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A

Role of Visual Experience in Human Voluntary Eye Movement

by

Elaine C. Hall

A dissertation submitted to the Graduate Faculty in Psychology
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy, The City University of New York.

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James Gordon
Chair of Examining Committee

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Date

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THE CITY UNIVERSITY OF NEW YORK

Abstract

ROLE OF VISUAL EXPERIENCE IN HUMAN VOLUNTARY EYE MOVEMENT

by

Elaine C. Hall

Advisor: Professor James Gordon

This research tested the proposition that childhood and/or ongoing visual experience affects voluntary production of eye movements in adults. Computer-generated verbal instructions were used to elicit voluntary eye movements in the dark (without visual stimuli, vision, and/or a mental visual frame of reference) from three groups of adults (N=49) whose visual experience differed. Visual experience of groups: Congenitally blind-- $\leq$12 years; adventitiously blind-- $\geq$ 13 years; sighted-- normal vision. Requests were to move the eyes to the extremes of the vertical and horizontal oculomotor range, halfway toward these extremes, and, repeatedly, "straight ahead." Eye movements were videotaped under infrared illumination. Videotapes were digitized using an eye tracker targeting the pupil. Entire responses (not individual saccades and fixations) were evaluated graphically and statistically. Clear group differences emerged despite the lack of within-group uniformity in visual experience of adventitiously versus congenitally blind participants, and the wide time window associated with the "congenitally blind" classification criterion. Voluntary oculomotor control increased with years of visual experience until reaching mature, relatively stable, levels, indicating that vision experienced during approximately the first eight-ten years of childhood is most salient for subsequent voluntary oculomotor control (although data were not available from participants with four, five, six or seven years of visual experience.). After long-term adventitious blindness a small amount of degradation of human voluntary oculomotor control was revealed. Measures including response amplitude and direction of vertical and horizontal responses, and variability within- and across-trial of requests to "look straight ahead" were profoundly attenuated in cases of little or no visual experience (except midposition scaling accuracy, which yielded questionable results). This study contributes to knowledge of the nature and extent of the neural plasticity inherent to the relationship between visual experience and voluntary oculomotor control. It supports the idea that voluntary oculomotor control retains a degree of plasticity well into childhood. Theoretically and perhaps clinically, this research indicates that oculomotor control adequate to subserve vision might be anticipated in individuals with even a short period of prior visual experience, were it possible to restore function to the other components of the visual system.

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In thanks to God.

For my family, most especially for my mother and in memory of my father.

FL--There can be no way truly to say how profoundly grateful to you I am. Though I am compelled to try to speak to you in this regard, each thought formulated in words falls short and isn't it. You have extended yourself unimaginably on my behalf; your confidence in me, your courage, wisdom, generosity, patience, encouragement, and when all else failed, humor, have seemed to know no bounds. Directly and by example you have provided me the means with which to proceed in earnest, to question, to serve, to engage in meaningful and effective struggle. In this your gift to me is the capacity for joy. I know that at this point I have only a small sense of what has been accomplished here, and of what may come of it. While my gratitude cannot be framed in language, I give you my word that I will try to use well all that I have learned from you.

* * *

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INTRODUCTION

The function of eye movements in human vision is to place a visual image on the fovea, the area of the eye's retina that affords best vision. The present research concerns the relationship between voluntary oculomotor control and visual experience. Voluntary eye movements here are those which are clearly intentional, as differentiated from visual image stabilizing phenomena which may have some volitional component; these distinctions are discussed at greater length below. Visual experience, particularly ongoing postnatal visual experience, has been assumed to be essential to the production and continued display of human voluntary eye movements (e.g., Hainline, 1993; Preston & Finocchio, 1993). For example, in a discussion of motion detection, Hainline has stated "Because feedback about retinal and stimulus movement is instrumental to many forms of eye movement control, oculomotor development must be related to the development of the infant's ability to detect and respond to the movement of a stimulus" (1993, p. 60).

Under normal circumstances an interdependence exists between visual and oculomotor development and function in humans. But while vision often is studied in the absence of oculomotor control, for example, by paralyzing eye muscles or otherwise immobilizing the orb, it has been observed that investigation complementary to these lines of research has for the most part been neglected (see, e.g., Kompf & Piper, 1987). This includes quantification of human voluntary eye movement in the absence of visual stimuli, vision, and/or a mental visual frame of reference. Such an approach was employed in the present study, to add to previous descriptions and to provides new quantification of links between visual experience and human oculomotor control. Relevant past research and theory are considered next, followed by a detailed presentation of the present experiment and a discussion of its outcomes.

Research into Human Eye Movement System Function Development

The development of human oculomotor functioning in infancy and throughout the lifespan has been considered in various ways in order to better understand vision. Oculomotor research experiments most frequently have involved eye movement either contingent upon or otherwise related to visual stimulus presentation. The premise of these experiments is that the act of moving the eyes (in the waking state) is most often mediated visually. That is, a feedback loop links visual input to oculomotor control such that eye movements occur to place or maintain the retinal image on the fovea. Conclusions are drawn based on analyses of responses made to known, controlled, visual stimuli.

Infant Oculomotor Orientation

One way to investigate how visual experience may affect human voluntary oculomotor control is to attempt to elicit, and then to evaluate, eye movements in those with little or no visual experience. Human infants essentially fit this description and have been the subject of systematic observation in experimental designs utilizing visual and non-visual stimuli. Vision, visual stimuli and visual experience in the context of eye movement control have received greater theoretical and empirical emphasis in general with regard to this population than with adults. Indeed, over the past decade or more, much of the work of Hainline and her colleagues at the Infant Study Center laboratory within Brooklyn College of The City University of New York has focused on human infant eye movement, in research employing various instruments and study populations. To illustrate the area's scope and depth and to provide relevant context for the present investigation some of this work is noted next.

In 1984 Hainline, Turkel, Abramov, Lemerise & Harris used an infrared corneal reflection eye movement recorder to relate stimulus attentional value to characteristics of infant and adult eye movements. The same device was used by Hainline, Lemerise, Abramov & Turkel (1984), to investigate characteristics of infants' optokinetic nystagmus (OKN), an identified pattern of reflexive eye movements.

Not insignificantly, debate surrounds the use of the term "reflexive" in the context of oculomotor control. For example, the issue of whether some eye movement classes should be characterized in terms of their being reflexive versus volitional has been described as a "tempting dichotomy" (Hainline, 1993). Because deliberate, intentional, control of eye movements was evaluated in the present research, it is outside the present scope to attempt to solve this definitional problem. Where appropriate, however, evidence presented here which bears on this issue is noted as such.

In the latter study cited (Hainline, Lemerise, Abramov & Turkel, 1984), stimulus presentation included gratings moving either horizontally or vertically to induce OKN, as occurs typically when portions of the visual field are in continuous motion. Also, although concentrating on infants' orientational asymmetries in small-field OKN, the authors further considered infants' OKN in relation to those of other species and in adult clinical patients with eye movement disorders. It should be noted that Hainline & Lemerise were prompted later (1985) to re-examine interpretations of data pertaining to the scanning extensiveness of infant pattern perception obtained using infrared corneal reflection techniques, citing technical limitations of work reported earlier. This and subsequent reports describing technical drawbacks, advantages and advances of this and other approaches to eye movement data collection have proven invaluable in planning and executing the present study (for a review see also Young & Sheena, 1975). For example, it was decided that pupil tracking of recordings made under infrared illumination would be employed, rather than (infrared) corneal reflection recording and tracking.

In 1988, Harris, Hainline, Abramov, Lemerise & Camenzuli studied free-scanning infants and naive adults in an investigation of distributions of fixation durations. Fixation duration was found to be divisible into two types: the alpha-period is described as a refractory period, fluctuating across fixations, during which a saccade does not occur. The beta-period is a waiting-time for a saccade that occurs with constant probability per unit time, and is a random variable intrinsic to each fixation. Overall, results showed that as stimulus size increased, mean fixation duration decreased. It was further concluded that saccades triggered by non-foveal stimulation terminate fixations.

More recently, using a television-based corneal reflection eye tracker, Hainline, Harris and Krinsky (1990) found that infants (19-388 days, N=73) refixating a 1.5 degree square peripheral target displayed refixation variability most often larger than that of adults, as quantified by mean standard deviation (sd) =.8 degree. Adults instructed to carefully fixate the target had the lowest variability (mean sd=.1 degree), while uninstructed adults were intermediate in this regard (mean sd=.4 degree). No trend in relation to infant age was discerned. Attentional factors were implicated as limiting the scatter of refixations more than were sensory factors or oculomotor immaturity. That same year, paraxial photorefraction was used by the Infant Study Center laboratory to detect refractive errors during infant vision screening (Abramov, Hainline & Duckman, 1990). In this study, photographs were made of accommodation responses (which corresponded to distance of stimulus presentation). Photographs showing fundal reflections were compared subsequently, permitting unequivocal diagnosis of severe myopia and hyperopia, anisometropia, heterotropia, and anisocoria. It was noted also that paraxial photorefraction results are quantifiable and may be compared with retinoscopic refraction.

Eye position data obtained using paraxial photorefraction was used subsequently to evaluate the development of accommodation and convergence before age 1 (Hainline, Riddell, Grose-Fifer & Abramov, 1992). Results showed that most infants at all ages demonstrated appropriate convergence for target distance (200-25 cm), regardless of refractive error. Convergence preceded accommodation developmentally, with the lag eliminated after age 2 months, except in those with myopic or hyperopic manifest refractive errors.

Recently, again by photographing eye movements, it was shown that when estimating angle of strabismus, the same average Hirschberg ratio (i.e., 22 prism diopters/mm) can be used across age (Riddell, Hainline & Abramov, 1994). This addressed the question "Does eye growth in infants age 27-365 days render use of the Hirschberg ratio inappropriate?" The authors noted, however, that when evaluating angle of deviation based on measures using the Hirschberg test it is important also to consider change in angle lambda, the angle between the line of sight and the pupillary axis. Axial growth of the eyes was assumed to account for observed rapid declines in angle lambda, from an extrapolated value of about 8.4 degrees at birth to near 5 degrees at 5 months.

Thus, areas related to eye movement considered by Hainline's group have included human eye and vision development, human eye movement pathology and selected non-human species comparison. The study methods used by these researchers are attractive because they are non-invasive and render verbal feedback unnecessary while still yielding valuable eye movement data whose limitations are quantifiable.

A small number of investigations involving assessment of infant oculomotor behavior have not used visual stimulus presentation, or have combined it with other types of stimuli. In 1961, Pendleton and Paine used manual rotation and rotation by means of a table driven electrically to elicit rotatory and post-rotatory nystagmus of the vestibulo-ocular reflex, also known as the vestibulo-ocular response (VOR) in 28-42 week old infants with and without central nervous system (CNS) disorders. Direct observation, electro-oculographic (EOG) and photographic assessment techniques were employed. Normal infants displayed rotatory and post-rotatory nystagmus associated with VOR production; these behaviors were either absent or attenuated in those with CNS disorders.

Also in 1961, Wertheimer presented auditory stimuli (toy "cricket" clicks) close to each ear of a neonate two-ten minutes after birth. Two independent observers determined that "localizing" eye movements were made toward the stimulus source, leading the author to conclude that the observed behaviors constituted "directional oculomotor (perhaps visual?)" responses (p. 1692, 1961).

Later, in 1975, Hammer and Turkewitz used EOG recording to measure "towards turning" and "away turning" eye movements made in two-day old infants presented with auditory stimuli to either ear. Also in 1975, Slater and Findlay demonstrated binocular fixation (to distances including approximately 25 and 50 cm) in newborns, using a corneal reflection technique. In 1976 Mendelson and Haith used infrared corneal reflection recording to assess visual activity in four studies of newborns (one-to-four days old). The series of experiments was conducted to investigate the relationship between audition and vision in newborns: one study is particularly relevant to the present work. It evaluated the effects of sound (at midline) on scanning, in the dark and in a lit, formless, field. In darkness. "newborns maintained better eye control, centralized fixations, scanned with smaller eye movements, scanned less dispersely, and were wider eyed." Except for constraining fixations, in the dark sound had little effect on scanning. Sound (compared to silence) with the lit field "caused newborns to maintain better eye control, centralize fixations, scan with smaller eye movements, constrain fixations, and be wider eyed."

In 1980, Lawson and Turkewitz reported direct observations of infants (mean age 53 hours) who produced eye turns in response to visual and auditory stimuli. Some time later, (1982) Haith and Goodman videotaped monocular eye movements of newborn infants (24-72 hours) under light and dark conditions. In contrast to previous reports, out-of-control eye movements were more frequent in the light than in the dark. The authors asserted that this evidences a distinction between exogenous and endogenous newborn infant eye movement control, in that earlier opposite findings regarding such eye movement activity were not attributable to monocular conditions or to the distracting contours of an eyepatch.

Within the past decade older infants, six to eighteen months of age, have been observed to produced directed eye movements in the dark (i.e., in the absence of visual stimuli) in response to vertically oriented sources of auditory stimuli (Morrongiello, 1987). A forced choice procedure was employed to elicit eye movements directed toward sound sources located at eccentricities ranging from zero to +/-16 degrees in the median sagittal plane. Although the purpose of Morrongiello's study was to evaluate preference for higher signal frequency as a function of age, and to compare this with known adult tendencies, the observation that "minimum audible angle" decreased with increasing age indicated an increasingly fine partitioning of auditory space over this time period.

The infant work described to this point establishes that organized oculomotor capacities exist at or very soon after birth. This body of research outlines identifiable changes in oculomotor behavior which takes place over time, and furthermore documents the integration of oculomotor control with such non-visual factors as auditory mapping. It contributes immeasurably to scientific understanding of human vision generally and infant vision in particular. In light of the foregoing, it would seem optimal to assess eye movements of infants in order to further the goal of the present study, i.e., to increase knowledge of the influence of visual experience on human voluntary oculomotor control. This might be done by comparing age-matched infants with differing visual experience, e.g., comparing congenital cataract patients pre- and post-surgery within-group and in relation to normal controls. However, consideration of the known obstacles to productively conducting infant eye movement research prompted close examination of such an option in the present study.

Difficulties of Infant Oculomotor Research

Methodological and theoretical constraints associated with including infants in research plague the study of eye movement development and functioning. This is in part because central structures controlling infants' eye movements are largely unknown and methods for determining what they may be are lacking (Hainline, 1993). The choice of data collection techniques used to evaluate infant eye movements often is subject to unique technical, scientific and ethical considerations (Hainline, 1993; Preston & Finocchio, 1993). Use of a search coil, for example, would be unacceptably invasive (and perhaps infeasible) as it involves placement of apparatus in direct contact with the eye. Recording difficulties vary similarly with the data collection technique employed; they can include large amounts of extraneous (non-stimulus-induced) eye movements, or data obtained may be unusable due to equipment calibration problems (as has been noted by Hainline, 1993 and by Preston & Finocchio, 1993). The experimental design, furthermore, used in infant eye movement studies must be constructed in a way mindful of infants' abilities and behavior patterns. Because periods of alertness tend to be brief and infrequent, narrow "windows of opportunity" exist within which the infant is in an arousal state when data collection can begin. State changes during evaluation (e.g., the infant falls asleep) can terminate data collection (see, e.g., Bloch & Carchon, 1992), limiting that session's data.

Less concretely, as alluded to earlier, the volitional nature of eye movements may be questionable under certain circumstances. This problem is compounded in work with infants both because the motivation of such research "participants" cannot be assessed and because no unassailable physiological evidence has yet been put forth which permits one to separate reflexive from volitional eye movements based on stimulus presentation or other techniques (Hainline, 1993). Data collection difficulties arising from infants being easily "bored" with visual stimuli (used with adults successfully) have been identified also, and workable solutions are not yet standard (Hainline, 1993).

These and many other drawbacks to the use of human infants in research have led Hainline (1993) to call for more ingenious investigative solutions to the problem of how oculomotor orientation develops and how it dovetails with vision. In consideration of the factors set forth above, it seemed desirable in the present research to assess the eye movement patterns of adults rather than those of infants, and to seek alternate approaches to the study of the relationships among vision, vision development, and intentional eye movements. Hainline (1993) has identified three structural and organizational components of visual system functioning which should be taken into account when considering the development of eye movement control. These include sensory, attentional/motivational and motor aspects of vision possibly involved in eye movement (for additional treatment of these and related topics, see, e.g., Monty & Senders, 1976; Senders, Fisher, & Monty, 1978; Fisher, Monty & Senders, 1981).

Accounting for the independent or integrated influence of these three factors is a tall order. Considerations may include: (a) Can the research participant see a target, does it matter to him/her that it is there, and how long and intensely will he/she pay attention to it, and (b) after adjusting for the participant's age, are the anatomical structures one uses to produce the various kinds of eye movements normal, fully functional and mature?

Separable conceptually, difficulty may arise in separating these aspects of the visual system operationally, although at the same time their interrelations cannot be ignored (Hainline, 1993). To design and conduct new investigations in this area thoughtfully, the foregoing needs to be kept in mind, along with results of related studies already performed.

The design of the present experiment was based on consideration of relevant sensory, attentional/motivational and motor eye movement/vision findings, as well as on technical aspects of anticipated data collection. The past research into infant eye movement considered here clearly also has constituted an important foundation for the present study.

Eye movement abilities of infants exist in the context of a limited period of visual experience. Differences between capacities of normal infants and those of older individuals lacking childhood or ongoing visual experience therefore may be related to differences in duration of visual experience, and/or to the loss of capacities that were initially "built in," i.e., present in early infancy. The past infant oculomotor research discussed above demonstrates that under normal circumstances directed oculomotor behavior exists, to some extent, at or soon after birth; changes then take place systematically until identifiably voluntary responses which could be termed "mature" or "adult-like" are displayed. This leaves open the question of whether and how, over time, visual experience may influence post-natal voluntary oculomotor control. Having resolved in this study to attempt to answer this question by assessing voluntary eye movement patterns in adults, consideration is next given to other relevant past work. Discussed next are some past empirical studies germane to the present research. Each has incorporated one or more of the three components Hainline recommends for research into oculomotor control development.

Human Oculomotor Orientation with Non-visual Stimuli

Prior to the present investigation human eye movements had, to a limited extent, been separated from vision temporarily and evaluated in adults under visual and non-visual stimulus conditions. Areas of theoretical and experimental interest in oculomotor control in the absence of visual stimuli (e.g., in the dark) included eye position sense, target accuracy, maintenance of gaze fixation, and accuracy of refixation, along with saccade number, duration, frequency, velocity and amplitude. Formal investigation along these lines can be traced historically to the late 1800's (for a discussion see Steinman, 1975). Various hypotheses were put forth regarding whether and how eye position information may be obtained in the dark and how under these conditions eye movements are directed and controlled. One explanation of eye position sense (presumably regardless of illumination) has been called the "outflow hypothesis," and was first promulgated by Helmholtz. Outflow theory held that we are directly aware of the will we use to move the eye and furthermore can remember the (internal) instruction for some time. Ethologists including Von Holst later extended outflow theory in the "reafference" model of motor control, followed by various adaptations within engineering; these may be characterized by the presence of a "comparator" monitoring execution of a movement and acting to correct errors (for a discussion, see Hinde, 1970). Some experimental evidence has been put forth which supports the outflow model in relation to control of voluntary eye movement (see, e.g., Steinbach & Held, 1968, specifically in relation to visual tracking). An alternative "inflow hypothesis," attributed to Sherrington, (see Steinman, 1975), posited that extraocular muscle mechanoreceptors tell us how the eye is oriented within the orb, but considerable evidence has cast doubt on this model.

More recently it has been suggested that specifically in darkness, eye position and movement information comes simply from proprioception, or either from corollary discharge associated with instructions to the eye movement system or from feedback coming directly from the oculomotor nuclei (Heywood, 1973). Steinman (1975), has asserted also that "some non-visual afferents can be used to control eye position" (p. 406).

Although studies evaluating these and other hypotheses have yielded mixed results, findings have become increasingly conclusive; this has coincided with advances in experimental apparatus and design. Disparate methodologies may be inferred to account further for some of the contradictory results obtained. For example, eye position sense and oculomotor control in the dark have been recorded using a variety of techniques, including self-report, electro-oculographic and photographic. Select examples of research in this area are discussed below.

It should be noted that several of the studies considered next refer to "primary position" (although this term is occasionally used to describe an external location, it most often describes the state of an observer). Primary position has been defined variously, but of interest with regard to the present research is that the definitions often are suggestive of a vision-primary position homeostasis. Examples include: "The position of the eyes when the head is erect and the two eyes are fixating into the infinite distance along a horizontal plane; the position from which a pure horizontal or vertical movement is not associated with any tilt (that is, false torsion) of the vertical meridian of the eyes (that is, of the corneas) with respect to objective vertical." (Ciuffreda & Tannen, 1995, p. 3); and "The primary position is assumed by the eye when one is looking straight ahead with body and head erect." (Von Noorden, 1996, p. 54). Given the homeostatic element of these primary position definitions it could be inferred that primary position would be assumed by the eyes whether or not one were fixating visually, so long as the other criteria were met. Indeed, primary position has been referred to in reports of experiments involving participants who are blind (e.g., Leigh & Zee, 1980; see also section below, "Human oculomotor orientation without visual experience") as well as in reports of research involving oculomotor behavior in relation to non-visual stimuli.

Maintenance of gaze fixation (i.e., keeping the eyes relatively immobile for some time period), in the dark has for several decades held theoretical and experimental interest within the area of oculomotor control (see, e.g., Merton, 1961). Heywood (1973) pointed out that maintenance of fixation in the dark, upon a target previously fixated visually, concerns the ability of the oculomotor system to detect and correct error (such as drift) which arises despite the instruction given to the system. In 1970 Skavenski and Steinman found that in the absence of a visual error signal, i.e., in the dark, eye position control was maintained effectively. Attempts to fixate "primary position" and positions ten degrees to the left and right of primary position were evaluated. After more than 2 minutes in the dark, fixation was maintained, via saccades, within two degrees of positions viewed previously; shorter durations were characterized by keeping the eye much nearer to target position. A number of possible confounds were ruled out as having produced the observed "effective position control," including tactile cues from the conjunctiva, participant torso orientation, and self-selected eye movement patterns. Later, Steinman (1975) noted that slow control (characteristic of visual fixation) in humans is lost "when visual stimulation is not available" (p. 397). More recently, it has been observed that "In both foveate and afoveate animals, the eyes tend to drift significantly in the dark even when the subject has been given instructions or is trained to keep the eyes still. In contrast, eye drift is substantially reduced in the light, implying the presence of a mechanism that provides for stable vision even when the head and the environment are not moving" (Hainline, 1993, p. 48). The mechanism(s) underlying the difference in gazeholding (maintenance of gaze fixation) under light versus dark conditions is not yet understood fully. Physiological and motivational hypotheses continue to prompt empirical investigation of the phenomenon.

Research with adults on directing the eyes in the dark has revealed remarkable "target" accuracy (about one degree) when room illumination and a visual stimulus are "turned off" (Merton, 1961, see below; and for a discussion see Carpenter, 1977 p. 241). Phenomena relevant to the present investigation, from among the available reports regarding voluntary eye movements made in response to visual and non-visual stimuli, are considered next.

In a series of experiments, some of which involved tactual/proprioceptive input, Merton (1961) used a photographic technique to measure binocular and monocular eye position in the dark. Maintenance of gaze fixation in darkness was approximately plus or minus half a degree in the horizontal direction; in the binocular condition this refers to the mid point between the two fixation points. Independent of fixation, "convergence changes" took place during the first few seconds of darkness. When the task involved fixating a point in the dark which had been fixated in the light previously, i.e., refixation, the standard deviation around the mean of successive attempts was approximately plus or minus one degree in both the horizontal and vertical directions. Errors were larger when the participant was required to look toward an object located tactually, or if the object moved between attempts.

Heywood (1973) set out to determine how accurately, in the dark, an outward-going saccade may be matched by a return saccade and how target eccentricity may affect accuracy. Handedness and eye dominance were taken into account, the latter determined by having participants "look through a monocular viewer and sight a target with a finger" (Heywood, 1973, p. 83). Fifteen adults took part, including those classified as "left handed, left eyed" (LL, N=4), "right handed, right eyed" (RR, N=6), "left handed, right eyed" (LR, N=3) and "right handed, left eyed" (RL, N=2). Calibration of electro-oculographic recording equipment was performed initially, involving dark-adapted participants' fixating visually upon a series of visual targets under dim red illumination. Stimuli were mounted on a surface 24 inches from the participants' eyes. One-degree targets were situated three, fifteen, and thirty degrees to the left and right of primary position.

Participants in Heywood's study were instructed to fixate upon an indicated position just prior to room lights' being turned off, then (in darkness) were asked to saccade toward and away from it. Periodic visual refixations (about every eleven seconds) served to separate trial blocks and were used between phases of the experiment to recalibrate the recording equipment.

Overall, participants were more accurate when producing outgoing saccades than when returning the eyes to the desired target. Refixation accuracy in the dark was affected by target location, direction of prior eye movement, and cerebral dominance. When returning the eyes to a target position, i.e., refixating, left-handed participants with left eye dominance and right-handed participants with right eye dominance showed performance differences. This was most true for magnitude of error (target accuracy) but was displayed also with regard to "amount of undershoot" and for the number of saccades produced. Refixation accuracy of LL participants was lower when returning the eyes from the right than from the left, whereas for RR participants the opposite was the case. LL made more multiple (corrective?) saccade returns when returning from the right and RR made more returning from the left. "Thus in that direction in which error is larger there is greater instability of eye movement, shown by increased likelihood of failure to bring the eyes back to the target with a single saccade" (Heywood, 1973, p. 85). RR and LL made errors returning to center of between 3.3 and 5.5 degrees. Return to periphery (i.e., non-central targets) ranged between 4.5 and 9.5 degrees for these groups. The mixed dominance groups performed slightly less well on this measure, although no consistent effect was reported in LR or RL attributable to handedness or eyedness. As to the latter point, while not noted by Heywood, it would seem that small group sizes could have precluded detection of such effect.

Regardless of direction of return or hand/eye dominance, participants were better at returning the gaze to "primary position" than to a peripheral target. The author suggests that this may be in part because the saccades away from peripheral targets were larger than those from the center, and this may have inflated error in attempts to return to the peripheral targets. This is consistent with the observation, furthermore, that large centrifugal saccades (i.e., those moving away from center) toward a specific position were performed less precisely in the dark than were large centripetal ones. Data were analyzed for effects arising from practice; neither improvement nor attenuation of performance was observed, allowing the author to rule out both increase in eye instability and practice effects.

Heywood attributed the observed performance asymmetries to "a cortical mechanism concerned with the registration of information about saccadic eye movements" (1973, p. 93) and considered the lateralization findings to be related importantly to manner and site of saccade information processing and storing. Heywood asserted that for these tasks the frontal eye fields appear likely involved cortical regions, and although the most simple presumption therefore is that each frontal eye field has control of saccades to the contralateral side, he points out that other contradictory evidence precludes this explanation. The author suggested alternatively therefore that each hemisphere, via the corpus callosum, may provide the other hemisphere information regarding contralateral saccades performed. This information may be used in producing return saccades.

The error magnitude difference of central versus peripheral targets is explained as possibly relating to the neural activity underlying fixation as well as to differential saccade size. Heywood suggested that the larger amount of neural noise associated with peripheral eye position, along with the corresponding information about it being delivered elsewhere in the brain, may make establishing peripheral gaze versus central gaze more difficult.

Some difficulty exists in evaluating Heywood's results in the context of previous reports. Whereas Merton (1961) reported refixation accuracy of about a degree, and Skavenski and Steinman (1970) reported refixation values of less than two degrees, gazeholding was not investigated in Heywood's work. This precluded possible "long-term corrective adjustment" which may have taken place in other studies.

A number of additional studies have reported on saccade number, duration, frequency, velocity and/or amplitude, as elicited under total or partial dark conditions. In 1974, Riggs, Merton and Morton found saccades of particular amplitudes to be slowed in total darkness. EOG recordings were produced as eight saccades were made to fixation lamps in the light, followed by eight saccades made in the dark immediately after the fixation lamps were extinguished. Velocity diminished and duration increased. In darkness, saccades of ten, twenty and sixty degrees were slowed by a factor of approximately two, 1.5 and 1.2 respectively. Interestingly, however, these authors reported that the largest saccades possible "are not apparently slower in darkness." (p. 1008, 1974). Riggs, Merton and Morton furthermore noted that "saccades in the dark are not multiple or otherwise broken up." (p. 1008, 1974).

Snodderly (1987) evaluated the fixational saccades of two Macaque monkeys and two humans; responses were made in response to unpredictable dimming of fixation spots in the dark and in the normally lit laboratory. Fixational saccades often were characterized by complex wave forms wherein two or more saccadic displacements occurred with no intervening drift period. Saccade cluster frequency was lower (.15-.61 per second), and magnitude of eye displacement was larger in the dark than in the light. Human participant mean eye position did not change when testing was performed in the light after having been carried out under the darkened stimulus conditions, nor was direction of saccadic displacement very much affected. The light effects, more pronounced for the Macaques than for the humans, were attributed to "an interaction between foveolar and peripheral retinal inputs" (P. 401, 1987). These results led Snodderly to suggest that one role of fixational saccades may be to stimulate pathways originating in the peripheral retina, which influence fixational control systems.

In 1975 Koerner recorded non-visual saccades electro-oculographically under a variety of conditions. Participants had normal oculomotor function, complete or partial homonymous hemianopia, or bitemporal hemianopia. The study focused on non-visual sensory inputs' possibly possessing some role in non-visual saccade amplitude and velocity or duration, and on secondary ("corrective") saccades made in the dark.

Participants with normal vision tried but failed under non-visual conditions to reproduce accurately mean amplitudes of saccades made under normal viewing conditions. Koerner found also that "Human saccadic eye movements executed in the dark are slower than under normal viewing conditions" (p. 568); "dark eyes open" saccades were slower in relative velocity than visually guided saccades, and "eyes closed dark" saccades were slowest of all. Accuracy of non-visual saccades was not improved by tactile or auditory inputs, nor did these factors facilitate any increase in the reduced saccade velocity.

As may have taken place in Heywood's 1973 study, secondary, or "corrective," saccades were observed. Surprisingly, positive (characterized by "overshoot") or negative ("undershooting") corrective saccades were displayed in about as high a percentage following "eyes open dark" saccades as following visual saccades. Their function, Koerner suggested, may be to correct for an inaccurately executed cortical signal for visual or non-visual saccades, evoked by an extra-striate internal feedback loop (perhaps sending proprioceptive afferent information from the eye muscles to the cerebellum). Koerner submitted further that if this were true, then there would also have to be a lower oculomotor brain stem neuron firing rate, and on this basis posited a mechanism for brain stem neuron inhibition via a secondary activating pathway leading from the frontal eye fields.

In a later phase of the study, Koerner predicted and confirmed that when individuals with hemianopia direct saccades toward regions of visual field defect, saccades with relatively slow velocities result. A "sensoric" interpretation of the saccade slowdown observed in hemianopic individuals was next examined by evaluating five participants with bitemporal hemianopia. Eye movement velocity was reduced only when directed toward the temporal, blind, half-field of either eye.

OKN of participants with complete homonymous field defects and those with bitemporal hemianopia was evaluated also. OKN asymmetry was evidenced when recordings were made with monocular occlusion. In the latter group, with one eye open, low amplitude and slow phase velocity characterized OKN in the direction corresponding to that eye.

Koerner concluded that maximum saccade velocity depends not just on a small visual target but on "structured visual input to that hemisphere, which also receives the information from the visual goal." (1975, p. 568). He suggested also that a lack of visuo-sensory facilitation of oculomotor neurons, via a corticotectal pathway, might be responsible for the observed directional slowdown of saccades in the hemianopic participants.

The studies just discussed relate to human oculomotor orientation with non-visual or attenuated visual stimuli. In addition some of the results reported by Koerner relate saccadic characteristics to vision (field) loss. They do not address specifically nor reveal completely, though, whether and how visual experience as distinguished from visual stimuli may affect human voluntary eye movement control.

Human Oculomotor Orientation Without Visual Experience

Oculomotor disorders (such as various types of nystagmus) frequently coincide with blindness without being its primary cause. Little is known, though, about the eye movements of blind people fitting no such clinical description. The rehabilitation literature contains suggestions that individuals who are adventitiously blind may exhibit voluntary eye movements routinely, and that training can result in improved "targeted" eye movements toward an apparent point of regard (Paskin, 1977). The lack of mention of people who are congenitally blind in relation to pre- or post-rehabilitation of voluntary oculomotor control is striking, in that the feature differentiating these groups is visual experience. Several experimental studies have generated data investigating the eye movements of people who are blind. One in-depth study (Sherman, 1985; Sherman & Keller, 1986) was devoted primarily to how blindness affects the VOR. It included limited consideration of voluntary saccades and was designed chiefly as a vehicle for modeling neural processes. A small number of additional investigations (Leigh & Zee, 1980; Kompf & Piper, 1987; Leigh, Thurston, Tomsak, Grossman & Lanska, 1989) have centered upon how, in humans, chronic deprivation of visual feedback due to blindness may affect characteristics of voluntary eye movements, their neural guidance, and eye position sense. These studies are considered next, as they provide the most relevant and concrete context for the present research.

Leigh and Zee (1980) sought to investigate the effect of visual feedback on development and maintenance of function of the saccadic, pursuit and vestibular oculomotor subsystems. Electro-oculographs were made, with limited success, supplemented by motion picture recording and clinical observations. Eighteen adults who were either totally or "legally" blind participated in the study. Vision loss had arisen from "anterior pathway" damage caused variously, e.g., by retinopathy of prematurity (ROP, formerly known as retrolental fibroplasia), glaucoma, or trauma.

An inability to maintain a steady "primary eye position," with a consequent jerk nystagmus, was revealed in all participants. When attempts were made to hold the gaze in a vertical or horizontal direction, nystagmus increased and corrective saccades were displayed as gaze drifted to a "null point."

Congenital blindness was associated with an impaired vestibulo-ocular reflex and inability to voluntarily initiate saccades, although quick phases of nystagmus were displayed. By contrast, in adventitiously blind participants the vestibulo-ocular response was seen as relatively "well preserved," along with the ability to initiate voluntary saccades and to track self-moved targets smoothly. It should be borne in mind that a standard is lacking for use in designating "congenital" versus "adventitious" blindness. It is not sufficient to infer that those individuals classified as congenitally blind were born blind, i.e., as the word implies, blind "with birth." In general, congenital blindness is thought of as that which occurred at or relatively soon after birth whereas individuals classified as adventitiously blind include those the advent of whose blindness was significantly later in life. The distinction is complicated by a number of factors. These include the quality as well as the duration of any vision preceding blindness, and whether memory of that vision and the ability to visualize have been evidenced and are retained. Kompf and Piper have noted, furthermore, that often "the final occurrence of blindness can not be determined exactly" when vision deterioration has taken place gradually (1987, p. 341), as is frequently the case. When designing oculomotor or other studies involving blind participants in which age of onset of blindness may be salient, therefore, it is important in lieu of a standard to set forth operational definitions for these or related categories (such as "early blind" versus "late blind").

Leigh and Zee (1980) noted that oculomotor abnormalities similar to those they observed have been produced in animals via deprivation of cerebellar visual inputs and are known in patients with cerebellar lesions. Common features include inadequate gaze holding, post-saccadic drift and a "wandering null point."

