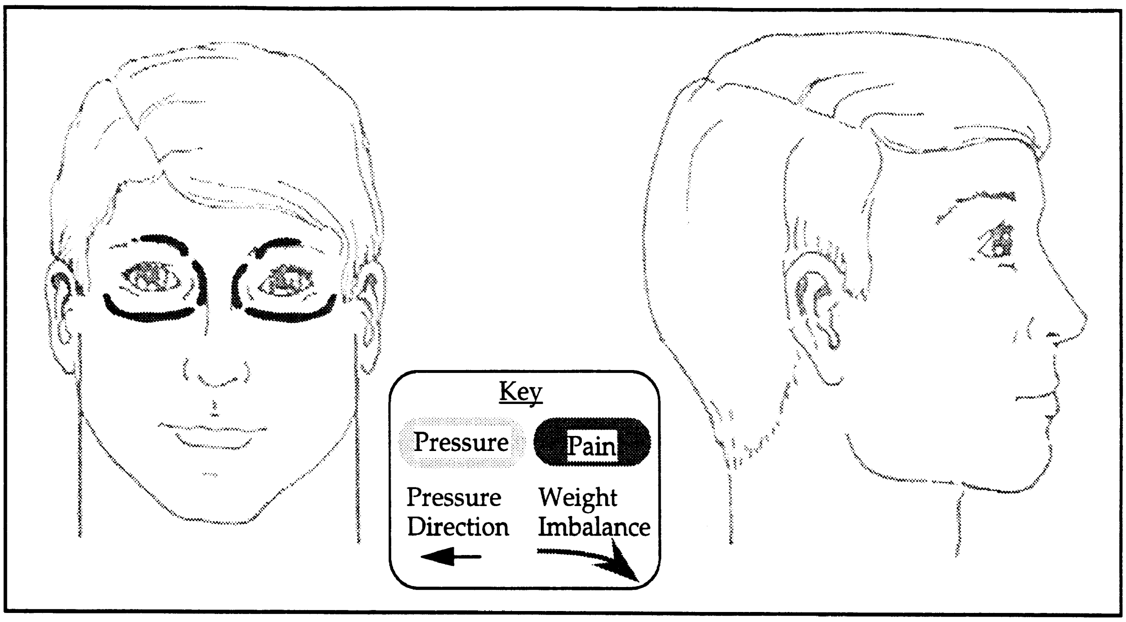

Figure 26. Illustration of discomfort from wearing the Ober2 headpiece.

Table 9. Discomfort ratings for Ober2.

Rating Scale:
1 Just noticeable
↓
9 Unbearable

	Ober2 Discomfort Ratings			
Time Elapsed (min.)	Pain and pressure	Weight	Imbalance	Freedom of movement
0 to 15				
16 to 25	5	2	2	1
26 to 35	7	4	3	1

The Ober2 goggles caused some pinching against the face. The plastic/rubber edges are not rounded and therefore felt as if they were digging against the bridge of the nose and under the eyes. The discomfort caused by this pinching was comparable to the other cameras' discomfort problems. The weight of the Ober2 was satisfactory, even up to 35 minutes. The discomfort from imbalance of the Ober2's headpiece was rated as acceptable even up to 35 minutes. The simple goggles and minimal wiring of the Ober2 made restrictions on movement just noticeable. The only wiring was ribbon cables that were bundled in the front and had a neck strap to remove the weight from the headpiece. Also, due to the rubber frame construction of the goggles, they seemed more durable (and less injurious) than the metal components of the other systems.

The most prevalent cause of discomfort from the eye cameras tested was the headpieces' physical mountings. No completely comfortable means of securely fitting the headpiece was seen. Because absolute stability is imperative for calibration maintenance, the headpieces rely on straps or bands that must be snug (sometimes beyond tolerable levels).

Another major comfort factor with most systems is imbalance. Sensors that are mounted high and perched out over the eyebrows cause a significant imbalance. As a result, the headbands must be tightly adjusted to prevent slippage. In this case, the neck still has much static tension put on it. Although overall weight is a contributing factor, imbalance was felt to be a more uncomfortable characteristic. A custom counterweight added to an imbalanced headpiece can prolong a test session, provided the overall weight does not then become intolerable. To a limit, if a tradeoff has to be made for weight or balance, a balanced system is preferred here.

Accuracy

The numeric data collected from the eye camera systems were plotted to reveal the quality of the data recording. Figure 9 in the Methods section shows the paths of the target. Unless otherwise indicated, all four plots in each set were from the same session, with the same calibration, and were run in the order of horizontal, vertical, diamond, and diagonal.

Some inevitable differences between systems are due to inconsistency in calibration. Some systems had manual calibration and some had automatic. For the manual systems especially, calibration can almost always be improved by additional (sometimes infinite) fine tuning. The experimenters tried to limit calibration time to one-third of the total comfortable wear time. For most systems, the total comfortable wear time was between 20 and 30 minutes. For the systems on which the experimenters became experts only for this study (the ASL 210 and the Ober2), calibration skill level was difficult to measure. If calibration for data collection did not proceed well, or was taking excessive time, the experimenters assumed it was their own limitations, and the tracking task was not run at that time.

Each systems' accuracy can be seen in their plots (Figures 27 through 33). Straighter lines indicate accuracy does not vary by location. If the horizontal and vertical plots are orthogonal, this indicates consistent tracking near the edge of the range. A slight curvature in the plots of the horizontal task is to be expected, since it reflects the curve of the video monitor used for presentation.

Full page plots with data point markers are in the Appendix. Some aspects of eye camera behavior are better indicated by those plots. The jumps from the tracking path are seen to consist of only a few points diverging due to blinks. It is also more apparent that the jittery trace of some systems, like the NAC model V, is due to discretely-quantized data.

ASL 210

Plots from two subjects tested with the ASL 210 are shown in Figures 27 and 28. Data were collected at 30 Hz.

For the ASL 210, the calibration sheet included in the user's manual was used. These points were inside of the target's range of motion. As a result, the output at the outer edge of the plot potentially could have been cleaner. For instance, the skewing in the lower right corner would have been detected at calibration time, and possibly corrected. The bending to the bottom left seen in the vertical tracking task demonstrates the interference caused by eyelashes. Eyelash interference is worse closer to the bottom, since the subject's eyelids are lowest at this point. The calibration of the 210 also was distorted by the parallax between the scene camera and the subject's eye view.

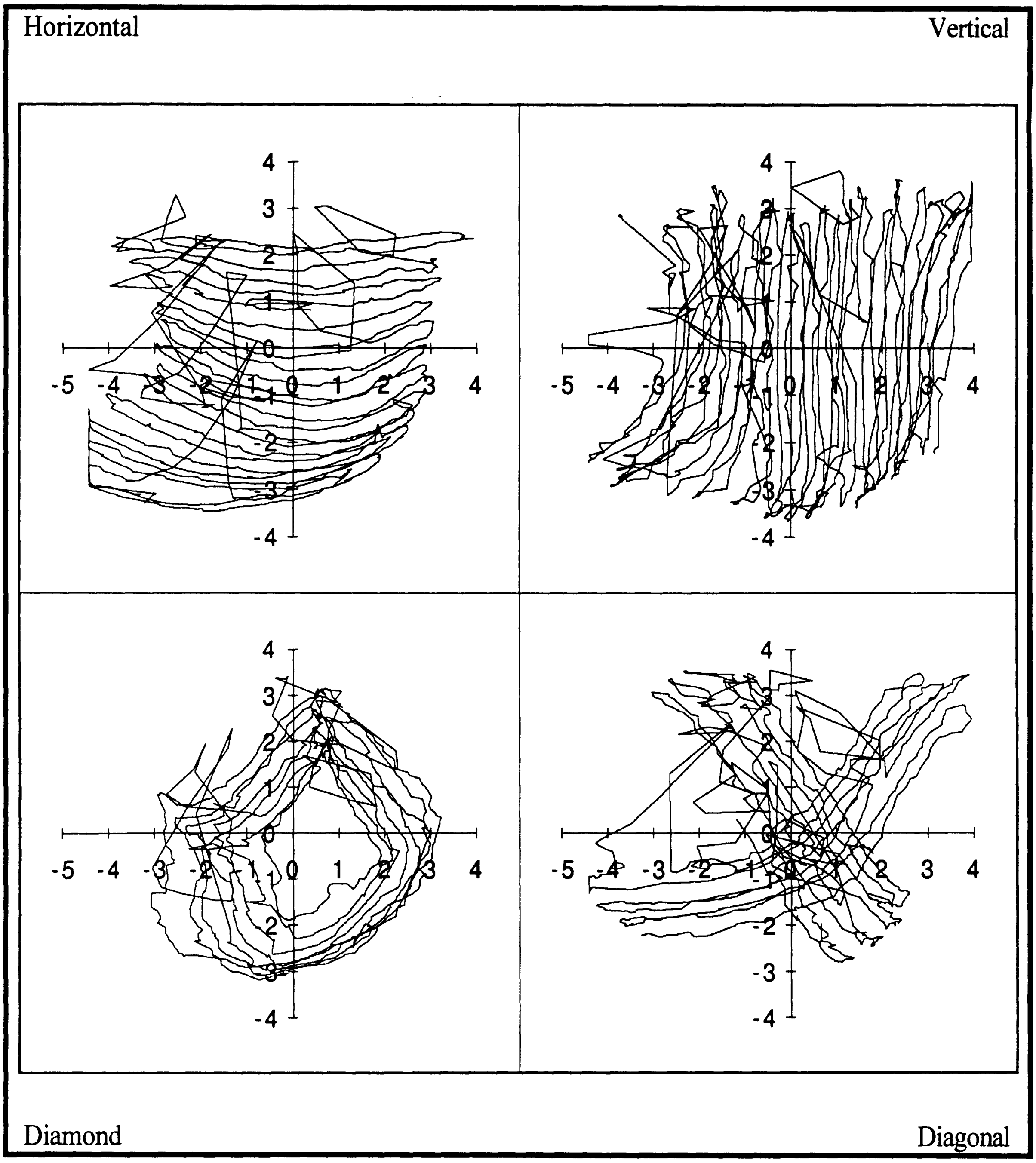

Figure 27. Tracking plots for subject A using the ASL 210.

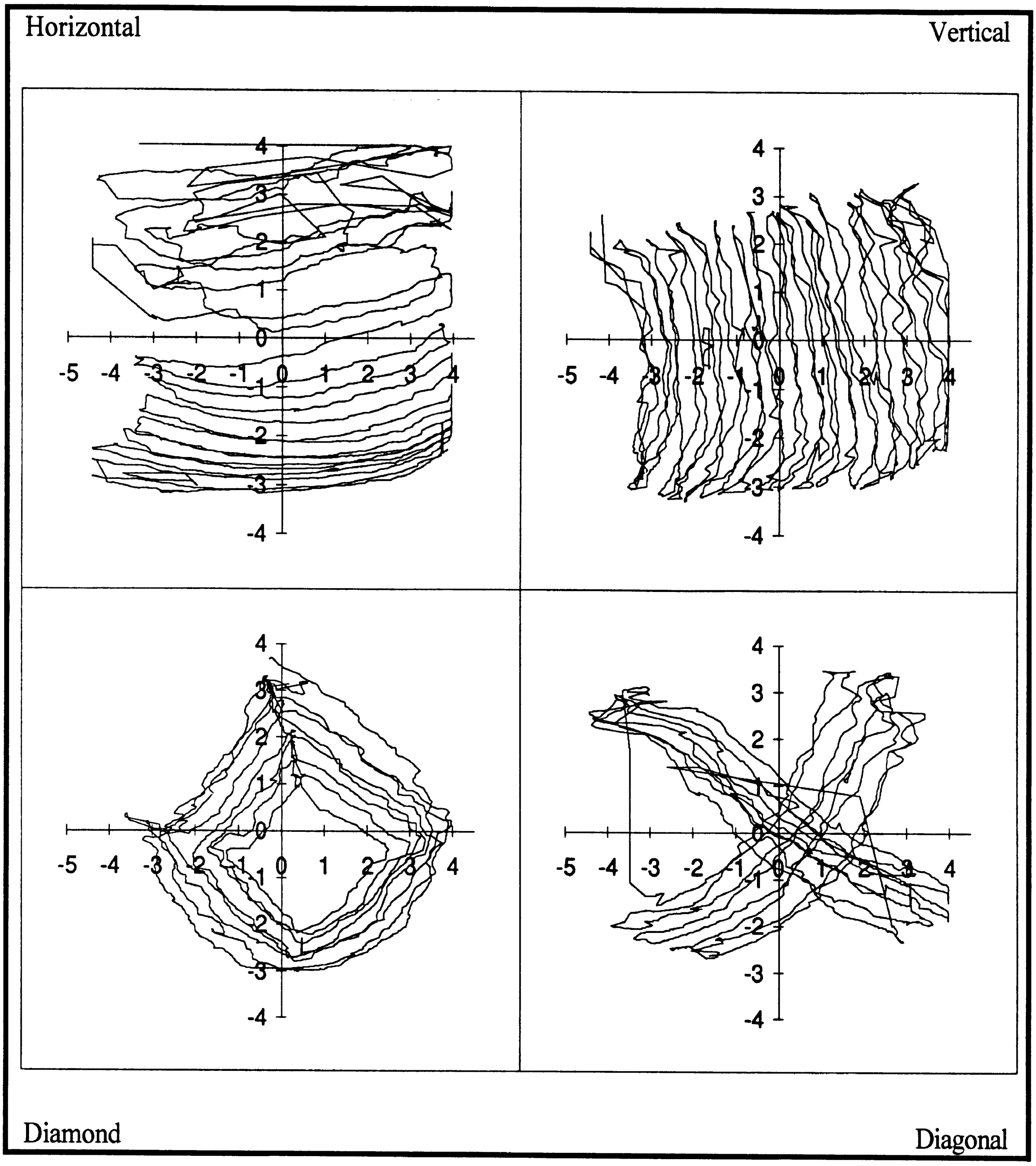

Figure 28. Tracking plots for subject B using the ASL 210.

ASL 4000

Due to difficulties with the data collected by the experimenters, these plots (Figure 29) were generated from data collected at Applied Science Laboratories. Data collection was performed by expert staff at the company. Data were collected in a darkened room with nine-point calibration at 60 Hz.

This system was calibrated for the corners and edges of the monitor. This helped the system retain the orthogonality of the trace shapes. The jumps in the upper left corner are probably caused by the system losing track of one of the eye features.

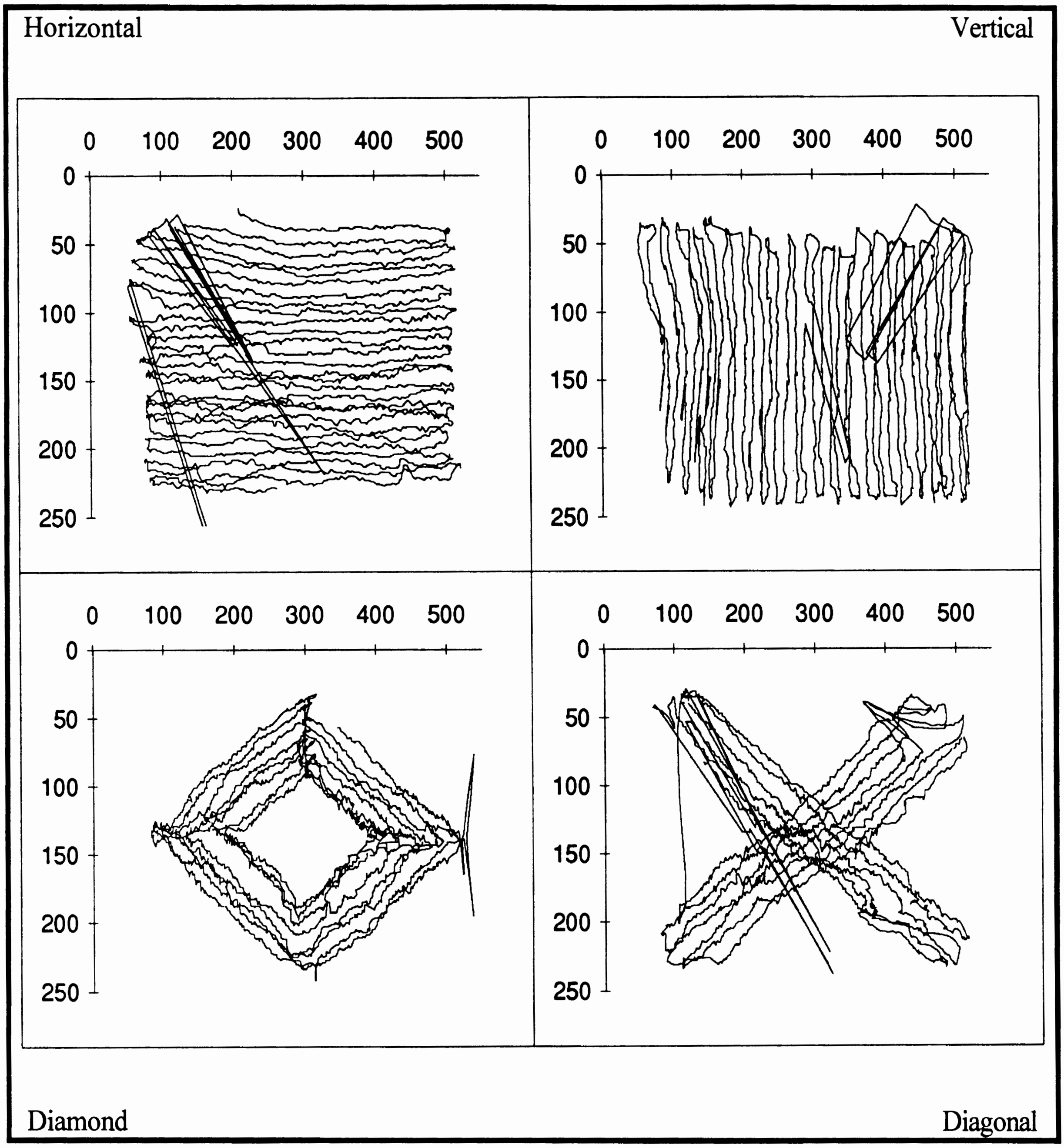

Figure 29. Tracking plots for subject C using the ASL 4000.

ISCAN

Data collection was not setup for the system the authors examined. Replacement data were run (see Figure 30) by experts at the ISCAN company using the same protocol as the other systems.