Leigh and Zee suggested that, taken together, these results implicate the vestibulo-cerebellum and dorsal vermis as neural systems possibly using visual information to monitor and sustain appropriate eye movements. They argued that these structures receive visual inputs and seem important in saccadic accuracy, appropriate vestibulo-ocular responses and normal holding of the gaze.

The Leigh and Zee (1980) study may be viewed as no less than pioneering. Technical and other limitations of their approach, however, render difficult interpretation of the results reported. No screening is mentioned for possible confounding (clinical) abnormalities of the eye movement system, extraocular muscles, or associated structures, e.g., arising from injury or disease coincident with the visual impairment.

More importantly, while all participants were termed "legally blind," some were referred to as "partially sighted." Legal blindness is a designation differing among states in the United States, but a corrected Snellen visual acuity of no better than 20/200 in the better eye is typical. Individuals whose Snellen acuity approaches 20/200 are not without ongoing visual experience (and may function more as sighted than as blind people). It would therefore seem inappropriate to use data from the participants with attenuated but possibly useful vision to conclude that observed abnormal eye movement patterns stem from lack of visual experience. Inclusion of partially sighted participants leaves open the possibility also that some of the eye movements recorded in the experiment were guided visually.

Several of these problems were avoided subsequently in the 1985 Ph.D. thesis work of Keith Sherman (see also Sherman & Keller, 1986). The stated aim was to investigate the effect of visual experience on development and maintenance of the VOR. Vestibulo-ocular responses, and to a limited extent voluntary eye movements, were elicited, measured and evaluated in blind versus sighted adults. None of the blind individuals could detect light reliably. As in the Leigh and Zee (1980) study, vision loss had arisen from "anterior visual disorders" and included eye, retina, or optic nerve disease or injury. Of the fourteen participants who produced useable data, five were classified as congenitally blind, six as adventitiously blind, and three as normally sighted. Participants who had never had "form vision" were classified as congenitally blind, and as adventitiously blind if they recalled visual experiences but no longer had form vision. Thus age two years was the criterion adopted to distinguish between adventitious and congenital blindness, although only one participant in the adventitious category had become blind prior to adolescence.

Eye movements were recorded in the dark using photoelectric limbal tracking. This prevented sighted participants from producing visually guided eye movements. Measurements were made as individuals were rotated about a vertical axis. Gain and phase lead were computed for each trial and considered in relation to the various frequencies of rotation employed. VOR gain, denoting the "size" of the eye movements, was taken to be the ratio between mean peak slow phase eye velocity and head velocity.

VOR phase quantified eye versus head movements in relation to a standard, "characterized by a single dominant time constant determined by the frequency at which 45 degrees of phase lead develops" (Sherman & Keller, 1986, p. 1158).

Dramatic inter-group differences in the VOR led to the following observations: "It is concluded that vision has an essential influence on VOR development. When blindness occurs congenitally, development is impaired and the VOR essentially eliminated. In addition, vision has a differentiable influence on VOR maintenance throughout life. When blindness occurs adventitiously, VOR gain decreases and phase lead increases. Simulations and sensitivity analyses predict that the neural structures associated with the velocity storage mechanism and or the neural integrator produce these changes" (Sherman, 1985, p. 1-2).

Interestingly, sighted and adventitiously blind participants could voluntarily change their vestibulo-ocular "reflex" gain by changing their "mental set." When imagining an Earth-fixed reference point, VOR gains were higher in these groups than for a head-fixed reference point during rotation at all frequencies. This illustrates, once again, the definitional problems encountered in characterizing certain types of eye movements as volitional versus reflexive.

While the effect of visual experience on the VOR was central to Sherman's investigation, some attention was paid to voluntary oculomotor control: "Subjects were asked to make small and large eye movements to the left and to the right." (Sherman, 1985, p. 32). All of the sighted and adventitiously blind participants except the adventitiously blind participant who became blind earliest demonstrated oculomotor control, whereas none of the congenitally blind participants did; "Five of the six adventitiously blind subjects were able to generate voluntary saccades, and to hold these eccentric fixations." (1985, p. 32). Visual experience further distinguished Sherman's groups in that "Compared to sighted subjects performing the same task in total darkness, the adventitiously blind individuals had more difficulty controlling the amplitude of their saccades." (1985, p. 32).

In 1989, Leigh, Thurston, Tomsak, Grossman & Lanska used magnetic search coils to study effects of vision loss on gaze stability. Horizontal and vertical movements of both eyes were measured in one bilaterally congenitally blind participant, four participants with monocular vision loss, and two normally sighted (visual acuity 20/20 bilaterally, control) participants. The participant who was blind bilaterally was asked to imagine a target "straight ahead," while participants with vision attempted steady binocular fixation of a visual target. A wandering null point and nystagmus, with horizontal and vertical components, were displayed in the participant who was blind bilaterally. The authors took this as an indication of an "abnormal neural integrator." Participants with loss of vision in one eye exhibited greater vertical and horizontal gaze instability in that eye. This was true when compared either with their own other eye or with monocularly occluded eyes of control participants. No "gaze-evoked" nystagmus was detected in the monocularly blind group; the authors attributed the observed gaze instability in this group to "low frequency, low amplitude" predominantly vertical drifts and unidirectional drifts with predominantly horizontal nystagmus. They suggest that the phenomenon "may reflect destruction of 1, a monocular visual stabilization system, 2, fusional vergence mechanisms, or 3, both." (Leigh, et al, 1989, p. 288).

In 1987 Kompf and Piper assessed the effect of chronic deprivation of visual feedback upon oculomotor control in one blind child (age seven years) and twenty blind adults (ages 34-82 years). Four of the individuals taking part in the study were born blind; seventeen lost their vision later. In no case did visual acuity exceed 1/35 (N=14); light perception alone was reported in seven participants. Vision loss in all cases arose from diseases affecting anterior visual pathways. Data included clinical observations and examinations (neurological, ophthalmological), photographs, motion pictures, and electroencephalographs (EEGs). Electro-oculographic recordings were possible in fourteen participants (seven participants had attenuated corneo-retinal potentials, which can preclude EOG recording). To study the condition of the extraocular muscles, orbital CT scans were performed in individuals who were born totally blind. OKN responses were elicited using a light band projector and panoramic screen. Rotational tests and sinusoidal horizontal angular rotation were used to elicit vestibulo-ocular responses. The authors divided participants into three major groups. One classification was that of congenital blindness, into which those with no visual experience were placed (N=4). The other categories were "early acquired blindness" (N=9), in which the age of onset of blindness ranged from childhood to 55 years, and "late acquired blindness" (N=8). This approach to classifying blind individuals on the basis of visual experience would appear to emphasize duration of vision loss in relation to the individual's age at the time of testing, rather than on the time elapsed between birth and blindness. The visual status of those particularly in the late acquired blind group, who were not totally blind, was termed "sehblindheit," literally "sight blindness;" these individuals were characterized as being "functionally blind for social practical purposes" although not experiencing "Lichblindheit." literally "light blindness," or total blindness (1987, p. 338).

All four participants classified as congenitally blind exhibited spontaneous eye movements; none could sense eye position or were subjectively aware of these behaviors. The VOR was not detected in any of the congenitally blind participants, nor could any "track their outstretched thumb in a self-induced movement" (p. 338). None demonstrated an ability to voluntarily initiate saccades.

In the group possessing "early acquired blindness." The mean duration of vision loss was 36.3 years; the blindness durations ranged from 10-73 years. Four individuals had become blind at ages one, five, five and nine years of age respectively; vision loss in the remaining five took place at approximately ages 30-55. Two participants possessed residual vision in at least one eye, four had lost all vision except light perception, and three were totally blind. In contrast to the participants classified as congenitally blind, none with early acquired blindness displayed "gross fluttering eye movements." Two participants produced a VOR lasting in excess of 30 seconds, although among the remaining individuals the VOR was absent (N=2) or markedly reduced (< 15 seconds, N=5). In no case of early acquired blindness could an optokinetic response be elicited, despite the presence of low vision in some. This group additionally was characterized by retention of eye position sense and the ability to direct the eyes voluntarily.

The EEGs of participants in both the congenital and early acquired blindness groups generally revealed a low amplitude dominant occipital alpha rhythm of 20 to 30 microvolts. An exception was one participant with amplitudes up to 80 to 120 microvolts. Eye opening induced clear alpha blockage in this individual but was not elicited reliably in the other cases.

Participants in the "late acquired blindness" category demonstrated OKNs and normal VORs. All "were able to maintain a steady eye position without any spontaneous eye movement phenomena, to sense the eye position, and to start and execute saccades and self-induced slow [own thumb pursuit] eye movements voluntarily" (1987, p. 339). EEG dominant occipital alpha rhythm amplitudes were in the range of 40 to 80 microvolts.

In discussing their results, Kompf and Piper speculate that the "abolition" of the VOR in people born blind may be attributed to progressive degradation of underlying primarily incompletely matured neural structures, taking place over long periods of time (many years or decades), and that the consequent absence of permanent accurate calibration (generally required by an operating open loop system) leads to an irretrievable loss of vestibular connections. They assert that VOR development and VOR adjustment depend on visual experience and visuo-vestibular interaction, although they note that recent visual loss (as in the group classified as late acquired blind) does not affect the VOR substantially, and that even long lasting deprivation with prior vision can only weaken and not completely abolish the VOR (as in the participants classified as early acquired blind).

Another conclusion drawn was that "control of eye position is abolished in blind subjects." However, the oculomotor behavior of the participants in the late acquired blind category was characterized as "comparable to that of healthy individuals moving their eyes in total darkness" (Kompf & Piper, 1987, p. 339). These two statements would seem to contradict one another, especially in light of the results (regarding ability to produce voluntary saccades) presented both for the groups with early and with late acquired blindness. To resolve this dilemma, it may be inferred that the observed oculomotor patterns shown by the individuals in the late acquired blind group were attributed to the small amounts of vision each of these participants retained.

Interestingly and unequivocally, Kompf and Piper state that without prior vision "the sense of eye position or change in direction of gaze does not develop, and therefore voluntary saccades cannot be made" (1987, p. 339).

Reformulating this proposition, the hypothesis can be set forth that the ability to produce voluntary saccades depends on the development of sense of eye position or change in direction of gaze, which depends on visual experience. If the hypothesis were to be tested in its entirety, it would seem important first to demonstrate convincingly whether the ability to produce voluntary eye movements, including saccades, indeed depends on development of sense of eye position or change in direction of gaze. In that this is a developmental issue, evaluation of the proposition would furthermore most preferably begin by studying voluntary eye movements in the youngest individuals in which such behaviors are found. Some of the problems with utilizing such "research participants" have been elaborated upon above; here they would be complicated more specifically by the lack of an obvious way to assess sense of eye position or change in direction of gaze in infants in whom voluntary saccades may confidently be inferred (e.g., via "object permanence" experiments). Short-circuiting the Kompf and Piper hypothesis, one could simply ask whether the ability to produce voluntary eye movements depends on visual experience.

Rationale and Design of Present Research

Much of the foregoing suggests that visual experience exerts a profound effect upon human voluntary oculomotor control. Do normal voluntary human eye movement patterns depend on vision? The conceptual and empirical work discussed to this point which bears directly on this question has for the most part evaluated the relationship between visual experience and voluntary oculomotor control qualitatively. The purpose of the present research was to quantify whether and how visual experience affects human voluntary oculomotor control. An experiment therefore was conducted to elicit voluntary eye movements by groups of adults with differing visual experience. Control of voluntary eye movements made in the absence of visual stimuli, vision, and/or a mental visual frame of reference was evaluated subsequently. The methodology is described in detail in the next section, but essentially involved videotaping and evaluating the eye movements of blind and sighted research participants, including groups comprised of those classified as congenitally blind and those classified as adventitiously blind. Eye movements made in response to computer-generated verbal instructions coupled with beep tone stimuli were recorded in the dark under infrared illumination; these features were included to reveal whether and how visual experience, as distinguished from visual stimuli, may contribute to human voluntary eye movement control. An eye tracker was used to create digital representations of the videotaped pupillary movements; this allowed the responses to be recorded at an adequate sampling rate, then evaluated relatively easily.

In designing the eye movement experiment a number of the ethical and practical considerations outlined above were taken into account. For example, adult volunteers served as participants, as they could respond to verbal instructions. Criteria for classifying participants who were blind, as either "congenital" or "adventitious", had to be considered and adopted. Confounds which had to be identified and avoided included a lack of head stabilization causing "false" eye movements arising from movements of the head. In addition two calibration studies were conducted. This was to determine how to quantify the experimental data, since the particulars of how the selection, placement and/or use of data gathering apparatus affect digitization of raw data by the eye tracker. Factors affecting calibration precision include: physiological error and variability associated with fixating upon targets, stimulus (target) variability, target spacing and error/variability in measuring inter-target distances, participant variability, idiosyncrasies of data gathering apparatus (including the placement of camera versus participant), and idiosyncrasies of analysis software and hardware. Calibration data were gathered (with the lights on) and evaluated; data consisted of videotaped eye movements toward known (measured) target locations. Analyses compared tracker versus measured values in order to quantify how the eye tracker digitized images of pupillary movement produced and recorded in the eye movement study. Three major aspects of tracker operation had to be evaluated to render the eye tracker output meaningful. First it was important to determine whether the tracker was generating output linearly in relation to measurements of known target location. After that it was necessary to quantify the relationship between degrees of visual angle (produced by calculable excursions of the eye) and the number of arbitrary eye position units created by the eye tracker. Finally it was essential to confirm that the tracker provided a true and consistent representation of pupil movement as an eye deviates from primary position throughout its horizontal and vertical oculomotor range. Calibration results were key to conducting the eye movement study as planned using the available setup.

The hypothesis underlying the eye movement experiment was that visual experience affects production of adult human voluntary eye movement patterns, including extremes of gaze, movements to locations between straight ahead and these extremes, straight ahead fixation, convergence and drift. That is, the question to be addressed most immediately upon analysis of experimental data was "Do eye movements to the extremes of gaze, eye movements to positions between straight ahead and these extremes, eye movements intended to simulate convergence, and gazes intended to simulate primary position differ on the basis of visual experience (e.g., among sighted adults with normal vision and two groups of blind adults)?"

Eye movement pattern characteristics predicted to be affected by lack of childhood and/or ongoing visual experience primarily included response amplitude and direction, and secondarily average velocity and midposition scaling accuracy. To evaluate the research hypothesis, data analyses were performed by production and visual inspection of graphs and by appropriate statistical tests. The statistical null hypotheses were that without visual stimuli (a) sighted, adventitiously blind and congenitally blind adults can produce the selected eye movements upon request, and (b) no significant difference exists within each voluntary eye movement pattern among these groups. The next section describes the calibration and eye movement experiments. Results of the eye movement experiment are considered in the final section, in the context of past related work.

EXPERIMENTS

Calibration Study 1

Calibration study 1: Subjects

Participants (N=4) included adult volunteers with uncorrected 20/20 Snellen visual acuity or better in each eye (evaluated as described below) and were assumed to have normal peripheral vision.

Calibration study 1: Apparatus

Lightbox-illuminated Lighthouse Early Treatment Diabetic Retinopathy Study (ETDRS) eye charts were used in visual acuity testing. Seating for acuity testing and eye movement recording was provided using standard office chairs (the seat height for the latter was adjustable).

A Bausch and Lomb forehead/chin rest was used during eye movement recording to preclude eye movements arising from large movements of the head and other possible sources such as cervical positional nystagmus (Dichgans, 1975).

Eye movement recording was done using a GBC video camera model CCD500, with a Fuji zoom lens model C6X17.5 set to 75 mm. The camera was located 198 cm from the participant, on axis with the eyes. This rendered negligible any potential confounding effects of small intersubject differences (of a few millimeters), in location of the eyes in the head or of head location within the headrest, due to the relatively large distance from the camera. Images captured by the camera were sent both to a Sony video monitor model CVM-131 (used to ensure proper placement and focus of the image on the videotape) and to a Panasonic videocassette recorder (VCR) model PVM4962. All videotapes were recorded at (an interlaced) 60 video frames per second (frames/s). At this distance, with the zoom setting used, a portion of the participant's face, dominated by the eyes, measuring 9 cm high by 11.5 cm wide filled the camera's field of view. Also visible was a light emitting diode (LED, discussed later) taped to the headrest above one eyebrow.

Twenty-two visual targets forming an array were placed at various distances opposite the camera in the eye movement recording laboratory. Each target was produced by drawing a cross in the center of a small square of paper (5x6.5 cm). The center of each cross measured 0.5x0.5cm.

The array consisted of five rows of targets (with the camera lens forming one "target"). The upper two rows had five targets each, the middle row 4 targets and the camera, and the lower two rows four targets each. Targets were located in vertical planes at a number of distances from the vertical plane of the participant's eyes. The upper three rows of targets were in a vertical plane 253cm from the participant. The bottom two rows of targets were in a vertical plane 199cm from the participant. Exceptions were the target at the left end of the second row, the middle target (the camera lens) in the third row, and the middle target in the fourth row, which were in vertical planes 165, 178, and 194cm from the participant, respectively. Physical constraints of the laboratory precluded use of a large symmetrical array, in a single plane, of sufficient distance from the participant.

Calibration study 1: Procedures

Each participant who agreed to volunteer for the study was scheduled for testing and was met by the experimenter and a research assistant at the laboratory at an agreed upon time. The research was described to the participant upon his/her arrival, and any questions he/she posed were answered. Each participant then read and signed an "informed consent" form.

Data collection was done by a research assistant, beginning with visual acuity testing. The participant was seated (the prescribed) four meters from a lightbox-illuminated Lighthouse Early Treatment Diabetic Retinopathy Study (ETDRS) eye chart. Participants wearing spectacle correction were asked to remove their glasses (no contact lens wearers took part). The individual was asked to indicate which eye, if either, seemed "better, or stronger," and was then asked to cover that eye using a hand-held occluder. Room lights were extinguished and testing proceeded monocularly. Letter identification was begun about 4 or 5 lines from the top. This was to preclude fatigue with decrease in letter size. The participant was instructed to identify each letter, reading each row from left to right until all rows were completed. In instances of uncertainty the individual was prompted to guess. Once the bottom row was completed, the top few rows which had been skipped were returned to and completed. The participant was given an opportunity to rest his/her eyes, then the procedure was repeated to test the remaining eye.

All correct and incorrect responses were noted on a form created for this purpose, (see Appendix A). Scoring was done using the whole line increments method in which the entire line is considered to have been read correctly if 3 out of the 5 letters are identified correctly (for a discussion, see Arditi & Cagenello 1993).

A participant code, for subsequent identification of the individual, was written on the back of the participant's informed consent form. The camera was focused (based on inspection of the video image) and the code was videotaped in preparation for eye movement calibration data collection. The participant was shown the forehead/chin rest and asked to position his/her face appropriately; adjustments to chair height were made for comfort as needed. One eye was occluded using an eye patch. Bright room lights produced target luminances of 200 cd/m^2, rendering the targets well illuminated. Each participant confirmed that he/she could see the calibration targets clearly with each eye, without vision correction.

The camera was focused again if needed and recording began. Each participant next was videotaped fixating upon the center of each target according to the following instructions: "Look straight at the camera." "Look at the left-most target in the top row of targets." "Move your eyes one target to the right." "Move your eyes one more target to the right." This pattern was repeated until all targets in the top row had been fixated upon. A brief pause was made between delivery of each instruction. Instructions then were to "Drop down a row and look at the right-most target in the second row." "Move your eyes one target to the left," etc., until all targets in the second row had been fixated upon. This zigzag pattern was followed until the bottom-most target was reached, at which point the participant was asked to "Move your eyes directly back to the camera." This procedure was repeated with the remaining eye.

Calibration Study 1: Results

The first step in data analysis was performed using a computer-based DBA Systems PC Tracker model 626 eye tracking system at the Brooklyn College Infant Study Center. The tracker is a software/hardware configuration used to digitize videotaped data, an essential intermediate step in the analyses. A research assistant operated the tracker and a standard videocassette playback device cabled to it. Videotape playback resulted in delivery of video signals to the tracker. The tracker's "image grabber" used these signals to produce a corresponding image on the computer screen. The operator then marked the computer images in preparation for further tracker analysis; this was done by moving the computer's pointer to the image of the pupil.

Threshold parameters were set as appropriate, e.g., black-on-white versus white-on-black polarity, the ratio(s) of image-to-background contrast, the size and shape of a frame surrounding the image(s) to be tracked, whether or not tracking was to be done automatically (exclusively by the tracker) or at times manually by the tracker's operator, and the region(s) of the computer screen within which to track the particular image(s).

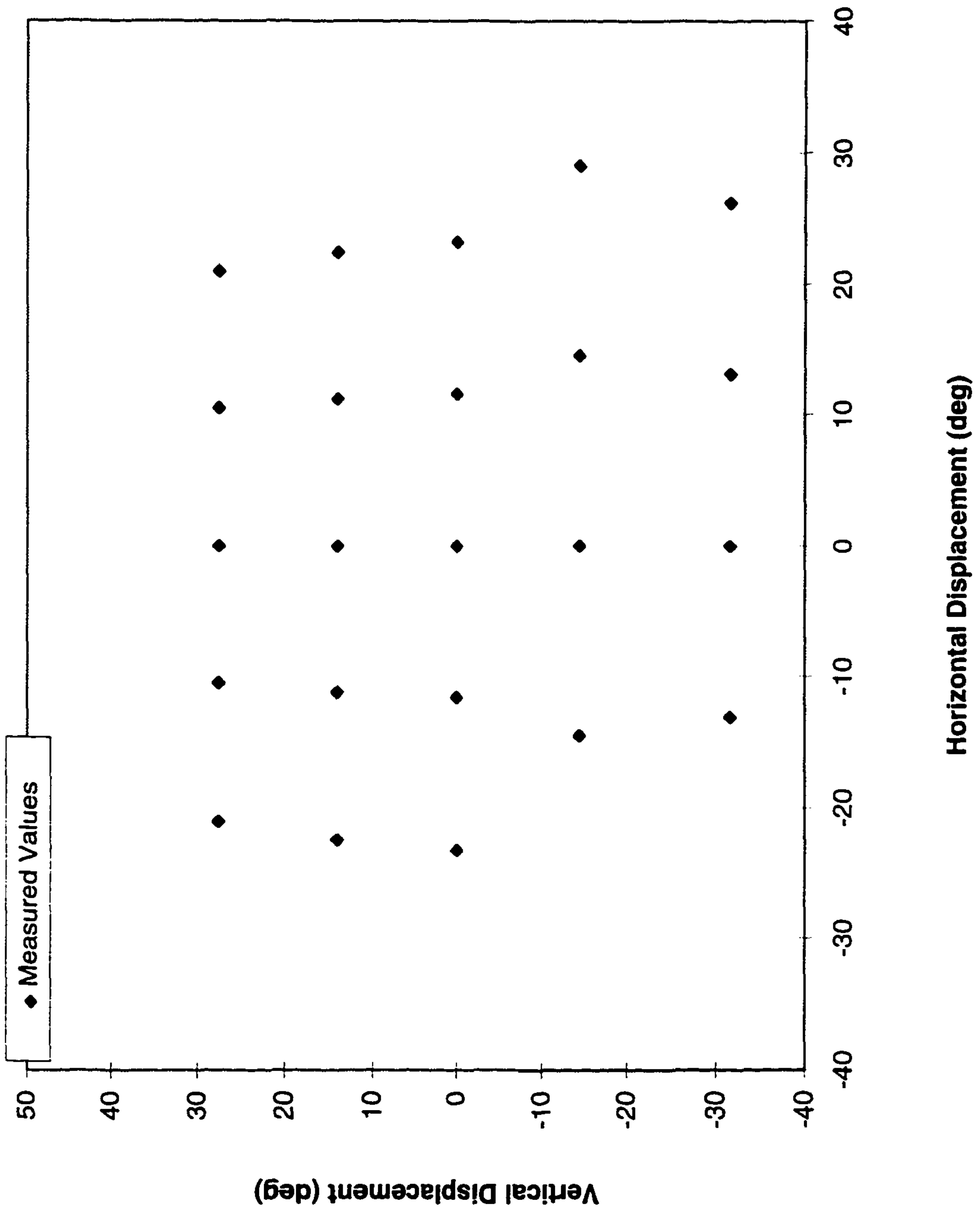
Once the pupil was indicated, the tracker "evaluated" the eye movements such that any displacements were digitized in relation to a coordinate grid pattern on which the image was arbitrarily superimposed. Tracker output included such factors as time elapsed, instances of tracker error, and vertical and horizontal displacement of the eyes. All tracker output was saved on computer diskettes in the form of "tracker collection files.". These were used to produce "text" files for subsequent analyses employing Microsoft Excel spreadsheet software.

Calibration data were examined to evaluate relevant characteristics of tracker output; the approaches used are detailed below following a description of necessary alterations made to tracker data. One aim of calibration analyses was to determine what mathematical function(s) would appropriately describe tracker digitization of horizontal and vertical eye displacements. This was because the relationship between tracker units and actual eye movements in the vertical or horizontal dimension can in theory be linear, geometric, parabolic, etc. Analyses were needed also to determine the scale(s) of horizontal and vertical tracker displacements in relation to degrees of visual angle. For example, a vertical eye displacement may be represented as smaller than a horizontal one of the same magnitude, or vice versa. In such a case, separate conversion factors for vertical and horizontal tracker unit components must be calculated to convert each to corresponding components of degrees of visual angle. The "degree of visual angle" unit is desirable for comparative purposes, since "point of regard," i.e., where an eye is pointing, is most often quantified using this measure. To analyze calibration and subsequent experimental data according to convention, therefore, comparisons had to be made between values measured in degrees of visual angle and those generated by the eye tracker.

To quantify locations of targets in the eye movement laboratory, measurements were made of inter-target distances and distances between the targets and the location of the participant. The average distances between targets located on each row and column were then obtained. Trigonometric calculations were made using these averages to yield the measured values, i.e., the average number of degrees of visual field eccentricity for targets in each row and column.

A plot of the measured values was produced by varying horizontal displacement of eye position on the horizontal axis, and vertical displacement on the vertical axis; the units marking off both axes are degrees of visual angle (see Figure 1).

Figure 1. Measured values for Calibration Study 1.

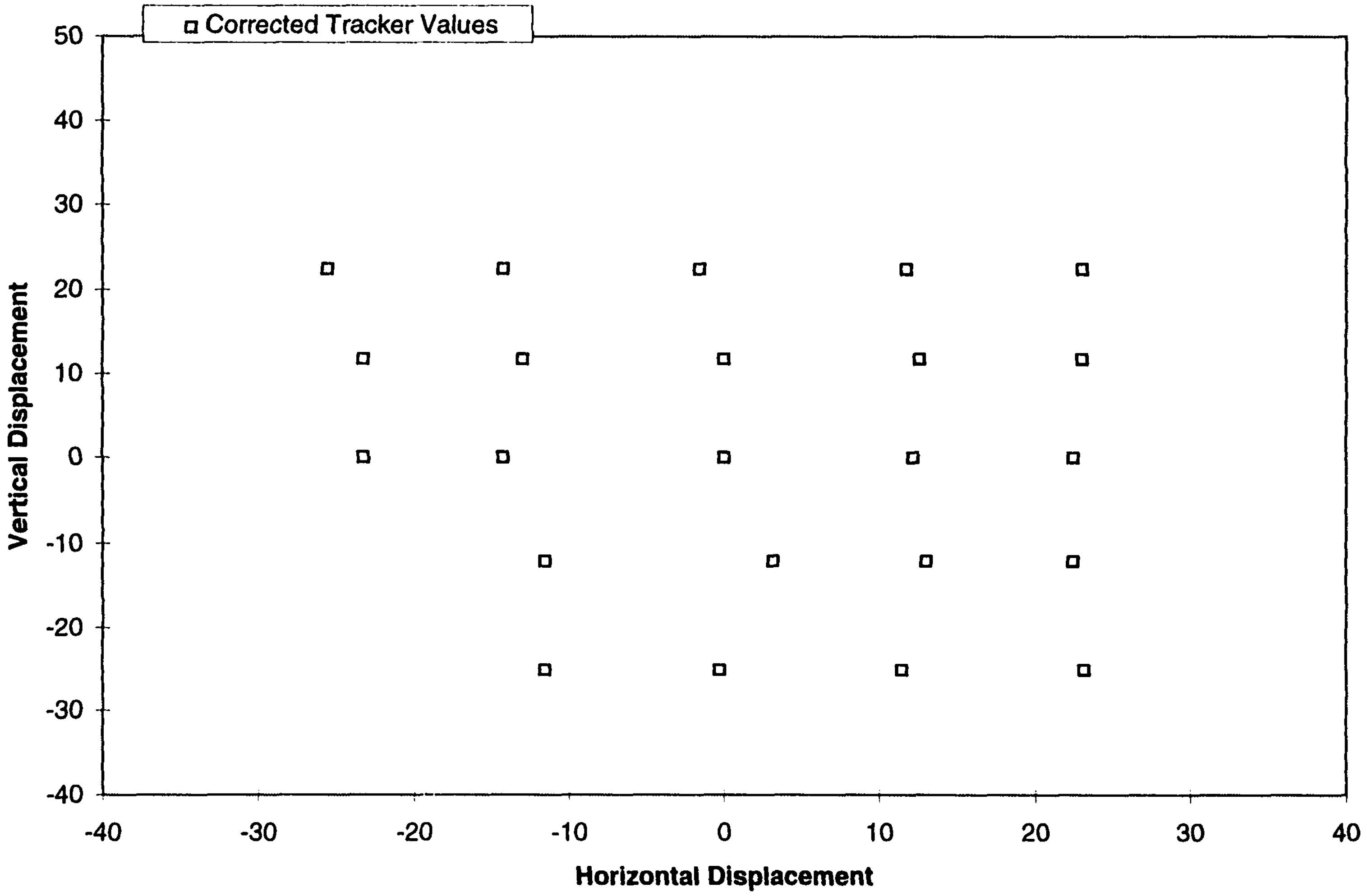

◆ Measured Values
Vertical Displacement (deg)
50
40
30
20
10
0
-10
-20
-30
-40
Horizontal Displacement (deg)
-40
-30
-20
-10
0
10
20
30
40

tracker values were next calculated for each target location. Figure 2 shows the mean points of regard, in vertical versus horizontal tracker units.

To plot tracker units for purposes of calibration analyses, it was necessary to determine, within each tracked eye movement calibration record, where an undisplaced eye was represented within the arbitrary coordinate system created by the tracker. Of the four participants recorded, seven monocular records were useable and analyzed. Each dataset contained monocular eye movement information; these were imported into separate spreadsheets in preparation for graphing and subsequent statistical analysis.

It was reasoned that a "straight ahead" fixation involves little or no change in eye position, and that therefore tracker-generated representations of such fixations could be "set" to 0,0 on a polar plot. "Straight ahead" fixations were identified by several research assistants' performing visual inspection of graphs of tracked calibration data. These graphs showed vertical or horizontal eye position versus time (and contained multiple instances of "straight ahead" fixations). Averages were obtained of any non-zero horizontal or vertical displacements for all of the "straight ahead" fixations within each set of tracked calibration data. This yielded an average horizontal and vertical offset for each dataset. The average offsets were added or subtracted as needed to all tracker-generated eye position values within a dataset. The effect of these manipulations was to "correct" the representations of straight ahead fixations and to shift each overall pattern commensurately (without altering it in any other way). The corrected tracker values were graphed to show points of regard (in vertical versus horizontal tracker units); this

Figure 2. Corrected tracker values for Calibration Study 1.


□ Corrected Tracker Values
Vertical Displacement
50
40
30
20
10
0
-10
-20
-30
-40
Horizontal Displacement
-40
-30
-20
-10
0
10
20
30
40

corrections procedure forced the points representing each participant's "straight ahead" fixations to superimpose upon one another at or near the origin. Means of the corrected Analyses described to this point produced two polar plots, one of "measured values" (of targets in the laboratory)and the other of "mean corrected tracker values" (of tracker-generated representations of fixations upon these targets); each plot possessed its own set of axes. These two types of polar plots were superimposed upon one another and compared (see Figure 3). Inspection of the resulting figure revealed good overall correspondence between the patterns of measured and corrected tracker values. Disparities between the superimposed plots were sufficient, however, to prompt further (statistical) evaluation. A number of statistical comparisons therefore were made between corrected tracker units and measured values. To reiterate, this was done with two calibration analysis goals in mind. First the purpose was to find the mathematical function or functions which best described tracker digitization of video signals depicting vertical and horizontal eye movement. Second it was to pinpoint whether and how the horizontal and/or vertical component of a tracker unit would need to be altered for ultimate conversion to degrees of visual angle. Analyses of calibration study 1 data showed that the tracker performed nearly linearly in both the horizontal and vertical directions. This was determined by graphing the group mean corrected tracker data versus the measured values (Figures 4 and 5), by use of "r," the Pearson product-moment correlation coefficient, and by linear regression analyses. Correlation coefficients, shown in Table 1, were calculated to further quantify corrected tracker units in relation to measured values, both for horizontal and for vertical eye displacement. The graphs of

Figure 3. Measured and corrected tracker values for Calibration Study 1.

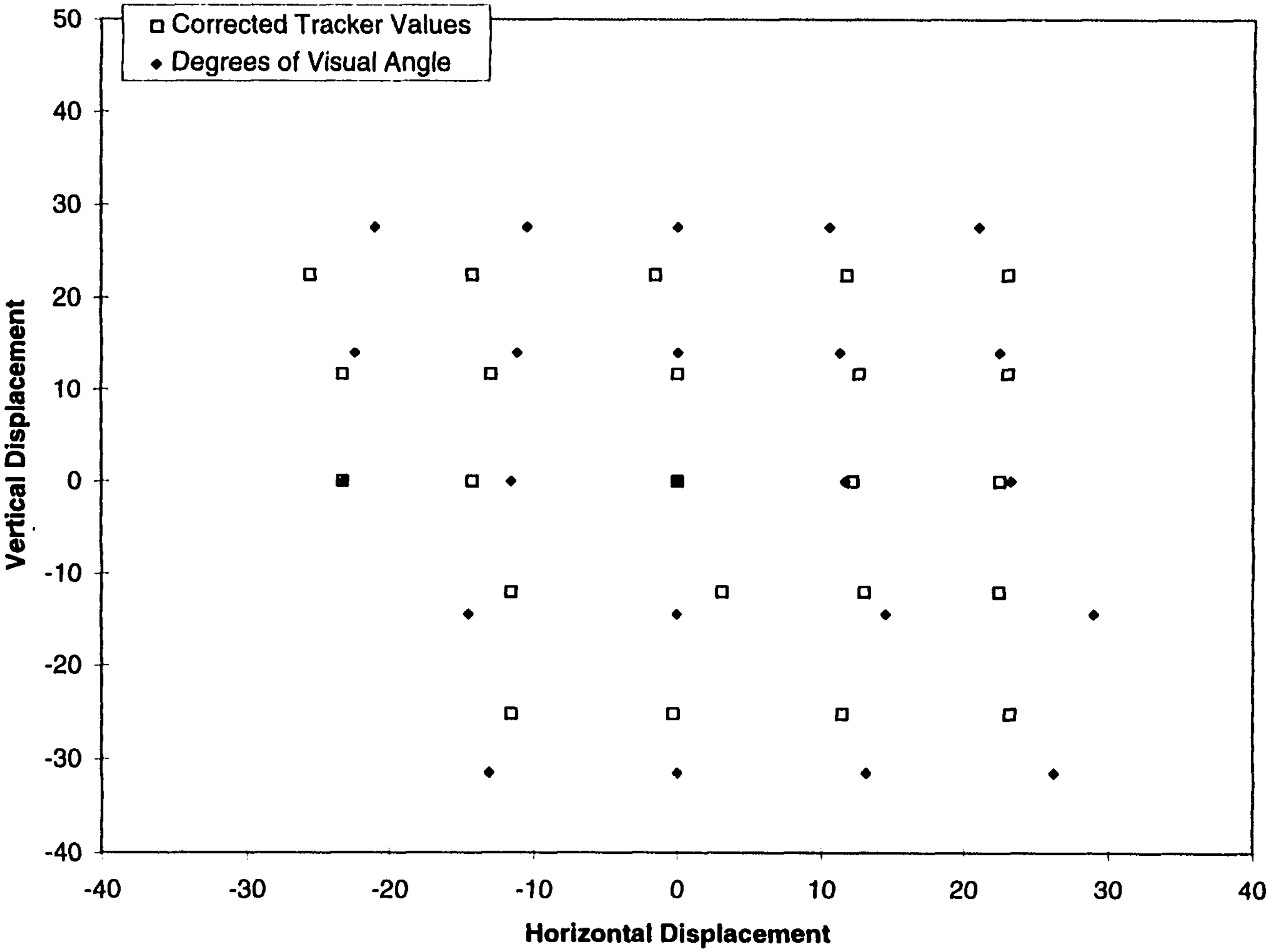

□ Corrected Tracker Values
◆ Degrees of Visual Angle
Vertical Displacement
50
40
30
20
10
0
-10
-20
-30
-40
Horizontal Displacement
-40
-30
-20
-10
0
10
20
30
40

Figure 4. Regression of group corrected tracker vertical values as a function of measured vertical values for Calibration Study 1.