The latest version of the eye camera system was used in a well-lit room. Data were collected at 60 Hz after a quick five-point calibration.

The ISCAN maintained well the orthogonality of the tracking path. The data are a little noisy, and the larger plots included in the appendix reveal some of this to be due to quantization of the data. The long jumps to coordinates 0,0 are blinks. These would be easy to filter in post-processing.

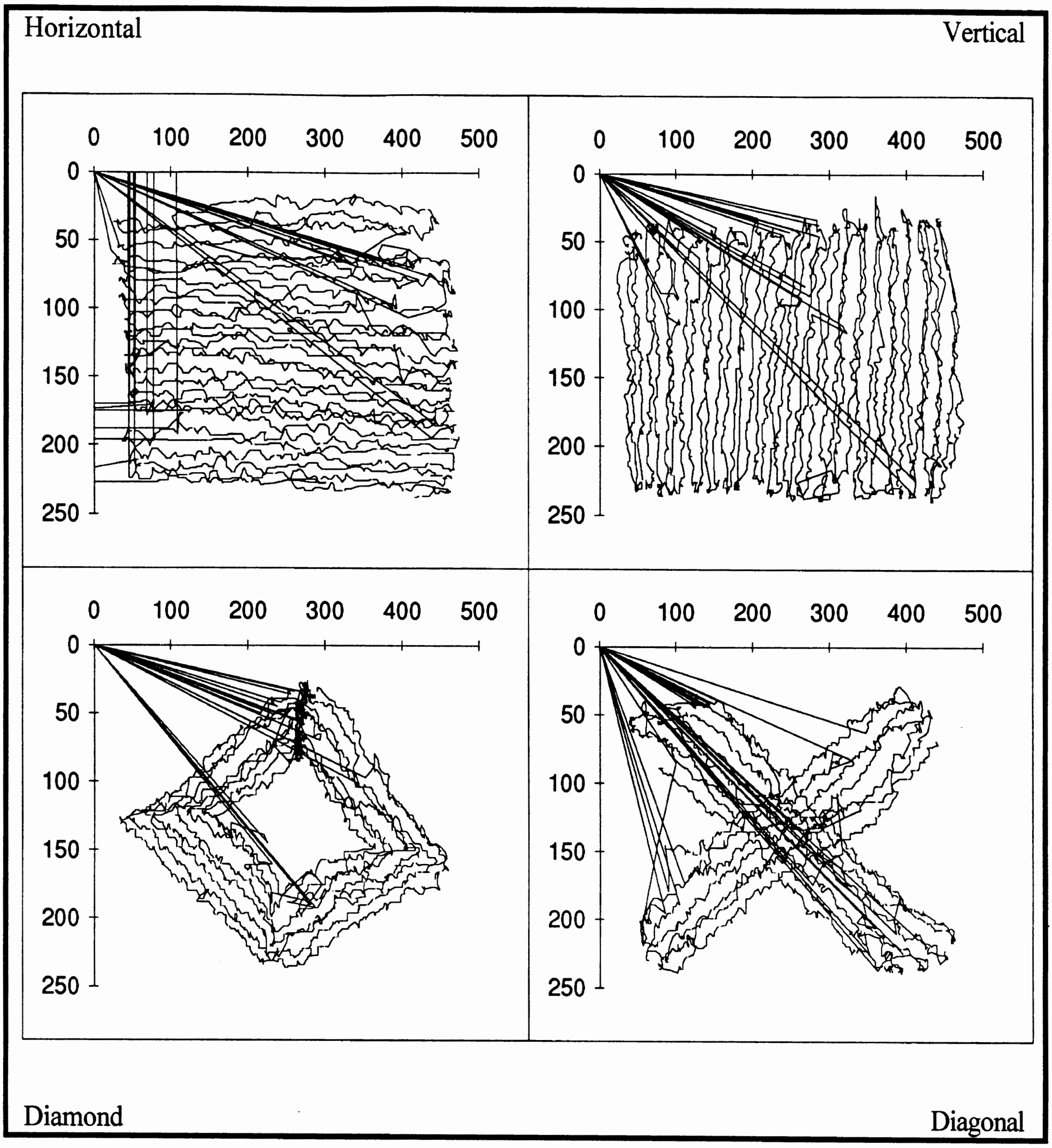

Figure 30. Tracking plots for subject D using the ISCAN.

NAC V

Plots from two subjects tested with the NAC model V are shown in Figures 31 and 32. Data were collected at 30 Hz. The experimenters had the most experience calibrating and collecting data from this system.

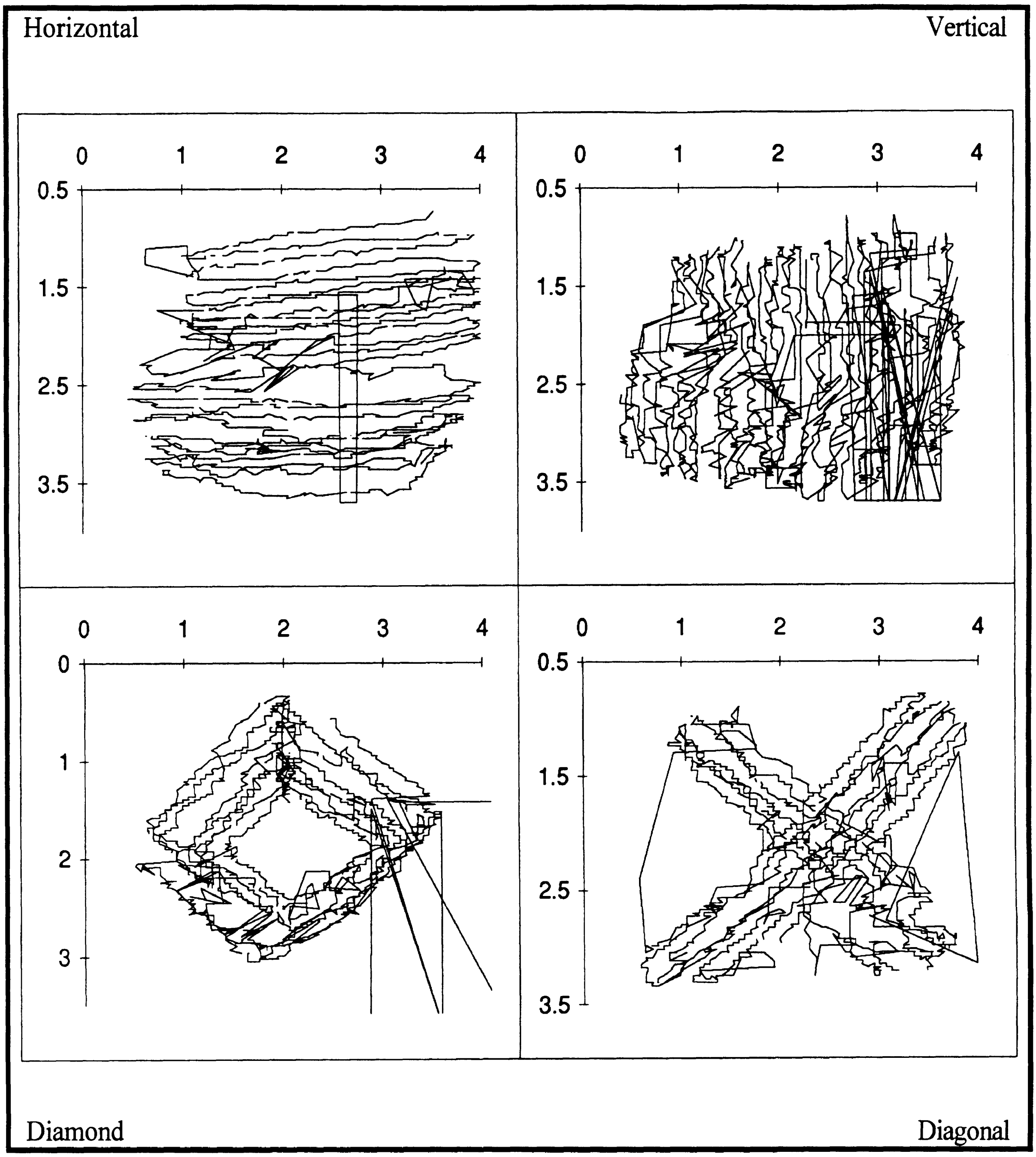

Figure 31. Tracking plots for subject A using the NAC model V.

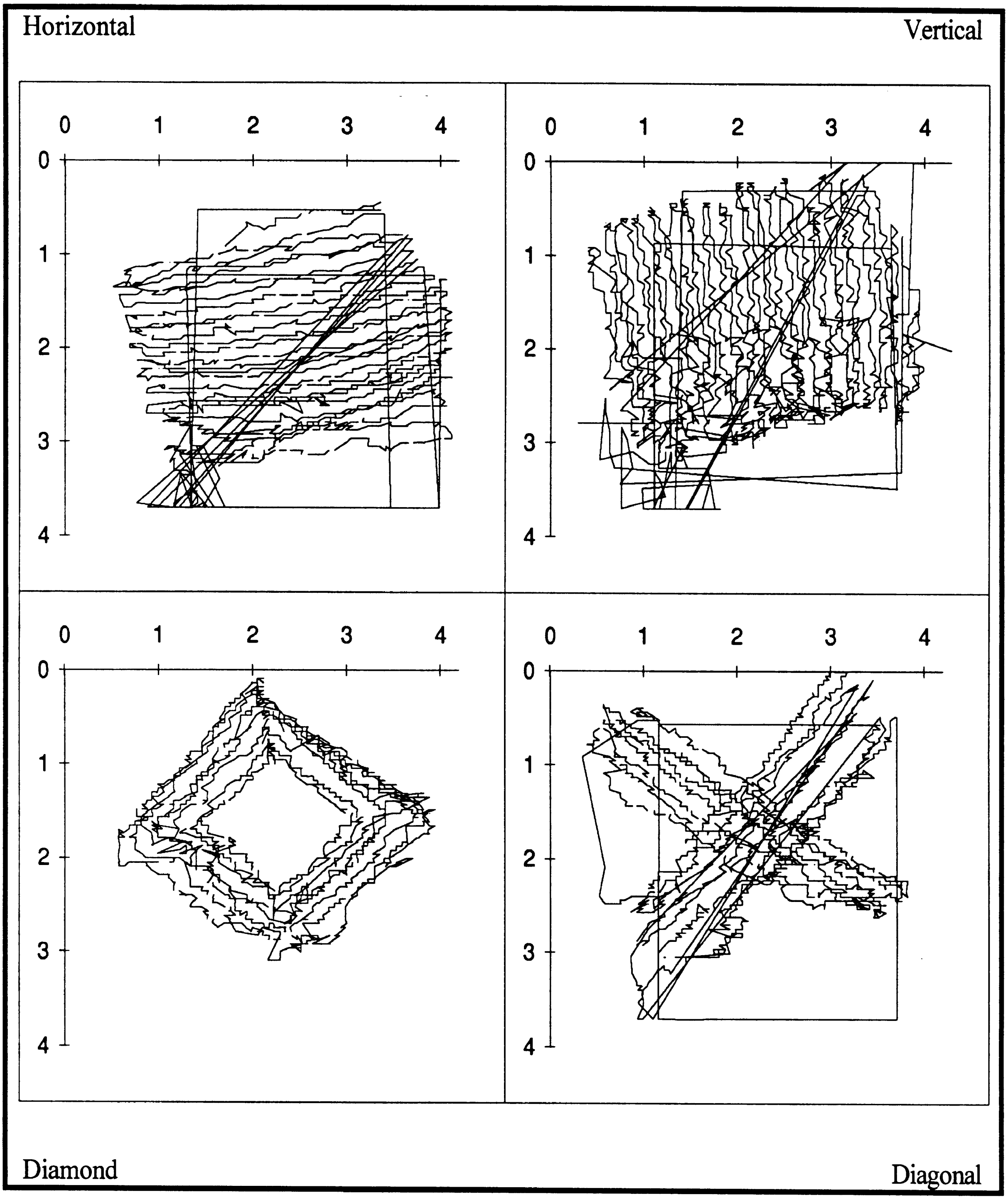

Figure 32. Tracking plots for subject B using the NAC model V.

This system has difficulty tracking the right eye to the upper right corner, as can be seen in the vertical plots of both subjects. As it approaches the upper right corner, the eye marker jumps to a much lower location due to the LED reflecting off the sclera. The system has only 8-bit resolution for the horizontal and vertical. This causes the stair-step appearance of the diamond and diagonal plots.

Extensive practice is needed before consistent calibration can be obtained with this system. The output quality is directly related to the time and effort put into the calibration procedure. A higher quality of output may have been obtainable if more time had been spent on calibration, but then the total session time would have exceeded the comfortable wear time.

Ober2

Plots from two subjects tested with the Ober2 are shown in Figures 33 and 34. Data were collected at 30 Hz. The data for the vertical plot of subject B (Figure 33) were collected in a separate session. The x and y data plotted here are an average of the x and y data the Ober2 records for both eyes. Individual plots for each eye are included in the Appendix.

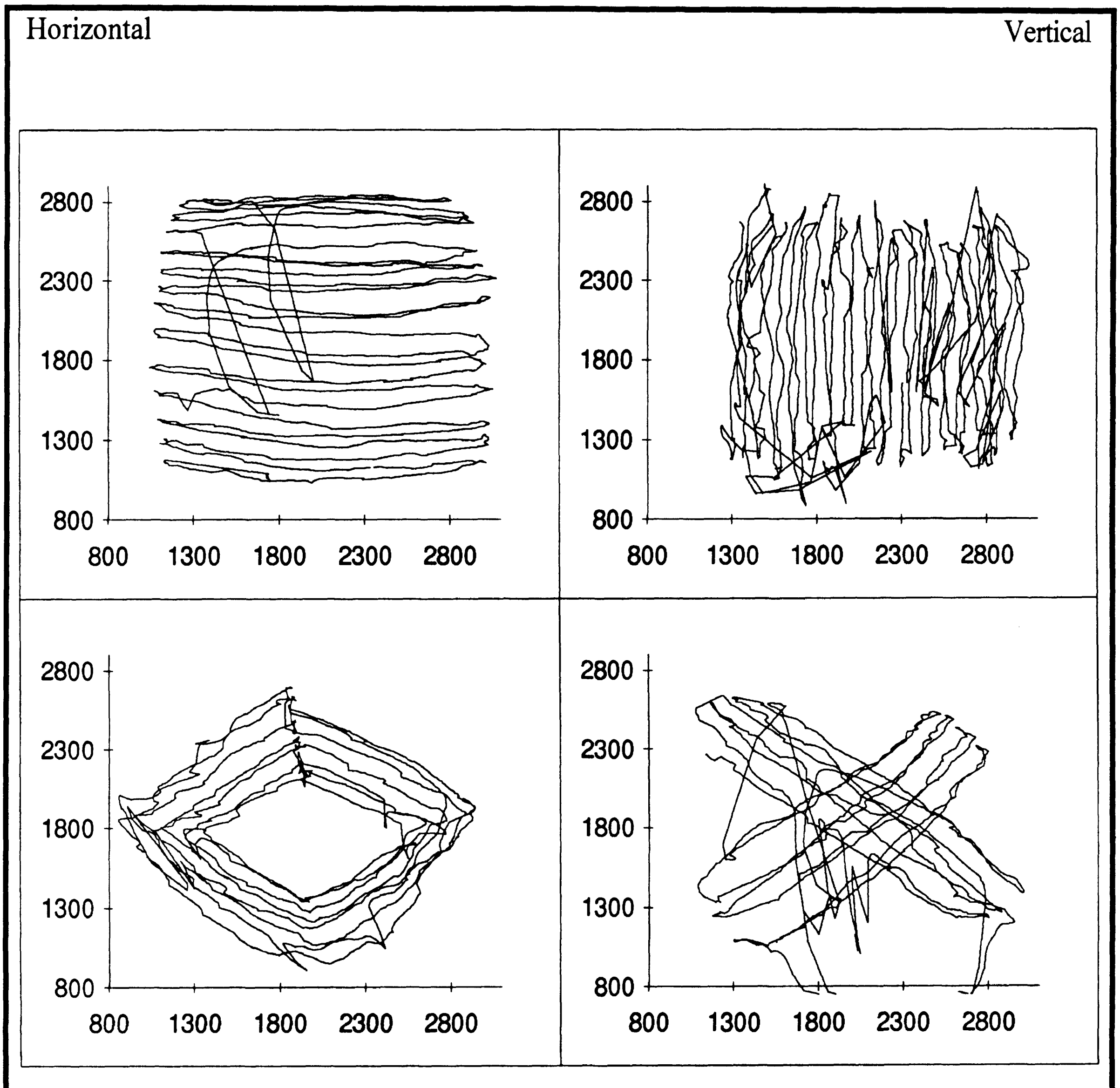

Figure 33. Tracking plots for subject A using the Ober2.