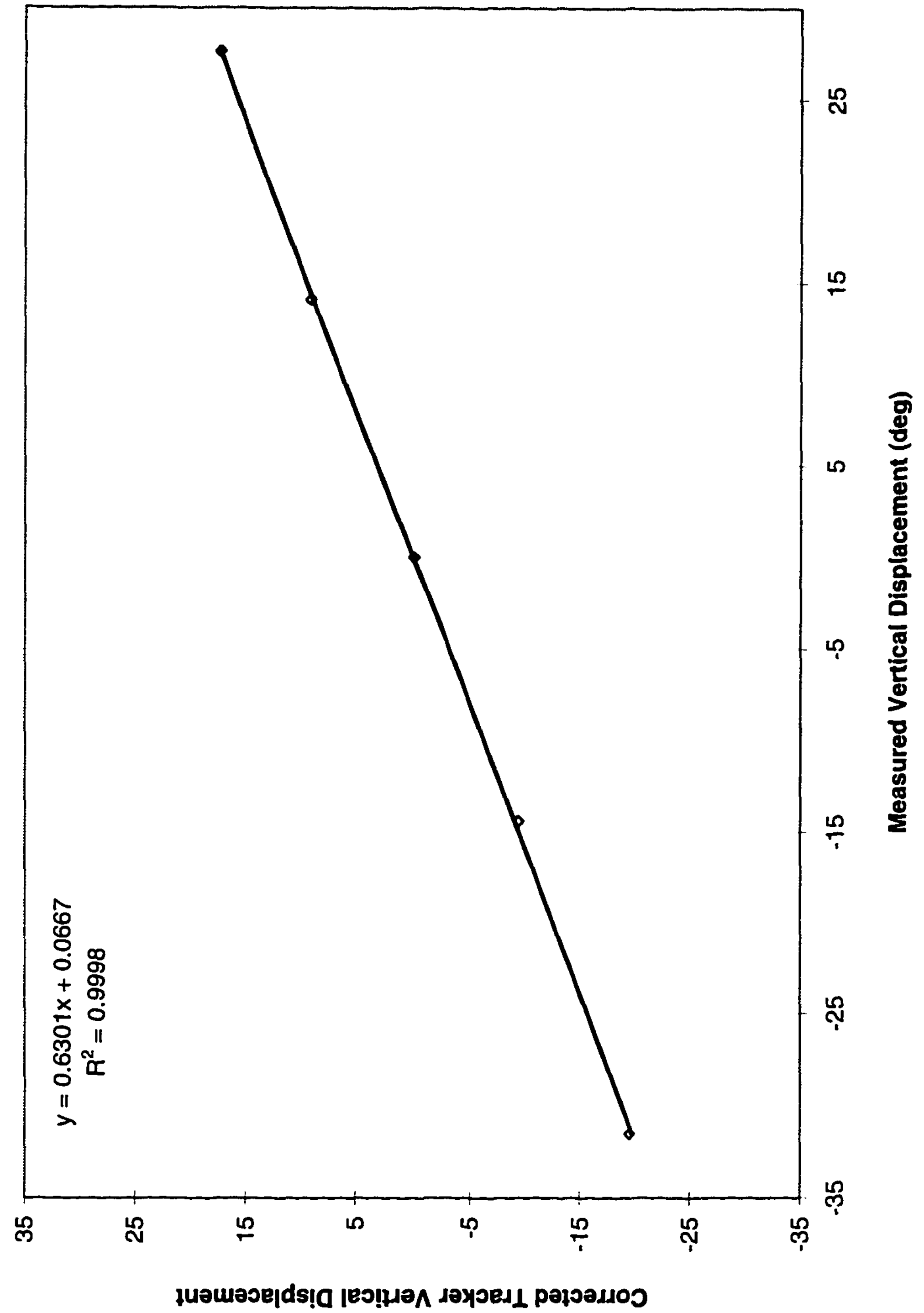
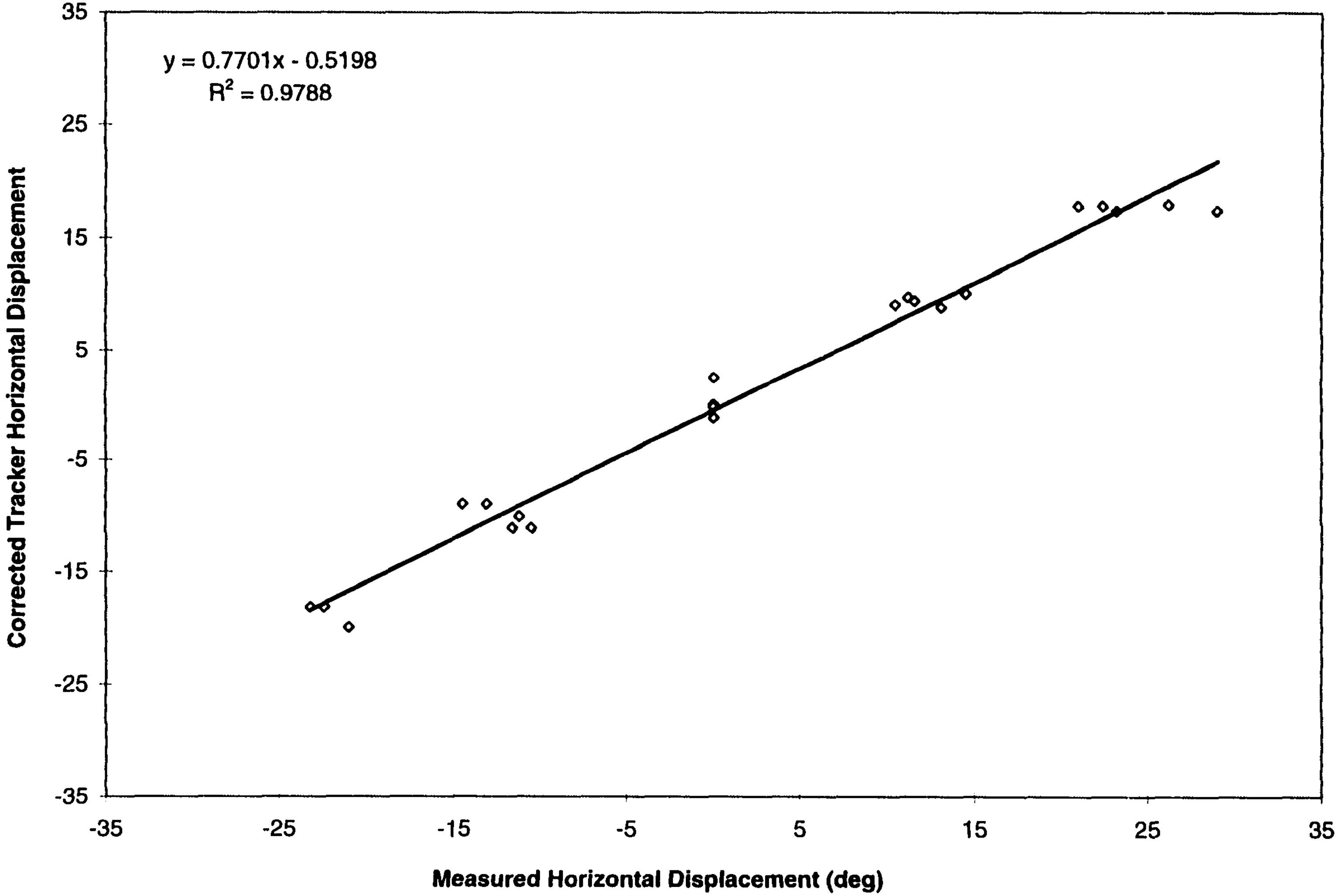

y = 0.6301x + 0.0667
R^2 = 0.9998
Corrected Tracker Vertical Displacement
Measured Vertical Displacement (deg)
35
25
15
5
-5
-15
-25
-35

Figure 5. Regression of group corrected tracker horizontal values as a function of measured horizontal values for Calibration Study 1.


y = 0.7701x - 0.5198
R² = 0.9788
Corrected Tracker Horizontal Displacement
35
25
15
5
-5
-15
-25
-35
-35
-25
-15
-5
5
15
25
35
Measured Horizontal Displacement (deg)

vertical and horizontal displacements were plotted with measured values on the x axis and corrected tracker units on the y, bearing in mind that fitting a regression line to this set of plotted points ideally would produce a straight line with a slope of one and a Y-intercept of zero (see Figures 4 and 5 and Table 1). To compensate for the lack of within-subject independence of right versus left eye data, each participant's right and left eye data next was averaged to obtain an adjusted r. Thereafter group means of averaged r's were calculated. As shown in Table 2, mean r for the group's averaged horizontal displacement = .97; mean r for the group's averaged vertical displacement = 1. For each of the grouped sets of individuals' averaged data, R^2 was calculated and the following results obtained; the slope of the regression line fit to the group averaged horizontal displacement data was .98, with a Y-intercept of -.73, while the slope of the regression line fit to the group averaged vertical displacement data was .82, with a Y-intercept of -.05.

The graphs depicting the fit of the regression lines plotted here underscore the linearity and low variability inherent to how the tracker digitized eye displacement in both the vertical and horizontal directions. As anticipated, small absolute values were obtained for Y-intercepts; this was in part due to the tracker values' having been corrected so that "straight ahead" would fall at or near zero. The slopes, however, show that tracker values "underestimate" degrees of visual angle. This was more the case for the vertical than for the horizontal tracker component. Evaluating the size difference statistically, a two-tailed t test for matched pairs yielded a significant difference- $t(3) = 3.19$, $p < .05$ (see Table 2). Ordinarily the next step would be to convert tracker units to degrees of visual angle either by calculating separate conversion factors as discussed above or by "scaling" one tracker

Table 1

Individual and Group Pearson r Values, Regression Line Slopes and Y-intercepts for Calibration Study 1

Participant Code	Horizontal Displacement			Vertical Displacement			Difference between slopes
	Pearson r	Slope	Intercept	Pearson r	Slope	Intercept	
GHCALD_L	0.98	0.93	-1.19	1.00	0.89	-1.01	0.04
JGCALD_R	0.98	1.05	0.83	1.00	0.85	-0.44	0.20
JGCALD_L	0.99	0.85	2.64	1.00	0.74	-0.36	0.12
TCCALD_R	0.97	1.02	-4.23	1.00	0.78	-0.72	0.24
TCCALD_L	0.95	1.04	0.98	0.99	0.80	2.44	0.24
TRCALD_R	0.97	0.98	-5.30	1.00	0.84	-0.13	0.14
TRCALD_L	0.98	1.05	1.60	1.00	0.77	0.82	0.28
Mean	0.97	0.99	-0.67	1.00	0.81	0.09	0.18
SD							0.09
SEM							0.03

Note. Slope means differ significantly at $p < .01$ by the two-tailed t-test for matched pairs ($t(6) = 5.17$).

Table 2

Individual Averaged and Group Pearson r Values, Regression Line Slopes and Y-intercepts for Calibration Study 1

Participant Code	Horizontal Displacement			Vertical Displacement			Difference between slopes
	Pearson r	Slope	Intercept	Pearson r	Slope	Intercept	
GHCALD_L	0.98	0.93	-1.19	1.00	0.89	-1.01	0.04
JGCALD AVERAGE	0.98	0.95	1.74	1.00	0.79	-0.40	0.16
TCCALD AVERAGE	0.96	1.03	-1.63	1.00	0.79	0.86	0.24
TRCALD AVERAGE	0.98	1.02	-1.85	1.00	0.81	0.35	0.21
Mean	0.97	0.98	-0.73	1.00	0.82	-0.05	0.16
SD							0.09
SEM							0.05

Note. Slope means differ significantly at $p < .05$ by the two-tailed t-test for matched pairs ($t(3) = 3.19$).

unit component appropriately to match the other prior to computing a single conversion factor. The difference in the size of the tracker unit's horizontal versus vertical component therefore was isolated by calculating the ratio of the slopes of the group averaged horizontal to vertical displacement, i.e., .98 divided by .82 equals 1.2. This indicated that the vertical component would need to be scaled up by 20% to match the size of the horizontal component, before tracker units could be converted to degrees of visual angle. At that point this process was suspended because overall these analyses highlighted the shortcomings of the available calibration data, namely the lack of measured and tracker data from eye movements spanning more of the horizontal and vertical oculomotor range. A second calibration study was therefore undertaken prior to calculating the tracker unit-to-degrees of visual angle conversion factor(s) to be applied to experimental data.

Calibration Study 2

Calibration Study 2: Subjects

Four adult volunteers took part; all had uncorrected 20/20 Snellen visual acuity or better in each eye (evaluated as described above) and were assumed to have normal peripheral vision.

Calibration Study 2: Apparatus

Placement of eye movement recording and visual acuity assessment equipment was as described for the first calibration study. A Radio Shack infrared light emitting diode (LED) number 276-143c was attached to the headrest within the upper left corner of the camera's field of view. The infrared LED (used to create timing marks) was switched on and off using an Alpha-bus interface (Alpha Corporation) model MB-120 wired between the LED and a Compusight (IBM clone) 80386 desktop computer. The computer controlled stimulus delivery including instructions, contained within text files, and beep tones used to signal the participant to respond. Instructions were delivered via G. W. Micro Inc. Vocal Eyes version 2.2 speech output software driving a DECTALK version 4.0 voice synthesizer housed in a Xerox Imaging Systems Reading Edge reading machine model 7315-60, cabled to the computer. The speech software alternated with software triggering the beeps and accompanying infrared LED flashes. The computer was located so that its internal speaker, which produced the beeps, was directly behind the camera. Upon the computer (thus also directly behind the camera) sat an external Radio Shack speaker, number 32- 2040; this was wired to the reading machine and was therefore where the instructions were heard to be coming from.

Eight visual targets were mounted on a square frame located in the vertical plane 15 cm from the participant's eyes. This preserved an unobstructed view of the camera along the participant-to-camera axis. Each target was produced by drawing a dot in the center of a small square of paper measuring 4.1 by 5.2 cm. The diameter of each dot measured 0.3 cm. Targets were placed individually for each participant, with the intention of eliciting fixations at his/her extremes and midpoints of vertical and horizontal oculomotor range.

Locations for the upper-, lower-, left- and right-most targets were established first. Their placement was based on feedback from the participant, who was asked to focus on the dot as the target was being moved along the surface of the frame "out of range" vertically or horizontally. Each target was affixed just short of where the individual indicated that its dot could no longer be seen clearly. It was emphasized that a clear image of the dot be maintained, to ensure center-of-gaze fixations.

Measurements were made of the locations of these targets; then the half angles of the four angles formed between the dots and the participant-to-camera axis were calculated. Four additional "midway" targets were placed on the frame based on the half angle calculations, such that the "line of sight" to the midway targets in each instance bisected the original angle.

Calibration Study 2: Procedures

As has been described for the first calibration study, participants were met at the laboratory, briefed about the research, and signed informed consent was obtained. Visual acuity was assessed, and in the laboratory used for eye movement recording participants were seated comfortably and familiarized with the forehead/chin rest. The camera was focused and participant codes were created and videotaped.

The participant was then asked to relax and listen to an example of the instruction set and corresponding signal tones used in the eye movement study (see Appendix B). The speaker volume was adjusted if required and the demonstration session was terminated once the participant had indicated that stimuli were audible and comprehensible. Next the entire stimulus set was described. This is presented in detail below, but briefly the "directional" instructions were intended to elicit responses consisting of attempts to achieve extremes and midpoints of the vertical and horizontal oculomotor range. The other requests were intended to elicit primary position and two variations of convergence.

The participant was asked not to close his/her eyes, swallow, speak or make any sounds or move his/her head during recording. In addition participants were requested to gently hold the upper eyelid(s) open when producing downward gazes. Eye movements made in response to the stimuli were first recorded monocularly with the right eye, then with the left eye, and finally binocularly.

Calibration Study 2: Results

Videotapes were digitized using the eye tracker described above. In addition to tracking one pupil, the tracker was set to track the light flashes made by the infrared LED. This required the research assistant to indicate the region of the image occupied by the LED; notably also it involved choice of a high contrast threshold setting in order for the flashes, some of which were quite faint, to be detected. As was done in the first calibration study, computer "text files" were produced from the digitized "tracker collection files," then each was copied into a computer spreadsheet. Each spreadsheet contained one participant's eye movement data for either the right or left eye.

A template spreadsheet was next created to modify these monocular datasets. Modifications within the template included deletion of tracker artifacts, and production of graphs showing eye movement data and stimulus timing marks (i.e., LED flashes). The timing marks were produced within 263 +/- 17 milliseconds (ms) following each beep tone stimulus. As distinguished from the previous calibration study, curves representing the eye's vertical and horizontal displacement over time were displayed on a single graph. A research assistant inspected these template-generated unmodified graphs as they appeared on the computer screen. The assistant added or subtracted a constant as needed to each set of tracker values (vertical and horizontal) to set the pattern of straight ahead gazes as close to zero as possible in relation to the vertical axis. This provided tracker values for the straight ahead gazes and for the extremes and midpoints of the vertical and horizontal eye movements. After each dataset was modified in this way it was moved out of the template into a new spreadsheet. New spreadsheets were thus created serially, each containing the newly modified monocular data.

The Pearson product-moment correlation coefficient, regression line, and Y-intercept were calculated (see Table 3) for each participant's measured versus tracker values (separate sets of measured values were needed since target locations varied among participants). As in calibration study 1, the lack of within-subject independence of right versus left eye data was compensated for. Each participant's right and left eye data were averaged to obtain an adjusted r, and means for the group's averaged r's were calculated (see Table 4). As before, results showed that the tracker performed nearly linearly in both the horizontal and vertical directions. Table 4 summarizes results of these analyses; group mean for individuals' averaged horizontal displacement $r = .96$, slope = .84, Y-intercept = -.76, and group mean for individuals' averaged vertical displacement $r = .98$, slope = .75, Y-intercept = .60. Consistent with the first calibration study, tracker units underestimated degrees of visual angle, to a greater extent in the case of the vertical than the horizontal component; a two-tailed t test for matched pairs yielded a difference which approached statistical significance- $t(3) = 2.44$, $p < .10$ (see Table 4). The ratio of the slopes of the group averaged horizontal to vertical displacement was calculated to gauge the relative sizes of the tracker horizontal versus vertical components, i.e., $.84/.75 = 1.12$.

It was decided that to convert tracker units to degrees of visual angle, the vertical and horizontal component slope values from both calibration studies would be considered. This was done in light of the consistent trend in size differences between the vertical versus horizontal tracker unit components across the two calibration studies. As is shown in Table 5, the following values utilizing all averaged and measured calibration data were

Table 3

Individual and Group Pearson r Values, Regression Line Slopes and Y-intercepts for Calibration Study 2

	Horizontal Displacement			Vertical Displacement			Difference
Participant Code	Pearson r	Slope	Intercept	Pearson r	Slope	Intercept	between slopes
AVCALR3	0.98	0.96	1.94	0.99	0.81	0.01	0.15
AVCALL3	0.99	0.98	-1.62	0.98	0.77	1.29	0.21
GWCALR	0.99	0.85	-0.62	0.99	0.77	1.14	0.08
GWCALR	0.96	0.71	-1.39	0.98	0.74	-1.26	-0.02
MBCALR2A	0.96	0.94	3.17	1.00	0.88	0.84	0.06
MBCALL2A	0.86	0.88	-5.93	0.99	0.81	0.80	0.07
WLCALR	0.99	0.74	0.71	0.90	0.53	1.69	0.21
WLCALL	0.95	0.66	-2.35	1.00	0.66	0.34	0.00
Mean	0.96	0.84	-0.76	0.98	0.75	0.60	0.09
SD							0.09
SEM							0.03

Note. Slope means differ significantly at $p < .05$ by the two-tailed t-test for matched pairs ($t(7) = 2.79$).

Table 4

Individual Averaged and Group Pearson r Values, Regression Line Slopes and Y-intercepts for Calibration Study 2

	Horizontal Displacement			Vertical Displacement			Difference between slopes
Participant Code	Pearson r	Slope	Intercept	Pearson r	Slope	Intercept	
AVCAL3 AVERAGE	0.99	0.97	0.16	0.99	0.79	0.65	0.18
GWCAL AVERAGE	0.97	0.78	-1.01	0.98	0.75	-0.06	0.03
MBCAL AVERAGE	0.91	0.91	-1.38	0.99	0.85	0.82	0.06
WLCAL AVERAGE	0.97	0.70	-0.82	0.95	0.59	1.01	0.10
Mean	0.96	0.84	-0.76	0.98	0.75	0.60	0.09
SD							0.07
SEM							0.04

Note. Slope means differ significantly at $p < .1$ by the two-tailed t-test for matched pairs ($t(3) = 2.44$).

Table 5

Combined Pearson r Values, Regression Line Slopes and Y-intercepts for Calibration Studies 1 and 2

	Horizontal Displacement			Vertical Displacement			Difference
Participant Code	Pearson r	Slope	Intercept	Pearson r	Slope	Intercept	between slopes
GHCALD_L	0.98	0.93	-1.19	1.00	0.89	-1.01	0.04
JGCALD AVERAGE	0.98	0.95	1.74	1.00	0.79	-0.40	0.16
TCCALD AVERAGE	0.96	1.03	-1.63	1.00	0.79	0.86	0.24
TRCALD AVERAGE	0.98	1.02	-1.85	1.00	0.81	0.35	0.21
AVCAL3 AVERAGE	0.99	0.97	0.16	0.99	0.79	0.65	0.18
GWCAL AVERAGE	0.97	0.78	-1.01	0.98	0.75	-0.06	0.03
MBCAL AVERAGE	0.91	0.91	-1.38	0.99	0.85	0.82	0.06
WLCAL AVERAGE	0.97	0.70	-0.82	0.95	0.59	1.01	0.10
Mean	0.97	0.91	-0.75	0.99	0.78	0.28	0.13
SD							0.08
SEM							0.03

Note. Slope means differ significantly at $p < .01$ by the two-tailed t-test for matched pairs ($t(7) = 4.17$).

therefore obtained: combined means for horizontal displacement Pearson r = .97, regression line slope = .91 and Y-intercept = -.75; combined mean vertical displacement Pearson r = .99, regression line slope = .78, and Y-intercept = .28. From these values the combined mean of the difference between the slopes was found to be .13, and a two-tailed t test for matched pairs was performed which yielded a highly significant difference- t(7) = 4.17, p < .01. Finally the reciprocals of the combined mean horizontal and vertical component slopes were calculated. Taken together, calibration studies 1 and 2 thus produced two conversion factors, i.e., 1.10 used to alter the tracker units representing horizontal displacements of the eye, and 1.28 to scale up tracker units representing vertical displacements. Calibration study 2 furthermore demonstrated that the tracker would not "saturate," i.e., cease functioning or yield erroneous values, when digitizing extreme pupillary excursions.

Eye Movement Experiment

Eye Movement Experiment: Subjects

Participants included adult volunteers with at least one eye. Sighted participants (N=14) had uncorrected 20/20 Snellen visual acuity or better in each eye (evaluated as described above) and were assumed to have normal peripheral vision.

Self-reported visual status of participants who were blind (N=35) was, in most cases, no better than light perception in either eye (see Table 6). Blind participants were classified either as congenitally blind (N=21) including those whose blindness preceded age 13, or adventitiously blind (N=10). Three individuals were classified as "mixed" with regard to visual experience: these were two bilaterally blind individuals and one individual with vision (20/20) in one eye only (i.e., monocularly blind). The remaining "blind" participant was partially sighted. Data from these participants were segregated for possible future consideration.

The congenitally blind, adventitiously blind, and sighted classifications employed in this research were used to organize data by group. Group assignments to the congenitally and adventitiously blind categories were made using the criteria set forth above, based on the self-reported visual history provided using a brief questionnaire (see "eye movement experiment procedures" section below; see also Appendix C). One participant (CAC1) was assigned to the congenitally blind group despite his having more than thirteen years of visual experience. due to the reported quality of the vision experienced prior to total blindness (extremely limited visual fields). Several factors contributed to the selection of self-report as the format used to obtain participant visual history. Self-report has been used previously in research to gather such information from blind participants (e.g., Sherman, 1985). It may be considered a useful, reliable and valid research tool particularly when used with blind participants. Reasons for this include that such information is commonly solicited from blind individuals in the course of daily life (e.g.,

TABLE 6. Participant information.

Code	Age	Sex	Years blind	Years vision	Snellen Acuity Right Eye	Snellen Acuity Left Eye	Vision History
APM1	40	M	15	25	N/A	N/A	Bilaterally very good childhood visual acuity in day light, poor night vision. Drove until early 20's. Gradual contrast loss led to cane use in mid-20's, but signs could still be read. Retains LP. OS may have 1% residual vision..
ABR1	49	M	2	47	N/A	N/A	OD, near-total vision loss in 1994 from glaucoma. Retains hand motion, form perception. Diagnosed with 5% residual vision. OS, total vision loss in 1987 from glaucoma.
ADS1	34	F	19	15	N/A	N/A	Bilateral 20/20 vision birth through May 1977. Blindness = optic nerve damage from meningitis. Vision was lost within 1 week. Transient LP at onset of bright indoor illumination. Strobe lights perceived as such.
ARC1	63	M	9	54	N/A	N/A	Bilaterally, age 22 = difficulty seeing at night; Age 30 = RP diagnosis; Early 40's = gradual loss of peripheral vision; Early 50's = beginning of central vision loss; 2/1987 = no residual vision.
AWW1	58	M	45	13	N/A	N/A	Blind bilaterally, cause unknown, possible infection. No visual impairment infancy-childhood. Acuity and color vision deteriorated starting age 10-11. Rapid deterioration after 13. Residual transient LP.
AYK1	42	M	23	19	N/A	N/A	Bilaterally, stable high partial vision birth-age 15; eyes "shake". No color vision? Glare problematic. Slow light/dark adaptation. Childhood/adolescent could read/ride a bike. Age 15-19 = rapid vision deterioration. Retinal degeneration. Residual transient LP.
ACC1	76	M	11	65	N/A	N/A	Bilaterally, vision loss from glaucoma began age 37. Total blindness in 1975; OS 12 months prior to OD. No LP.
ABC1	38	F	17	21	N/A	N/A	Bilateral 20/20 vision until early adulthood. Surgery (monocular?) at age 4 to correct crossed eyes. Diabetic retinopathy led to legal blindness during sophomore year of college. Laser treatment for 7 months. Total blindness in 1979.
ABH1	58	M	19	39	N/A	N/A	Juvenile diabetes at age 5 led to onset of bilateral diabetic retinopathy and consequent blindness in 1976.
AOR1	38	M	10	28	N/A	N/A	Bilateral myopia from birth. Age 14 = corrective surgery, led to scarring followed by glaucoma; blindness = 1985. OD, capsulitis = 1994. OS, retinal detachment = 1993.
CEL1	66	M	66	0	N/A	N/A	Bilateral atrophy of the optic nerve at birth.
CPD1	44	F	44	0	N/A	N/A	Bilateral ROP at birth. Born 2 months premature, received oxygen. Childhood LP, extended into adolescence/early adulthood. Adult diagnosis of glaucoma and cataract.
CJW1	52	F	49	3	N/A	N/A	Born two months premature. Bilaterally could count birthday cake candles = age 2-3, and identify objects in magazine pictures. LP retained until age 6-7. Bilateral?

CSM1	50	M	50	0	N/A	N/A	Bilateral ROP, born two months premature. OD, never any vision. OS, tiny bit of LP, stable throughout life. Sees the odd shadow, nothing substantial.
CPA1	39	M	39	0	N/A	N/A	Bilaterally blind from birth, cause unknown, no LP.
CJD1	28	M	19	9	N/A	N/A	Bilateral retinoblastoma at birth. OD, various surgeries, including cataract removal at age 9. Self-reported Snellen acuity of 20/400 peripherally, less centrally. OS, enucleation at age of 2.
CAS1	43	F	43	0	N/A	N/A	Bilateral ROP, blind from birth, never any LP.
CWM2	42	F	34	8	N/A	N/A	Bilateral congenital exudative vitreo retinopathy; pre-age 8 = partial vision, good color vision, read large print, independent mobility. Age 8 = sudden vision loss (blood vessel burst). 8-25 = LP. Lost LP gradually: cataracts.
CJC1	53	F	53	0	N/A	N/A	Bilateral Leber's congenital amaurosis, keratoconus, optic nerve atrophy. Cataract surgery in 1953= 3 surgeries within 3 weeks. LP.
CJD2	57	F	47	10	N/A	N/A	Bilateral retinal detachment. Normal vision before 1 year. Trauma age 1. Pre-age 10.5, color and form perception, unable to read, independent mobility. OD, retains LP. 1949 = unsuccessful corrective surgery. OS, vision lost age 5-6.
CVZ1	33	F	30	3	N/A	N/A	Bilateral congenital glaucoma. High partial vision until age 3. Totally blind since age 3.
CCL1	45	M	45	0	N/A	N/A	Bilateral ROP. Blind from birth. Also had glaucoma.
CKE1	52	F	52	0	N/A	N/A	Bilaterally blind from age 6 months. Cause unknown, but ophthalmologist believed that "eyes were misshapen; there was lack of connection."
CKG1	48	F	45	3	N/A	N/A	Bilateral congenital glaucoma and cataracts. Limited vision until age 26.
CMV1	57	F	57	0	N/A	N/A	Bilateral, origin unknown. Possible optic nerve damage/macular derangement/pigmental deterioration. Childhood color and movement detection, peripherally only. Adult LP, occasional movement detection. No childhood or adult form perception.
CAC1	42	M	24	18	N/A	N/A	Bilateral retinitis pigmentosa. Birth to 18 years = 10 degrees of visual field; 20/70 Snellen acuity. Good depth and color perception. Recalls producing head movements to compensate for lack of peripheral vision. Residual vision lost age 18 - 35.
CBG1	43	M	43	0	N/A	N/A	Bilateral ROP. Blind from birth.
CRW1	36	M	25	11	N/A	N/A	Bilateral congenital glaucoma OD, no vision. OS, childhood ability to read large print, ride bicycle, see colors, shapes and motion. Could not play ball or walk alone outdoors. Vision deteriorated age 11-18. No LP in adulthood.
CEB1	71	F	71	0	N/A	N/A	Bilaterally blind from birth, cause unknown.
CWM1	41	M	41	0	N/A	N/A	Bilateral ROP. Vision lost within first 3 months in the incubator.
CPL1	47	F	47	0	N/A	N/A	Bilateral ROP, blind from birth. Perception of shadows, <0.5 meters. Vision-dependent mobility = childhood.
SKD1	20	F	0	20	20/12.5	20/12.5	N/A
SRN1	25	F	0	25	20/16	20/16	N/A

STC1	33	F	0	33	20/12.5	20/25	N/A
SWL1	22	M	0	22	20/12.5	20/20	N/A
SRP1	48	M	0	48	20/20	20/20	Bilateral astigmatism college + graduate school, wore glasses, condition improved.
SGP1	33	M	0	33	20/20	20/16	Wore glasses as a child (4-11) to correct alignment problem.
SGW1	25	F	0	25	20/12.5	20/12.5	N/A
SAV1	27	M	0	27	20/12.5	20/12.5	N/A
SPB1	34	M	0	34	20/20	20/12.5	Possible bilateral strabismus in 1968-69.
SHD1	24	M	0	24	20/16	20/20	N/A
SMB1	45	M	0	45	20/20	20/16	N/A
SKB1	25	M	0	25	20/12.5	20/16	N/A
SNH1	32	F	0	32	20/12.5	20/16	N/A
SRS1	33	M	0	33	20/12.5	20/12.5	N/A
PVY1	38	F	0	38	N/A	N/A	Bilateral vision impairment since birth, cause unknown. Possible in utero influenza exposure/1st trimester. Self-reported visual acuity: 20/400. Unable to read print. Can distinguish black/white contrast, shape outlines; good form perception. No color vision.
XAM1	47	M	0	47	20/12.5	N/A	OD, N/A OS, vision lost day after 13th birthday (1962). Cause undisclosed.
XPV1	53	M			N/A	N/A	
XEH1	33	F	15	18	N/A	N/A	Bilateral congenital spherical retinal coloboma. OS, microophthalmic, amblyopic; childhood perception of hand motion. Retains LP? OD, high partial vision into adolescence, could read small print, play softball, ride bike/had good color vision. Age 13-18, vision deteriorated, retinal changes? Cataract formed about age 21. Retains LP.

Key: OD, right eye; OS, left eye; LP, light perception; ROP, retinopathy of prematurity.

in the form of such questions as "What happened to you?" or "Were you born blind?"), so the response typically is well-rehearsed and straightforward. In many cases the history itself is quite simple, so most blind adults may be expected to provide visual history information acceptably accurately and in sufficient detail. This approach was adopted furthermore because it would have been infeasible to attempt to obtain past medical records, or to arrange for a clinician to produce present or retrospective assessments of ocular/visual system conditions.

Eye Movement Experiment: Apparatus

Placement of eye movement recording and visual acuity assessment equipment was the same as for the second calibration study. Light (for the camera) came from two Kodak Wratten darkroom lamps model A. The lights were placed at eye level at a 45 degree angle to the participant in a vertical plane 30 cm from the participant's eyes and 25 cm to either side of the participant-to-camera axis. A 15 watt incandescent light bulb was used in each, covered by a Kodak Wratten Safelight model 11 circular infrared filter (filtering out all but the infrared illumination). Sound was recorded onto videotape during eye movement stimulus delivery via an American Printing House for the Blind-modified General Electric desktop audiotape recorder model 3-5194A cabled to the VCR.