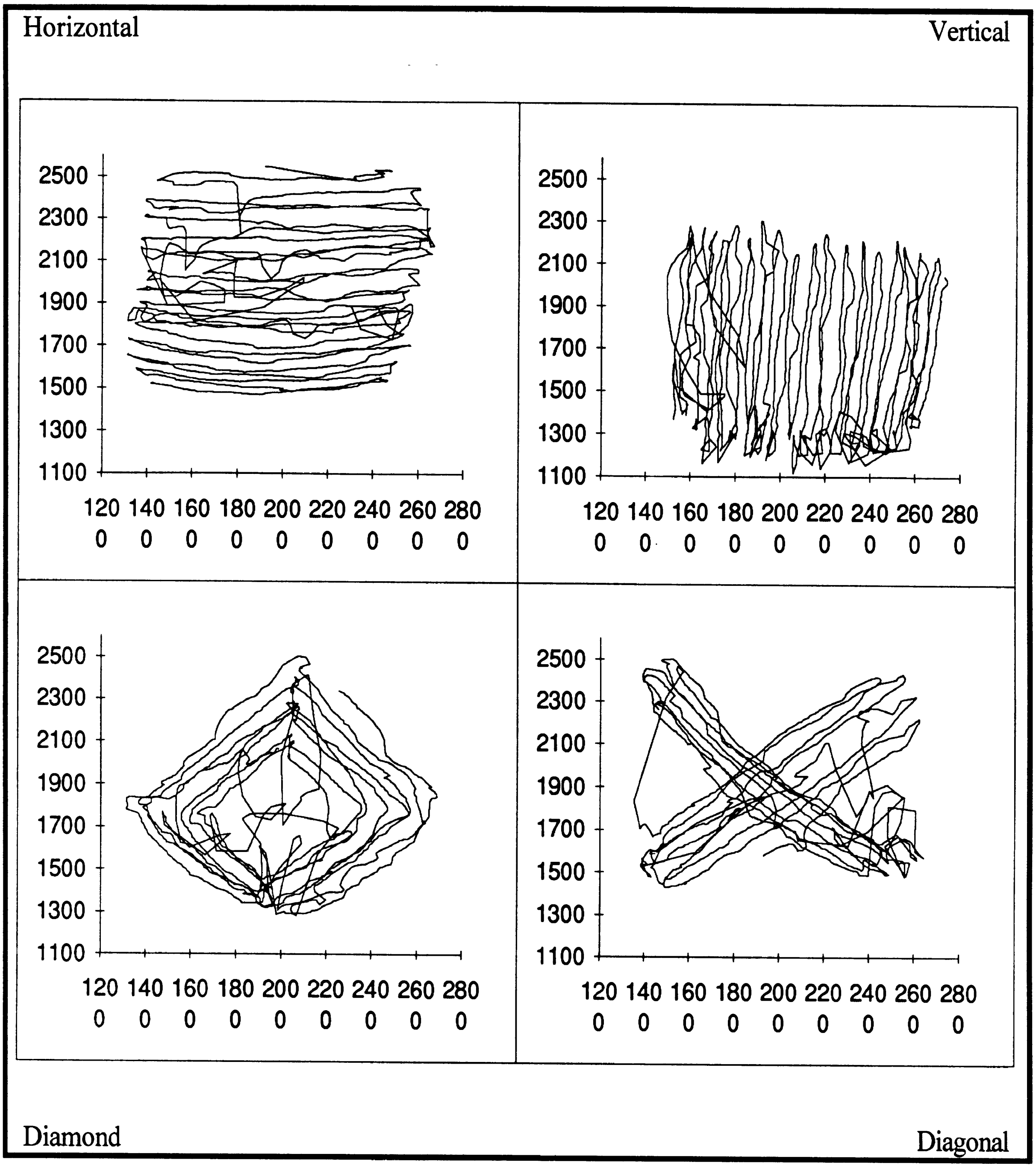

Figure 34. Tracking plots for subject B using the Ober2.

The smooth lines are the result of high resolution. The anomalies are generally caused by blinks. The foreshortening of some dimensions in the diagonal plots is due to the range of the system being slightly smaller than the range of the tracking task.

Subject Parameters

Some eye-movement monitoring systems can force experimenters to select from a restricted pool of subjects. Factors such as weight, head size, comfortable wear time, and compatibility with eyewear can limit the age, strength, body size, and vision correction of the subject base. Some designs are more affected than others by users wearing eyeglasses or contacts. No system evaluated in this test is able to function properly with a subject wearing bi- or trifocals.

The compatibility of each system with the subject parameters mentioned above is summarized below.

ASL 210

Eyeglasses cannot be physically accommodated with the sensor array of the model 210. Hard and soft contacts are acceptable, as they do not disrupt the function of this eye camera. Experimenters had difficulty adjusting the headband to fit solidly on a small head without having to overtighten the band across the forehead.

ASL 4000

Standard eyeglasses are compatible with this system, as are soft contacts. Hard contacts, however, seriously disrupt the calibration of the system. The headband was difficult to fit solidly on a small head, without sacrificing comfort.

ISCAN

Eyeglasses and contacts (both hard and soft) are compatible. The helmet version (weighing 0.5 kg) will place restrictions on the possible subject population, based on neck strength. The headband version is much lighter and should not limit the pool based on strength.

NAC V

Eyeglasses are partially compatible. If glasses are worn by a subject, extra calibration effort is necessary to avoid significant disruption to the output. Hard contacts can be used, but they add noise to the eye spot movement. Soft contacts are compatible. The unit is limited in its adjustability to various head shapes, especially small heads. This increases the discomfort for subjects the unit does not fit correctly.

Ober2

Eyeglasses will not physically fit with the goggles, though special goggles are available with corrective lenses. There are no compatibility problems with contact lenses.

DISCUSSION

An overall ranking of the systems studied is difficult to make, for a number of reasons.

- User needs vary significantly depending upon the experimental question. It is difficult to predict all of these needs and to apply them to one overall comparison.
- The systems were not equivalent and comparable. Some were manufacturers' demonstration models, others had been modified by the customer/laboratory who was using them, and one was a prototype.
- Systems were not evaluated under all of the same conditions. Some were brought to the UMTRI laboratory, others were evaluated at other laboratories, others were tested by the manufacturer, and some were evaluated at multiple sites.
- Results were taken from various sources, including manufacturers' specifications, objective laboratory testing, direct observation, and subjective evaluation.

Summaries of the evaluations of each eye camera system are given below, along with tables summarizing specifications and compatibilities across systems. Also included is a section of issues to be addressed before selecting or using an eye camera for studies of driving.

Summaries of Each Camera

ASL 210

As a reminder, a demonstration model of the ASL 210, leased from Applied Science Laboratories, was tested in an UMTRI laboratory. Overall, the system performed reasonably well for the tests done. The major drawbacks include uncertainty about its safe and reliable use in an on-road vehicle.

Calibrating the 210 is a moderately difficult task that requires a well-practiced experimenter. More so than other systems, the 210's controls interact with each other. Adjusting one control will improve the device's function on that dimension, simultaneously degrading it on another. The controls and displays are straightforward, but require knowledge of the factors that influence calibration accuracy. In terms of size, the control box is relatively compact and portable. The assignment of eyes for horizontal or vertical movement sensing is at the experimenter's discretion.

In terms of accurately tracking the moving stimulus, the results were reasonable. The main problems were skewing of the data near the bottom of the functional range, and overall noise. Potential use in a vehicle on the road is not known, nor is whether or not IR filtering would be necessary. If IR does cause interference, then custom shielding would have to be constructed.

When running a study with this system, researchers should expect that subjects will be moderately uncomfortable after a 35-minute test session. A custom counterweight may reduce some of the problem. In addition, if studies were to be done with regular drivers on public roads, the risk associated with drivers' reduced vision and potential for injury should be carefully considered. The subjects' field of view will be fairly restricted, especially in the central and upper areas, due to the positioning of the sensors. The risk of injury would be eliminated in a laboratory or fixed-base simulator; however, the field of view limitations and discomfort problems would remain.

ASL 4000

The ASL model 4000 tracking task was conducted at the manufacturer's laboratory, according to the test protocol developed by the authors. All other tests were conducted by the authors. The overall performance of the model 4000 was very good, in regards to both technical results and subject comfort. This model is one of the newest evaluated in this study.

Calibration of this system is semiautomatic, where the experimenter uses a mouse to indicate calibration points. The system's tracking reliability is high.

The size and weight of the control units makes it fairly unwieldy. Currently, this system does not function in a vehicle in daylight. It is not known if modifications will improve its function. There are difficulties with IR and the reduction in pupil size caused by bright sunlight. Shielding the device from light may improve its function for on-road studies, but the subjects' field of view could be impacted by altering the design. The system used for testing field of view in this study had been modified to reduce overhead light interference. The reduction in overhead field of view caused by this modification may be unacceptable for driving studies. Drivers may not be able to see either traffic signals easily while stopped at an intersection, or approaching highway signs. While there are no sensors directly in front of the eyes, the safety of the face plate visor in event of an accident is unknown.

Discomfort problems for the wearer include a slight imbalance of the headpiece. As the overall discomfort from the weight of the head unit is not great, a counterweight is an acceptable solution to the problem of imbalance.

ISCAN

The ISCAN used in this study for field of view and comfort evaluation was being loaned by the United States Air Force to Cybernet Systems Corporation, a company located close to the authors' laboratory. Employees of the local company conducted a calibration session and the authors conducted the remaining tests. (As a reminder, this unit is not the most recent model offered by ISCAN.) The performance of the ISCAN was hampered by atypical difficulties affecting calibration. (A striped screw prevented the experimenters from making stable adjustments to the reflecting monocle.) The age of the system must be taken into account when viewing the comfort ratings, as this system was installed on an older (and heavier) helmet than is currently available. Also currently available is an even lighter headband version that would not exhibit most of the comfort problems of this unit.

Calibration of the ISCAN during this evaluation session was difficult due to a damaged screw holding the reflective glass in place. As a result, the tracking task could not be completed at this site, and data were subsequently collected by ISCAN. The calibration procedure for the newest, PC-based unit is fully automated and software controlled. Based on the data collected by ISCAN the tracking accuracy is high.

The older unit had been previously used successfully in a Humvee military vehicle. It is not known what, if any, modifications were made for its use in-vehicle. The overall safety risk associated with its use in a car seems relatively low, as there is only the dichroic mirror in front of one eye and the unit is mounted within a padded helmet. The visual obstruction is very low, except for some slight blockage due to the scene camera mounting arm, and the cover over the optics and visor extending over the forehead. The older helmet resulted in poor subject comfort. Its weight was enough to cause some discomfort immediately after fitting. The loose fit also hampered freedom of movement. With some padding for stability, and a reduction in the overall weight, this helmet-mounted unit would not be so cumbersome. The optional headband-mounted unit was not evaluated.

NAC V

The NAC model V was tested by the authors at UMTRI. This unit has been accessible to the authors on long-term loan from Mitsubishi Motors Corporation, and had been modified for use in on-road experiments previously. The overall performance of the NAC was moderate, with the drawbacks being headpiece instability and calibration difficulty, but the great advantage being functionality in a high IR environment (such as a vehicle in sunlight). A newer NAC eye movement recorder, the Model EMR 7, will be available soon in the United States, with a redesigned headpiece. This new model is expected to have the same functionality when used in a vehicle.

Calibrating the NAC V takes some practice to achieve an acceptable setting. Calibration requires that adjustments be made to controls located on the headpiece. While other calibration controls are on a remote unit, allowing the experimenter to make the on-head adjustments, care must be taken not to jolt the headpiece out of its stable and semicalibrated position. Another large data collection unit is also needed, but its proximity to the subject is not as limited by cable length. Once a reasonable calibration is made, the tracking reliability is moderate.

Although not tested specifically for this study, this model has been used successfully by the authors in a vehicle. The sides of the headpiece and coated face plate serve as a filter for IR. Unfortunately, the headpiece frame that blocks out the IR also block the driver's field of view, especially in the periphery, increasing the risk associated with driving. Also, as there is much hard plastic material around the face, and an LED in front of one eye, the risk of injury in an accident is likely increased. The size of the headpiece also results in discomfort to the subject. The imbalance of the unit necessitates a tight (and uncomfortable) fit of the headpiece, to avoid slippage. The number and placement of cables that are connected to the headpiece can cause some restriction of head movement.

The NAC V can be, and has been, modified to increase driver's field of view and comfortable wear time. Removal of one side sensor piece not only creates a small side opening, but reduces the overall weight of the unit. A small counterweight can compensate somewhat for the resulting imbalance. Bundling the cables together can also improve the drivers' movement. While no additional modification is needed to make the NAC V function in an on-road environment, the limited field of view may make its use unsafe for on-road use.

Ober2

The Ober2 system was leased from the manufacturer and tested at the authors' site. The system for superimposing the eye mark on the forward scene had not been arranged to be leased by the project director. The overall performance of the Ober2 was high. Subject discomfort was minimal, and easily improved. Its adequacy for use in a car is not known, but the very limited field of view would likely be unacceptable.

Calibration of the device is fully automated. The reliability of tracking is high. The experimenter's only role is to define some parameters (such as lighting compensation, stimulus viewing distance, etc.). As a result there is no control equipment and all adjustments are made in software. The goggles are also very small and cause little discomfort to the wearer. The only problem noticed was the edge of the goggles pinching into the face. As the sensors are encased in soft plastic, no sharp objects are in front of the eyes. The most significant safety concern for use in a car is the tunnel vision resulting from the goggle design. This limited visibility may be suitable for use in a simulator, if the intended visual target areas are well defined and in a limited range of view.

Overall summary of cameras

A summary of the specifications of the eye camera systems are shown in Table 10. This information was taken from the manufacturers' literature. Table 11 shows a summary of field of view (FOV) limitations and calibration difficulty, issues that affect the nature of the experimental task and the acceptable length of test sessions. The compatibility of each camera's use with various eye wear is listed in Table 12. Finally, a summary of the relative discomfort issues for each of the tested systems is shown in Table 13.

Table 10. Summary of system specifications.

System	Method	Cost (U.S. $)	Horizontal Range (degrees)	Horizontal Accuracy (degrees)	Vertical Range (degrees)	Vertical Accuracy (degrees)
ASL 210	Varying IR reflection	11,625	±15	1	±15	2
ASL 4000	Video, dual feature identification	35,600 † 31,600††	50	1-2	40	1-2
ISCAN	Video, dual feature identification	32,000	±15	0.5	±15	0.5
NAC V	Video, single feature identification	15,000 (value)*	60	0.8-3.2	45	0.8-3.2
Ober2	IR sensor array	9,900§ 17,200§§	±25	0.5	±20	1

† Bright pupil system
†† Dark pupil system
* Unit no longer for sale from supplier
§ 120Hz maximum sampling
§§ 1200Hz maximum sampling

Table 11. Factors that may restrict the experimental task's target location and test session length.

System	Forward FOV Interference	Peripheral FOV Interference	Difficulty of Calibration	Headpiece weight (g)
ASL 210	High	Med	Med	448
ASL 4000	Low	Med	Low	507
ISCAN	Med	Med	Low	345†
NAC V	Low	High	Med	420
Ober2	Low	High	Very low	80

†Headband version

Table 12. Systems' compatibility with subjects' visual correction.

	Eye wear compatibility		
System	Eyeglasses	Soft contacts	Hard contacts
ASL 210	no	yes	yes
ASL 4000	yes	yes	no
ISCAN	yes	yes	yes
NAC V	no	yes	yes†
Ober2	no††	yes	yes

†Some distortion of calibration
††Optional corrective lenses available

Table 13. Summary of relative discomfort ratings.

System	Mean Discomfort Level				
	Pain/ pressure	**Weight**	**Imbalance**	**Freedom of Movement**	**Overall**
ASL 210	high	low	med	low	med
ASL 4000	med	med	med	med	med
ISCAN	high	high	high	high	high
NAC V	high	med	high	high	high
Ober2	high	low	low	low	low

Identifying Eye Fixation Measurement Needs

The first step in selecting an appropriate eye-tracking system is to identify exactly what needs to be measured and what limitations are tolerable. Measurement needs are the accuracy and the type of output. Limitations are those placed on experiments by direct interference with the subject's task. Safety considerations also limit the domain of testing situations. System compatibility limits the type of vision correction subjects can wear. Comfort can restrict possible subject types. Installation is affected by the size of the equipment and the maximum length of cabling. A complicated calibration procedure can make use in a vehicle or simulator much more difficult.

The method used by the system for determining eye location can affect the range of compatible environments. If the system is infrared based (as were all of the systems in this evaluation), then there is the possibility of interference with environmental infrared if the device is used in sunlight. For the high-end systems that track two eye features, the dark-pupil measurement is less susceptible to bright light, than bright pupil. In bright light, when the pupil is small, dark-pupil measurement makes it easier to distinguish from the corneal reflection and other stray reflections on the eye.

Accuracy

The necessary accuracy (in degrees of eye movement) can be calculated by drawing a diagram of the experimental setup and measuring the visual angle between typical objects of interest. If accuracy needs are on the border of a given eye system's capability, build a *simple* mockup and have the vendor demonstrate the unit to ensure that glances to objects of interest are distinguishable both on video and processed output data.

Output

Eye camera output is in several forms, video (with a superimposed indication of the eye-gaze location), analog output, and digital or serial output. The first usually requires only a standard

VCR; the second and third require a computer, interfacing, and data collection software. Both methods require additional data processing. Video data is usually analyzed by a person, though multimedia tools can make this a less arduous task. Computer data collection needs post-processing to determine fixations, transitions, and blinks.

If the gaze is measured relative to the head, computer data collection is meaningless unless the subject's head is fixed, or the data are analyzed with respect to a concurrent video recording. To record relative to the scene, the position of the subject's head also needs to be recorded.

For studying actual driving, it is necessary to have video output with a cursor indicating the eye-gaze location. Video output is the only means for identifying the object of the driver's fixation, especially if a head tracker is not used. If a head tracker is used, eye movements to objects fixed inside of the vehicle could be determined from a spatial mapping of the objects in the driver's field of view. This would not allow for identification of gazes to anything not fixed, such as the road scene, or objects in the car that move, like a cellular phone handset. Video output would also be necessary for recognizing when calibration has slipped or drifted. Some loss over time of calibration due to road vibration and driver head motion is inevitable during testing of actual driving.

For studies conducted in a simulator, video output is still the most reliable means of determining fixation locations. It is possible, with a head tracker and eye camera, to determine the object of each gaze since the controls in the vehicle are fixed, and the objects in the scene and their location are known at each moment. Video is still useful for determining the reliability of the data. Objects that usually move relative to the driver, like a remote control for a navigation system, can be studied only by video analysis, unless they are permanently mounted in the driver's field of view.

Eye camera interference with the experimental task

Use of an eye camera, especially an on-head system, can interfere with the subject's natural performance of the experimental task. It is necessary to determine how much interference is acceptable before the test results will be significantly impacted or, in the case of on-road studies, the subject will no longer be safe. Items to be identified with regard to interference:

- The field of view needed by the subject to perform the task.
- Degrees of freedom of movement needed by the subject such that natural motion is not impeded. If freedom of movement is not needed, a bite-bar or cheek-rest greatly increase the accuracy of the data.
- The space around the subject's head needed to give the subject free movement when the eye camera is being worn.
- The total test time for each session. Ensure the system will be comfortable for the needed time period.
- The time for eye-camera calibration that can be spared from the total comfortable wear time. For most systems, higher accuracy means spending more time fine tuning the calibration, or calibrating the system for more points.

Physical structures, such as short cables and bulky headpieces, may limit drivers' freedom of movement in a car. Cables that are too short restrict head movements or cause the headpiece to slip off the head. On the other hand, if cables are too long, or are not tied together, they can get caught on other equipment or on the subject. Headpieces that are very large may not provide enough headroom for a tall subject in a car. Other mounting devices that protrude from the headpiece may contact the side window or headrest, causing the headpiece to slip on the head (and lose calibration) and potentially block the subjects' view of the road.