Eye Movement Experiment: Procedures

Individuals were contacted either by word-of-mouth or letter. One individual was included from among a few who responded to a mass mailing (85) of a participant recruitment letter supplied in print, Braille and audiotape. The mailing had been prepared based on a list of The Lighthouse Inc. consumers approved for such contact.

As has been described for the calibration studies, each participant came to the laboratory, was briefed about the research, and signed informed consent was obtained (the form was read aloud by a research assistant in the case of each blind participant).

Sighted participants' visual acuity next was assessed as has been described. Ensuing procedures were identical for all participants. Each was seated in the laboratory used for eye movement recording; the door was closed and black felt was placed at its base to prevent entry of light. Other potential light sources had been occluded previously.

All participants responded to a brief questionnaire (see Appendix C), administered verbally by the research assistant. Items pertained to past and present visual and medical history, date of birth, and sex (after the eye movement recording, see below, participant comments and responses to a follow-up question were added). At times the experimenter requested that the participant clarify or expand upon particular responses, which were entered into a computer by the research assistant. Information provided was then reviewed for accuracy and revisions were retained. Participant codes then were created and videotaped. In preparation for eye movement data collection, each participant was seated comfortably and familiarized with the forehead/chin rest. Room illumination was turned off briefly while the research assistant focused the camera (base on the video image of the participant's eyes).

As in the second calibration study, each participant was then asked to relax and listen to an example of the instructions used to elicit eye movements. The speaker volume was adjusted if required and the demonstration session was terminated once the participant had indicated that stimuli were audible and comprehensible. This was followed by a description of the stimulus set. The participant was asked not to close his/her eyes, blink, swallow, speak or make any sounds or move his/her head during recording, and was requested to signal (by tapping) if for any reason he/she wished to terminate eye movement recording once it had begun.

Room lights and all computer monitors were turned off and eye movement data collection proceeded. The purpose of minimizing illumination was to prevent sighted participants' producing visually guided eye movements.

Each participant was presented with a trial block of 21 eye movement requests. That is, in each trial the participant was asked to direct his/her gaze according to a specific instruction (see Appendix B). Eight "directional" instructions were intended to elicit responses consisting of attempts to achieve extremes and midpoints of the vertical and horizontal oculomotor range (midpoints were requested in order to later compare scaling of eye excursions). The other requests were intended to elicit an approximation of primary position and two variations of convergence; these were ("when you hear the beep") "look straight ahead," "pretend to look at the spot between your eyes," and "pretend to look at the spot halfway between your eyes," respectively. The "Look straight ahead" request, presented eleven times within the trial block, was always the first and last eye movement instruction presented, and was alternated between all other requests. Whenever a directional request was made, it was followed by a "straight ahead" request, then by its corresponding "halfway" instruction. The presentation sequence of these up, down, left and right directional subsets of requests were varied across group (although unequal sample sizes and technical problems resulted in imperfect counterbalancing). The final subset of all variations of the instruction set contained the two "extreme" and "halfway" convergence requests.

A beep was used to signal the participant to begin the requested eye movement. The signal to begin moving the eyes was a beep, rather than a word, such as "now," because using a word would have imposed an additional auditory (in this case linguistic) processing demand (along with the existing auditory demand to respond to the instruction precisely when the cue was given).

All sessions ended by noting the participant's comments and his/her subjective evaluation of oculomotor control during taping.

Eye Movement Experiment: Results

Videotapes of eye movements and accompanying LED flashes were tracked using the tracker already described. As with calibration data, the digitized "tracker collection files" were used to create "text files." Computer spreadsheet software was used thereafter to manipulate and analyze the experimental eye movement data. Each spreadsheet contained one participant's eye movement data for the right eye. Text files containing left eye data were removed from the dataset (to restrict it to manageable size) and were preserved for possible future consideration. Eye movement records from three of the participants classified as congenitally blind (i.e., approximately 14%) were not sufficiently "trackable" and were therefore not analyzed beyond this point. Factors responsible for an inability to track such data included gross image instability and/or the lack of a discernible pupil e.g., arising from eye abnormality or because eyelid droop obscured the pupil. A few other datasets (from the groups of participants classified as sighted or congenitally blind) became corrupted and had to be excluded during various phases of the analyses. For two of the congenitally blind participants, this was because the LED timing light had been (inadvertently) repositioned slightly, contaminating the videotaped data with spurious artifacts. In the remaining cases exclusion arose based on transcription errors made by research assistants. The following group sizes resulted after all unusable datasets had been excluded: congenitally blind N=16, adventitiously blind N=10, sighted N=9.

A template spreadsheet was created and used to modify the monocular datasets; modifications included deletion of tracker artifacts, and creation of graphs showing eye movement data and stimulus timing marks. In preparation for printing graphs of eye movement data, the curves which represented vertical and horizontal eye displacement were inspected visually and adjusted upward or downward (on the computer screen) until subjectively they were centered best about each graph's horizontal axis. Each dataset was saved in its own new spreadsheet.

Graphs were printed and examined for evidence of saccades, fixations, glissades and drift. A single response, comprised of one or more of these behaviors, was identified for each of the 21 instructions (i.e., trials) presented. The timespans of each trial's response was identified similarly. Coded labels representing each of these factors were penciled onto the printouts. Several research assistants worked together to produce consistent judgments of responses, based on guidelines developed for this purpose. The timeline (the horizontal axis) and the timing marks (denoting LED flashes) served additionally as guideposts. "No data" labels were entered in portions of some eye movement records, e.g., where a gap in the trace yielded an incomplete depiction of a response. That is, the "no data" designation typically arose from the deletion of tracker artifacts caused by phenomena such as blinks or momentary loss of the image by the tracker. At times this designation necessitated exclusion of entire responses (representing particular trials within an individuals' experimental session). All labels were added to the graphs in the computer, and to the appropriate locations in the corresponding spreadsheets. Appendix D contains graphs showing the labeled dataset of one participant from each of the three groups.

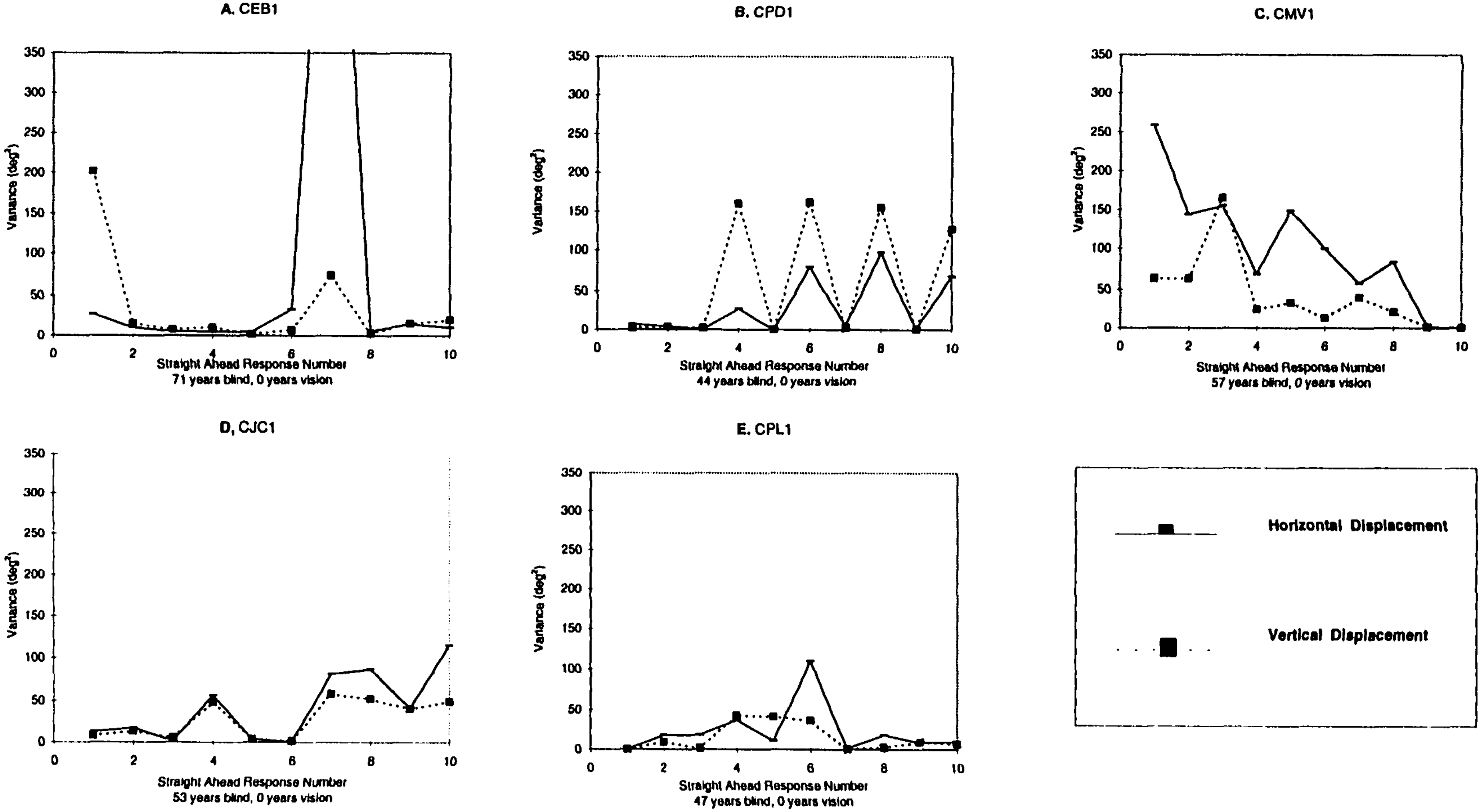
The next analysis phase was to isolate and quantify the sequences of digitized data identified as representing "straight ahead" (SA), "directional" and simulated convergence responses. Directional responses were defined as encompassing "up," "down," "left," "right" and corresponding "halfway" data. A template spreadsheet was created to perform calculations upon these portions of each of the labeled monocular datasets. Values representing all of the horizontal and vertical displacements which took place within each response were converted from tracker units to degrees of visual angle, via use of the calibration-generated conversion factors (see results section of calibration study 2). Standard units were chosen to express values of response direction (rotation in degrees), and time elapsed (ms or s). These steps permitted subsequent calculation to obtain measures, where appropriate, of total horizontal and vertical displacement, amplitude, i.e., vector magnitude, direction, duration, and average velocity of available SA, directional, and simulated convergence responses. Duration was defined as the time elapsed between the initial and final values of the response. Average velocity was obtained by dividing the amplitude of the response by its duration. Data from simulated convergence responses were plotted and have been included on some of the figures which follow, but most often were not evaluated further. This decision was based in part on reports from several participants regarding difficulties in interpreting the requests designed to elicit convergence responses. Inspection of the graphed response patterns obtained for this condition may be seen to reflect these ambiguities.

Straight Ahead Variability

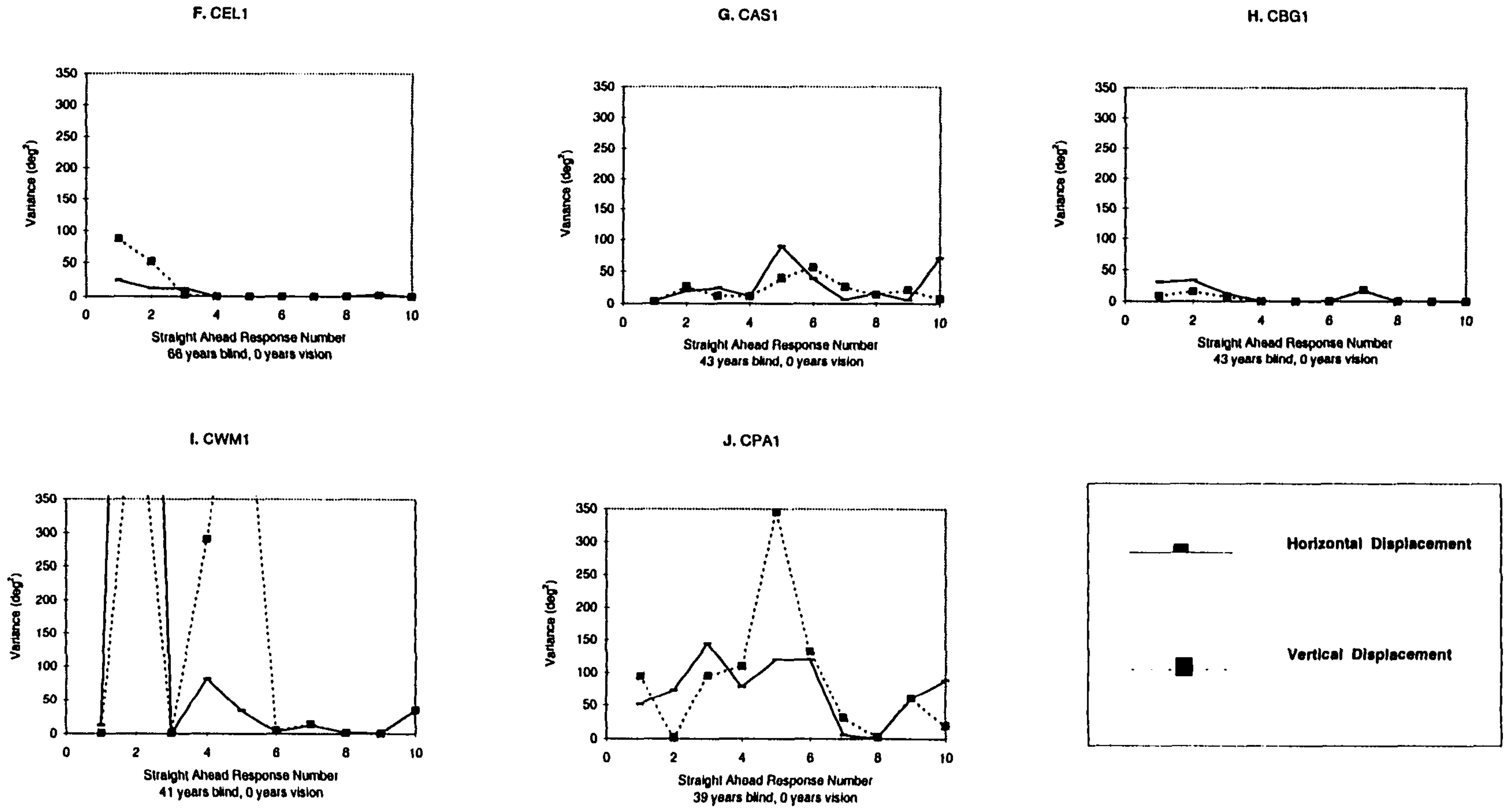
Response data pertaining to the "Look straight ahead" instruction were analyzed first. Initial statistical evaluation of SA data included the following treatment: The within-response variance (sample estimate of the population variance) was calculated of the horizontal and vertical displacement for each participant's SA responses. As many values as were available for each SA response were included in each of these calculations. Generally this yielded a maximum of ten horizontal and ten vertical SA variance datapoints per participant, because although eleven "Look straight ahead" requests were presented, graphed data for the final SA instruction were uncharacteristically ambiguous (to those coding the eye movement records) and therefore were most often not useable due to a lack of a clear end of that response. Figure 6A-AI shows the variance of each of the horizontal (dashes) and vertical (squares) components of individuals' SA responses. The limit of the vertical axis, denoting variance, in each case is 350 deg^2. This was the smallest variance range which could reasonably be used to depict the variability of eye displacement produced during the "straight ahead" responses while still encompassing most available data. Datapoints outside this range were: for CWM1, second SA response, horizontal component = 1581, second SA response, vertical component, = 538, fifth SA

Figure 6. Variance of horizontal and vertical components of straight ahead responses. Panels A-P show data of congenitally blind individuals (N=16), panels S-Z show data of adventitiously blind individuals (N=10), and panels AA-AI show data of sighted individuals (N=9).

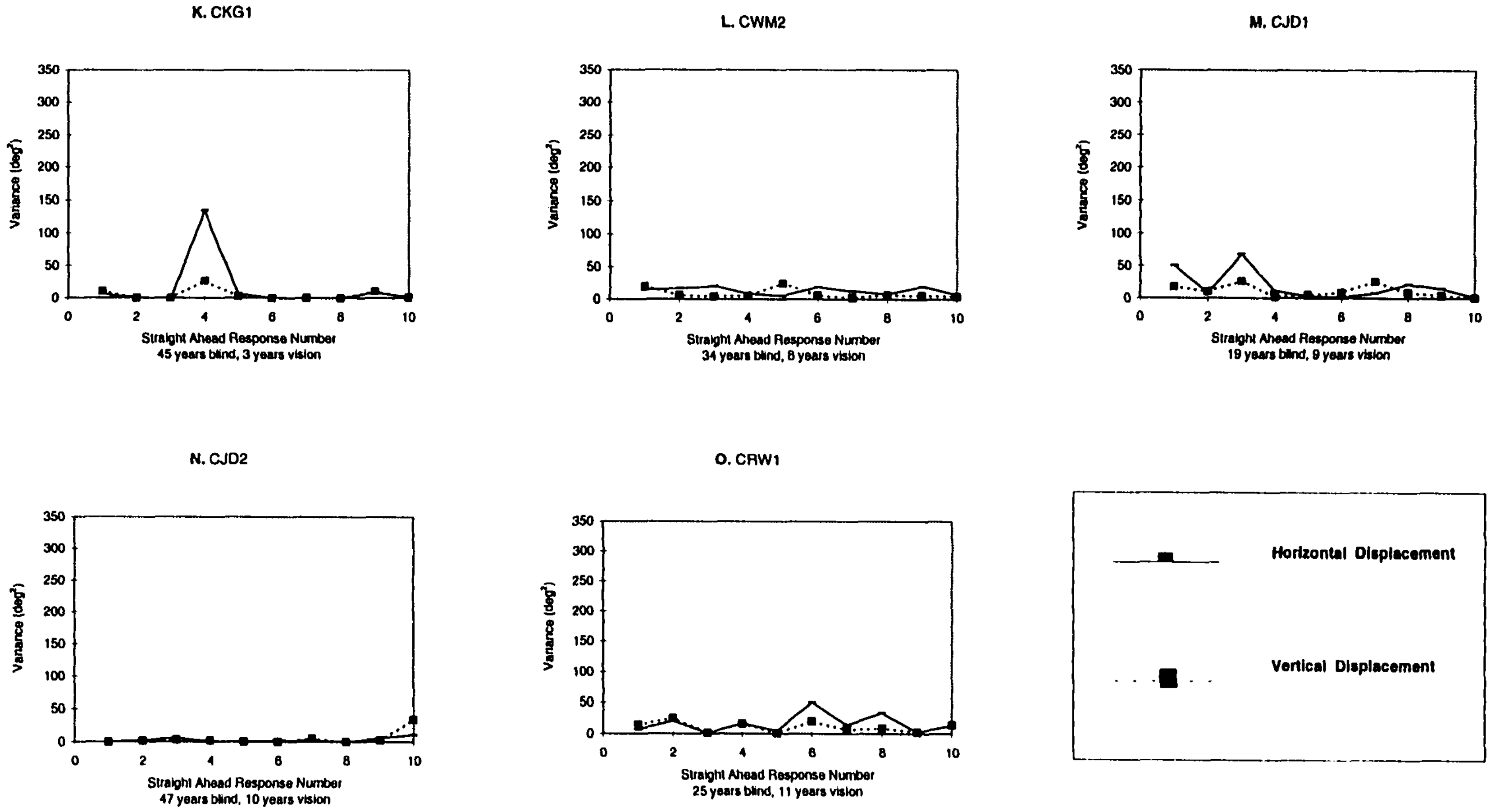
Congenital


A. CEB1
Variance (deg²)
Straight Ahead Response Number
71 years blind, 0 years vision
B. CPD1
Variance (deg²)
Straight Ahead Response Number
44 years blind, 0 years vision
C. CMV1
Variance (deg²)
Straight Ahead Response Number
57 years blind, 0 years vision
D. CJC1
Variance (deg²)
Straight Ahead Response Number
53 years blind, 0 years vision
E. CPL1
Variance (deg²)
Straight Ahead Response Number
47 years blind, 0 years vision
0
50
100
150
200
250
300
350
0
2
4
6
8
10
Horizontal Displacement
Vertical Displacement

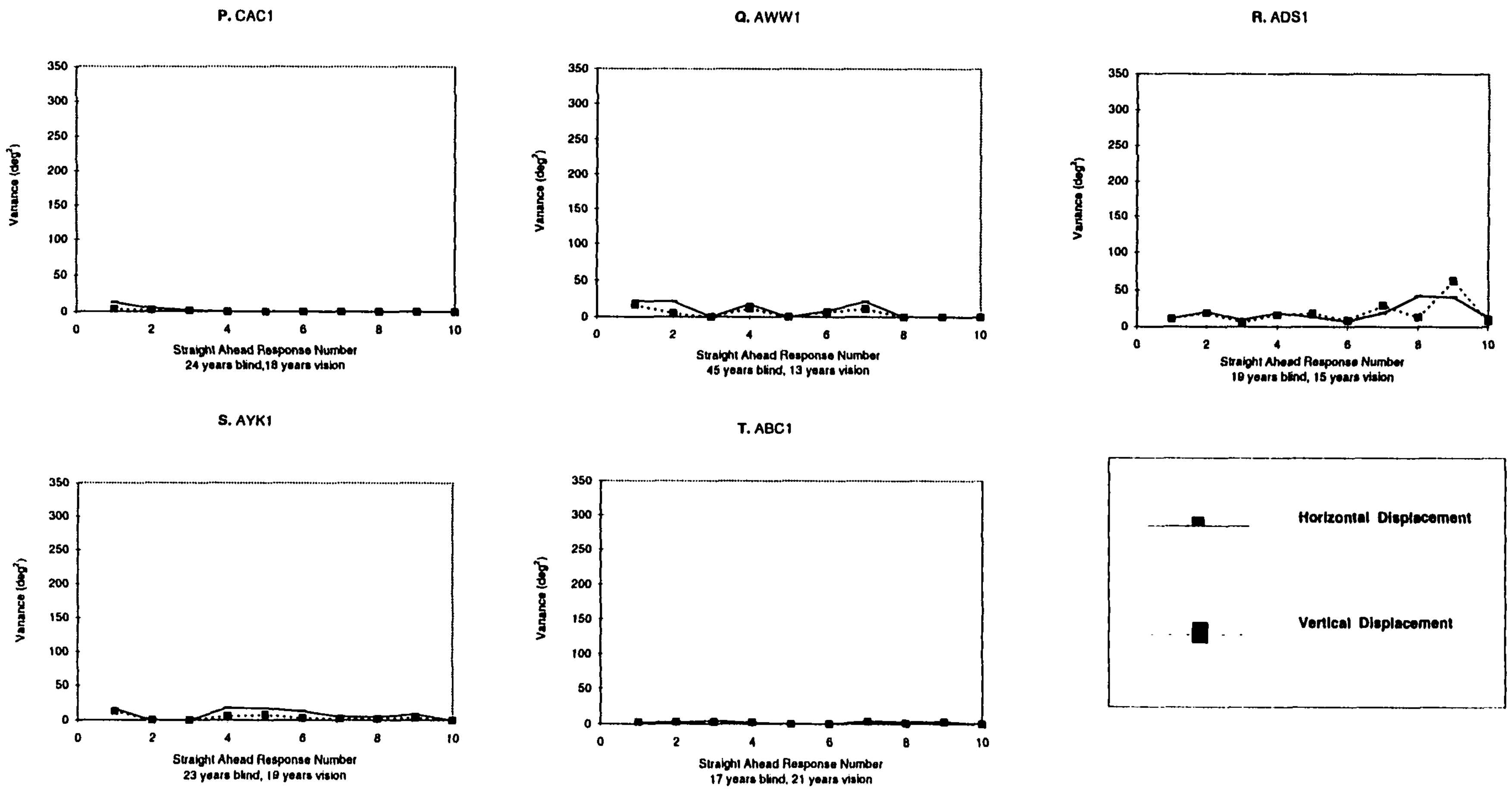
Congenital


F. CEL1
Variance (deg²)
350
300
250
200
150
100
50
0
0
2
4
6
8
10
Straight Ahead Response Number
66 years blind, 0 years vision
G. CAS1
Variance (deg²)
Straight Ahead Response Number
43 years blind, 0 years vision
H. CBG1
Variance (deg²)
Straight Ahead Response Number
43 years blind, 0 years vision
I. CWM1
Variance (deg²)
Straight Ahead Response Number
41 years blind, 0 years vision
J. CPA1
Variance (deg²)
Straight Ahead Response Number
39 years blind, 0 years vision
Horizontal Displacement
Vertical Displacement

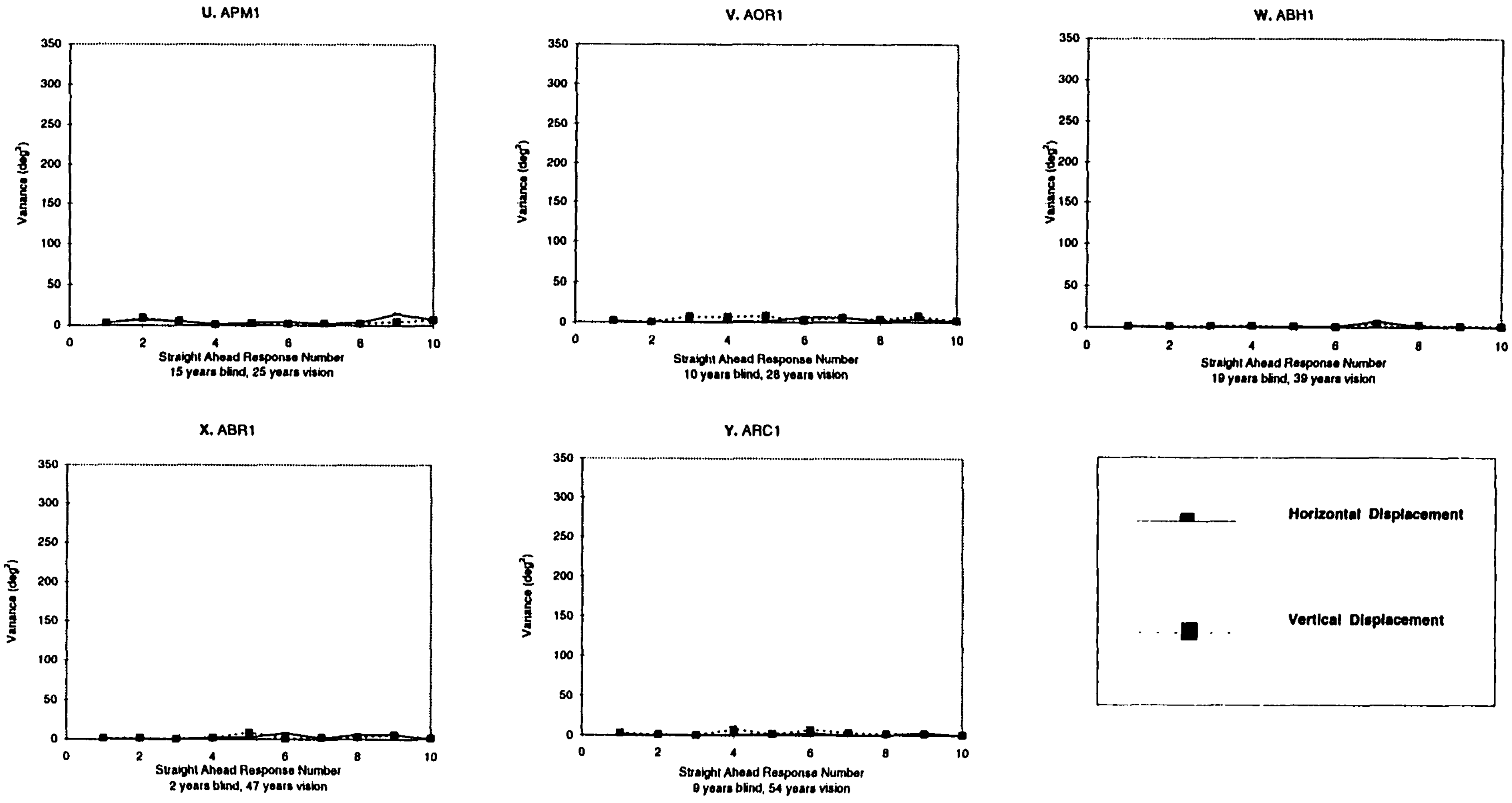
Congenital


K. CKG1
Variance (deg²)
350
300
250
200
150
100
50
0
0
2
4
6
8
10
Straight Ahead Response Number
45 years blind, 3 years vision
L. CWM2
Variance (deg²)
Straight Ahead Response Number
34 years blind, 8 years vision
M. CJD1
Variance (deg²)
Straight Ahead Response Number
19 years blind, 9 years vision
N. CJD2
Variance (deg²)
Straight Ahead Response Number
47 years blind, 10 years vision
O. CRW1
Variance (deg²)
Straight Ahead Response Number
25 years blind, 11 years vision
Horizontal Displacement
Vertical Displacement

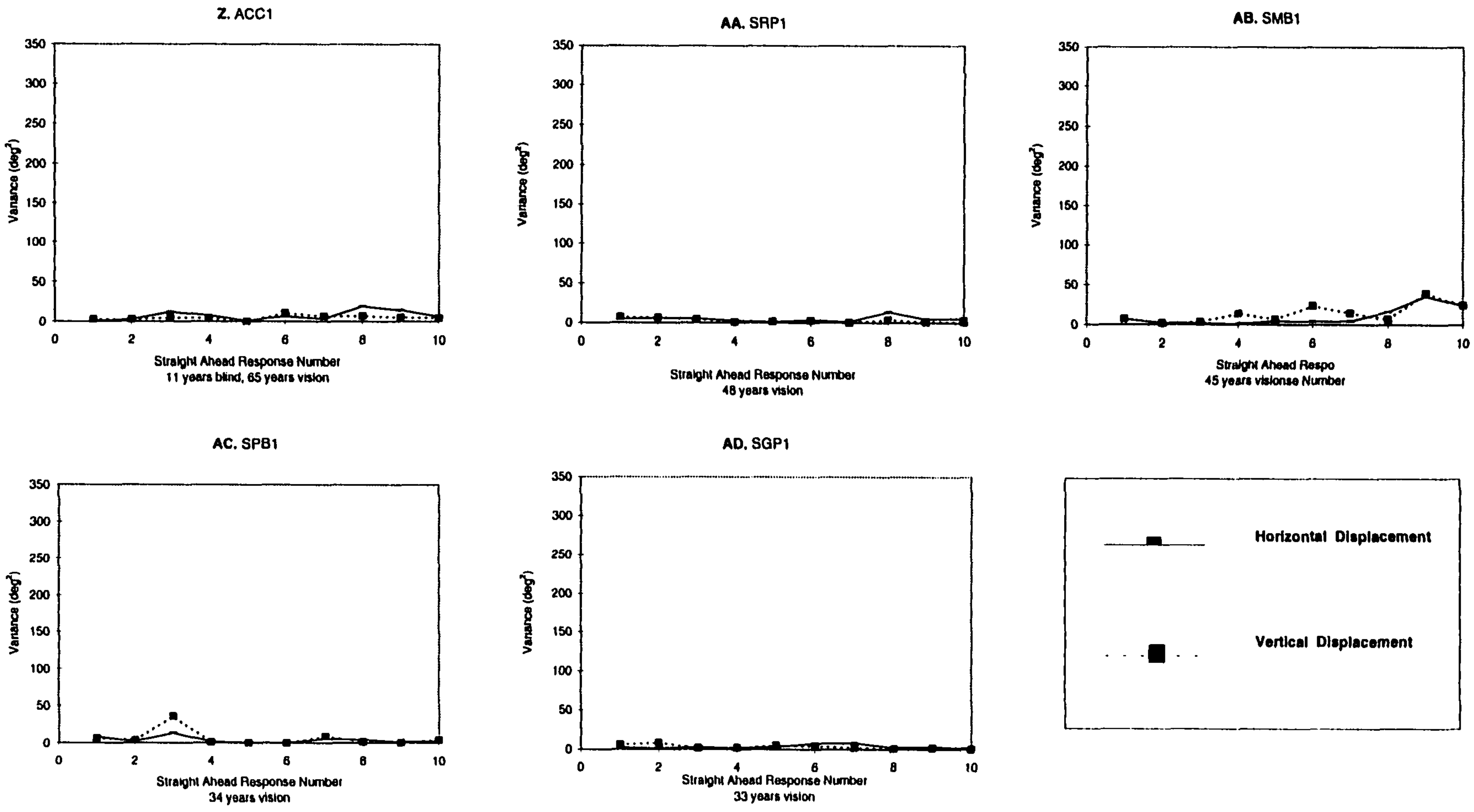
Congenital and Adventitious



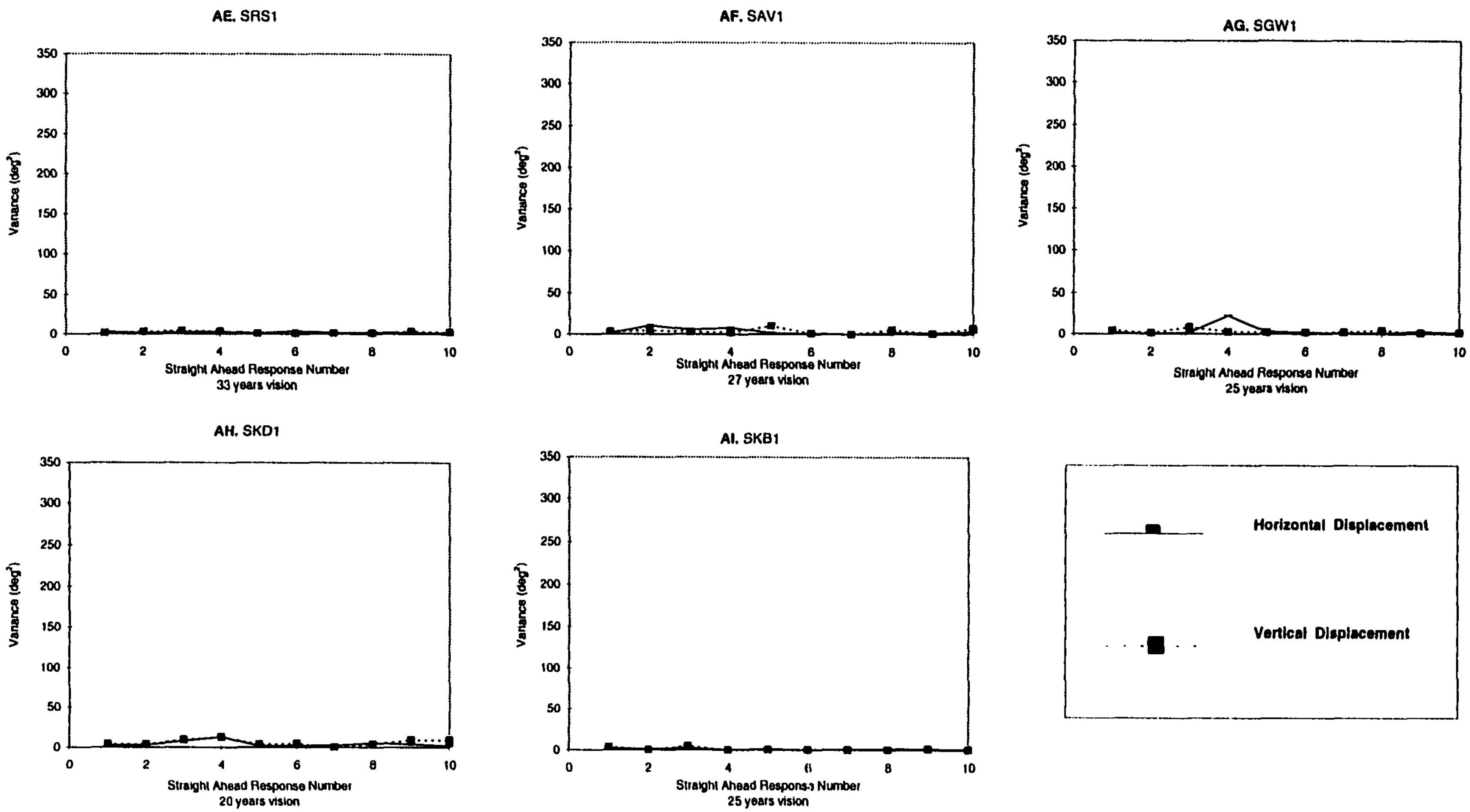
Adventitious



Adventitious and Sighted



Sighted


AE. SRS1
Variance (deg²)
350
300
250
200
150
100
50
0
0
2
4
6
8
10
Straight Ahead Response Number
33 years vision
AF. SAV1
Variance (deg²)
Straight Ahead Response Number
27 years vision
AG. SGW1
Variance (deg²)
Straight Ahead Response Number
25 years vision
AH. SKD1
Variance (deg²)
Straight Ahead Response Number
20 years vision
AI. SKB1
Variance (deg²)
Straight Ahead Response Number
25 years vision
Horizontal Displacement
Vertical Displacement