Likewise, if a headpiece is heavy, imbalanced, or obtrusive, it may interfere with the normal head movements and eye-glance behavior that occur with driving a car. Excessive weight and imbalance can cause neck strain, making it difficult or uncomfortable for subjects to turn their heads to check mirrors or displays. Thus, drivers may reduce their head movements or change their behavior to reduce muscle fatigue or discomfort. On the other hand, components of the headpiece that block the wearers view of the road or target may cause them to alter their glance behavior just to avoid the obstructions. Also, if the headpiece's method of being fastened to the head (e.g., adjustable straps) is not adequate and secure, subjects may be reluctant to move because the headpiece may slip.

Safety

Before running any subjects in on-road studies, especially public roads, the risk associated with the subject's task must be evaluated. The evaluation should consider at least the following issues:

(1) The increase in difficulty of safely performing the driving task due to reduced field of view and reduced motion from cable restrictions or weight.

(2) Crashworthiness of the head-mounted unit. The risk of injury from parts of the eye camera, especially in front of the wearer's face. The risk of injury due to broken pieces of the eye camera flying about.

(3) All supporting eye camera control units and recording equipment must be secured so they can not break loose and cause injury.

Subject constraints

Eye-camera systems may be limited in the type of subjects on which they can be successfully calibrated. Usually this is caused by visual correction disrupting the eye camera's function. Soft contacts are not generally a problem, but hard contacts can cause serious problems, and glasses often will not fit with the physical head unit. These limits need to be considered if the experimenters intend to draw from a broad subject pool, especially including older drivers, who often have corrected vision.

Comfort can also limit the segment of the population to be used in eye fixation studies. Eye camera weight limits the age of subjects to be run, or at least the length of comfortable wear time for some subjects.

Equipment size

Acquiring space for control and recording equipment is more difficult for in-vehicle studies than laboratory studies, though it is an issue for both. The space required for each type of system varies, as does the flexibility of system configuration. Some systems are piecemeal and the types of displays and computers are at the experimenter's discretion. This allows for acquisition of small, low-power units for in-vehicle use, or large, cheaper units if lab space is not a problem.

Cable length restricts the distance from the eye camera to the control and recording equipment. This can affect setup in a simulator, and can impact wearer freedom of movement in a vehicle setup.

Usability

Usability is convenience for accessing controls on a control box, a computer, and the on-head unit while seated in a vehicle. For a simulator laboratory or an actual vehicle, it may be difficult to install all control units within easy reach of the experimenter. If adjustments are required alternately on different units, it can be difficult for one person to access both. The most usable eye camera system for a vehicle setting is one where the units can be calibrated serially--finish one unit, move on to the next--so the experimenter is not forced to move repeatedly between units.

REFERENCES

Applied Sciences Laboratories, *Eye Tracking Systems Handbook*, Waltham, MA. (No date.)

Green, P. (1992). *Review of Eye Fixation Recording Methods and Equipment*, (Technical Report UMTRI-92-28). Ann Arbor, Michigan: The University of Michigan Transportation Research Institute.

APPENDIX A -- Manufacturers' Contact Information

Applied Science Laboratories
335 Bear Hill Road
Waltham, MA 02154
Tel: (617) 890-5100
Fax: (617) 890-7966

ISCAN Inc.
125 Cambridgepark Drive
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Cambridge, MA 02238
Tel: (617) 868-5353
Fax: (617) 868-9231

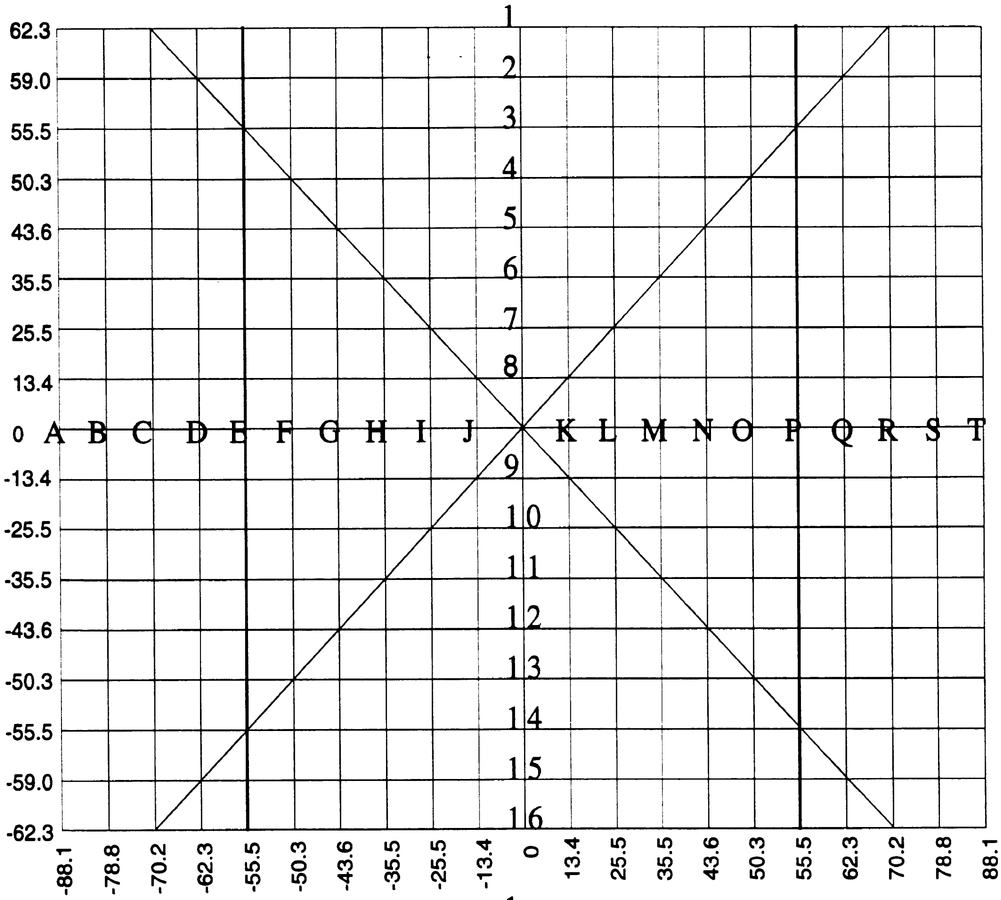
NAC Visual Systems
Instrument Marketing Corporation
1011-F West Alameda Ave
Burbank, CA 91506
Tel: (818) 840-2711
Fax: (818) 840-6898

NAC Image Technology & Equipment
2-7, Nishi-Azabu 1-Chome
Minato-ku
Tokyo, Nippon
Tel: 03-3404-2321
Fax: 03-3479-8842

Permobil Meditech
6B Gill Street
Woburn, MA 01801
Tel: (617) 932-9009
Fax: (617) 932-0428

Permobil Meditech AB
Box 120
S-861 00
Timra, Sweden
Tel: 46-60-572606
Fax: 46-60-575250

APPENDIX B -- Field of view form

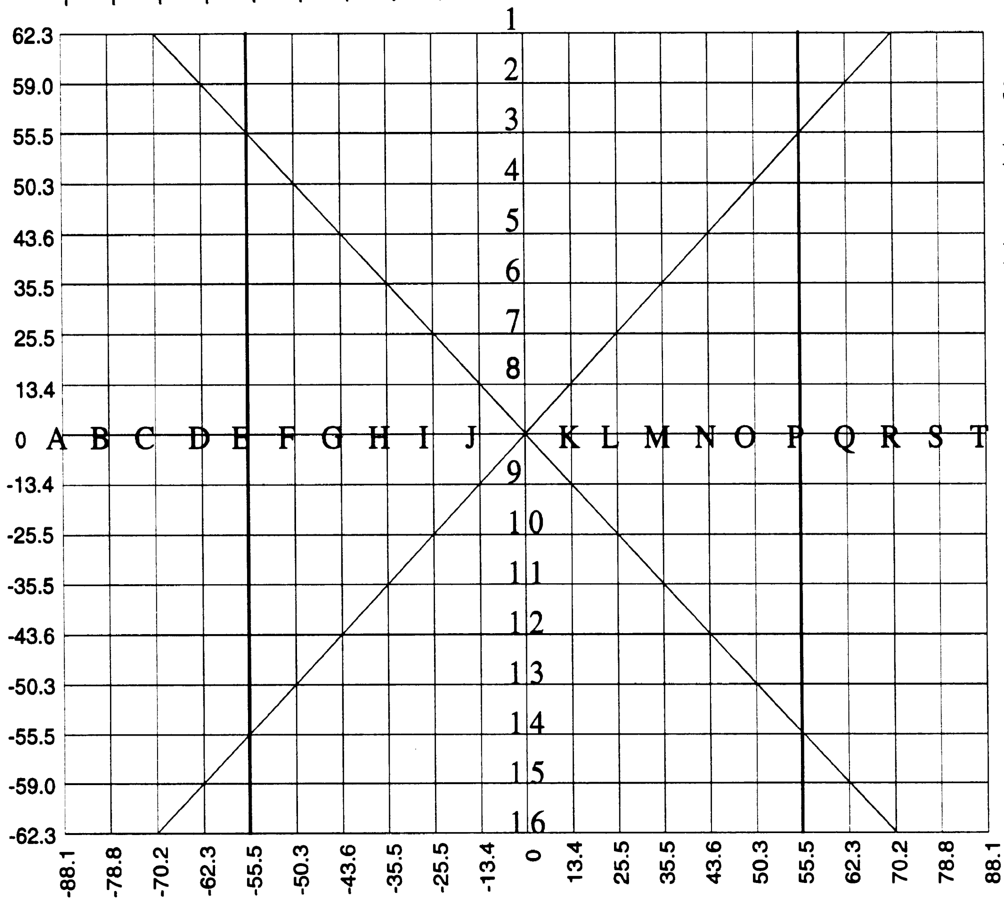


System:

Eye used:

Date:

Subject:



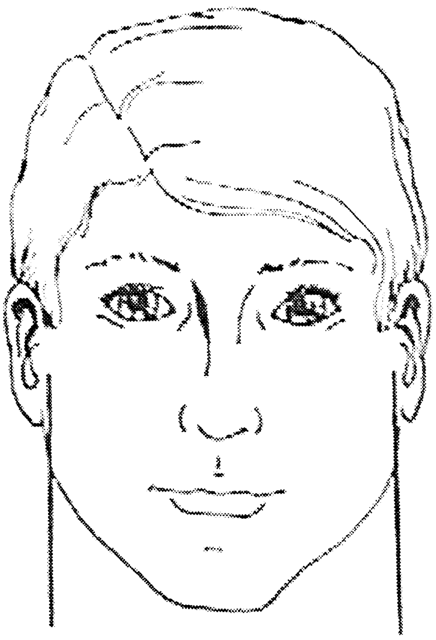
System:

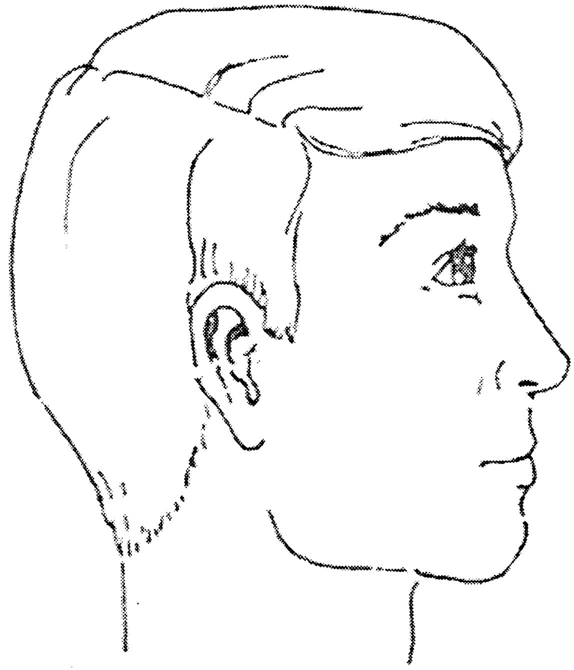
Eye used:

Date:

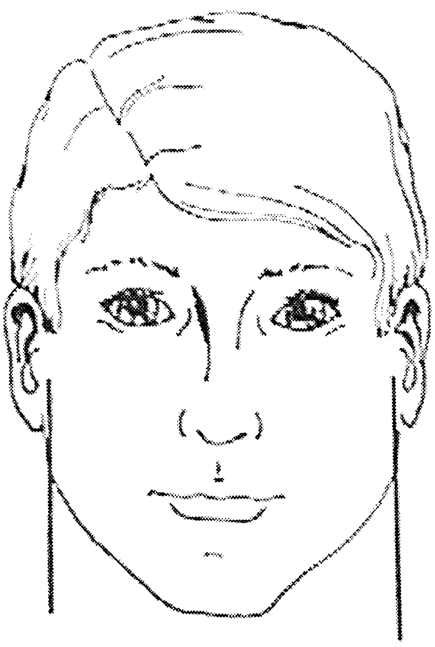
Subject:

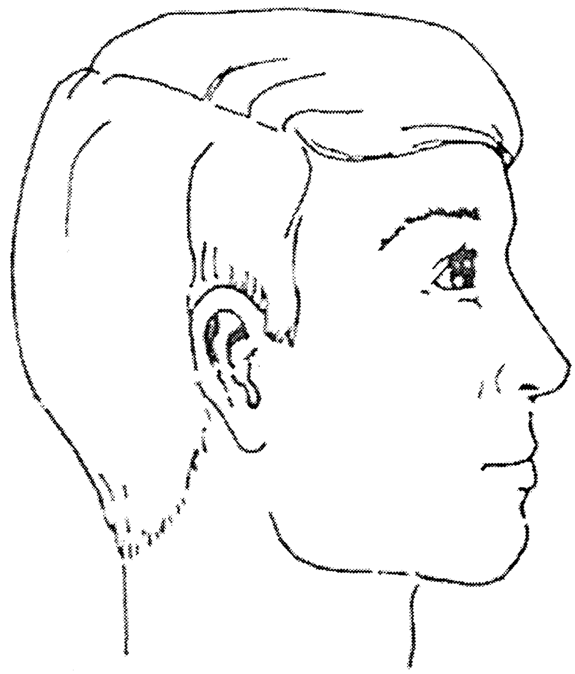
APPENDIX C -- Comfort form





Camera: Date: Subject: Duration of wear:

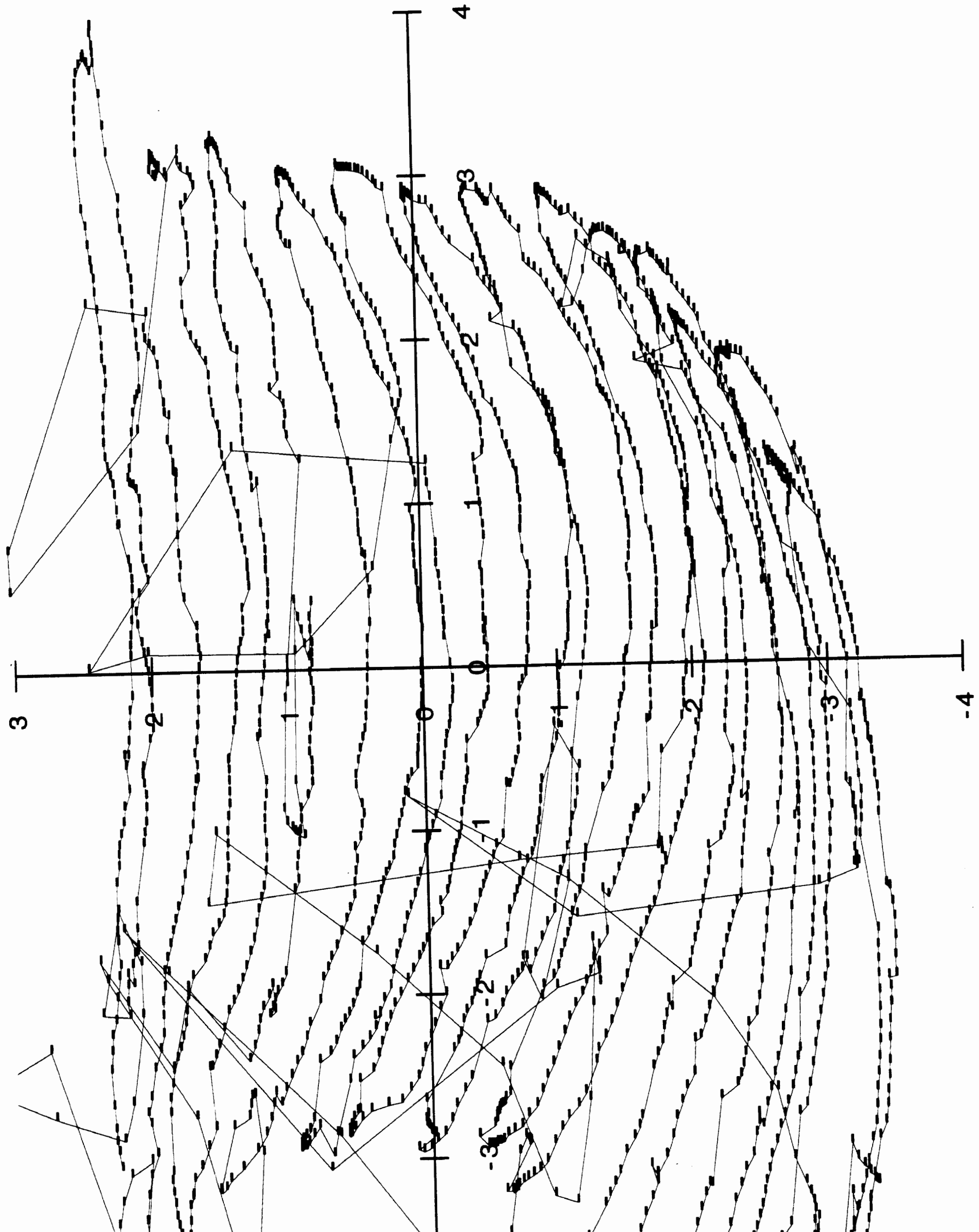




Camera: Date: Subject: Duration of wear:

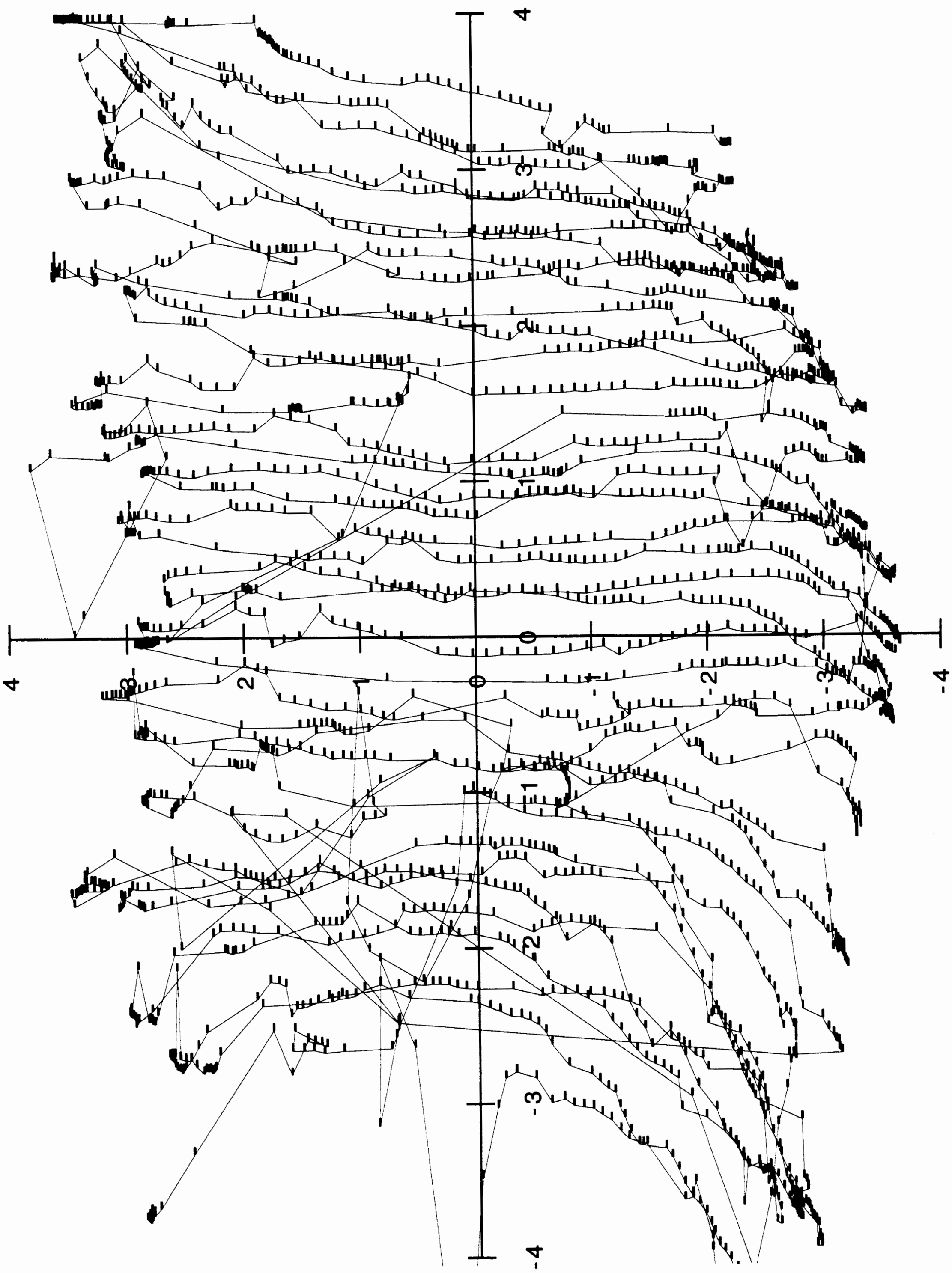
Drawings adapted from: Anthropometric Source Book Volume II: A Handbook of Anrthropometric Data, NASA Publication 1024, July 1978, pp. 35.

APPENDIX D -- ASL 210 Tracking Plots



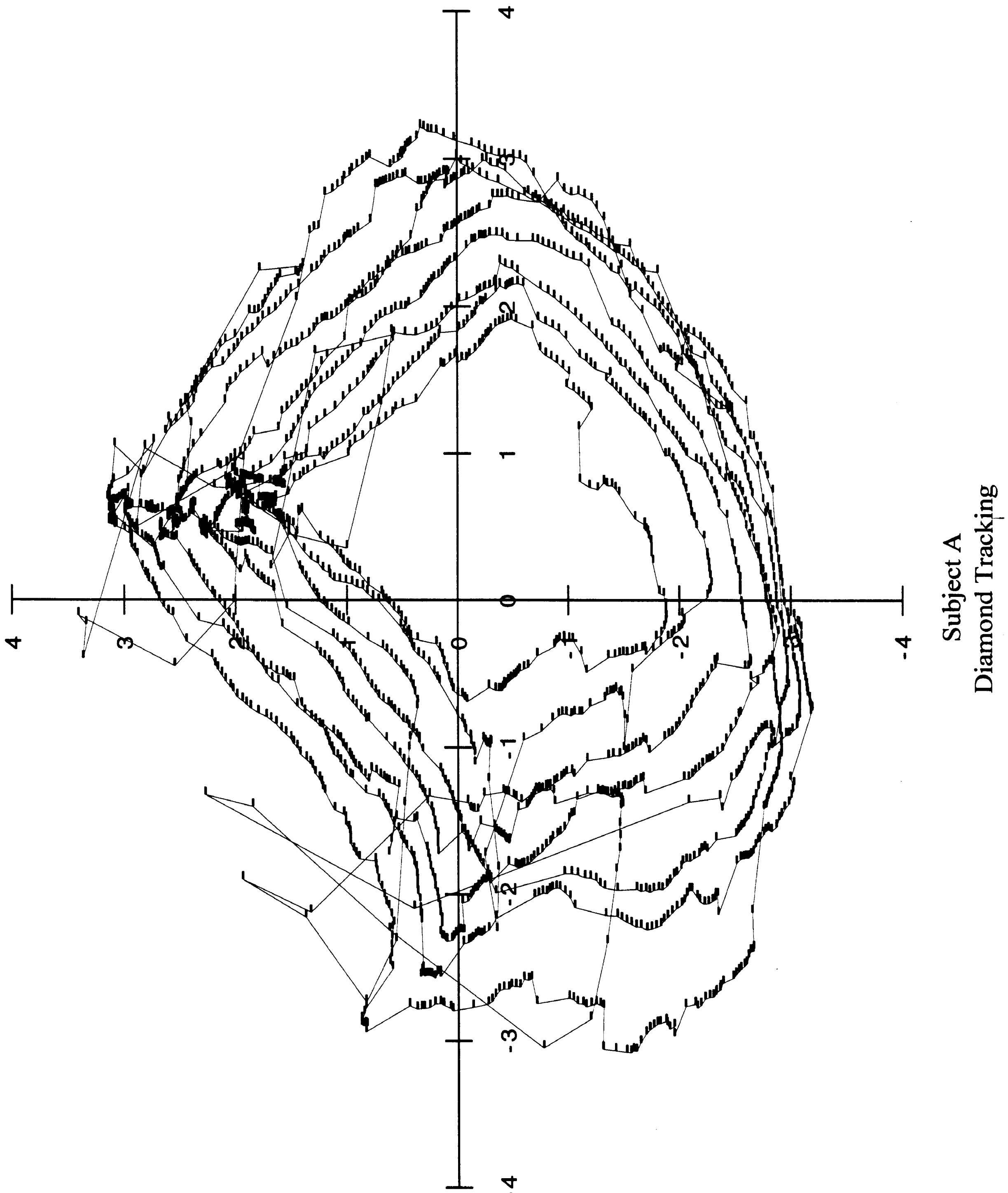
Subject A
Horizontal Tracking

APPENDIX D -- ASL 210 Tracking Plots (Continued)

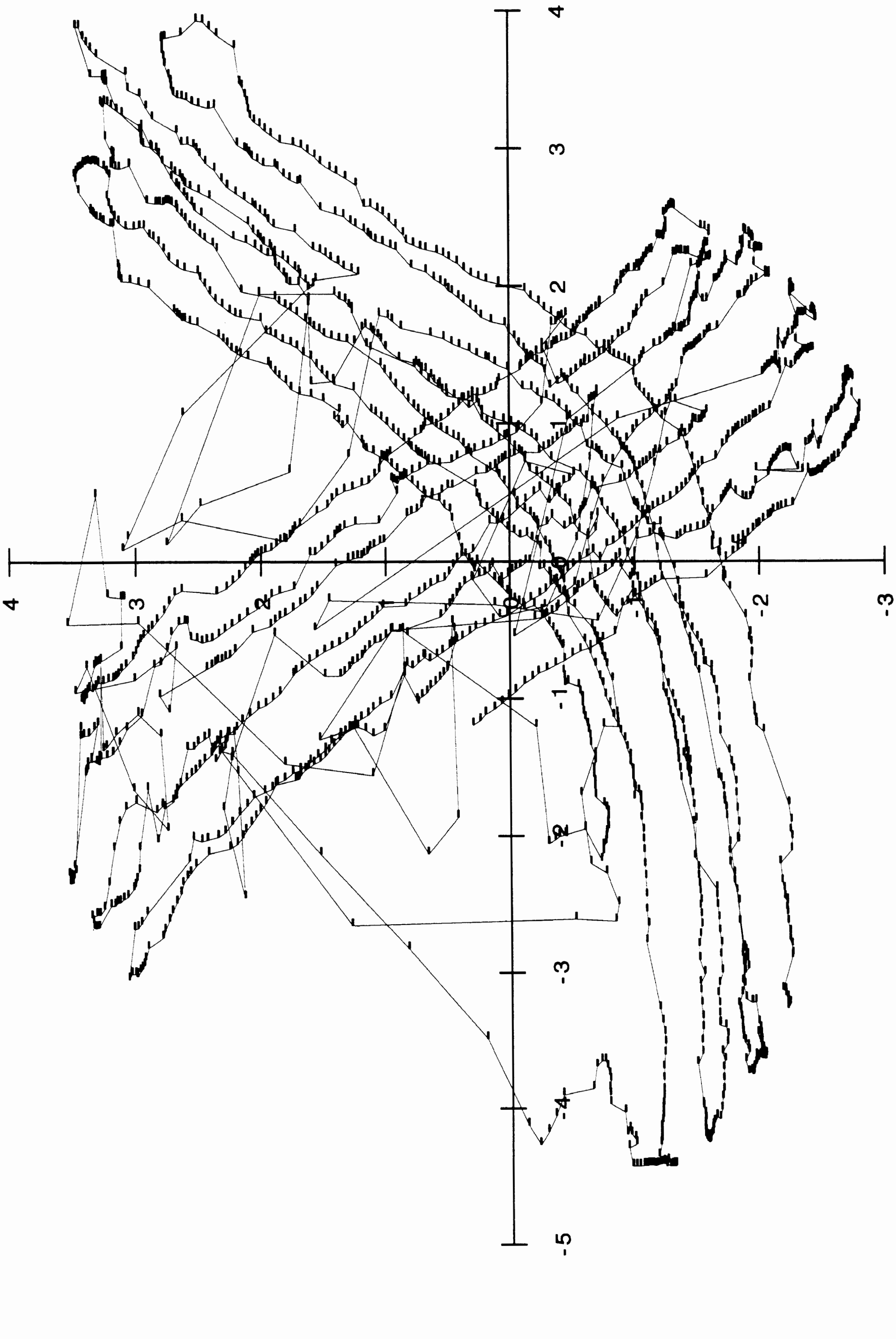


Subject A
Vertical Tracking

APPENDIX D -- ASL 210 Tracking Plots (Continued)

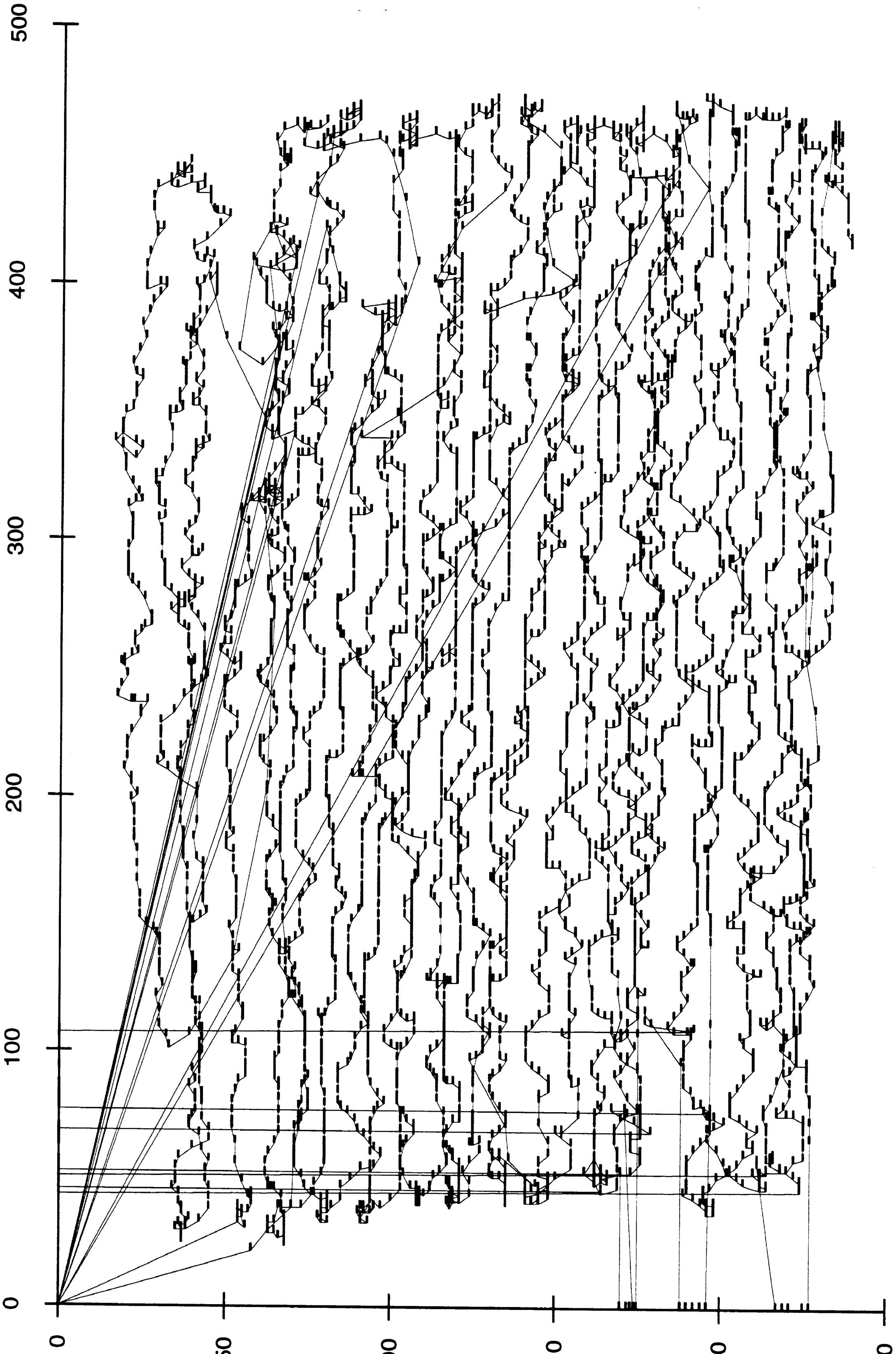


APPENDIX D -- ASL 210 Tracking Plots (Continued)