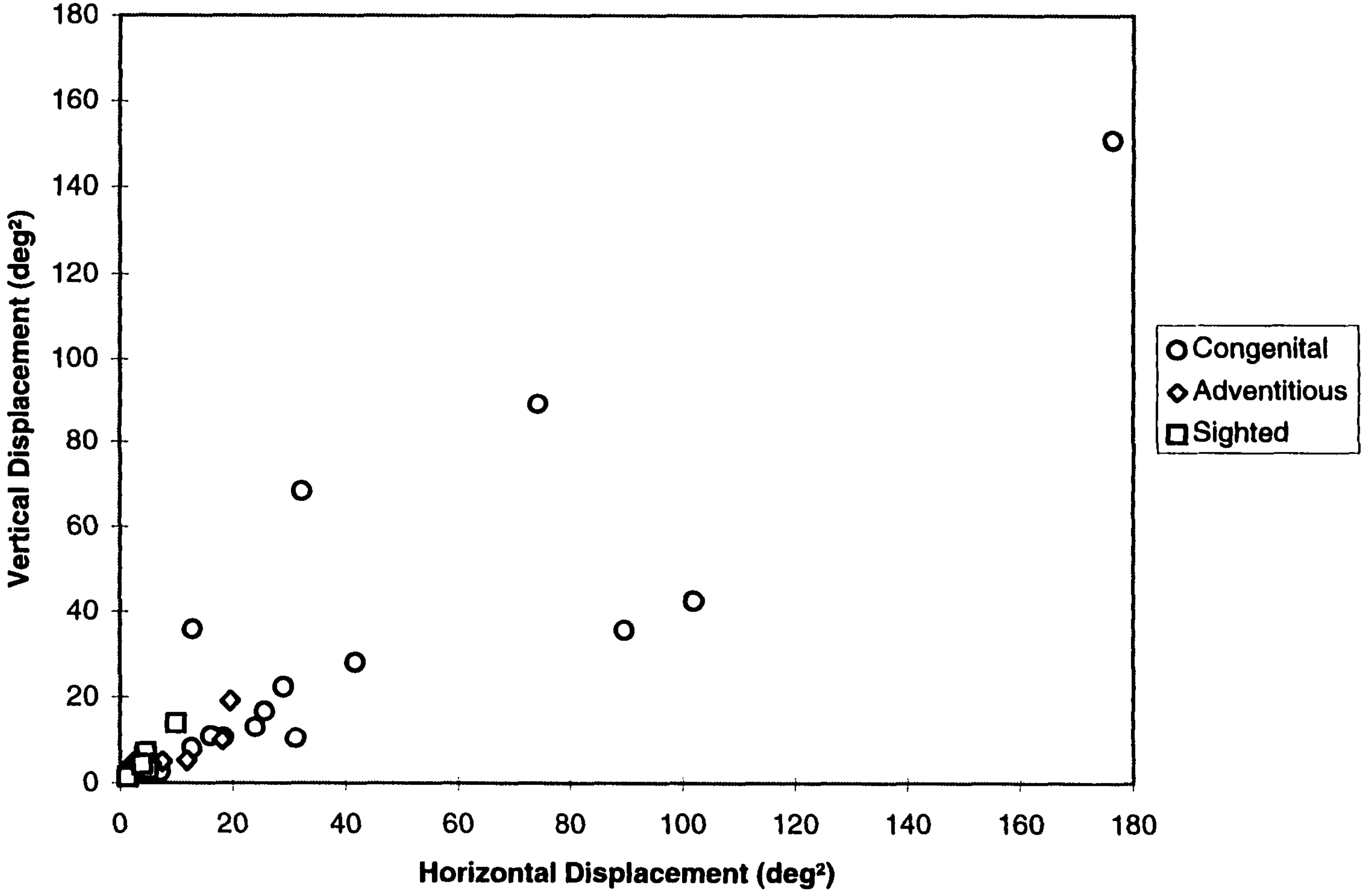
response, vertical component = 621; for CEB1, seventh SA response, horizontal component = 782. It is clear from these graphs that the group of congenitally blind participants displayed much greater variability both vertically and horizontally than did either of the other two groups.

To examine group tendencies more efficiently, averages of each participant's within-trial horizontal and vertical SA response variance were obtained and plotted. Figure 7 shows one datapoint per participant (squares denote sighted, diamonds adventitiously blind, and circles congenitally blind participants, respectively), representing the across-trial mean of his/her within-trial horizontal and vertical SA response variance. Datapoints representing participants classified as sighted and adventitiously blind are somewhat differentiable by group; datapoints denoting congenitally blind participants are widely dispersed and in general are distinctly separate from those of most of the others.

Relative Data Defined

Directional responses were considered next. It should be noted that unless otherwise specified, results were obtained using what are here termed "relative data." As defined here, relative data refers to the overall displacement of the eye during a response and the time taken to produce the response. Relative eye displacement is thus measured by subtracting the pre-movement eye position (separately for the horizontal and vertical components) from its position at the conclusion of the response.

Figure 7. Mean of straight ahead within-trial variances. Each data point denotes one individual's data. Datapoints representing sighted and adventitiously blind are somewhat differentiable by group; datapoints denoting congenitally blind are widely dispersed and in general distinctly separate from those of most of the others.


180
160
140
120
100
80
60
40
20
0
Vertical Displacement (deg²)
0
20
40
60
80
100
120
140
160
180
Horizontal Displacement (deg²)
○ Congenital
◇ Adventitious
□ Sighted

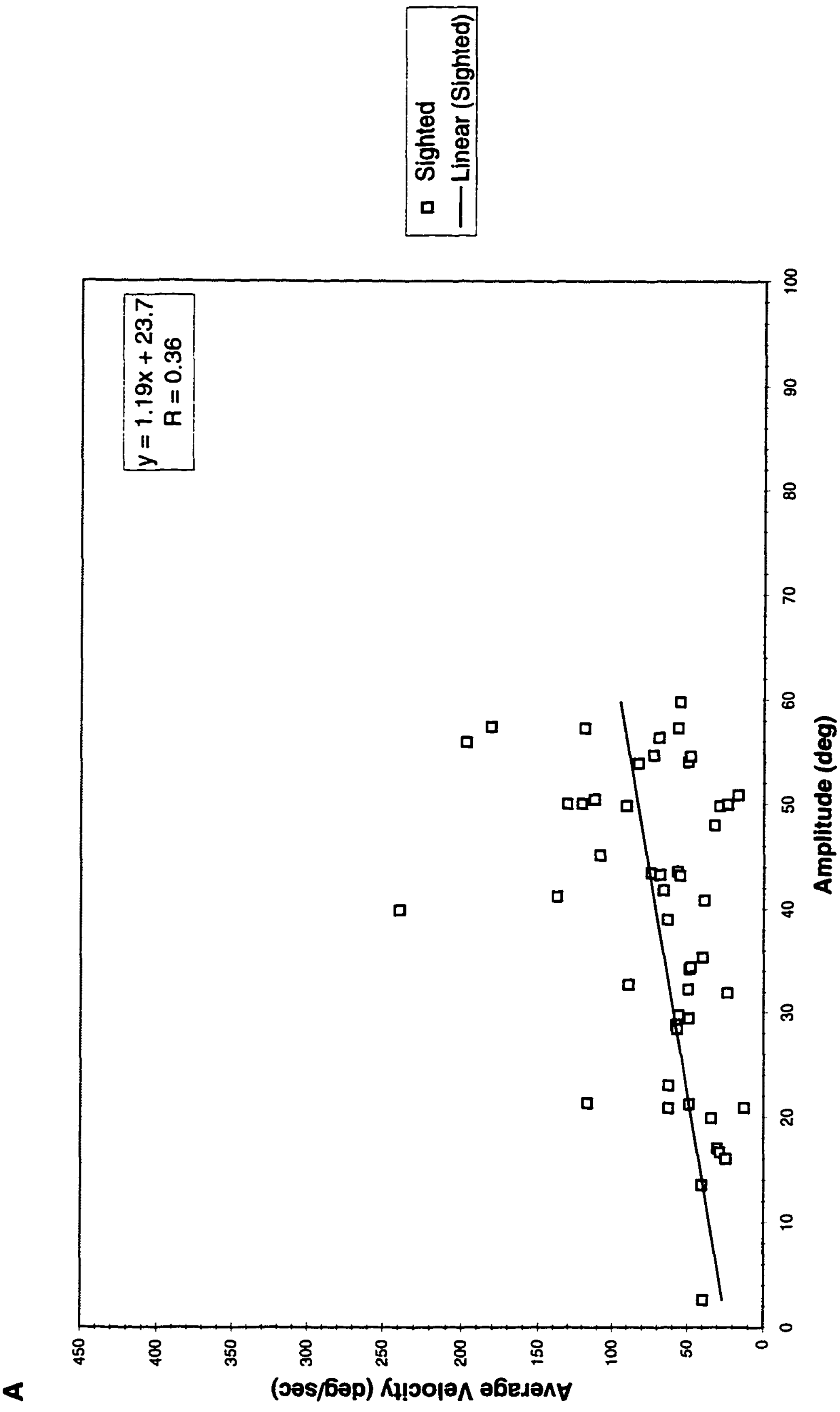
Main Sequence Approximations

Phenomena initially of interest included directional response vector magnitudes, i.e., amplitudes, and their associated rates of eye excursions. Directional responses were therefore evaluated initially by formulating approximations of various forms of the "main sequence." The main sequence refers to "the proportional relationship between saccadic amplitude and peak velocity" (Bahill, Clark & Stark, 1975; for discussions see also Becker, 1989; Hainline, 1993; Ciuffreda & Tannen, 1995). Here it was intended for use as a gross indicator of the function of the saccade production mechanism in the groups of blind participants, specifically of the "pulse component of the pulse-step neurologic controller signal for saccades" (Ciuffreda & Tannen, 1995, p. 54). The main sequence formula was adapted for these analyses in two ways. First, because the peak velocity of saccades exceeds the fastest sampling rate (60 video frames/s) afforded by the equipment available for this study, average velocity was substituted for peak velocity. Another adaptation of the classical main sequence was that much of the data consisted of responses which were larger than the prescribed 20 degrees (Bahill, Clark & Stark, 1975). This was unavoidable because, by design, many saccades (one or more of which often were contained within single identified responses) were expected to exceed the traditional limit, and because entire responses rather than individual saccades were considered. Main sequence approximations such as these have been employed successfully in the past (for a discussion see Becker, 1989) and were therefore considered appropriate for use here.

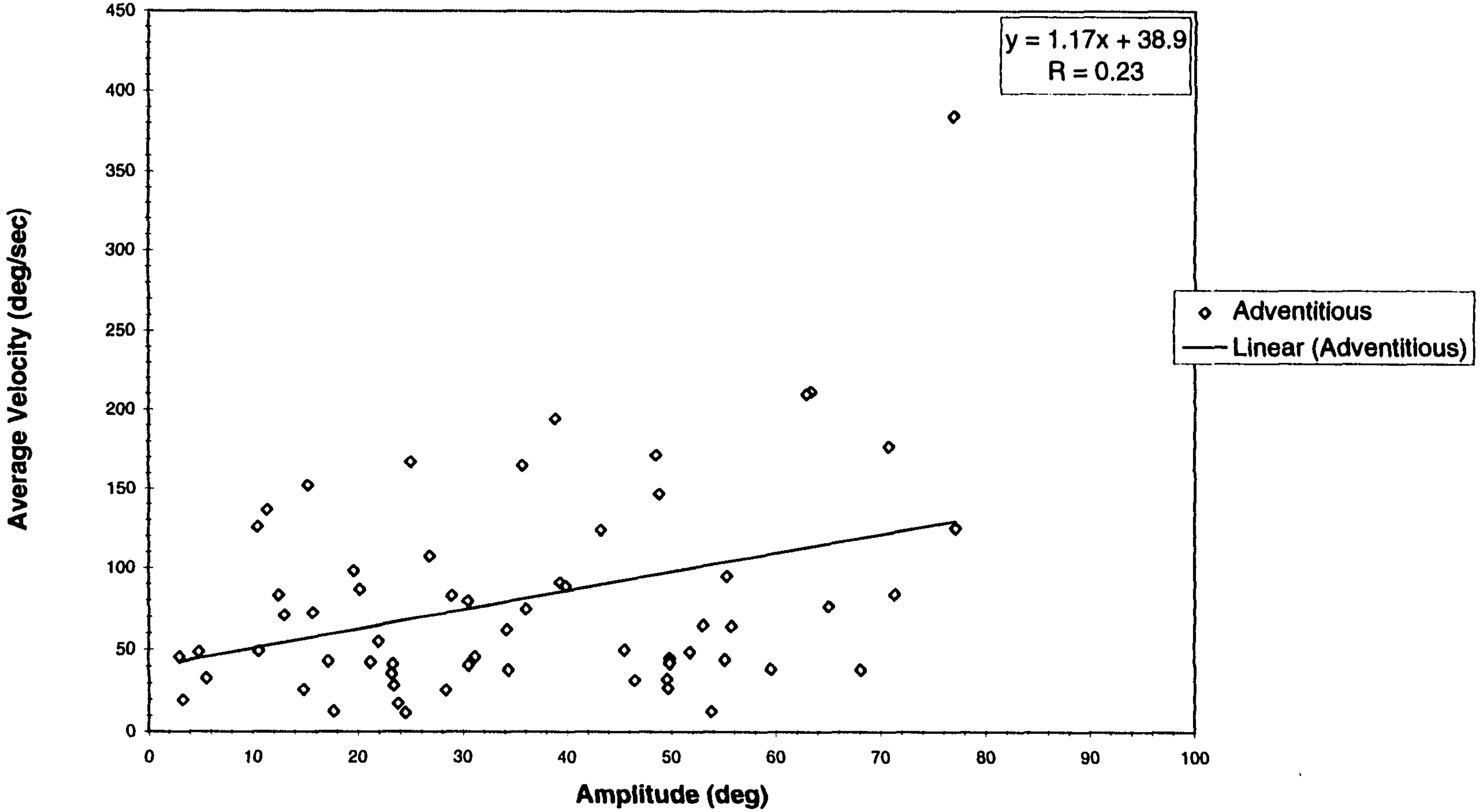
Figure 8A-D shows group plots approximating the main sequence in terms of average velocity as a function of directional response amplitude. Each datapoint represents one directional response produced by a participant from the group depicted. The sighted and adventitiously blind group data in general obeyed a lawful function wherein average velocity increased with amplitude. For the sighted and adventitiously blind groups this result implied that average velocity remained constant with respect to the other relevant main sequence variables, corroborating the trends shown below for the sighted group in the "duration versus amplitude" plots. Two graphs of data from the group of participants who were classified as congenitally blind are shown; one containing outlier data which was excluded from the other. Inclusion of both plots allows across-group comparison of (nearly all) the data plotted using scales identical to those employed for the other groups. The points representing the data from congenitally blind participants were widely dispersed in no systematic fashion. It would seem premature on the basis of this result to infer reduction, degradation or destruction of the pulse component of the pulse-step neural controller signal (as may be done upon detection of visually elicited saccades with reduced peak velocities), although these data bolster suspicions in this regard.

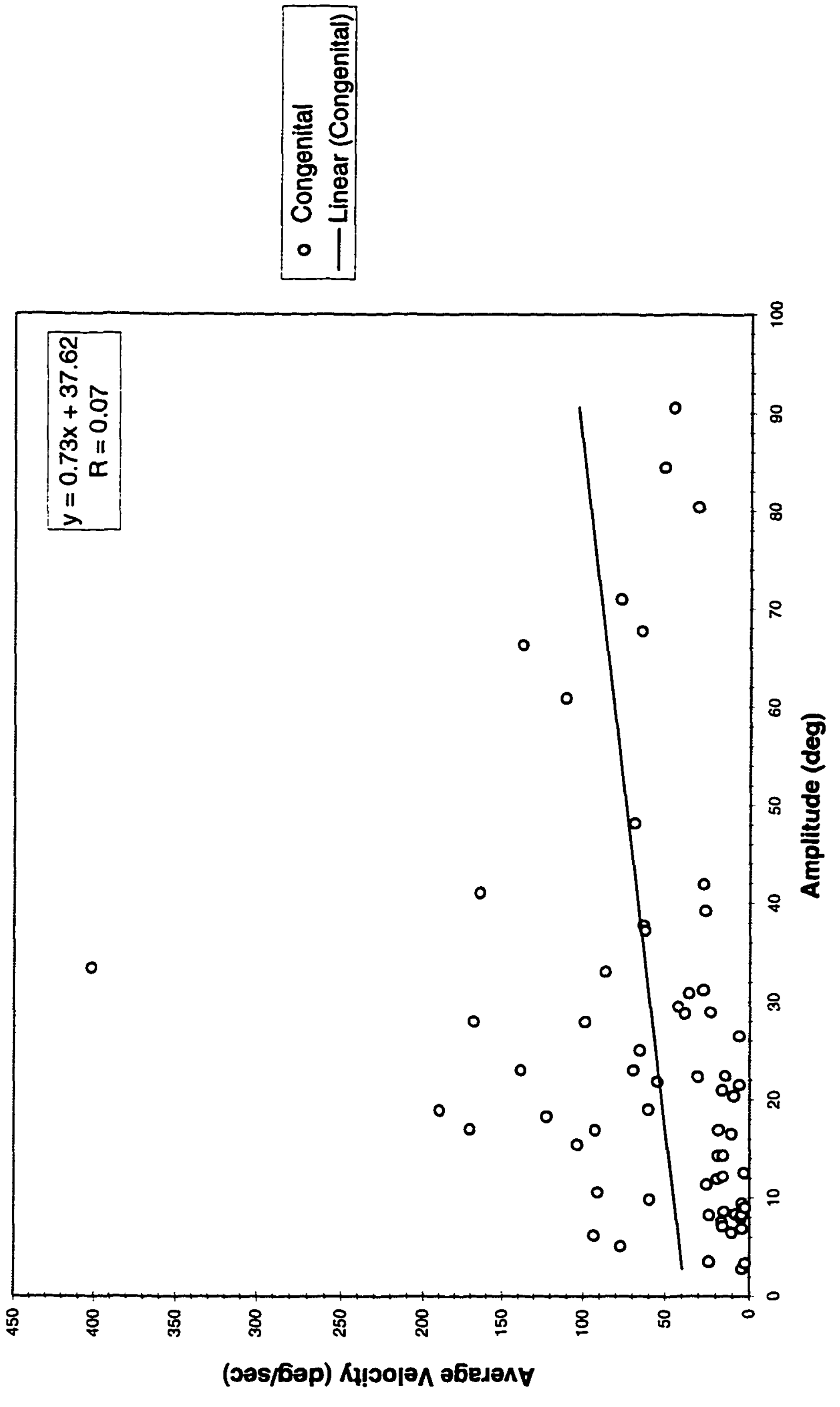
A simplified extension of the main sequence is pictured in Figure 9A-C, again showing the individual responses produced by the different groups. These formulations were intended to approximate relevant main sequence characteristics by depicting duration as a function of directional response amplitude. The long response durations were

Figure 8. Approximation of Main Sequence average velocity as a function of directional response amplitude. Panels A-C show group data for participants classified as sighted (N=9), adventitiously blind (N=10), and congenitally blind (N=16); panel D plots the latter group's data using an expanded scale displaying outliers. The regression line of best fit is plotted for each group.


A
Average Velocity (deg/sec)
0
50
100
150
200
250
300
350
400
450
Amplitude (deg)
0
10
20
30
40
50
60
70
80
90
100
y = 1.19x + 23.7
R = 0.36
□ Sighted
—— Linear (Sighted)

B


y = 1.17x + 38.9
R = 0.23
Adventitious
Linear (Adventitious)
Average Velocity (deg/sec)
0
50
100
150
200
250
300
350
400
450
Amplitude (deg)
0
10
20
30
40
50
60
70
80
90
100


y = 0.73x + 37.62
R = 0.07
o Congenital
—— Linear (Congenital)
Average Velocity (deg/sec)
0
50
100
150
200
250
300
350
400
450
Amplitude (deg)
0
10
20
30
40
50
60
70
80
90
100

C

D

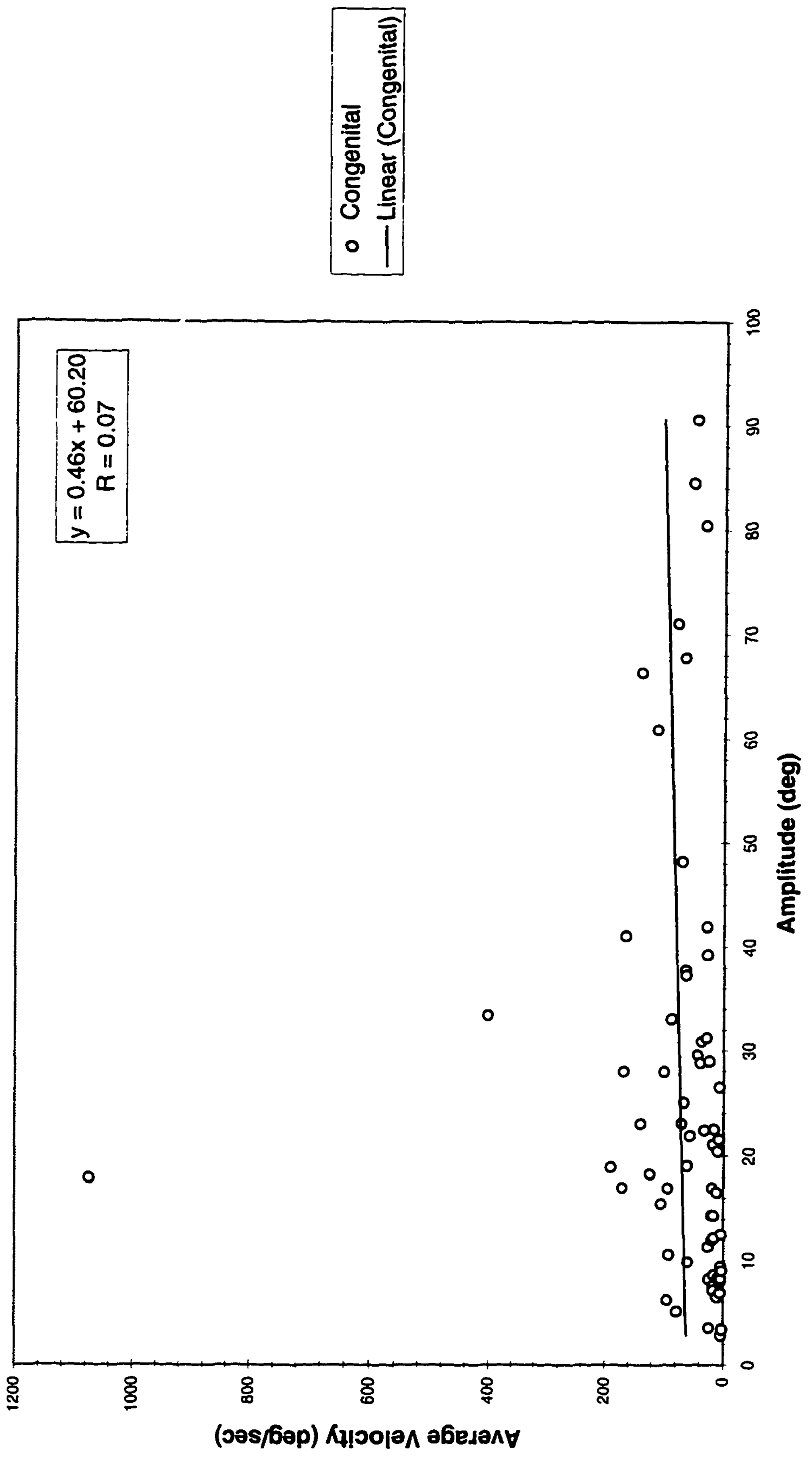
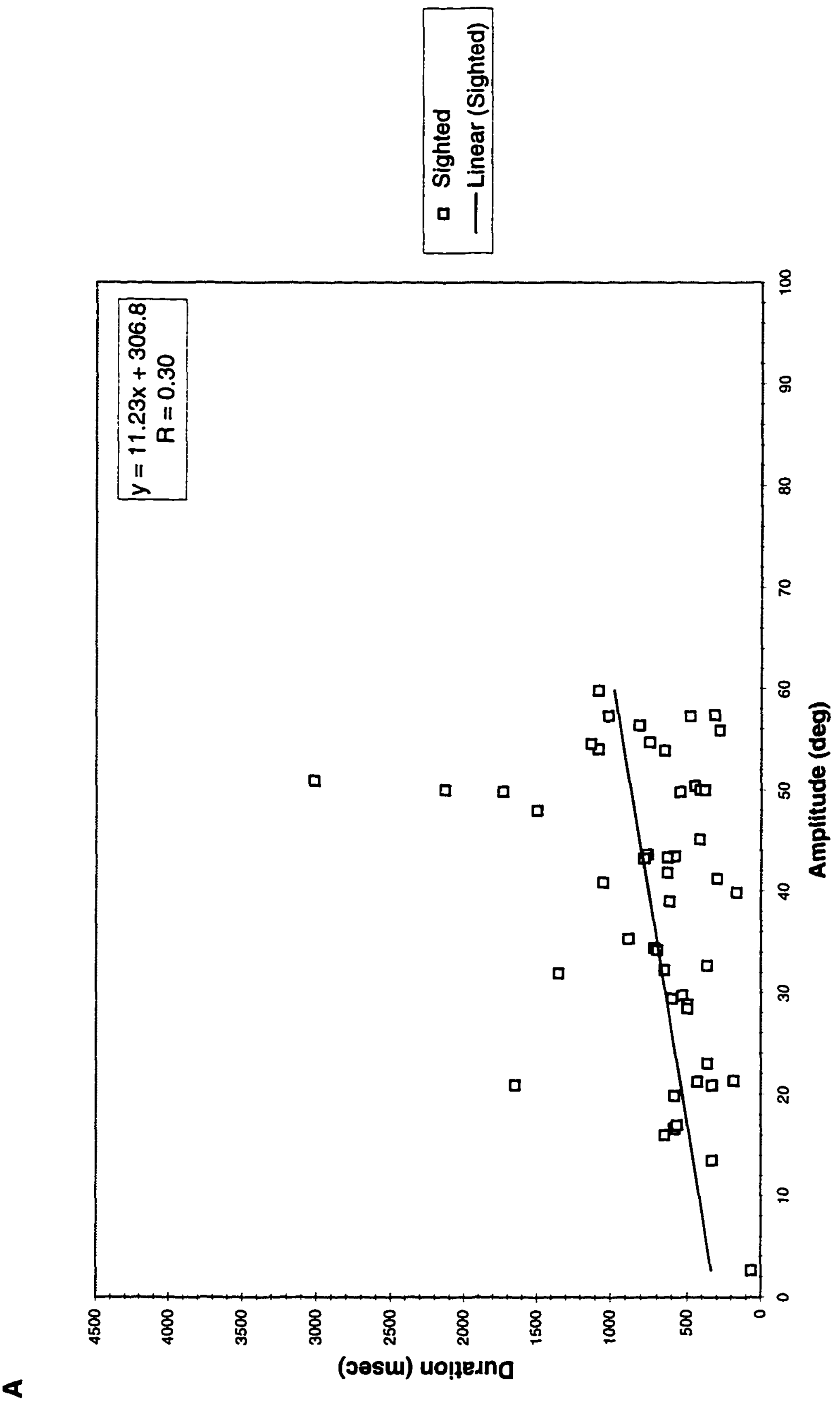
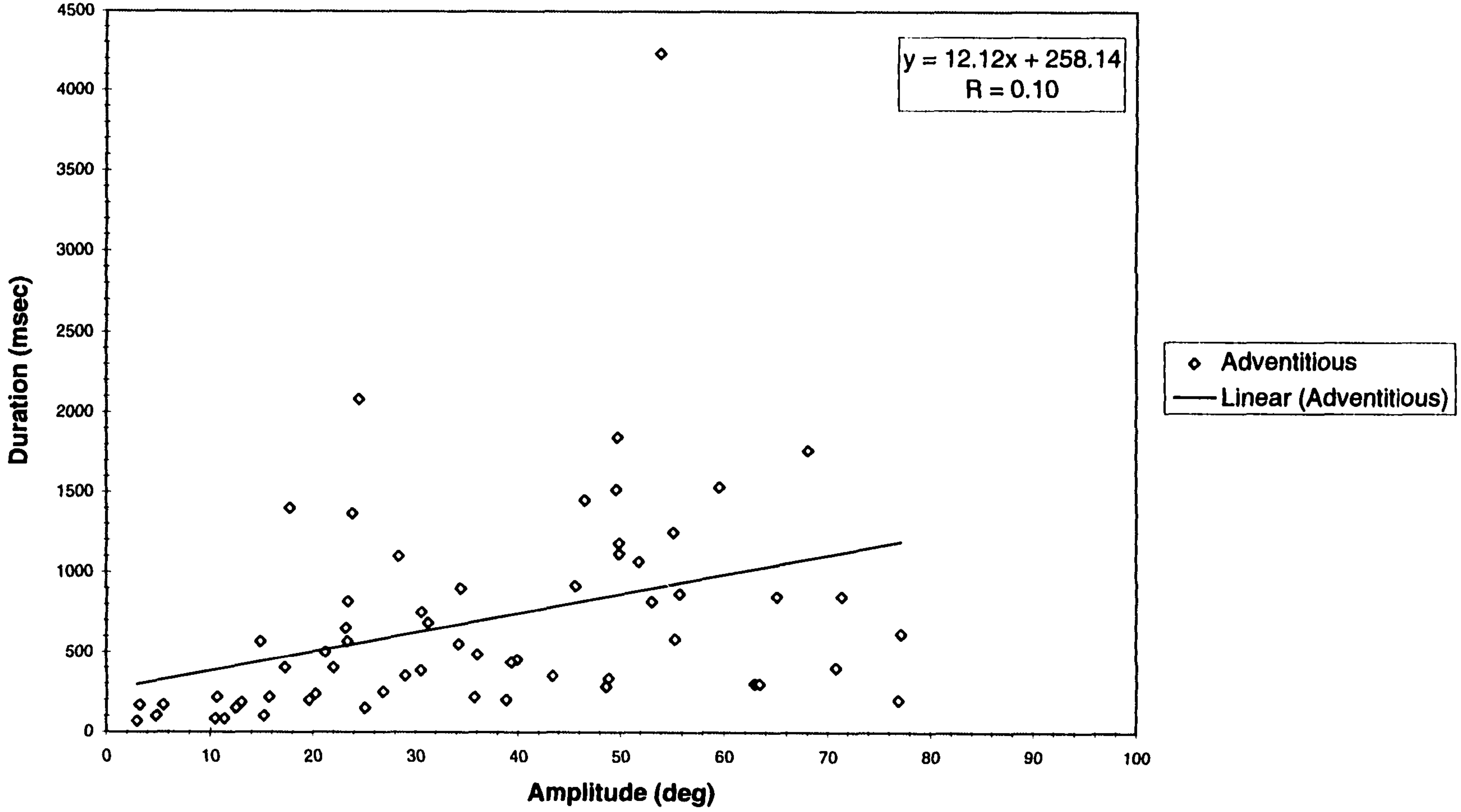

Average Velocity (deg/sec)
0
200
400
600
800
1000
1200
Amplitude (deg)
0
10
20
30
40
50
60
70
80
90
100
y = 0.46x + 60.20
R = 0.07
o Congenital
— Linear (Congenital)

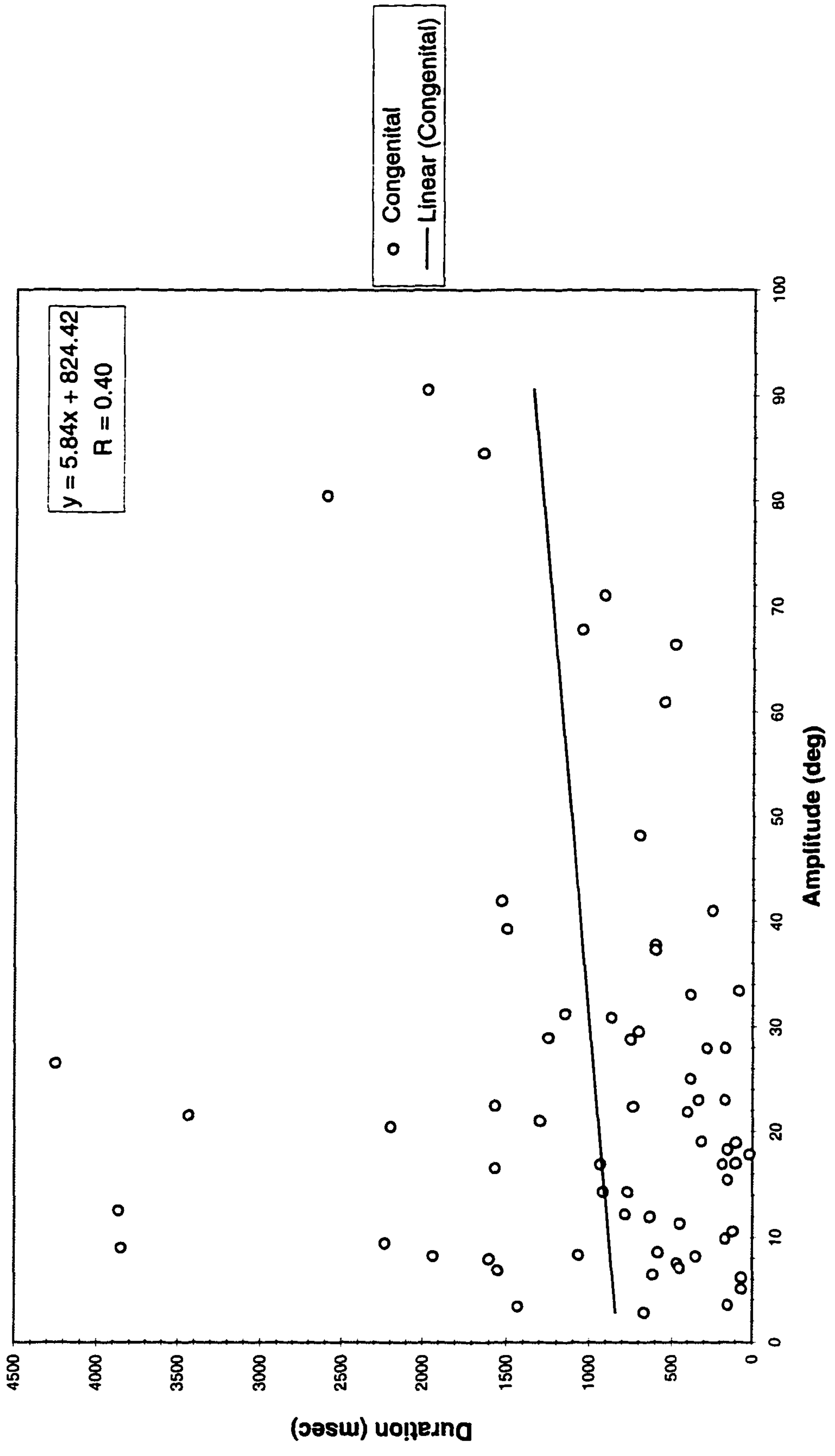
Figure 9. Approximation of Main Sequence duration as a function of directional response amplitude. Panels A-C show group data for participants classified as sighted (N=9), adventitiously blind (N=10), and congenitally blind (N=16). The regression line of best fit is plotted for each group.


A
Duration (msec)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
10
20
30
40
50
60
70
80
90
100
Amplitude (deg)
y = 11.23x + 306.8
R = 0.30
Sighted
Linear (Sighted)

B


y = 12.12x + 258.14
R = 0.10
Duration (msec)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
10
20
30
40
50
60
70
80
90
100
Amplitude (deg)
Adventitious
Linear (Adventitious)

C


Duration (msec)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Amplitude (deg)
0
10
20
30
40
50
60
70
80
90
100
y = 5.84x + 824.42
R = 0.40
o Congenital
Linear (Congenital)

immediately most obvious, arising in part from inclusion of entire responses rather than single saccades. In addition, the lack of visual input (blindness for two groups, total darkness for all groups) may have slowed saccades, as has been evidenced previously (see, e.g., Riggs, et al, 1974; Koerner, 1975; Ciuffreda & Tannen 1995). These graphs furthermore display large amounts of scatter in data from all three groups. Despite this dispersion and the stated drawbacks of this aspect of the analyses, a linear trend was discernible for the sighted and the adventitiously blind groups, indicating a scaling of response duration with response amplitude. Calculation of correlation coefficients revealed approximately the same, moderate, value representing this trend for the sighted and adventitiously blind groups: sighted group, $r = 0.3$; adventitiously blind group, $r = 0.4$. A test of significance of the difference between two correlation coefficients revealed no significant difference between the adventitious versus sighted group trends. This between-group result was not surprising, as a two-tailed test of the significance of r (for each group considered in isolation) had revealed that none of these r values were significant for linearity. The linear tendencies of the adventitiously blind and sighted groups may be contrasted with the very low correlation coefficient obtained for the group of congenitally blind participants, i.e., $r = 0.1$, from whose graphed data no linear trend emerged.

Absolute Data Defined

The next analyses of these data sought to relate the directional responses of each participant to his/her SA responses. In order to do this, an "absolute" gauge of eye displacement was developed. The broader utility of this approach included its potential for these results to be compared with those of other studies which incorporated SA-like responses (designed to generate approximations of primary position, see sections in Introduction regarding Human oculomotor orientation with non-visual stimuli and Human oculomotor orientation without visual experience). As explained above, the analyses conducted thus far had utilized what are here termed "relative" values of eye displacement. To establish the values of "absolute" eye displacement a within-participant offset was determined in each case. The offset was derived using the mean of the relative data representing the starting points of an individual's straight ahead responses. That is, the relative values of the initial position (separately for horizontal and vertical components) of each SA response were averaged to obtain the participant's mean startpoint offset. The value of the mean SA startpoint offset was subtracted from the relative value denoting the endpoint of each available directional and simulated convergence response. For each individual this yielded the total, or "absolute," vertical and horizontal displacement of every non-SA response, from his/her mean SA starting position. Appendix E presents values of relative and absolute data for selected variables.

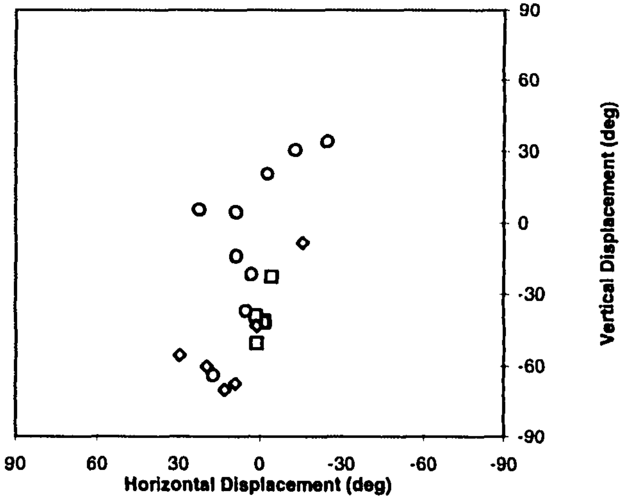
Relative and Absolute Eye Displacement

Figure 10A-J shows polar plots of group relative data for each of the eight directional and two simulated convergence responses, whereas Figure 11A-J shows polar plots of group absolute data for the directional and simulated convergence responses. One datapoint is shown for each of the available responses produced by the members of the group noted. Figure 12A-AI shows individual polar plots of the absolute eye displacements of all available directional and simulated convergence responses. That is, the set of all absolute data obtained for each participant is plotted separately. These graphs show the similarity in the eye movement patterns generated by the sighted and adventitiously blind groups and the distinctly different results of the congenitally blind group.

Inspection of the absolute plots focused on the scatter of the datapoints. Responses of sighted participants may be characterized generally as appropriate. In this group both the size and direction of the behaviors, depicted by the location of the datapoints, tended to correspond most closely to the instruction given. The response patterns of the adventitiously blind participants, as a group, overlapped somewhat with that of the sighted but were more widely scattered. A large proportion of the group of congenitally blind participants produced responses which clustered tightly around (0,0), indicating their having made few or no overt responses.

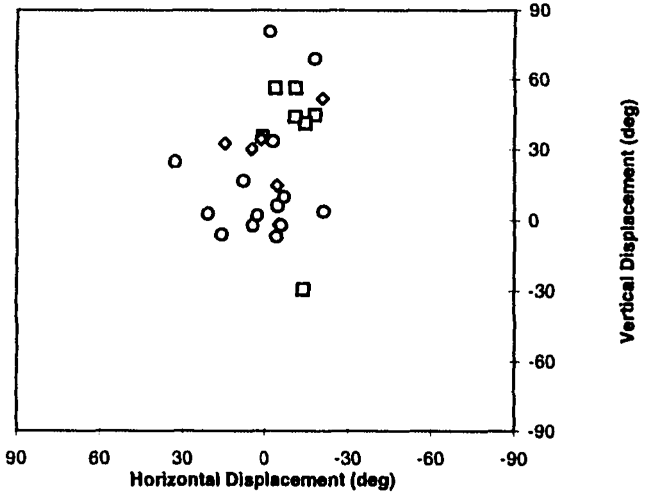
Figure 10. Directional and simulated convergence responses, group relative data. Panels A-J show polar plots of group data (sighted: N=9, adventitiously blind: N=10, congenitally blind: N=16) for each directional and simulated convergence response. Each data point denotes one individual's data.

A



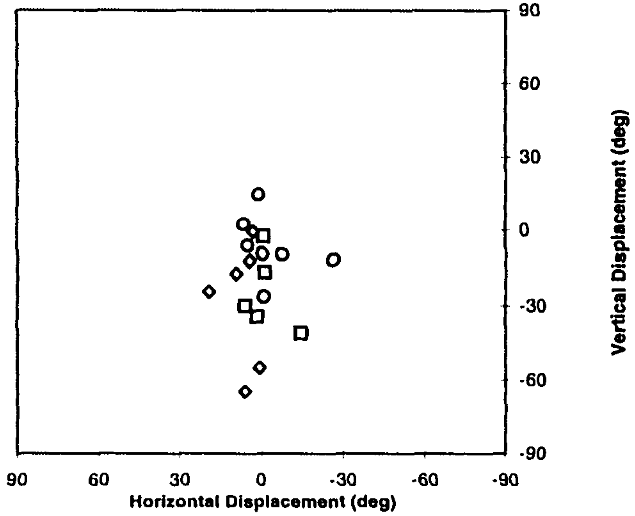
Down Extreme Group Relative Data

B



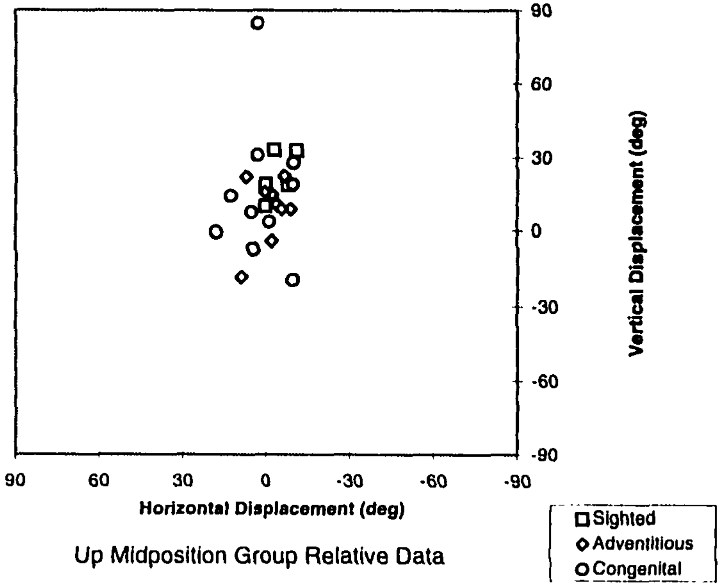
Up Extreme Group Relative Data

C



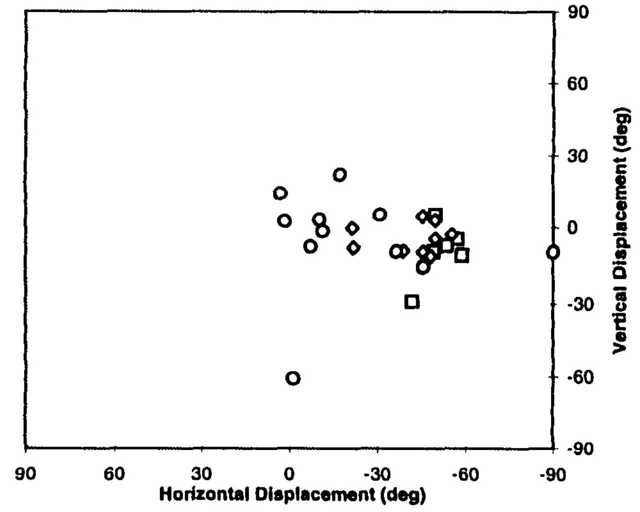
Down Midposition Group Relative Data

D



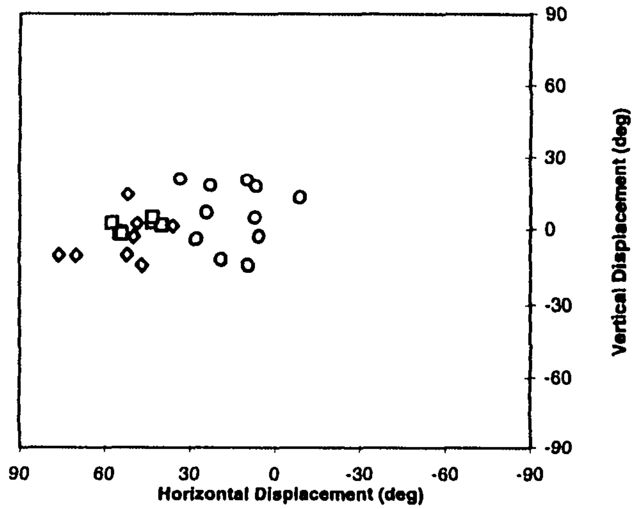
Up Midposition Group Relative Data

E



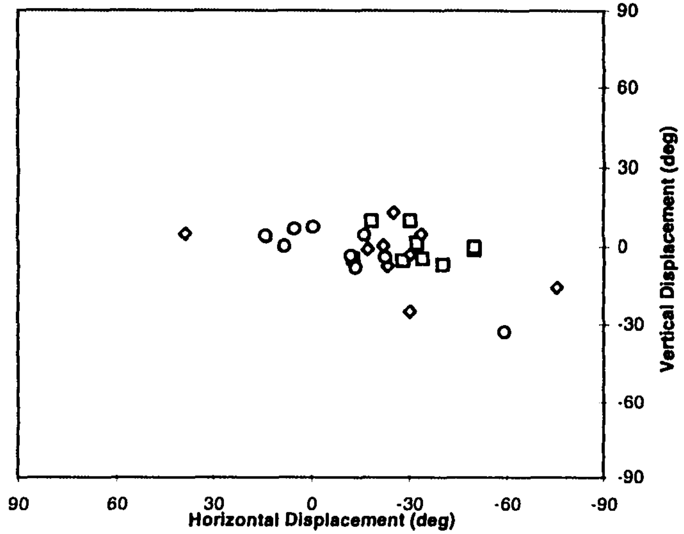
Right Extreme Group Relative Data

F



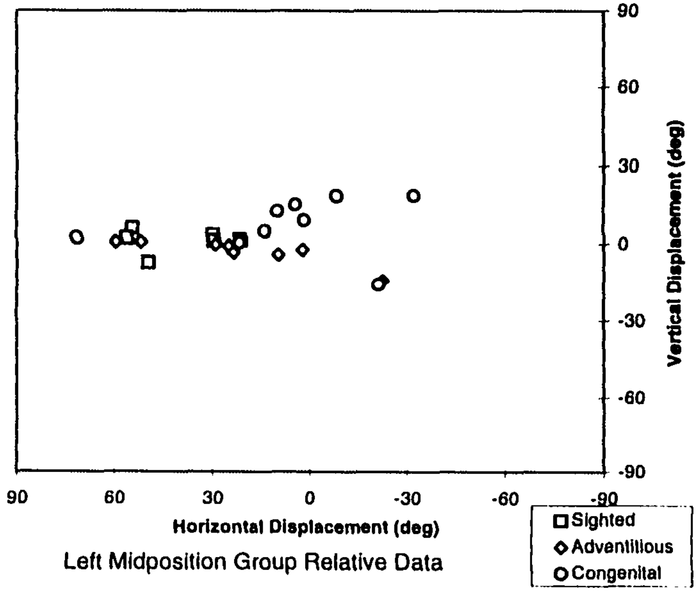
Left Extreme Group Relative Data

G



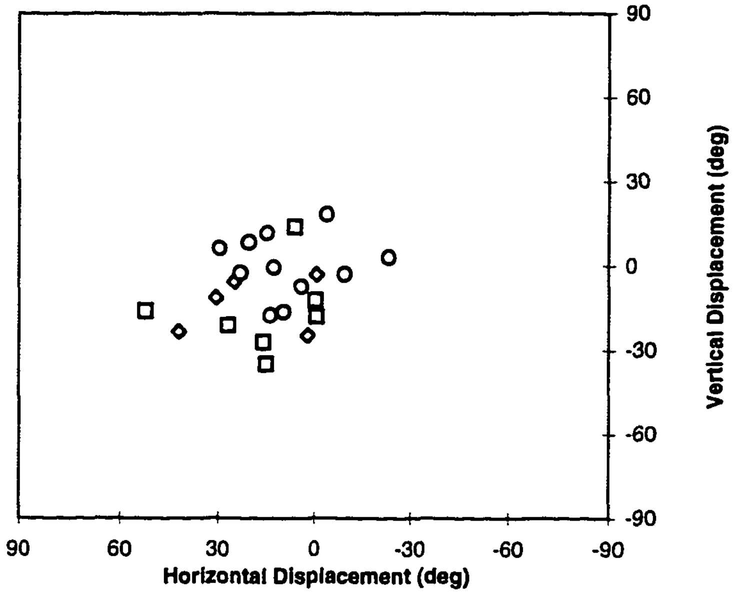
Right Midposition Group Relative Data

H



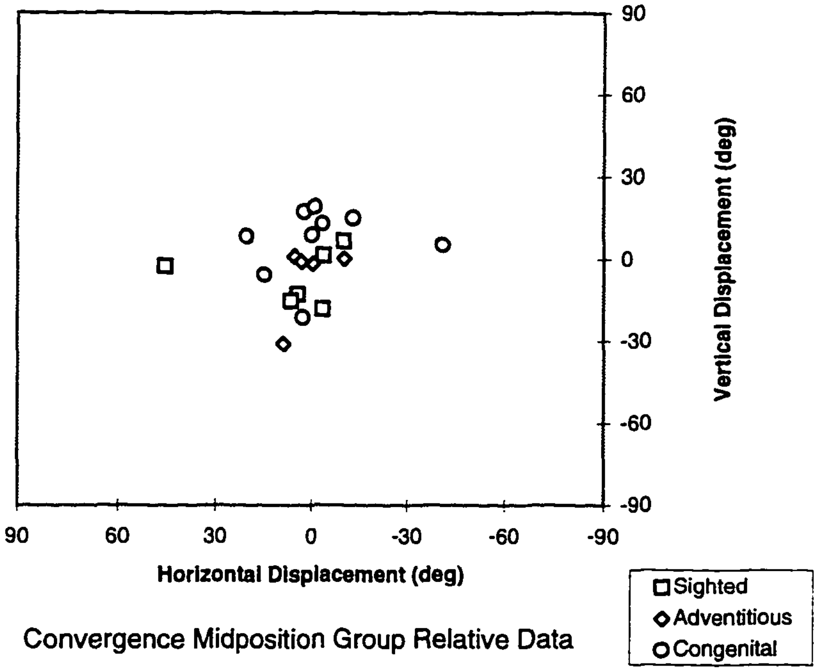
Left Midposition Group Relative Data

I



Convergence Extreme Group Relative Data

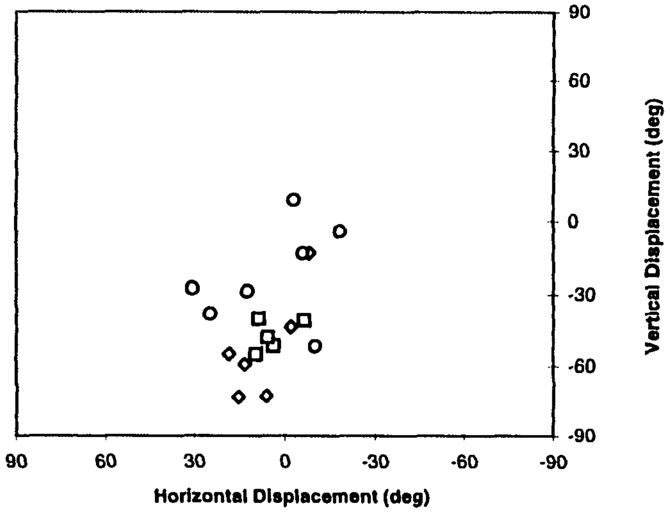
J



Convergence Midposition Group Relative Data

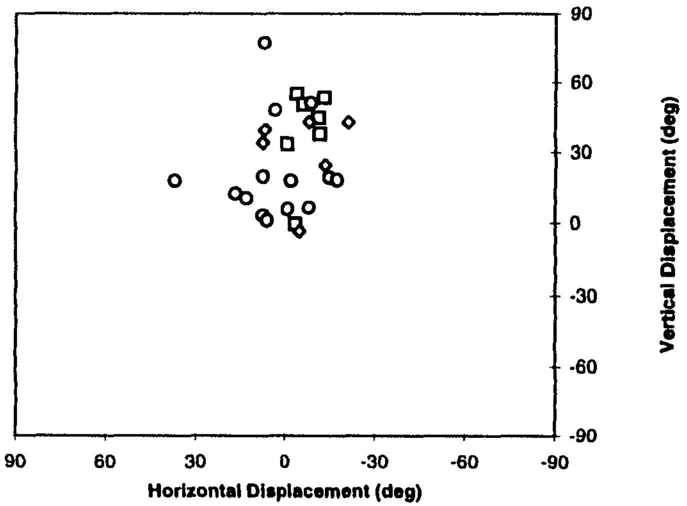
Figure 11. Directional and simulated convergence responses, group absolute data. Panels A-J show polar plots of group data (sighted: N=9, adventitiously blind: N=10, congenitally blind: N=16) for each directional and simulated convergence response. Each data point denotes one individual's data.

A



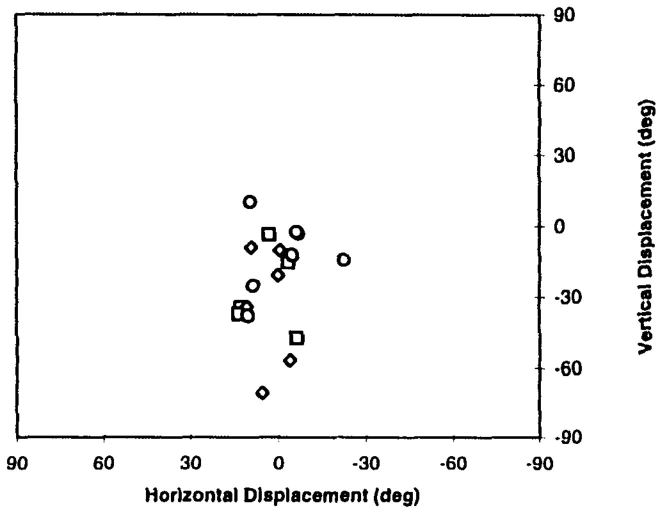
Down Extreme Group Absolute Data

B



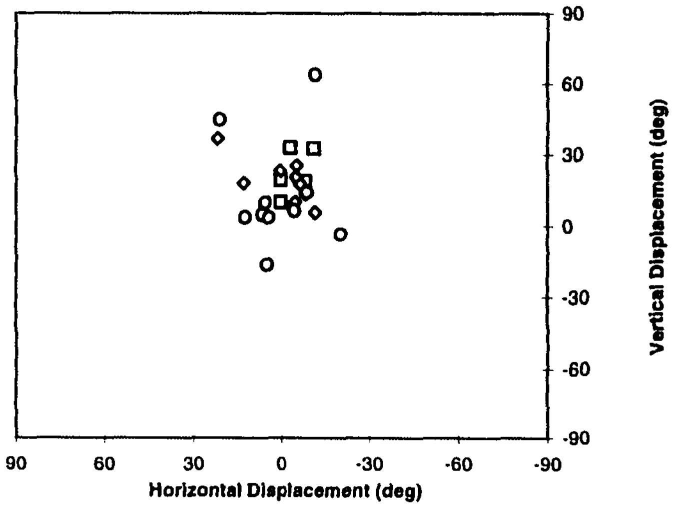
Up Extreme Group Absolute Data

C



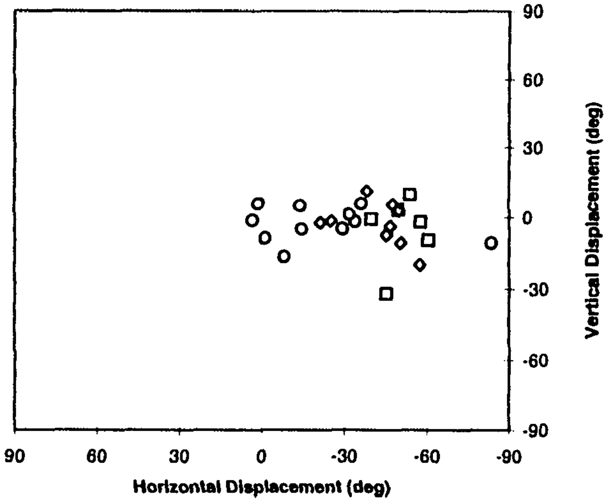
Down Midposition Group Absolute Data

D



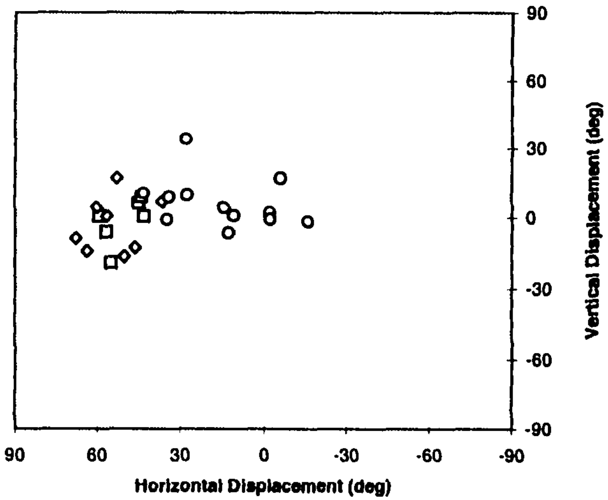
Up Midposition Group Absolute Data

E



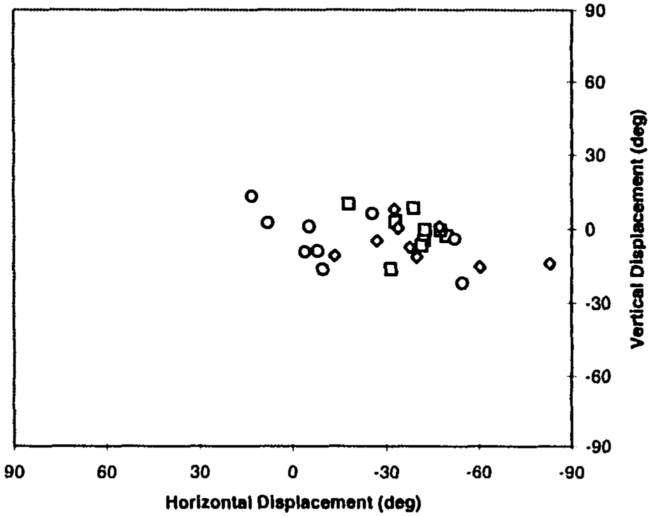
Right Extreme Group Absolute Data

F



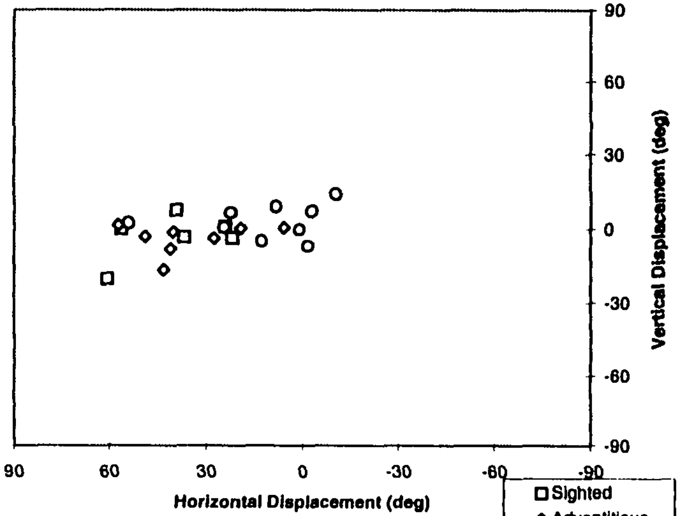
Left Extreme Group Absolute Data

G



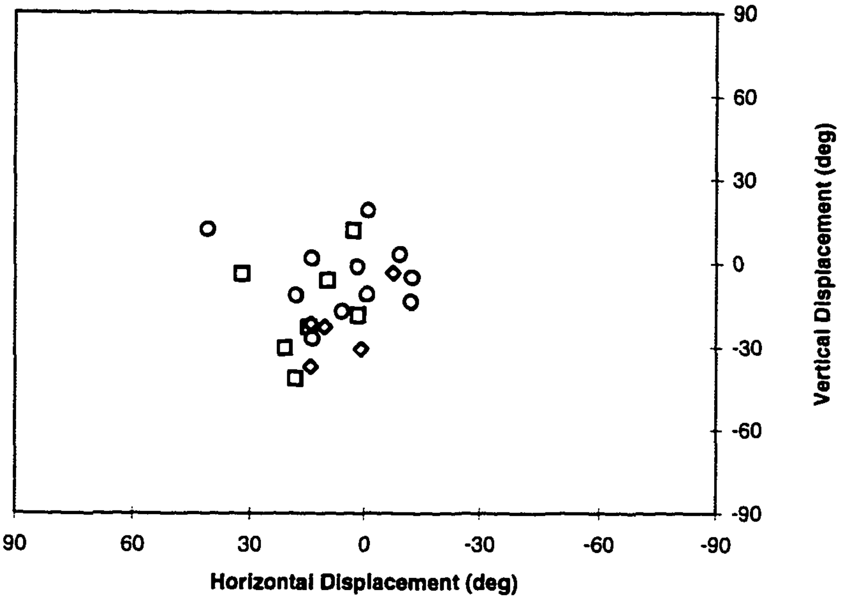
Right Midposition Group Absolute Data

H



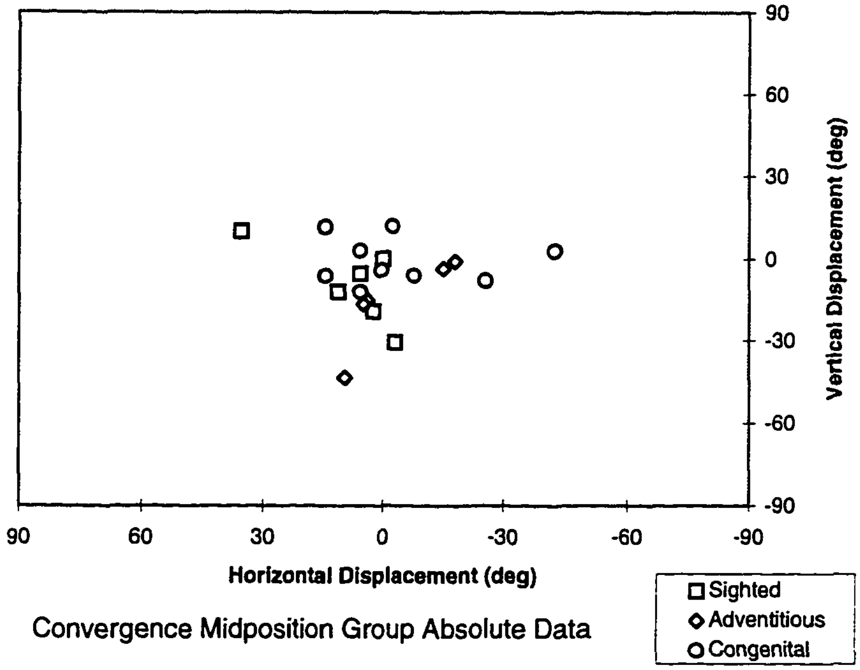
Left Midposition Group Absolute Data

I



Convergence Extreme Group Absolute Data

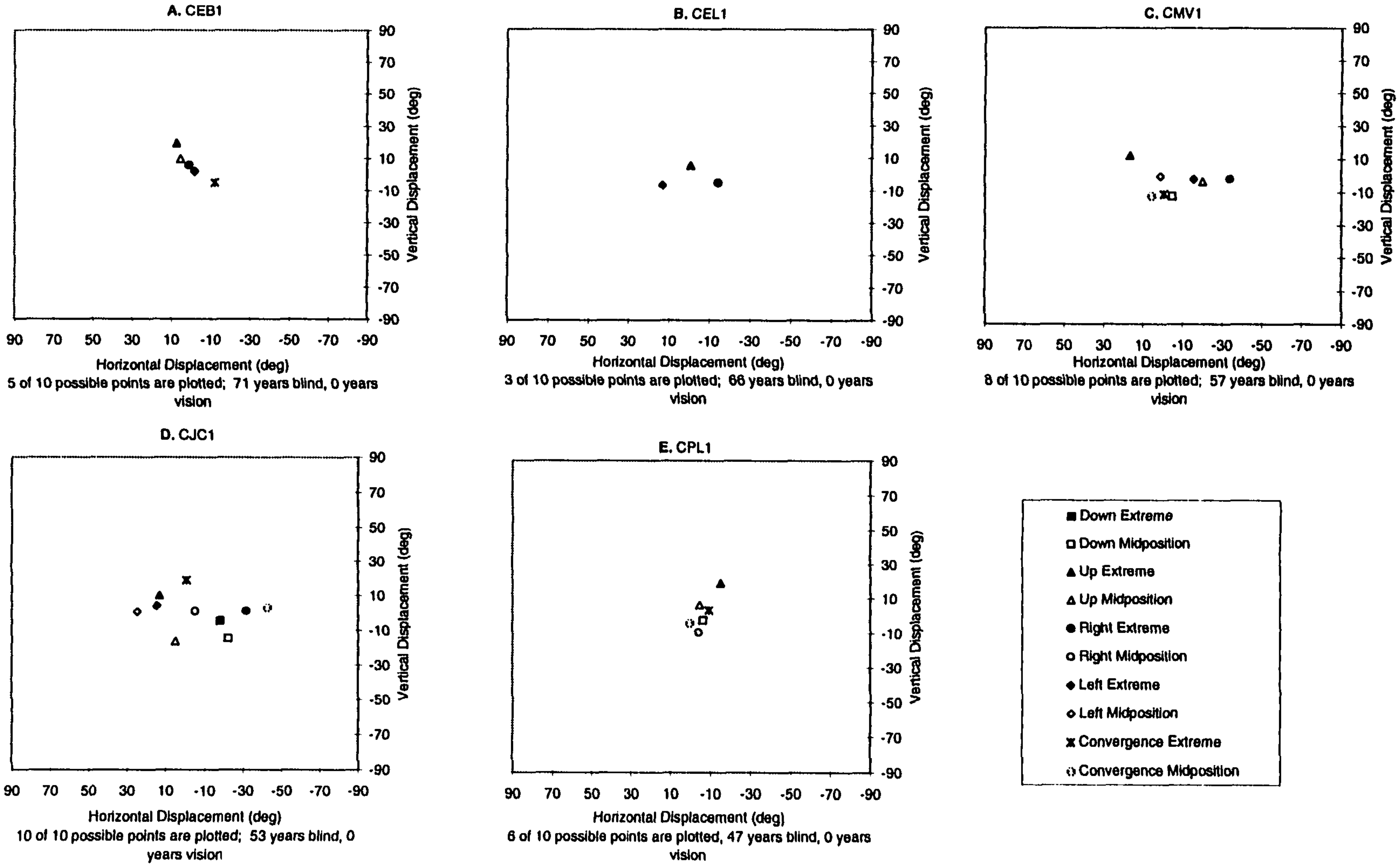
J



Convergence Midposition Group Absolute Data

Figure 12. Directional and simulated convergence responses, individual absolute data. Panels A-AI show individual polar plots of the absolute eye displacements of all available directional and simulated convergence responses. Years vision, years blindness, and number of datapoints plotted are shown.