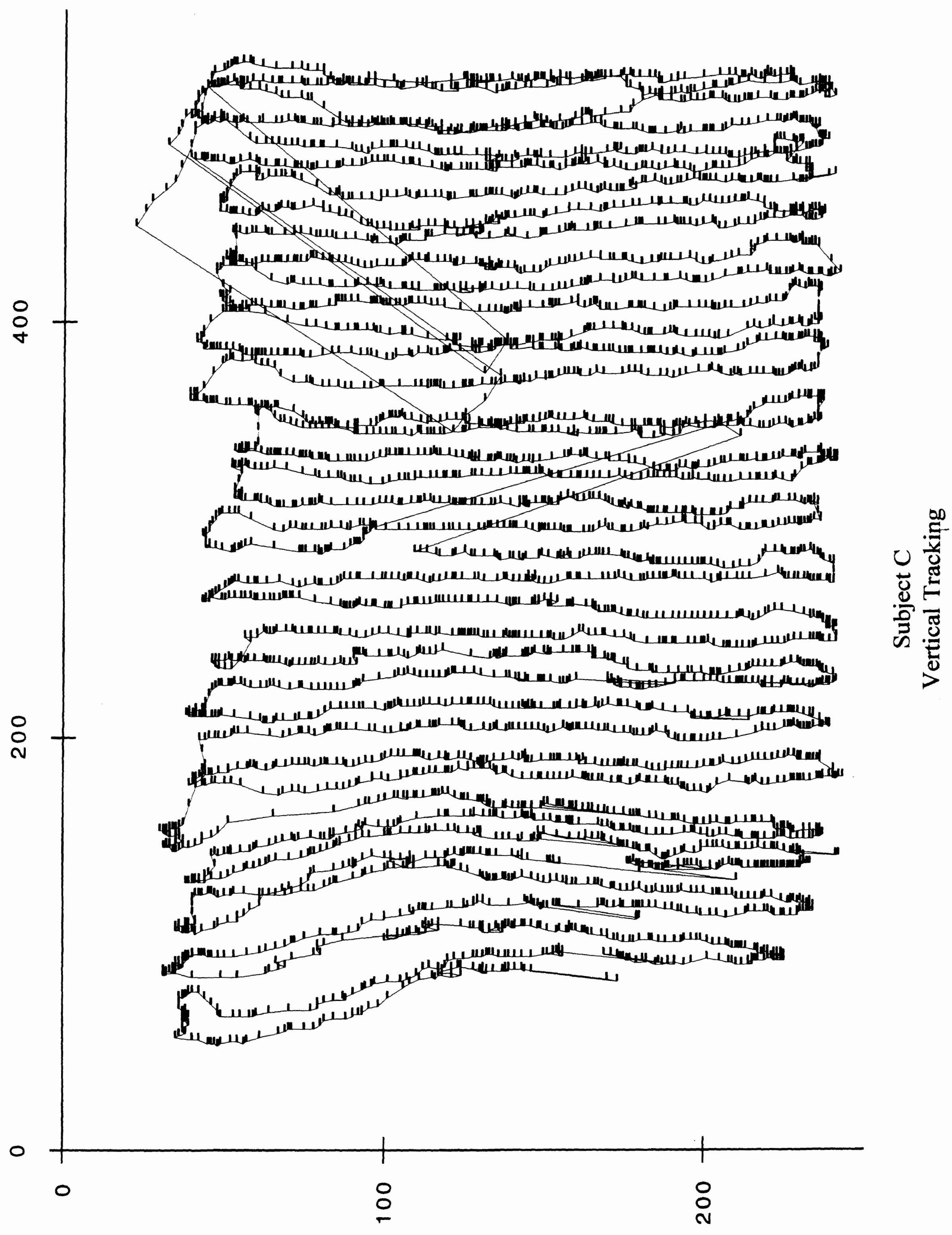
Subject A
Diagonal Tracking

APPENDIX E -- ASL 4000 Tracking Plots

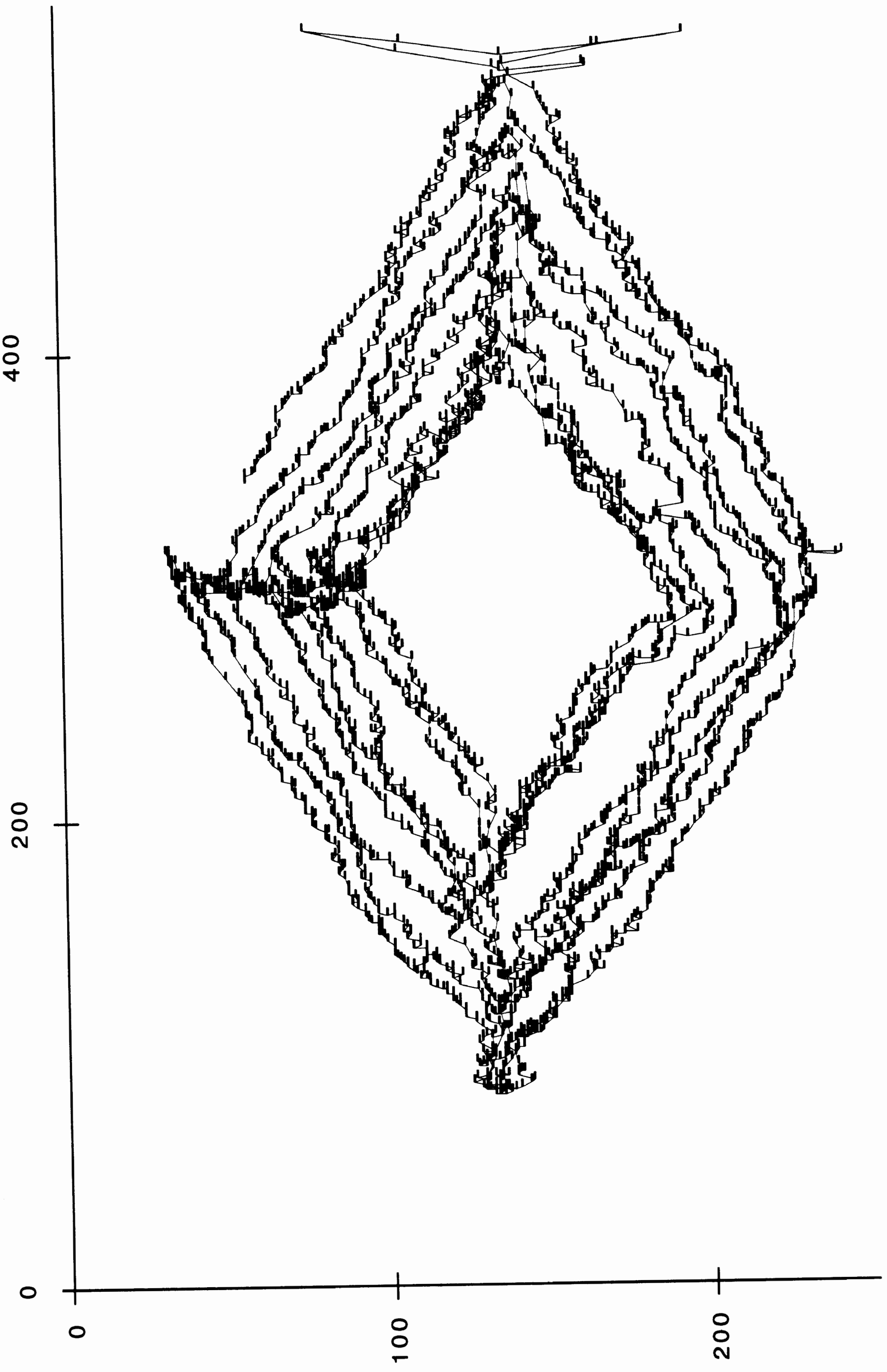


Subject C
Horizontal Tracking

APPENDIX E -- ASL 4000 Tracking Plots (Continued)

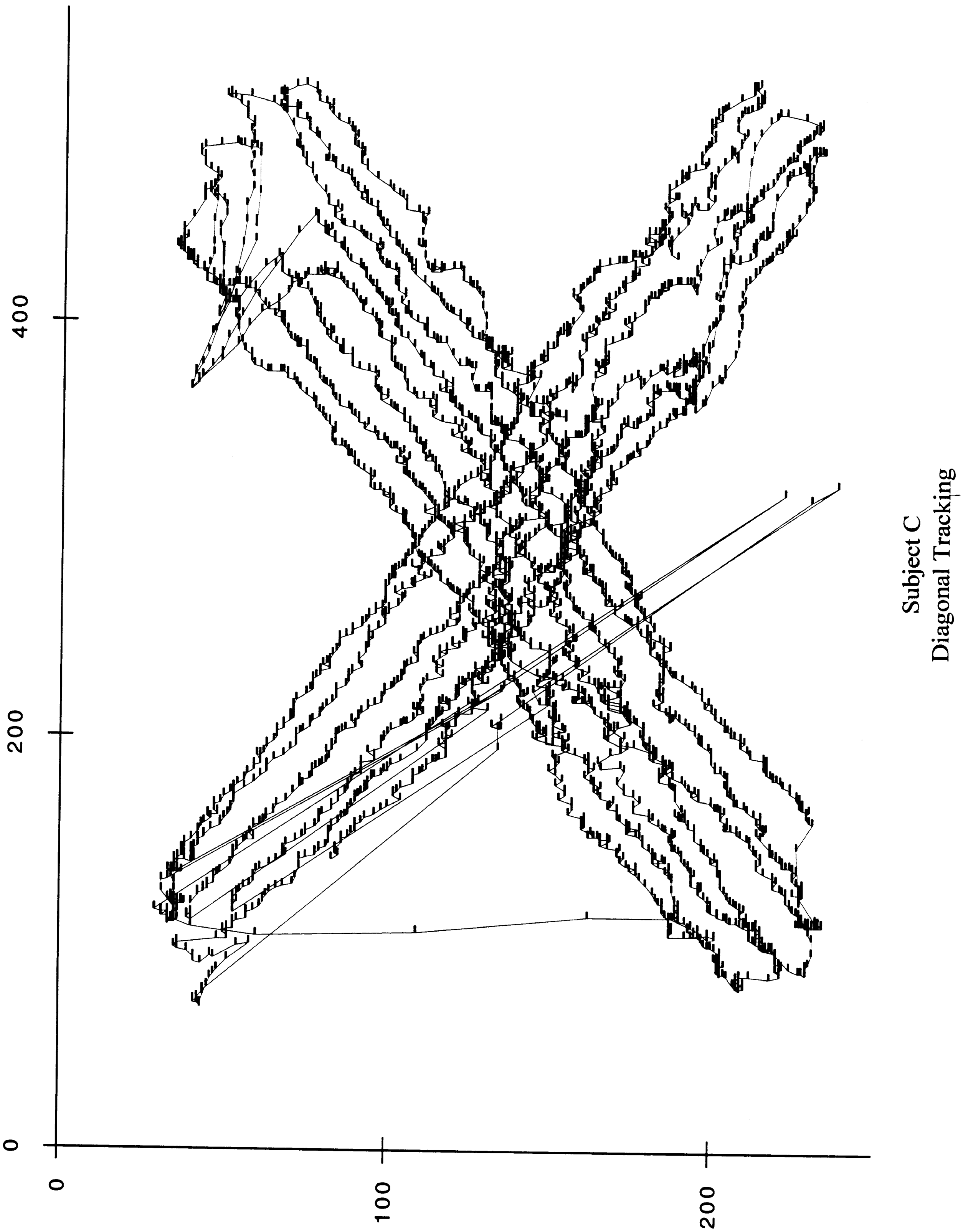


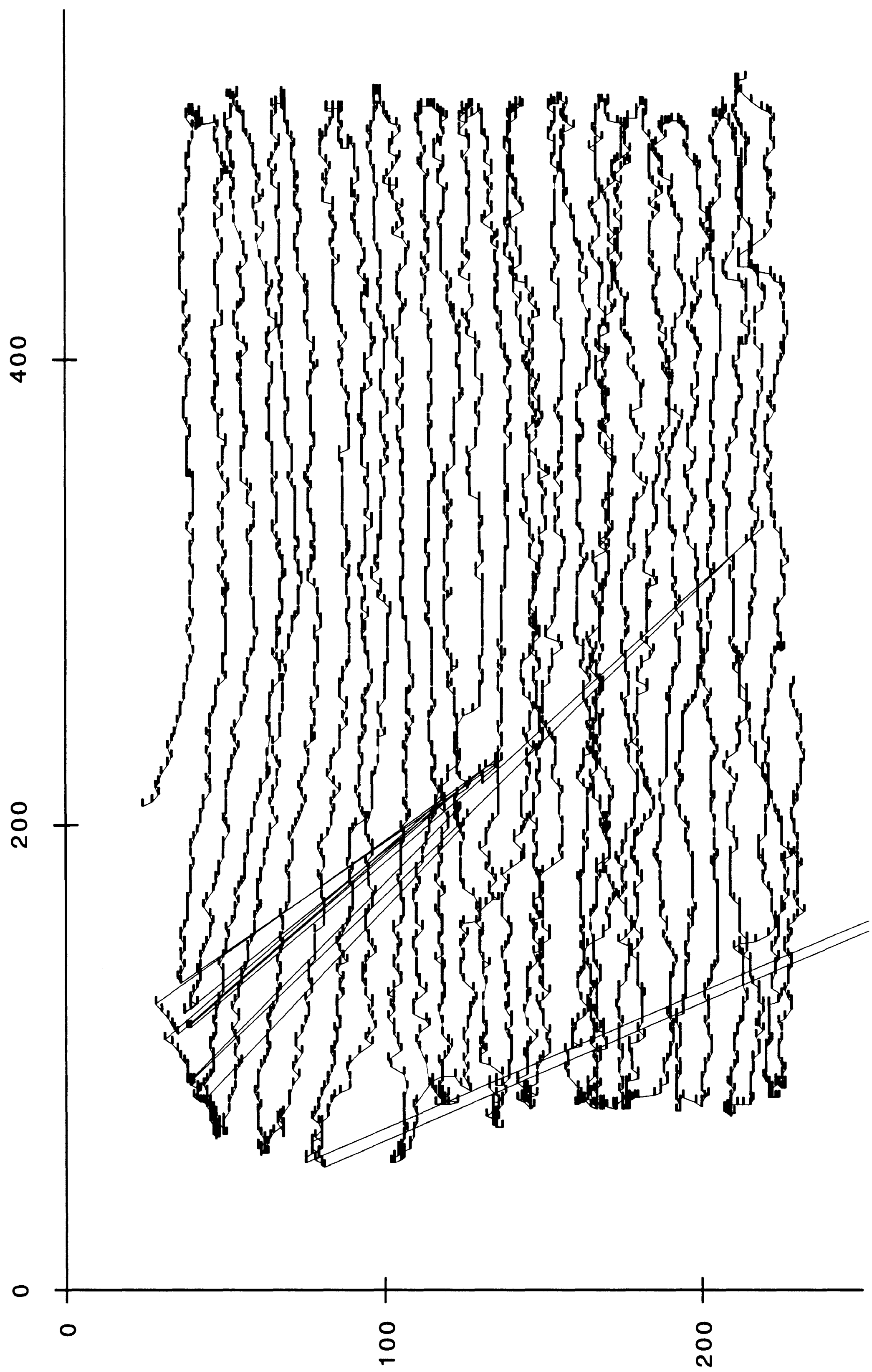
APPENDIX E -- ASL 4000 Tracking Plots (Continued)



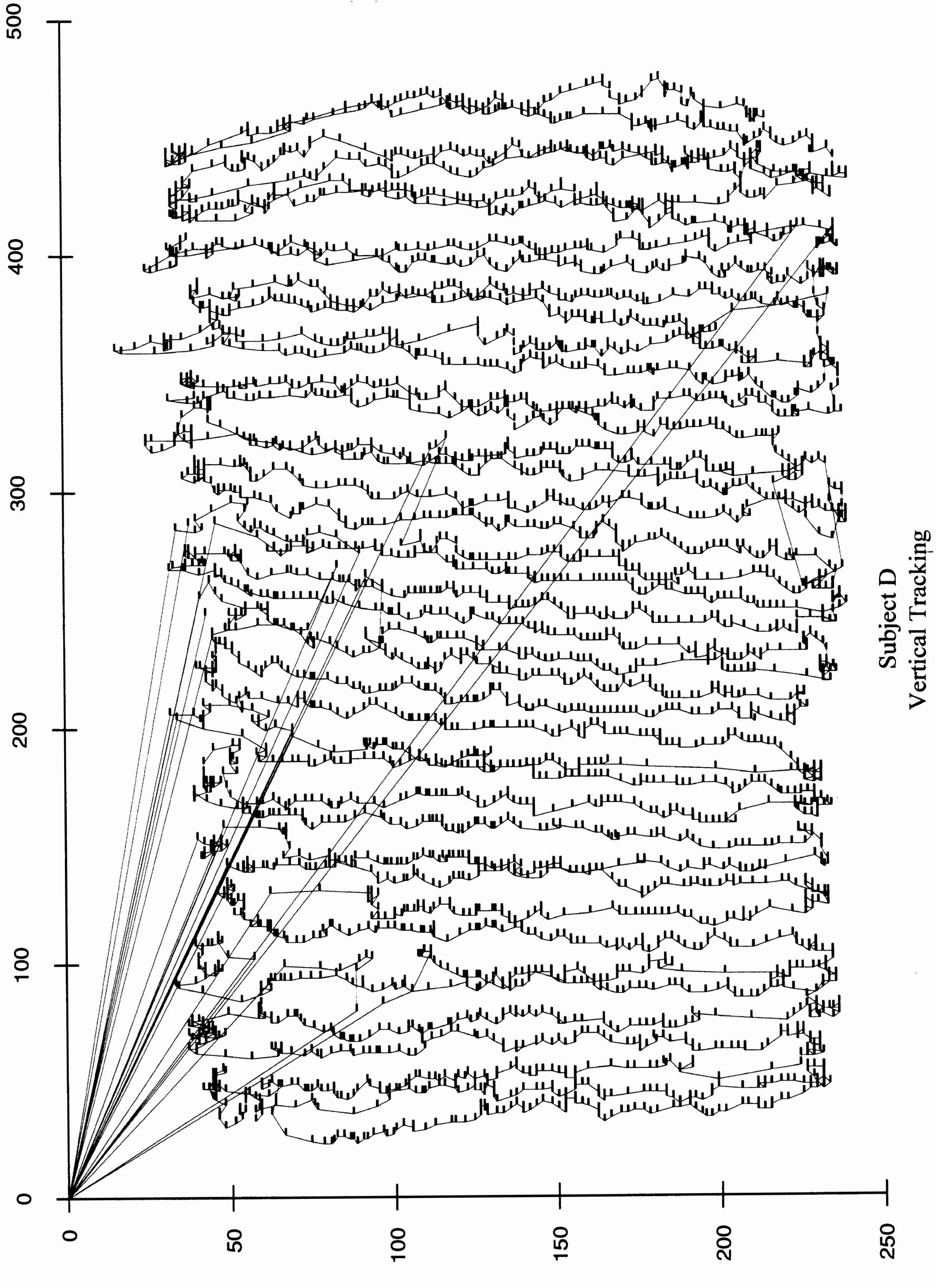
Subject C
Diamond Tracking

APPENDIX E -- ASL 4000 Tracking Plots (Continued)

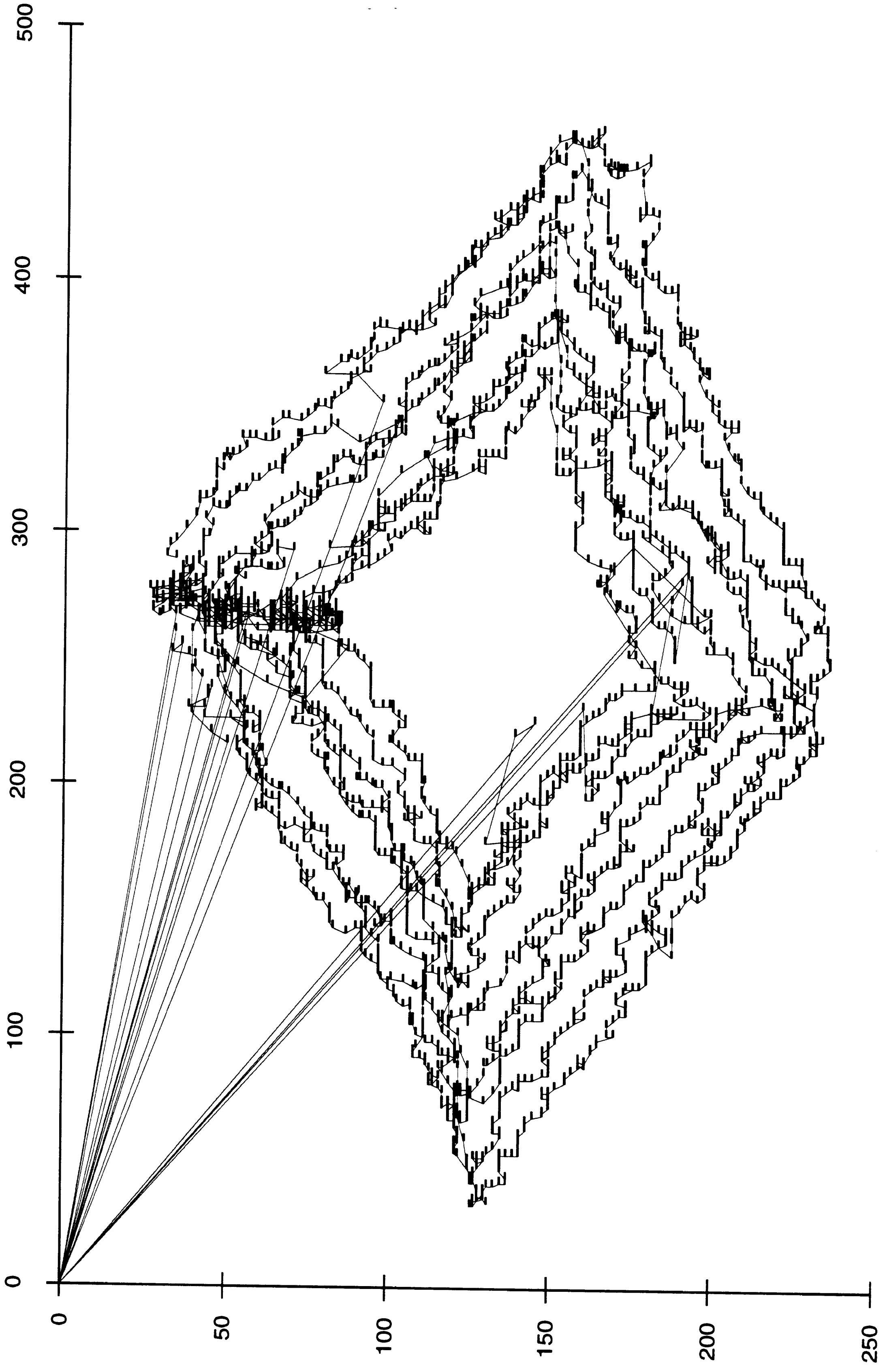



Subject D
Horizontal Tracking
0
200
400
0
100
200

APPENDIX F -- ISCAN Tracking Plots (Continued)