Congenital Absolute



A. CEB1: 5 of 10 possible points are plotted; 71 years blind, 0 years vision

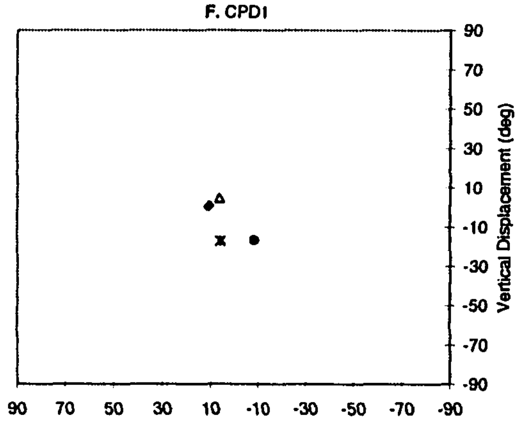
B. CEL1: 3 of 10 possible points are plotted; 66 years blind, 0 years vision

C. CMV1: 8 of 10 possible points are plotted; 57 years blind, 0 years vision

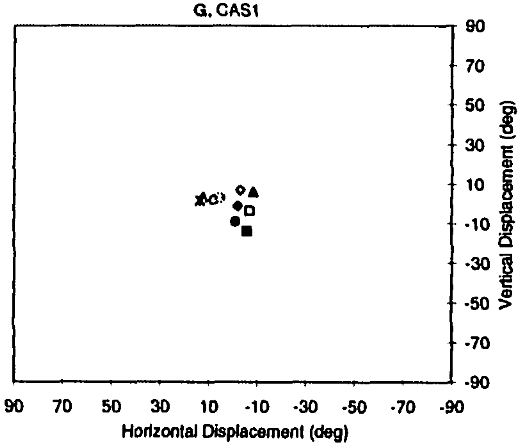
D. CJC1: 10 of 10 possible points are plotted; 53 years blind, 0 years vision

E. CPL1: 6 of 10 possible points are plotted, 47 years blind, 0 years vision

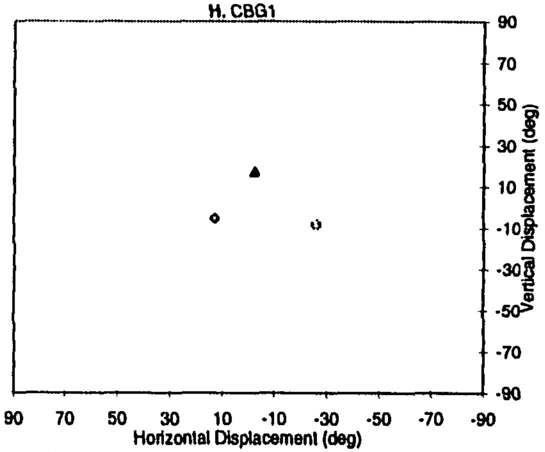
Congenital Absolute



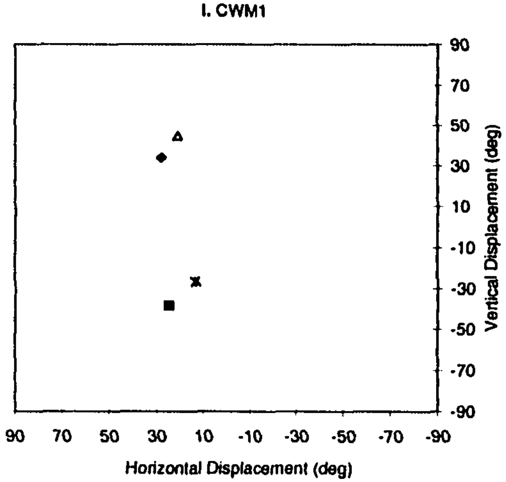
4 of 10 possible points are plotted; 44 years blind, 0 years vision



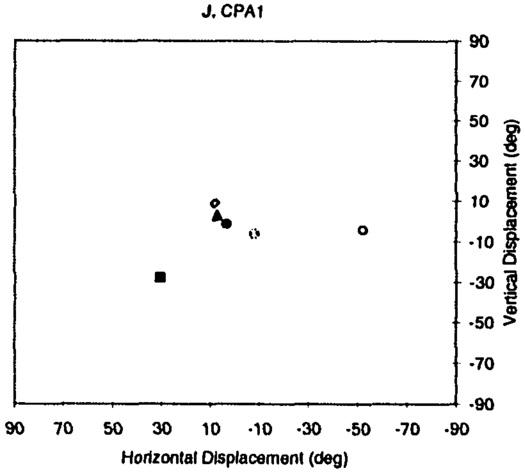
10of 10 possible points are plotted; 43 years blind, o years vision



3 of 10 possible points are plotted; 43 years blind, 0 years vision



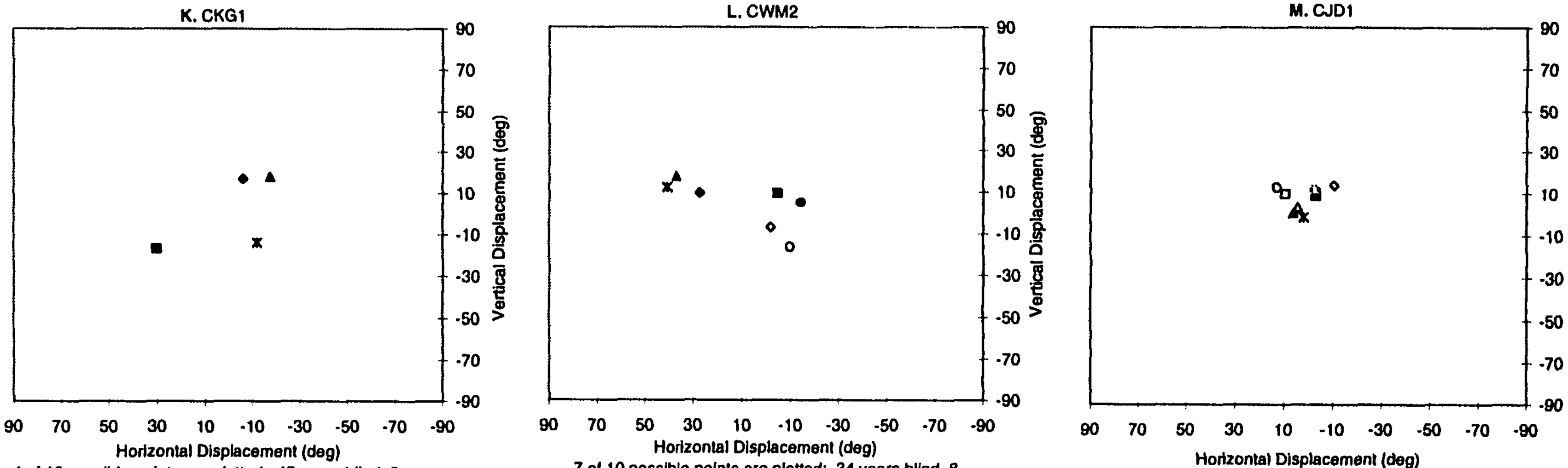
4 of 10possible points are plotted; 41 years blind, 0 years vision



6 of 10 possible points are plotted; 39 years blind, 0 years vision

■ Down Extreme
□ Down Midposition
▲ Up Extreme
△ Up Midposition
● Right Extreme
○ Right Midposition
◆ Left Extreme
◇ Left Midposition
✱ Convergence Extreme
☼ Convergence Midposition

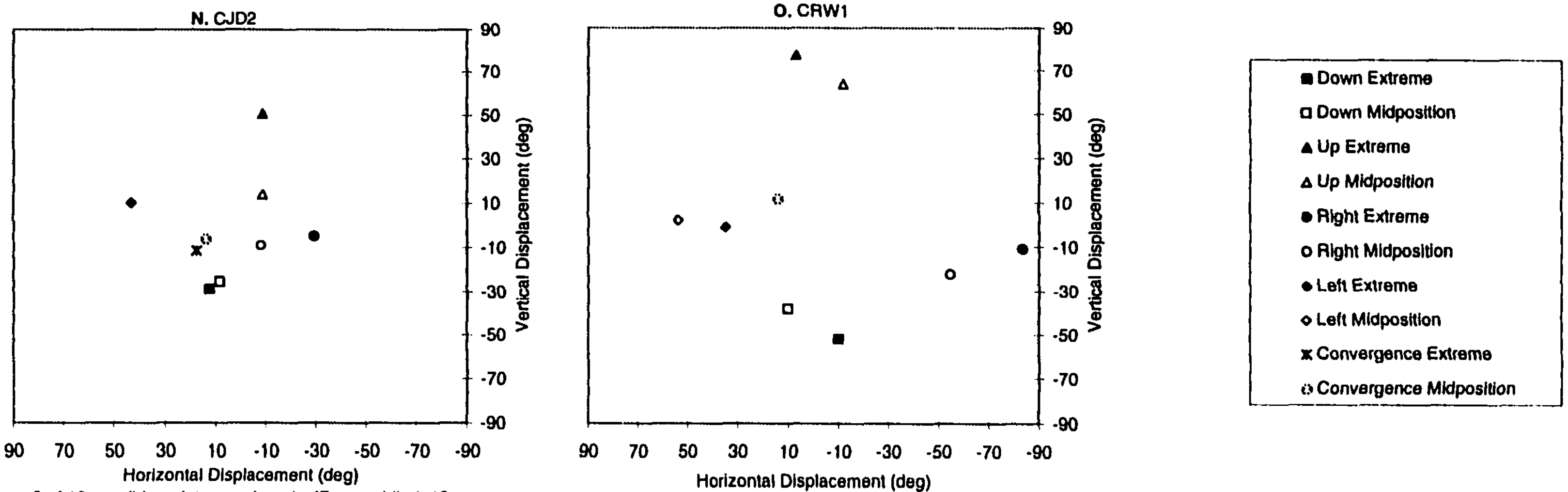
Congenital Absolute



4 of 10 possible points are plotted; 45 years blind, 3 years vision

7 of 10 possible points are plotted; 34 years blind, 8 years vision

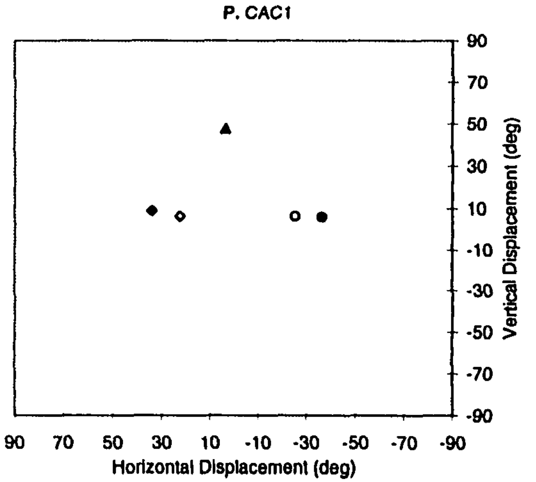
8 of 10 possible points are plotted; 19 years blind, 9 years vision



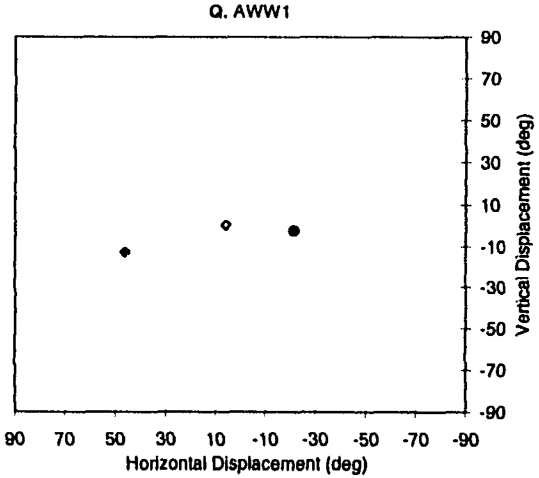
9 of 10 possible points are plotted; 47 years blind, 10 years vision

9 of 10possible points are plotted; 25 years blind, 11 years vision

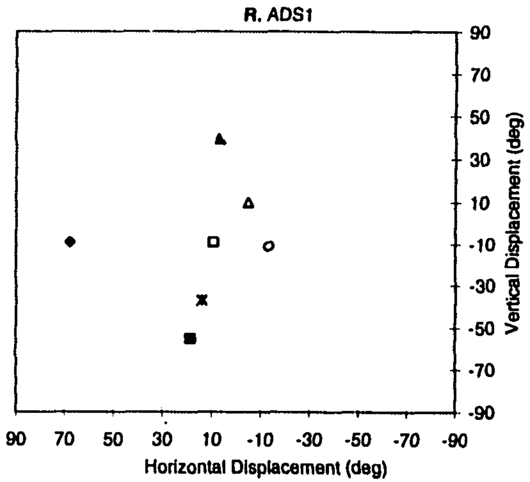
Congenital and Adventitious Absolute



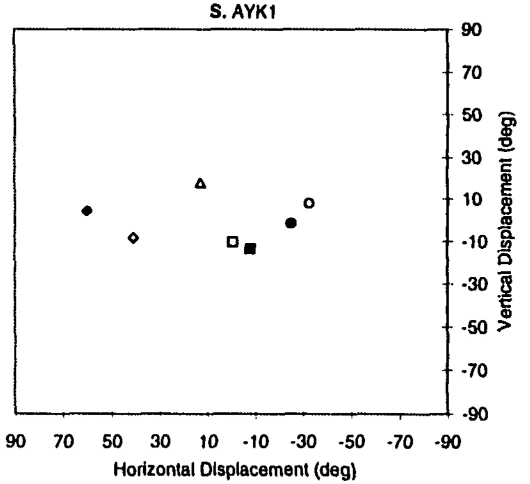
4 of 10 possible points are plotted; 24 years blind, 18 years vision



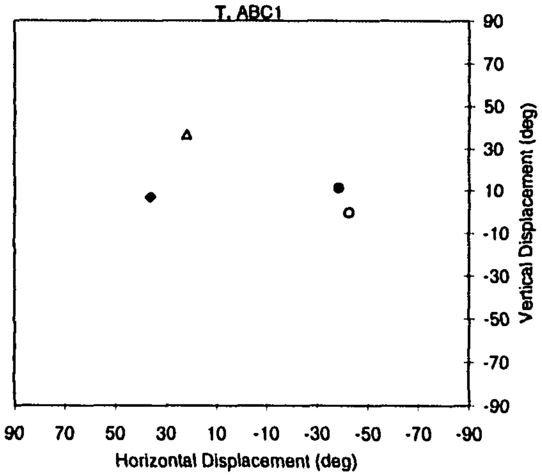
3 of 10 possible points are plotted; 45 years blind, 13 years vision



7of 10 possible points are plotted; 19 years blind, 15 years vision



7 of 10 possible points are plotted; 23 years blind, 19 years vision

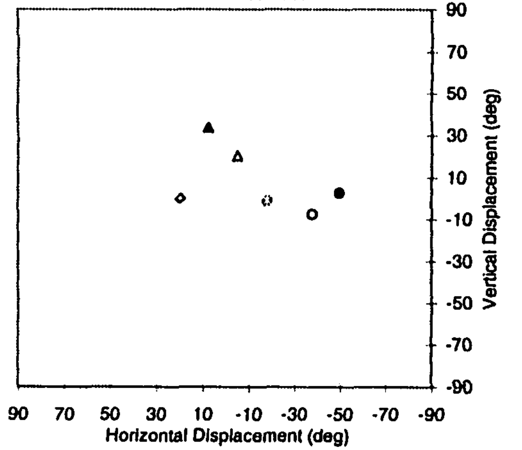


4 of 10 possible points are plotted; 17 years blind, 21 years vision

■ Down Extreme
□ Down Midposition
▲ Up Extreme
△ Up Midposition
● Right Extreme
○ Right Midposition
◆ Left Extreme
◇ Left Midposition
✱ Convergence Extreme
○ Convergence Midposition

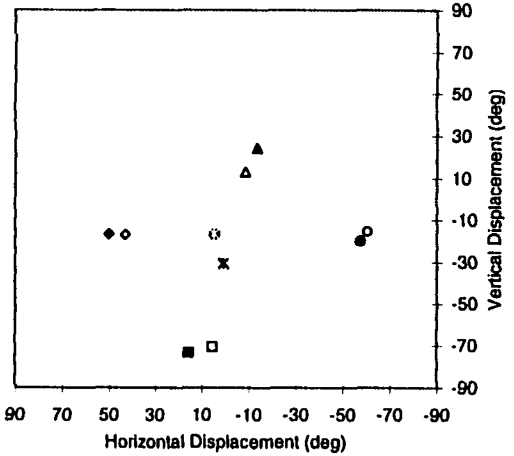
Adventitious Absolute

U. APM1



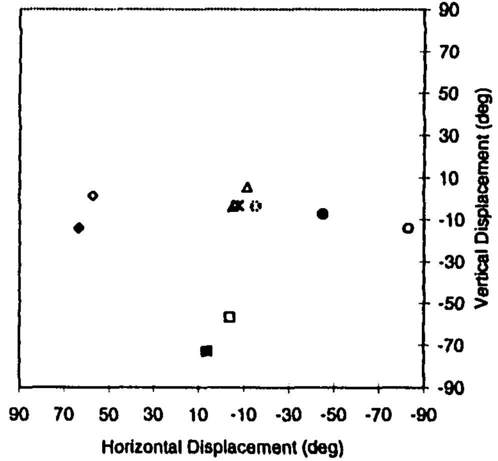
8 of 10 possible points are plotted; 15 years blind, 25 years vision

V. AOR1



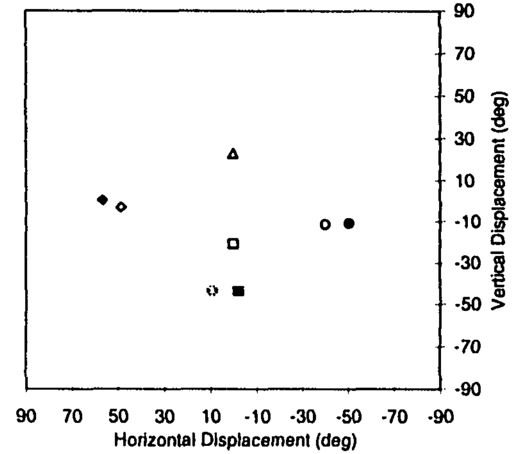
10 of 10 possible points are plotted; 10 years blind, 28 years vision

W. ABH1



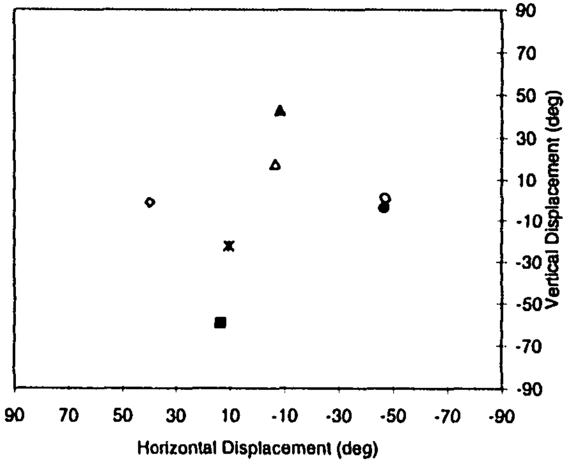
10 of 10 possible points are plotted; 19 years blind, 39 years vision

X. ABR1



8 of 10 possible points are plotted; 2 years blind, 47 years vision

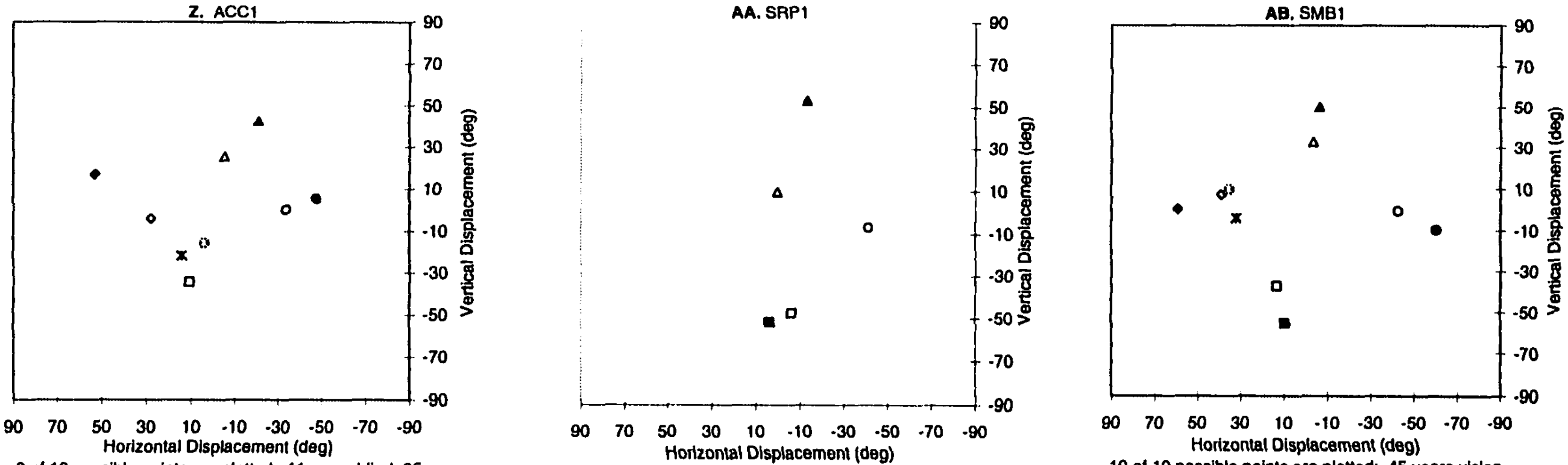
Y. ARC1



7 of 10 possible points are plotted; 9 years blind, 54 years vision

- ■ Down Extreme
- □ Down Midposition
- ▲ Up Extreme
- △ Up Midposition
- ● Right Extreme
- ○ Right Midposition
- ◆ Left Extreme
- ◇ Left Midposition
- ✱ Convergence Extreme
- ✲ Convergence Midposition

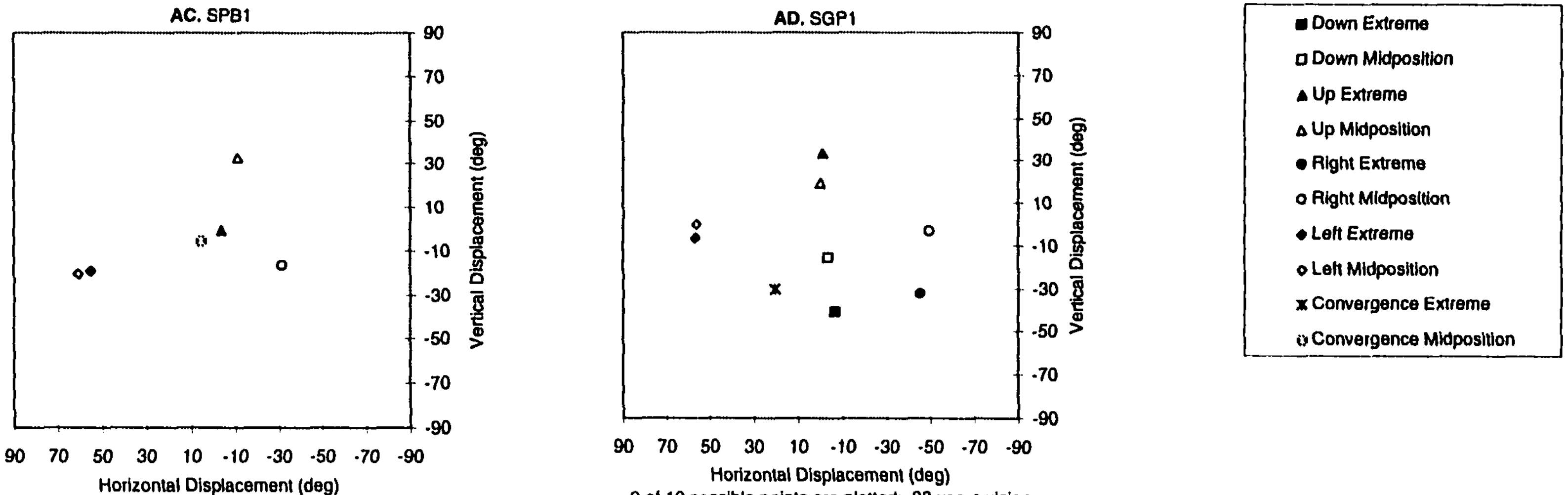
Adventitious and Sighted Absolute



9 of 10 possible points are plotted; 11 years blind, 65 years vision

5 of 10 possible points are plotted; 48 years vision

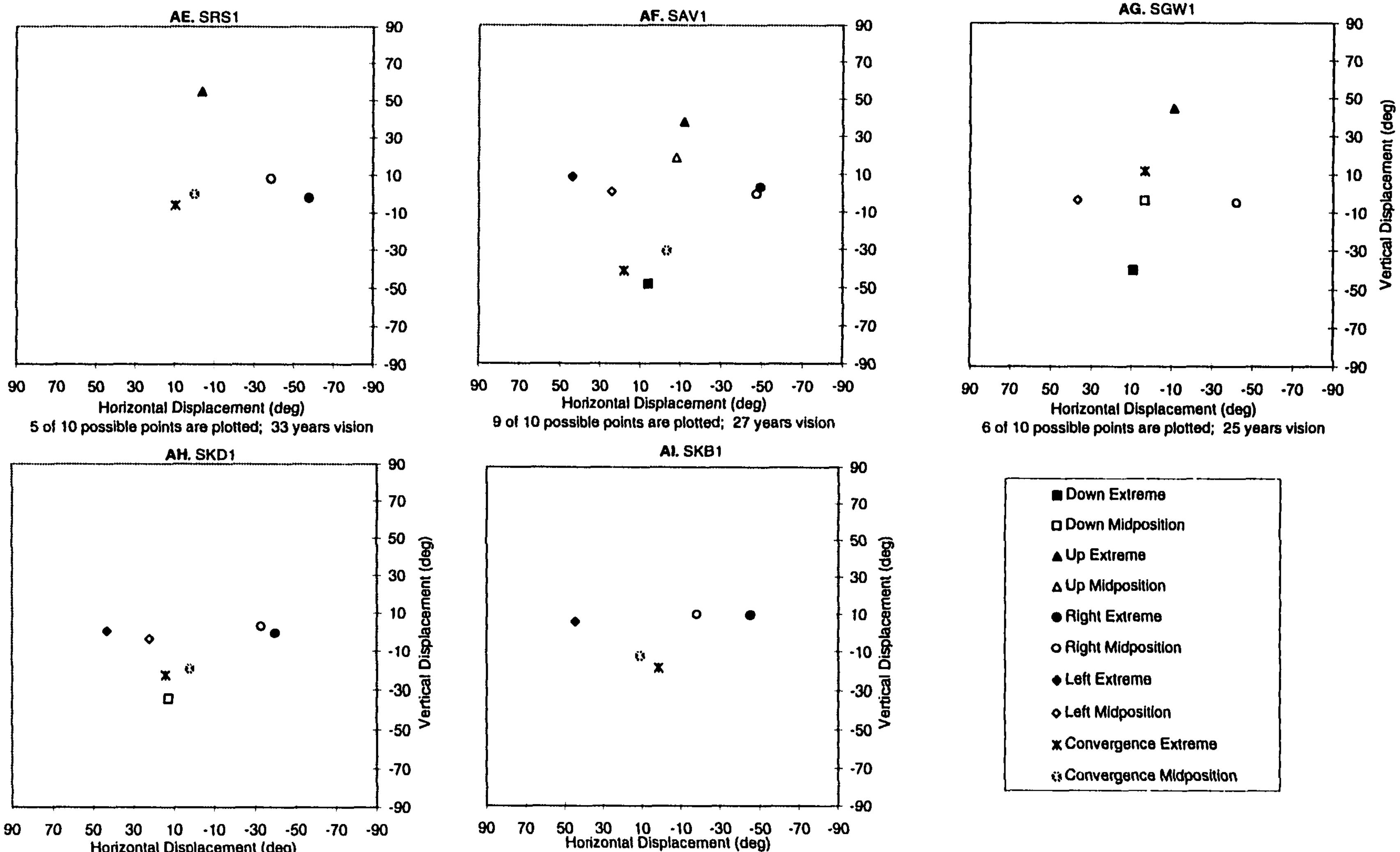
10 of 10 possible points are plotted; 45 years vision



6 of 10 possible points are plotted; 34 years vision

9 of 10 possible points are plotted; 33 years vision

Sighted Absolute



AE. SRS1: 5 of 10 possible points are plotted; 33 years vision

AF. SAV1: 9 of 10 possible points are plotted; 27 years vision

AG. SGW1: 6 of 10 possible points are plotted; 25 years vision

AH. SKD1: 7of 10 possible points are plotted; 20 years vision

AI. SKB1: 5 of 10 possible points are plotted; 25 years vision

On an individual basis, the sighted participants who responded most appropriately and for whom all/almost all datapoints were available include SMB1, SGP1 and SAV1. Most of the points plotted from SRS1 were relatively appropriate, as were those from SRP1. Sighted individuals whose patterns were less impressive include SKB1, SGW1 (although just six and seven datapoints were available from these participants respectively), and SPB1. Interestingly, the vision/medical history collected from SPB1 suggested that he may have been treated (successfully) for strabismus during childhood (see Table 6). The direction of responses produced by adventitiously blind individuals was correct nearly universally. Polar plots of absolute data from a few of the congenitally blind participants did appear similar to those of some of the adventitiously blind or sighted. Examples of tightly clustered patterns of congenitally blind participants, evidencing little if any voluntary oculomotor control, include those of CPL1 CJD1, CPD1, CAS1 and CEB1. Thus a division may be discerned among the patterns of the participants classified as congenitally blind, for example, those of CRW1 and CAC1 might be described as resembling patterns of either of the other two groups. Typically, these were individuals who had had vision for several years, underscoring the classification difficulties which were encountered in this study. In addition, patterns of certain of the congenitally blind participants are intermediate in scatter; this may be true, for example, of CBG1, although very few datapoints were available in this case. Of the congenitally blind participants whose graphs did denote some level of oculomotor control, more "mistakes" of direction appeared to have taken place: CWM1, for example, produced eye movements up and to the left equivalently, in response to both the "up" and "left" extreme instructions.

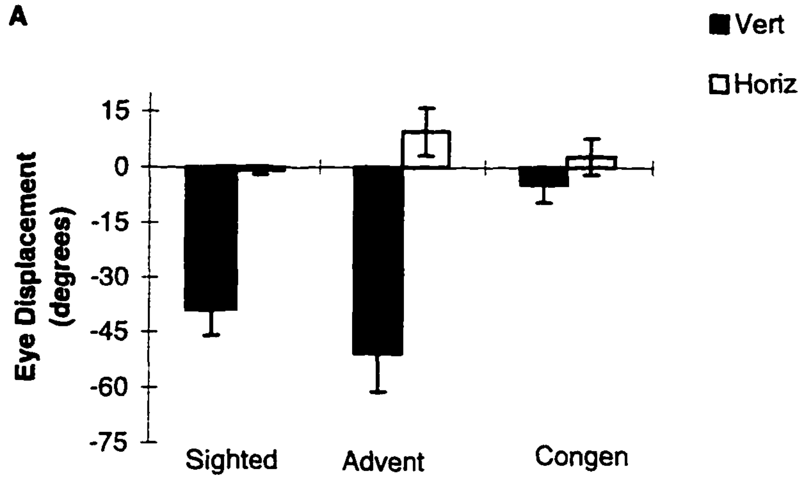
The evident disparities among the graphs plotted of individuals' data highlighted the need for more in-depth group data quantification and comparison. Within-group calculations were therefore performed to yield means (and the corresponding standard error of the mean, SEM), of the horizontal and vertical components of directional responses. Figure 13A-H contains bar graphs, with SEM error bars, displaying results of the calculations made using relative data, while Figure 14A-H contains analogous information obtained using absolute data. Clear group differences emerged despite the lack of within-group uniformity in visual experience of the participants classified as adventitiously versus congenitally blind. The group of sighted individuals was characterized generally by eye displacements which were largest in the correct direction. The group of participants classified as adventitiously blind displayed smaller displacements but produced patterns similar to those of the sighted group. An exception was that the sighted group showed smaller displacements in the correct directions in response to the "look down as far as you can" request. Values of eye displacement were very small in the group comprised of those termed congenitally blind, in either the requested or any other direction.

Visual Experience and Extreme Directional Responses

To examine the relationship between visual experience and oculomotor control in more detail than was possible via the foregoing analyses, another series of graphs was created (see Figure 15A-D). Using the appropriate component of the absolute data, the "extreme"

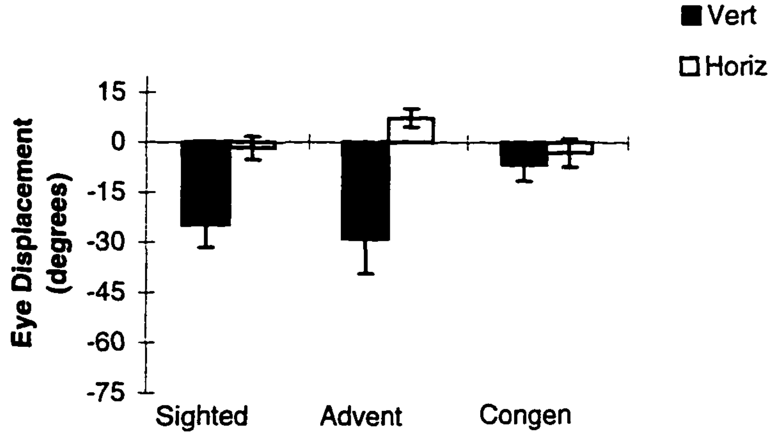
Figure 13. Mean of within-group horizontal and vertical components of directional responses, relative data. Panels A-H show data separately for each directional instruction. Error bars denote standard error of the mean, SEM.

A



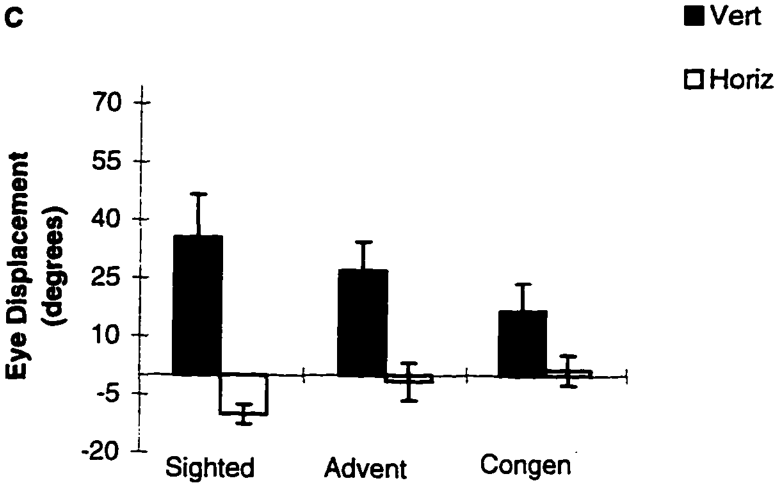
Down extreme group mean displacements, relative data.