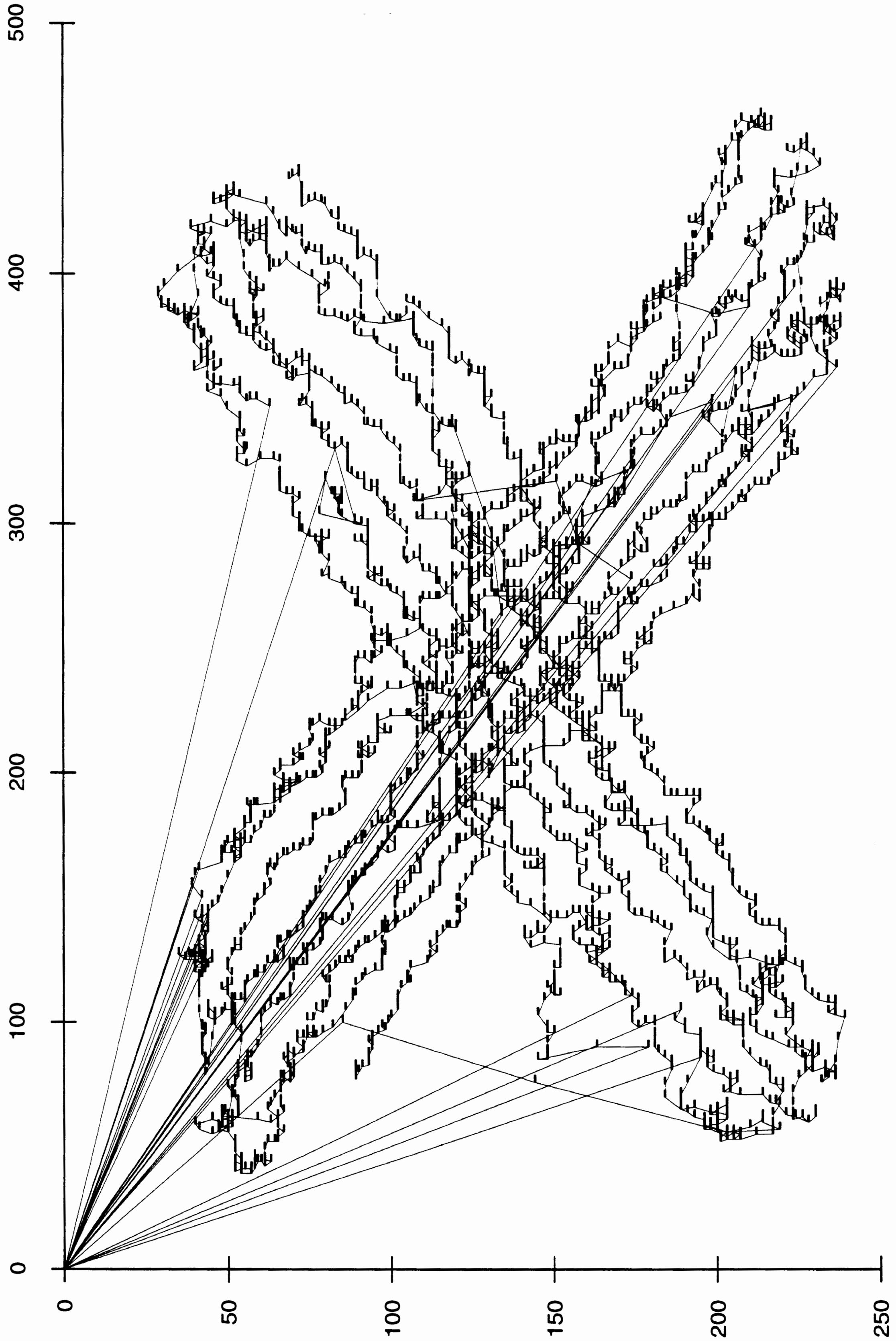


APPENDIX F -- ISCAN Tracking Plots (Continued)



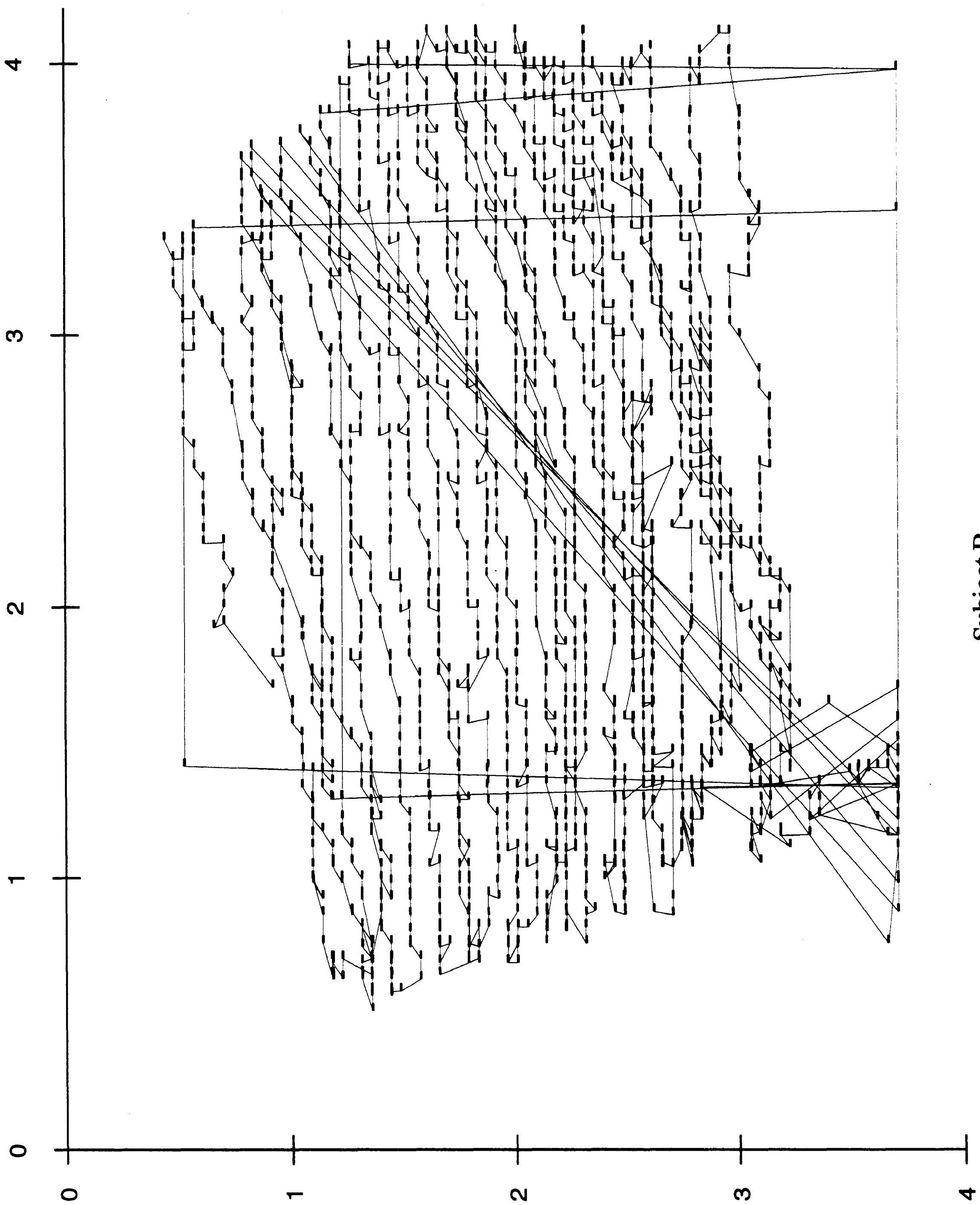
Subject D
Diamond Tracking

APPENDIX F -- ISCAN Tracking Plots (Continued)



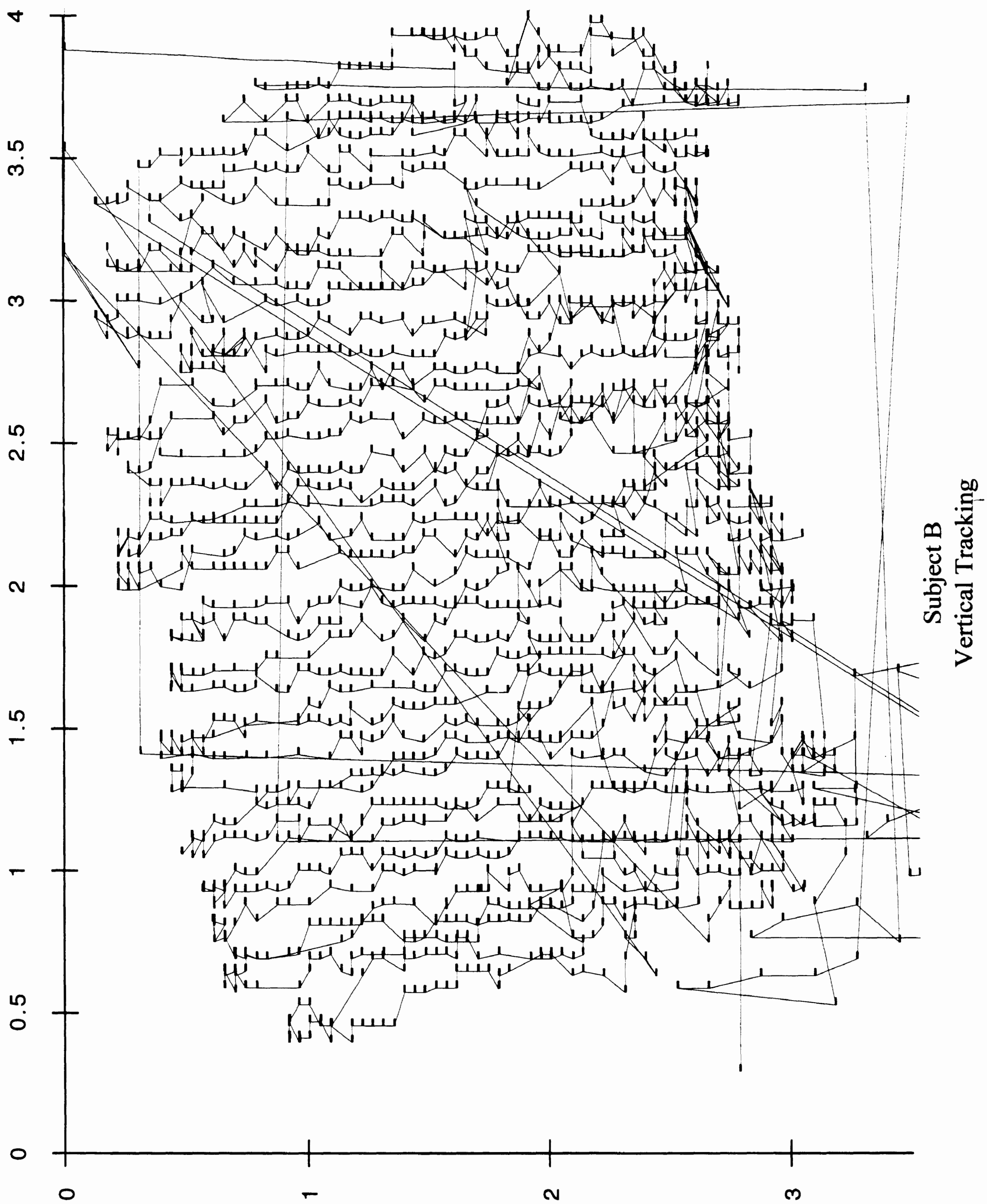
Subject D
Diagonal Tracking

APPENDIX G -- NAC V Tracking Plots

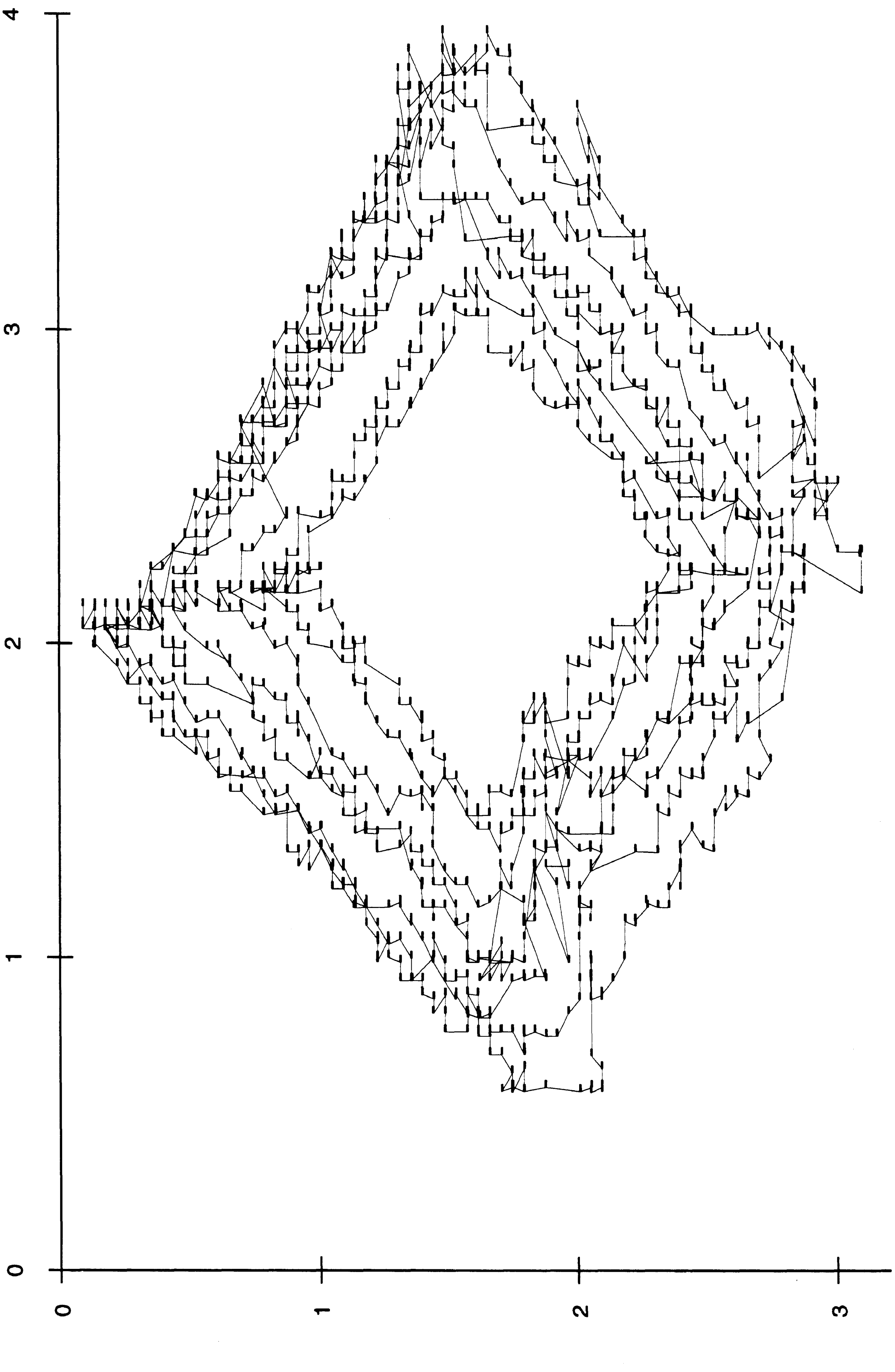


Subject B
Horizontal Tracking

APPENDIX G -- NAC V Tracking Plots (Continued)

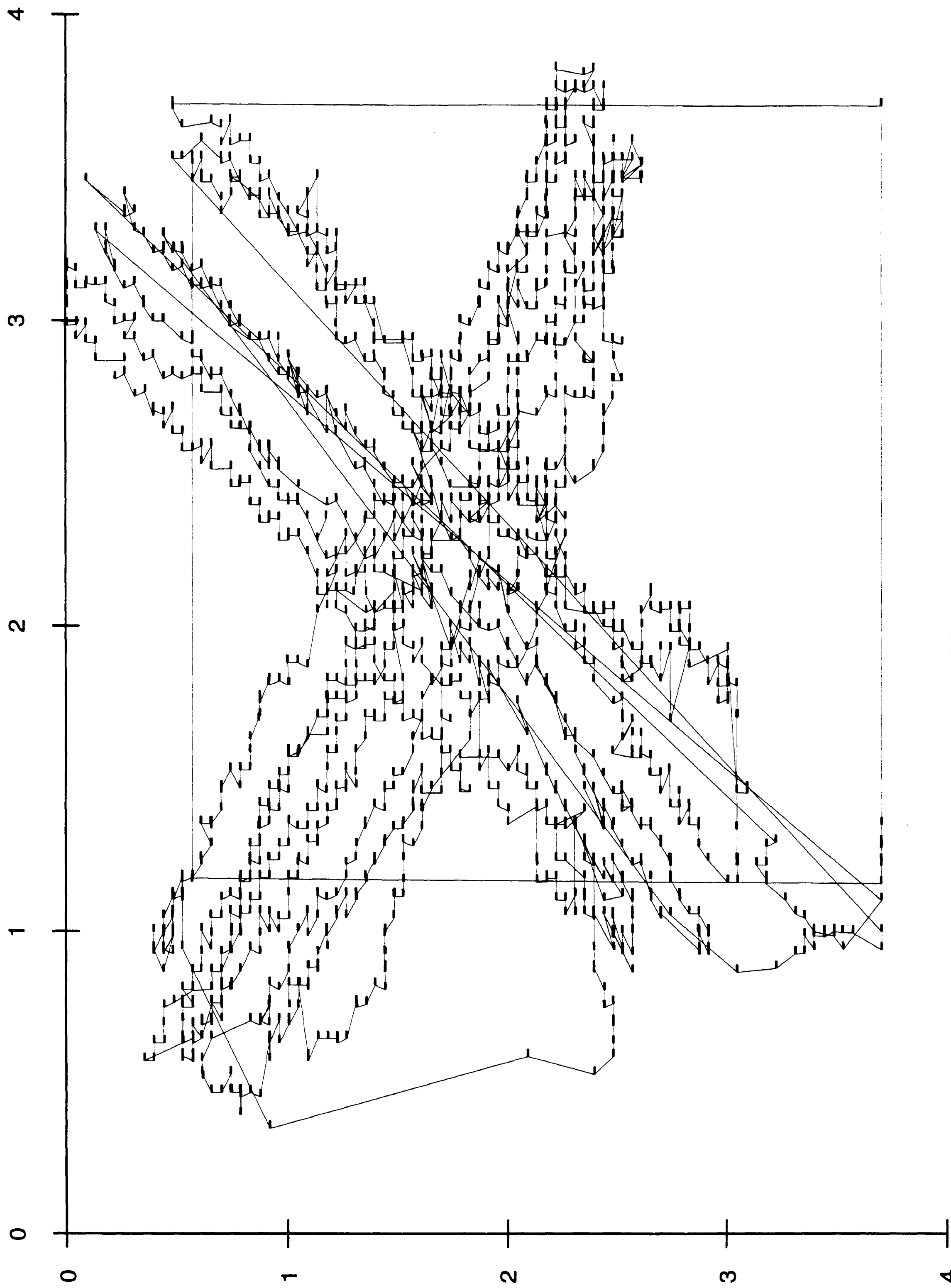


APPENDIX G -- NAC V Tracking Plots (Continued)



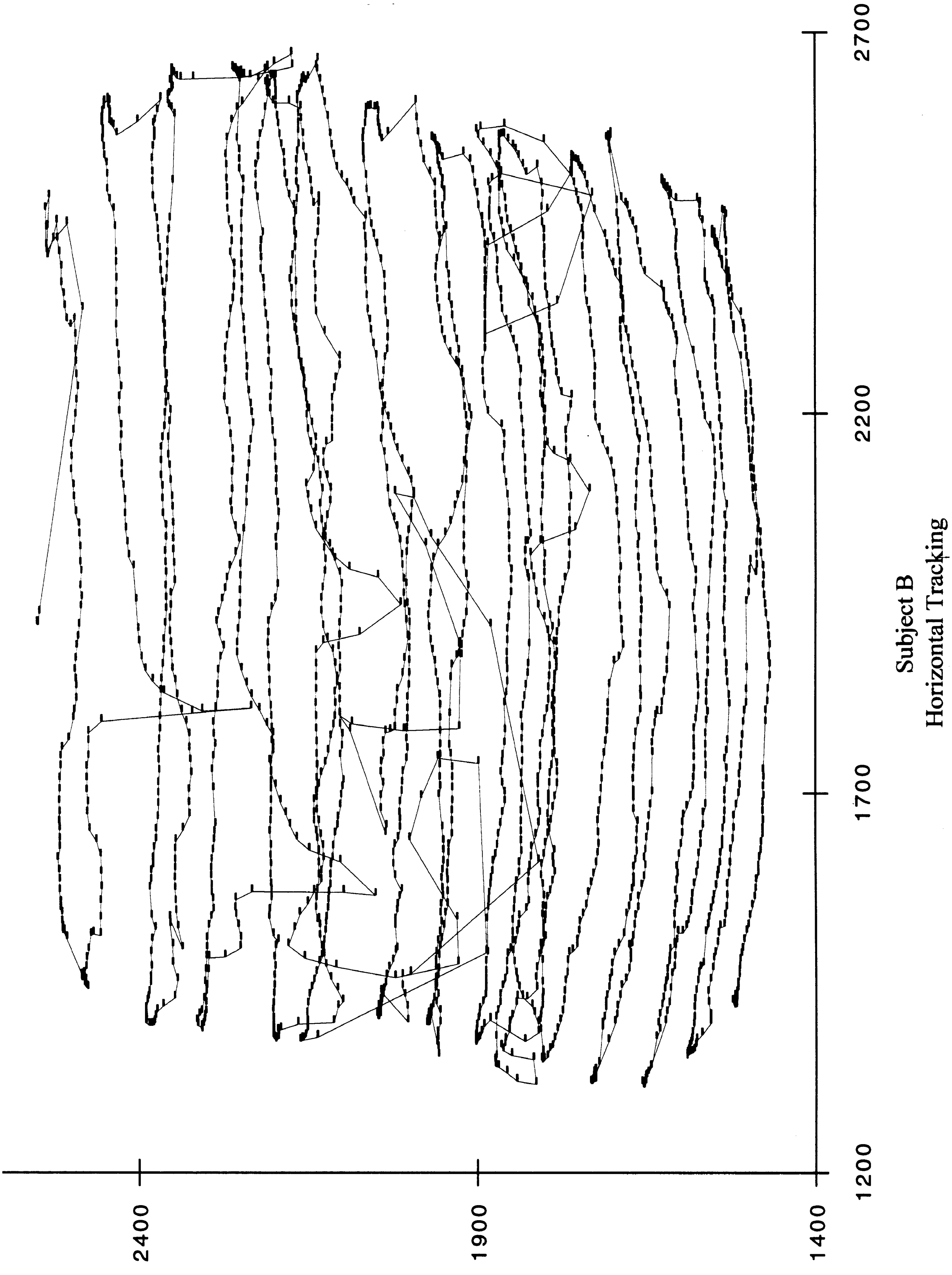
Subject B
Diamond Tracking

APPENDIX G -- NAC V Tracking Plots (Continued)

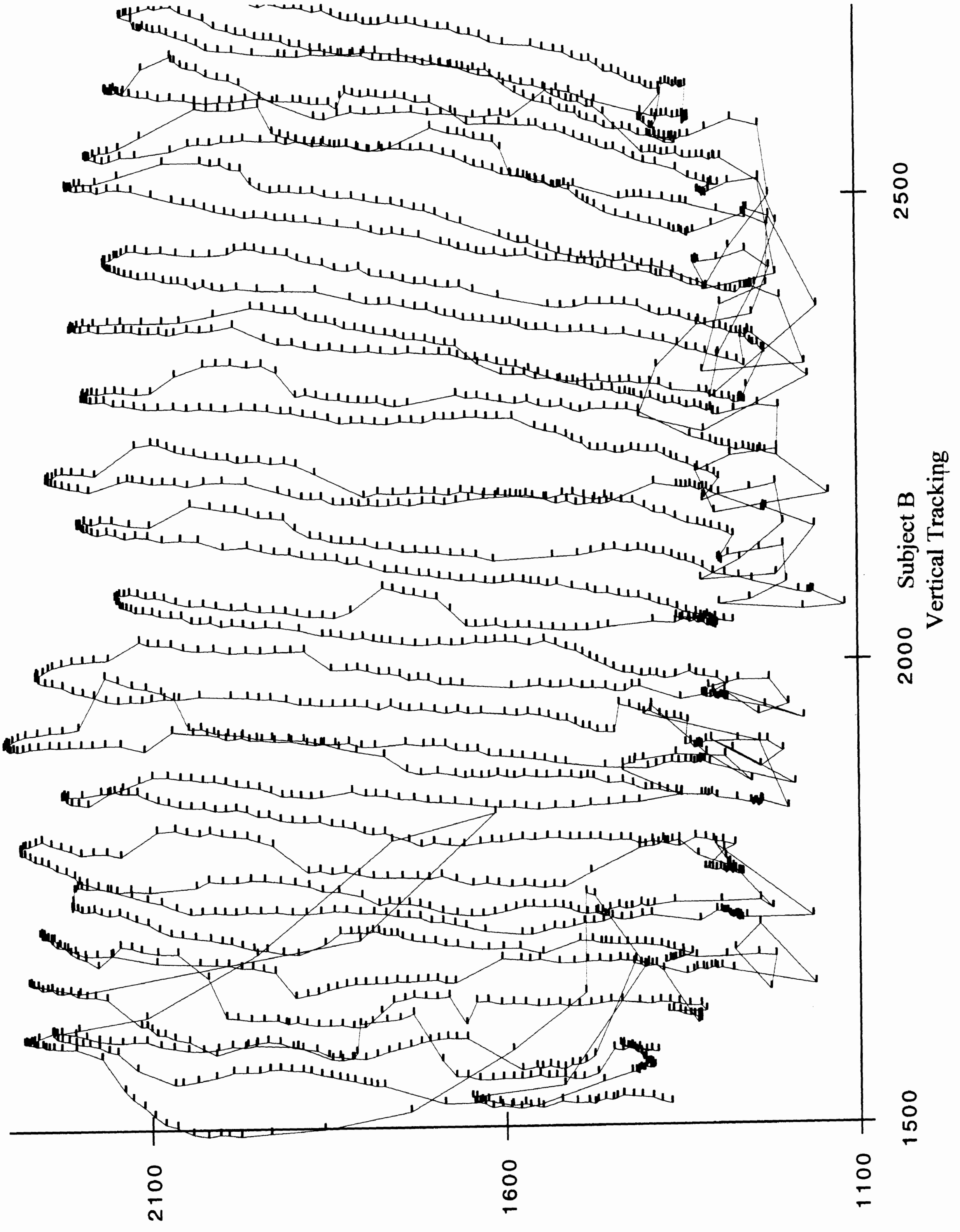


Subject B
Diagonal Tracking

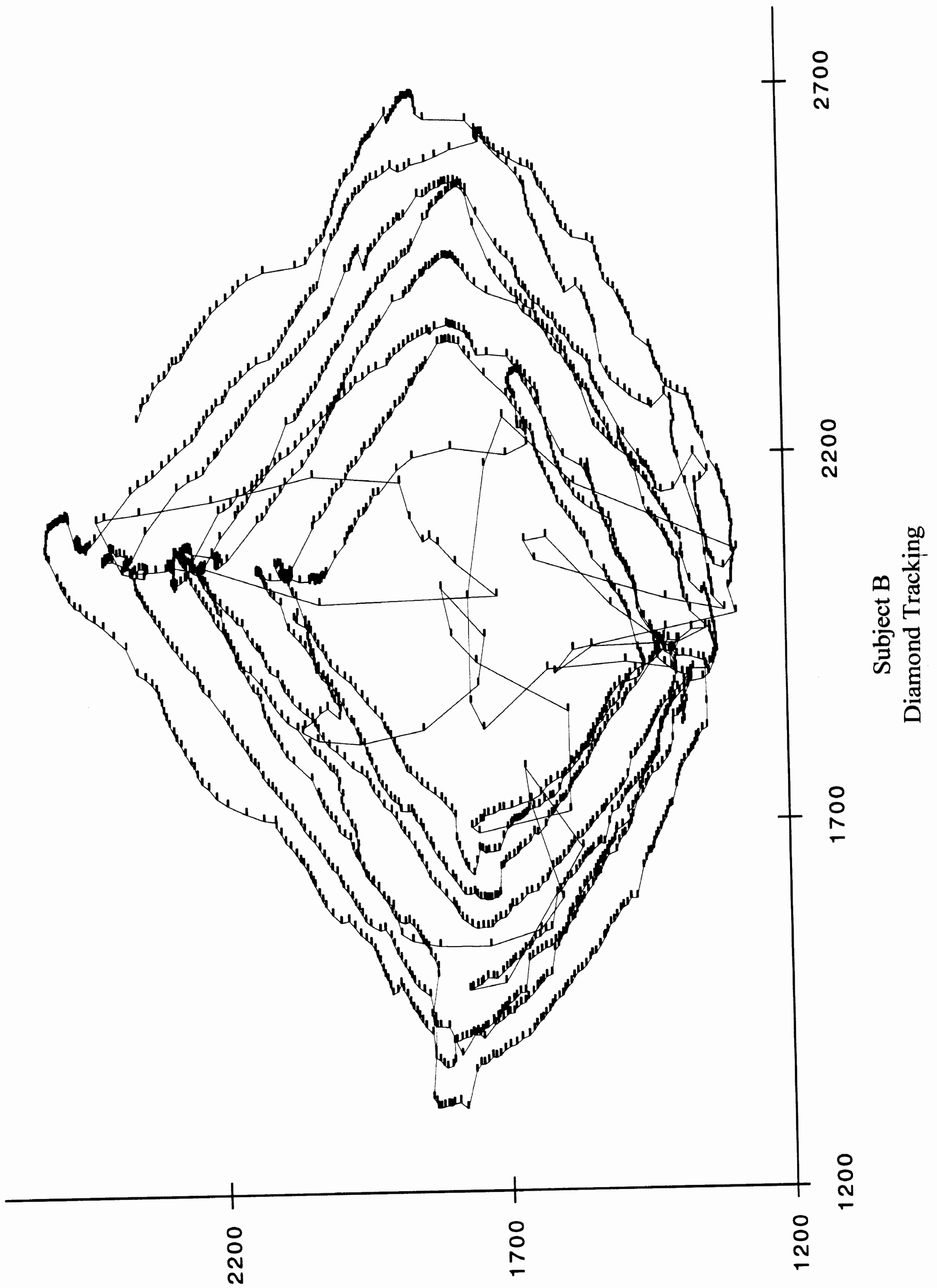
APPENDIX H -- Ober2 Tracking Plots -- Average of Both Eyes



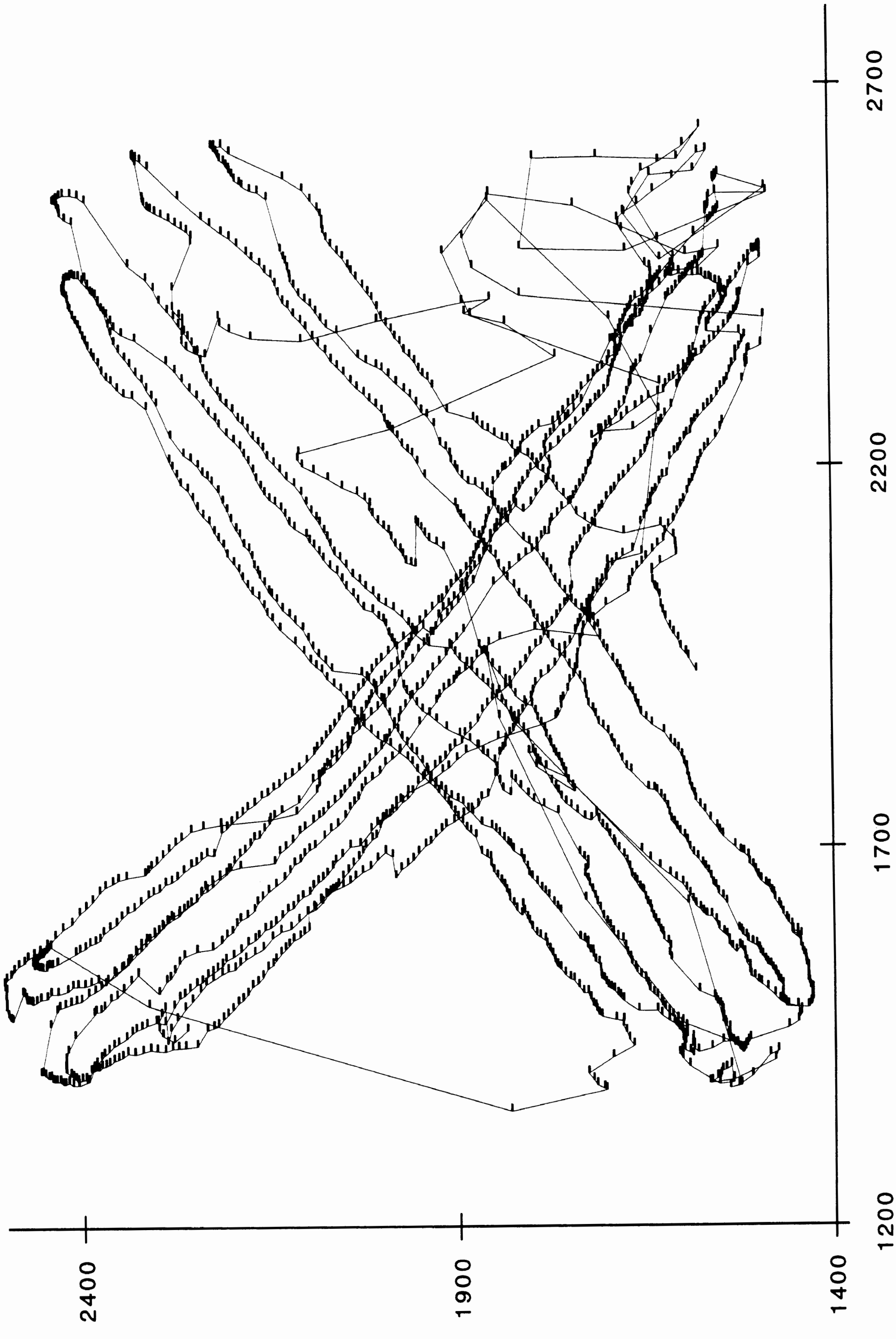
APPENDIX H -- Ober2 Tracking Plots -- Average of Both Eyes (Continued)



APPENDIX H -- Ober2 Tracking Plots -- Average of Both Eyes (Continued)



APPENDIX H -- Ober2 Tracking Plots -- Average of Both Eyes (Continued)



Subject B
Diagonal Tracking