B



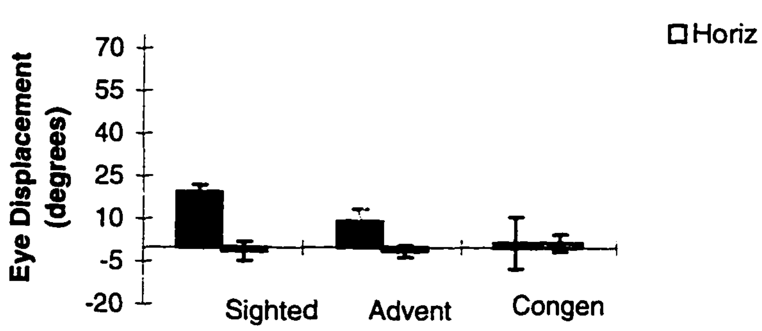
Down midposition group mean displacements, relative data.

C



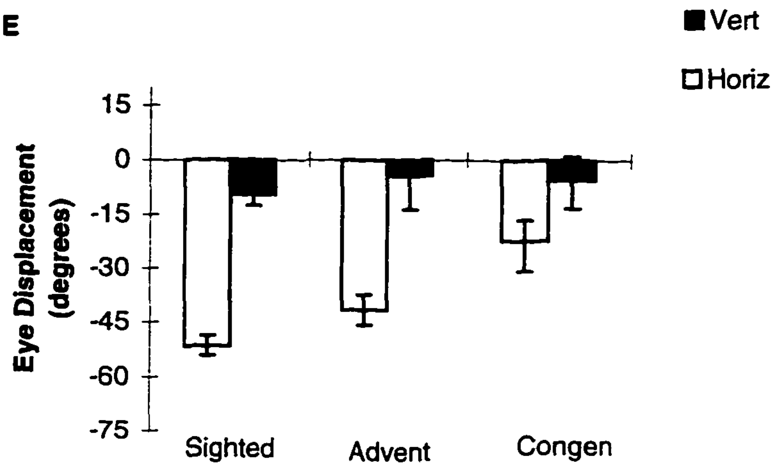
Up extreme group mean displacements, relative data.

D



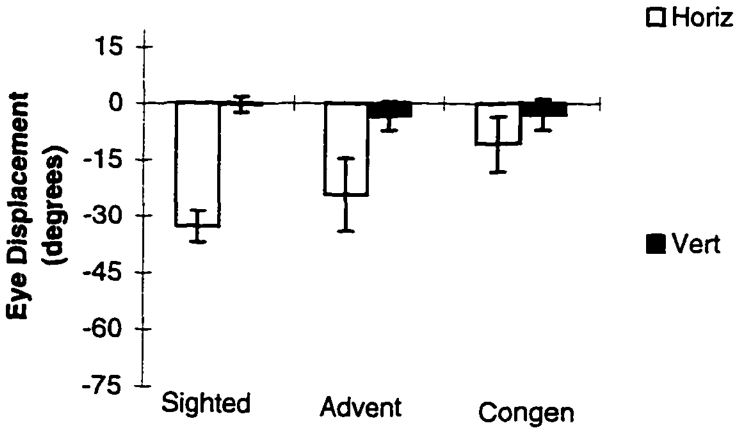
Up midposition group mean displacements, relative data.

E



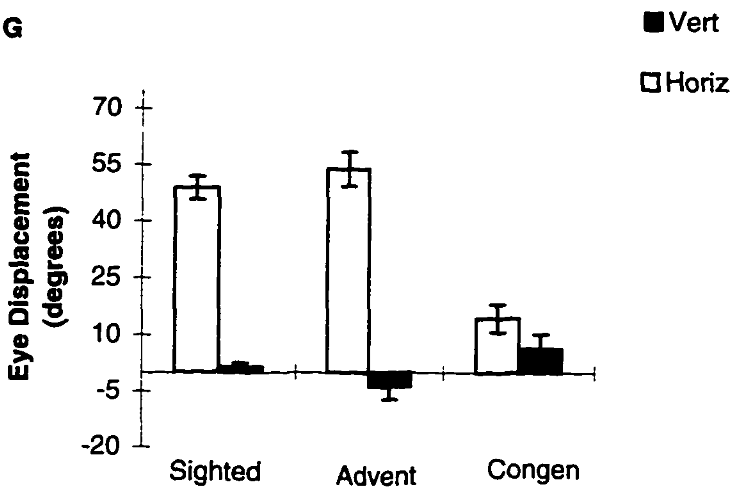
Right extreme group mean displacements, relative data.

F



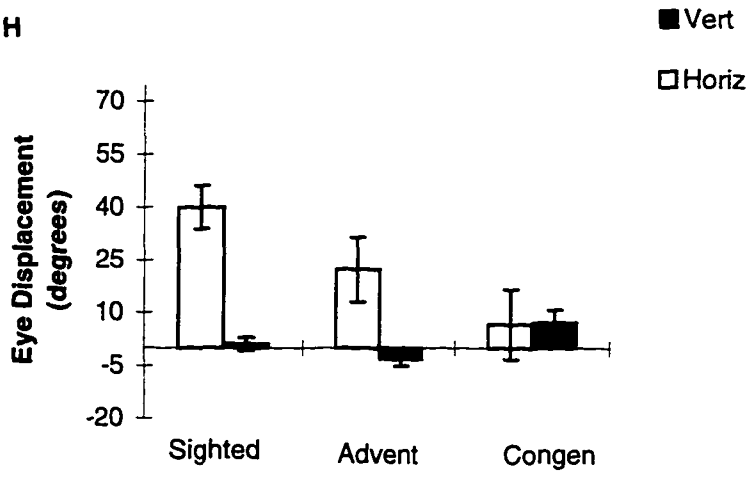
Right midposition group mean displacements, relative data.

G



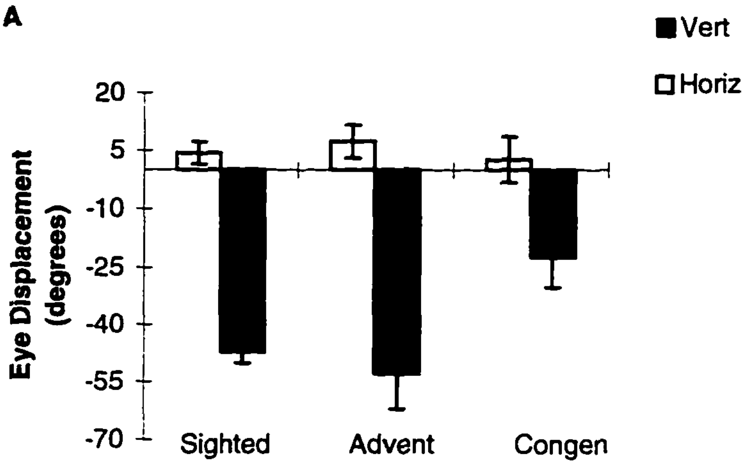
Left extreme group mean displacements, relative data.

H

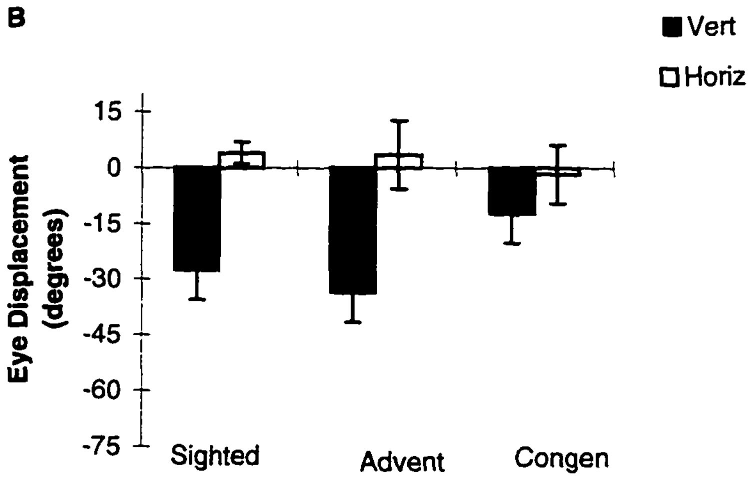


Left midposition group mean displacements, relative data.

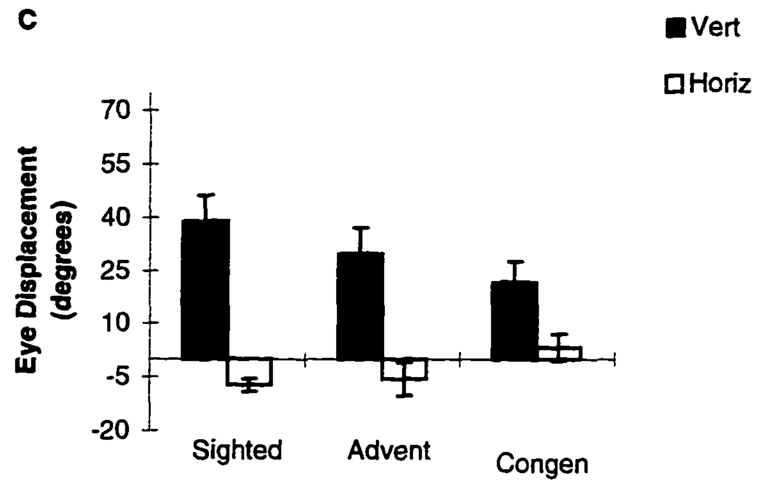
Figure 14. Mean of within-group horizontal and vertical components of directional responses, absolute data. Panels A-H show data separately for each directional instruction. Error bars denote standard error of the mean, SEM.



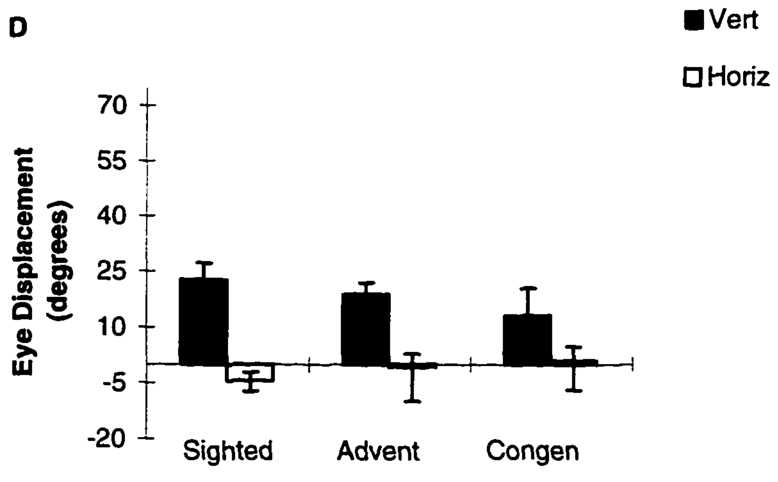
Down extreme group mean displacements, absolute data.



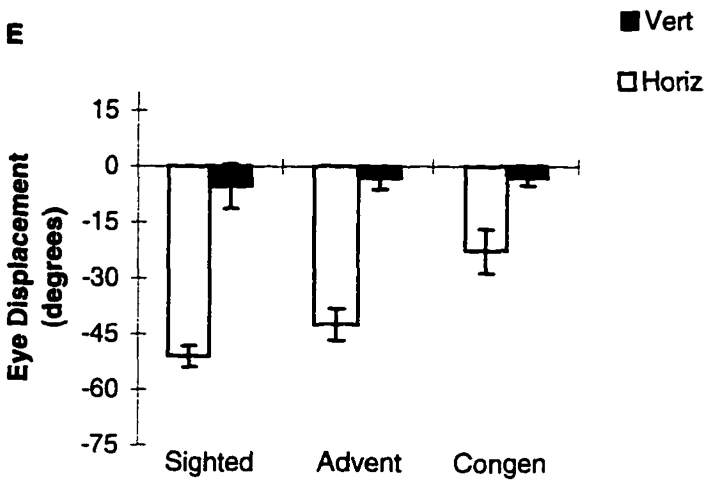
Down midposition group mean displacements, absolute data.



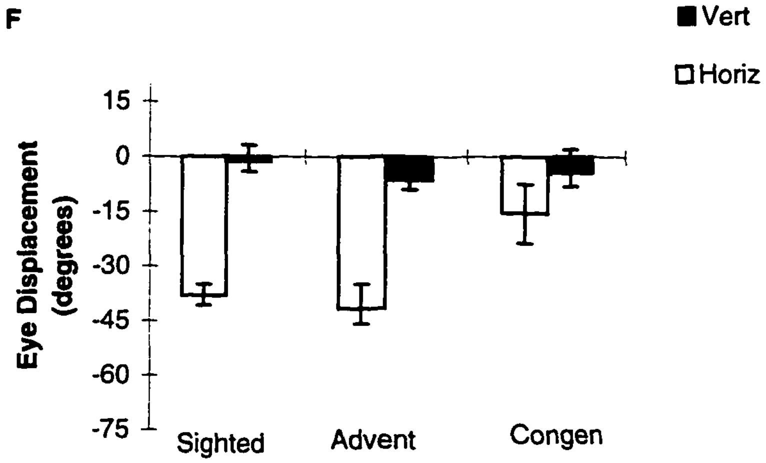
Up extreme group mean displacements, absolute data.



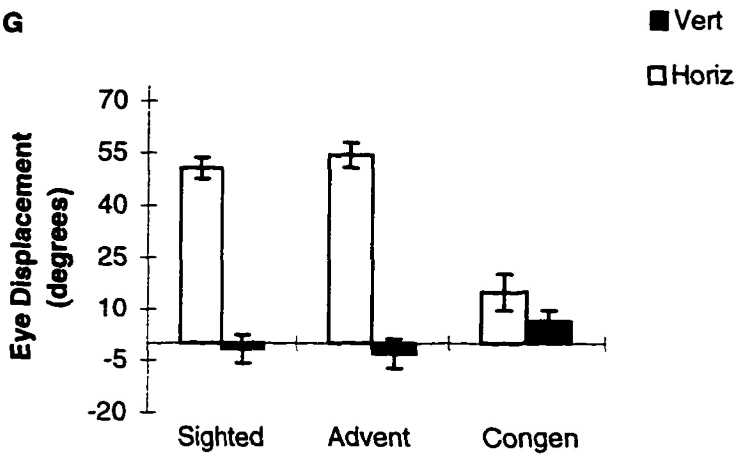
Up midposition group mean displacements, absolute data.



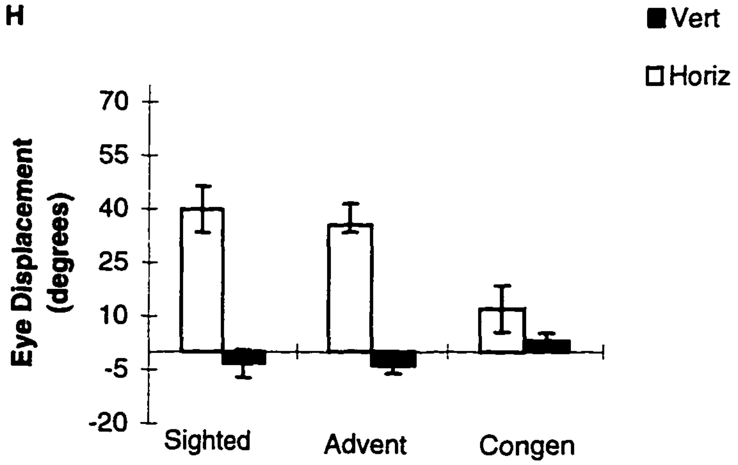
Right extreme group mean displacements, absolute data.



Right midposition group mean displacements, absolute data.



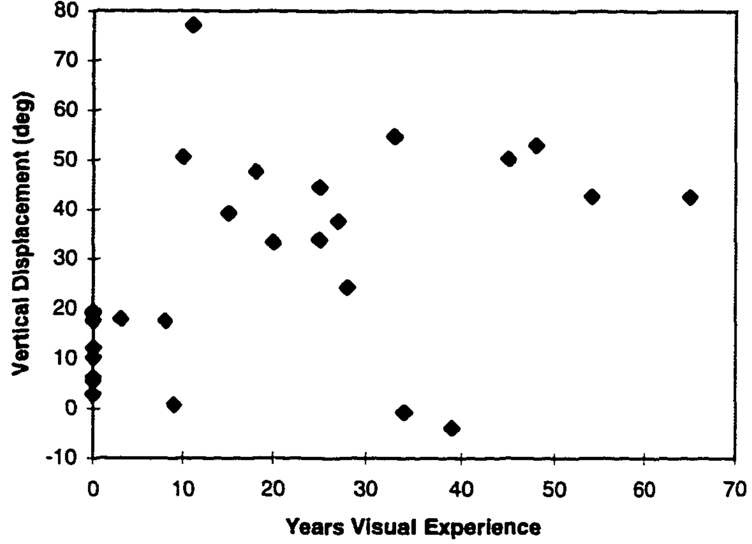
Left extreme group mean displacements, absolute data.



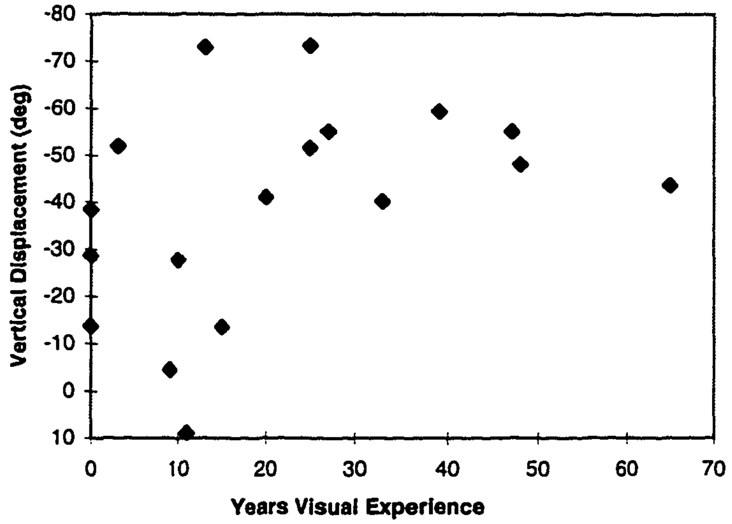
Left midposition group mean displacements, absolute data.

Figure 15. "Extreme" directional responses versus number of years of visual experience. Panels A-D plot either the vertical or the horizontal component of available absolute data, based on the corresponding direction of the "up," "down," "left" or "right" eye movement request.

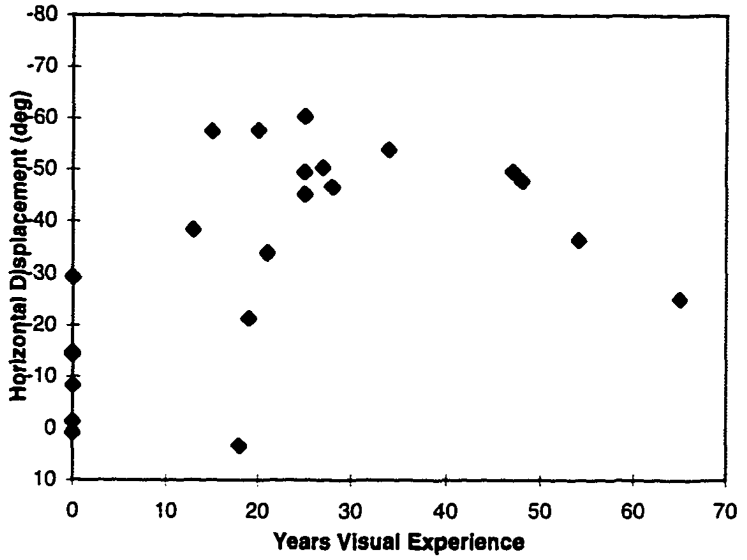
A Up extreme vertical absolute data versus visual experience



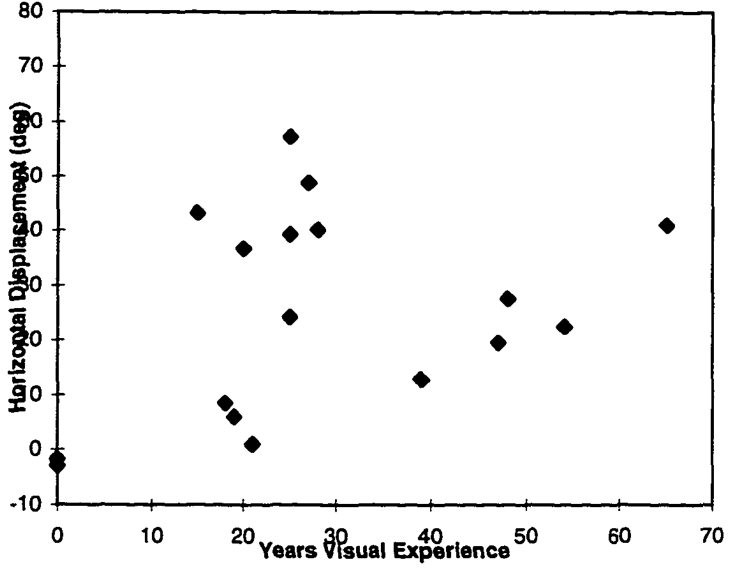
B Down extreme vertical absolute data versus visual experience



C Right extreme horizontal absolute data versus visual experience



D Left extreme horizontal absolute data versus visual experience

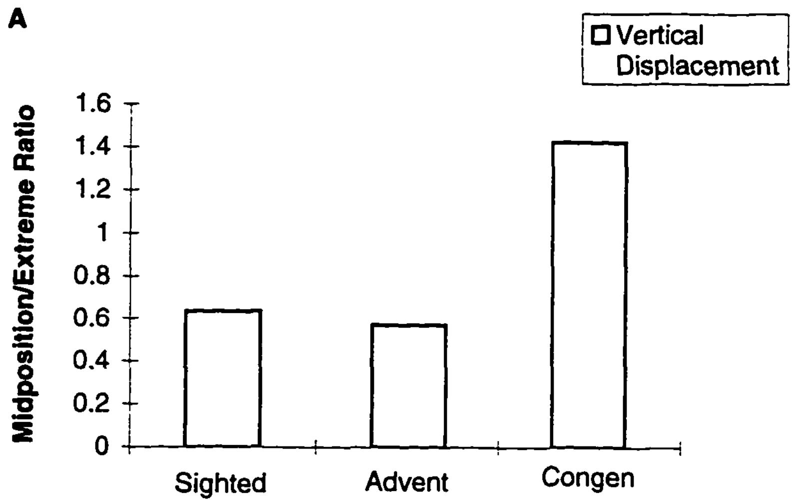


directional responses were plotted in relation to number of years of visual experience. That is, either the vertical or the horizontal component of available absolute data was employed, based on the corresponding direction of the "up," "down," "left" or "right" eye movement request. On the graph of responses made to the "look up as far as you can" instruction, a positive linear trend emerged for a portion of the data plotted. A regression analysis describing the line of best fit yielded an R^2 value = 0.18, and an r of 0.42. If data from the participants with zero years of visual experience were ignored, the linear trend displayed for part of the plot would disappear, resulting in scattered data and little or no trend upward. That is, there was a positive linear trend between absolute eye displacement and visual experience within the zero to five-to-ten years of visual experience time range. This trend is suggested although none of those who took part in this study reported having had either four, five, six or seven years of visual experience. Beyond approximately 10 years of visual experience, the datapoints form an approximately flat line centered between about 35 and 55 degrees vertical displacement. This overall pattern essentially repeats itself on each of the related plots of this type. The "down extreme" graph shows a fair spread of datapoints representing those with zero years of visual experience (to a greater degree than for the "up extreme" response), with vertical displacements of between -10 and -40, while those with over 20 years of vision are clumped between -40 and -60. An exception is a datapoint for one participant with about 2 years visual experience, plotting at around minus fifty. For the "left extreme" responses, more clustering at very small values of horizontal displacement took place than was seen in the "up" or "down" plots among participants with zero years vision, whereas the graph of the "right extreme" responses in relation to years of visual experience more closely resemble the "up" and "down" plots. The "left extreme" and "right extreme" graphs, taken together, differ somewhat from the "up extreme" and "down extreme" patterns. All four graphs denote that those participants classified as congenitally blind who had zero years of visual experience differed markedly from all of the other participants in this research.

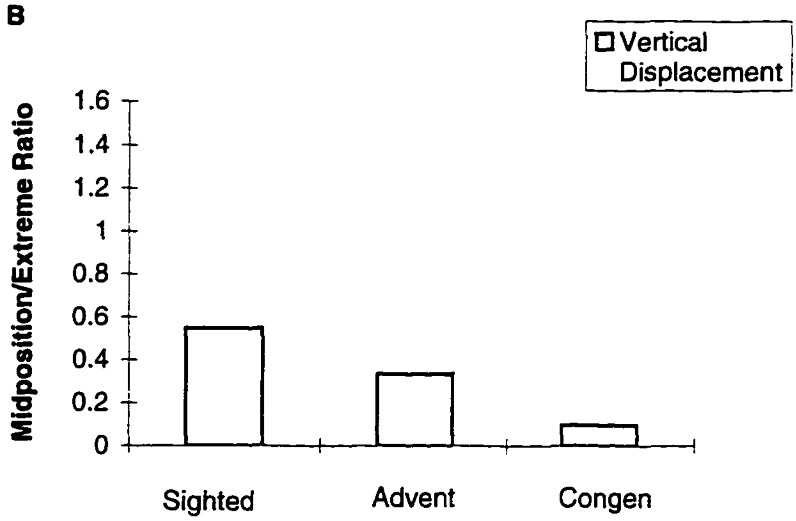
Midposition Response Accuracy

As a possible additional index of oculomotor control, "midposition response accuracy" was considered last. This was prompted by examination both of the individual and group polar plots. It was observed that the scaling of the size of movements made by adventitiously blind participants in response to "halfway" as compared with corresponding "all the way" instructions appeared to have been poorly controlled (see, e.g., Figure 12V, AOR1), although this was to an extent true of the sighted as well. Midposition ("halfway") response accuracy was defined as the ratio of the midposition response to its corresponding extreme ("all the way") response. On this basis the most accurately scaled midposition response yields a value of one half. Figure 16A-D and Figure 17A-D show the mean midposition scaling accuracy of the directional responses of each group, calculated using relative and absolute data respectively. Note that rather than plotting both the vertical and horizontal component of each response, only the component corresponding to the requested direction was graphed. Interestingly, the group of

Figure 16. Mean midposition scaling accuracy of directional responses, group relative data. Panels A-D show group data only for the component corresponding to the requested direction.

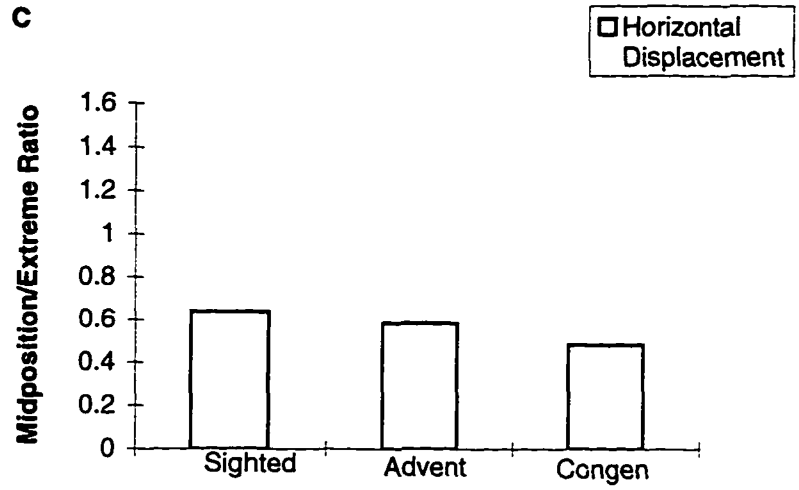


Down Midposition/Extreme accuracy, group relative data.



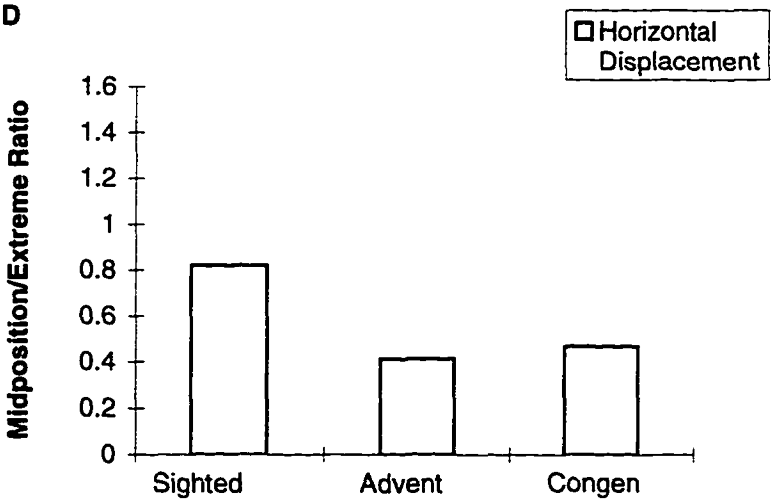
Up Midposition/Extreme accuracy, group relative data.

C



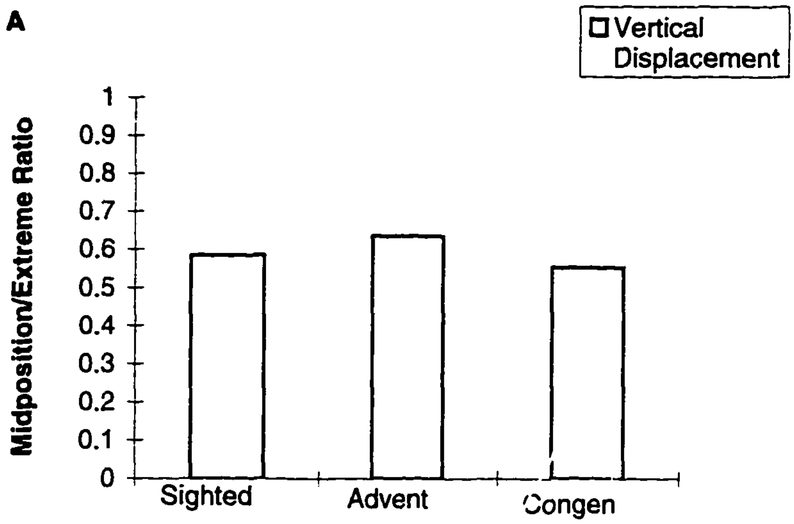
Right Midposition/Extreme accuracy, group relative data.

D

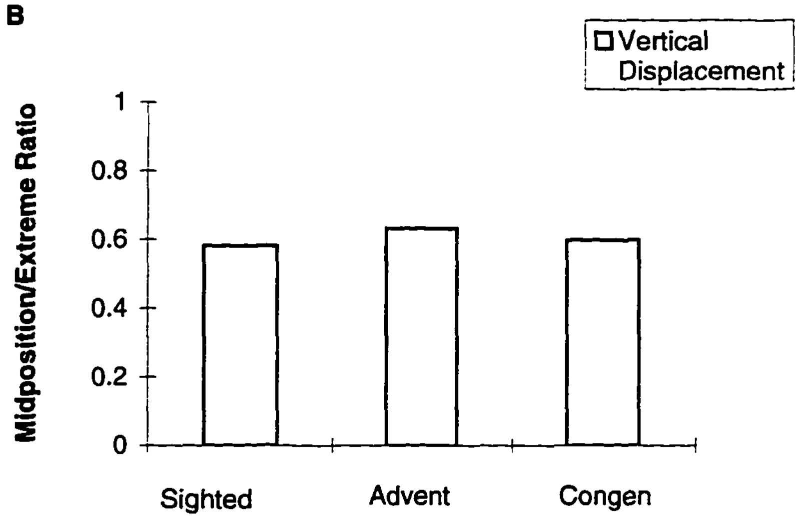


Left Midposition/Extreme accuracy, group relative data.

Figure 17. Mean midposition scaling accuracy of directional responses, group absolute data. Panels A-D show group data only the component corresponding to the requested direction.

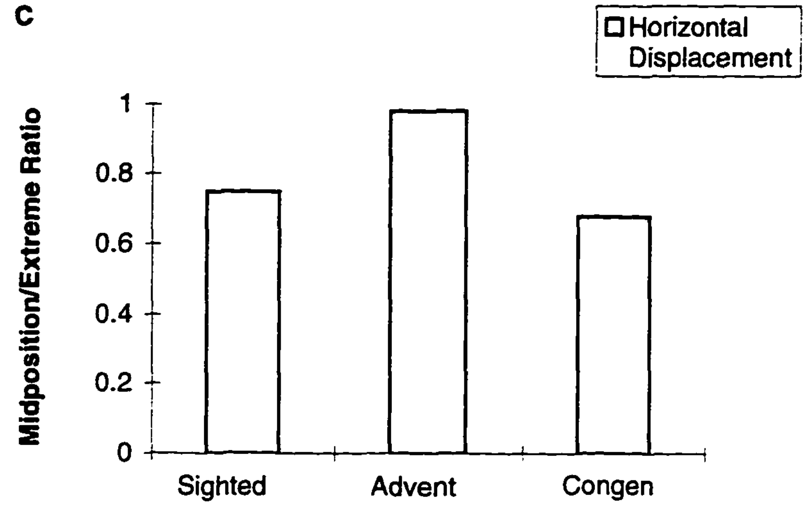


Down Midposition/Extreme accuracy, group absolute data.



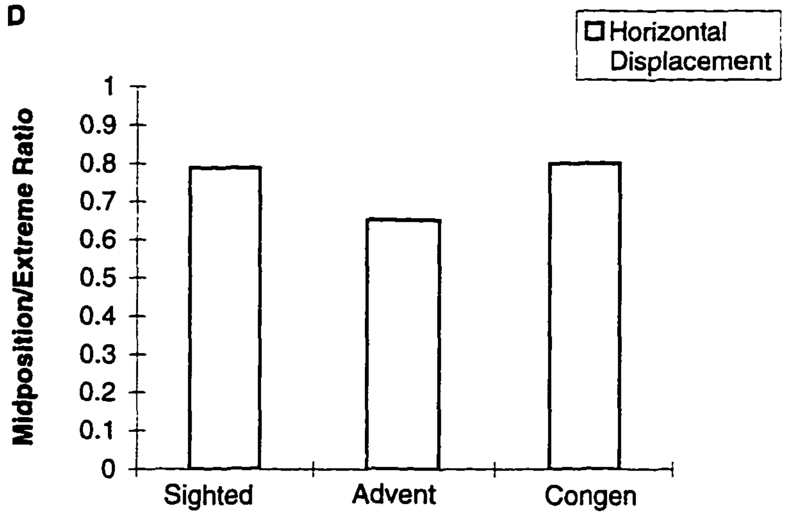
Up Midposition/Extreme accuracy, group absolute data.

C



Right Midposition/Extreme accuracy, group absolute data.

D



Left Midposition/Extreme accuracy, group absolute data.

participants who were classified as congenitally blind had ratios closest to 0.50 most consistently when calculations were made using absolute data, and on this basis could be termed most accurate. This may be misleading, however, in light of the extremely small displacements produced by the group of participants classified as congenitally blind; for example, it may reflect the general phenomenon in motor performance wherein accuracy tends to decrease with response size. Such an effect would have caused the ratios displayed by the congenitally blind group to appear more accurate in the context of the available data. It is unknown whether the groups of sighted or adventitiously blind participants could have produced equal or greater midposition accuracy values had they been requested (and been able) to make equivalently small responses. Another consideration in interpreting the application of the adopted definition of midposition accuracy for use in analyzing the available data is that the instruction set neither requested the individual to look halfway to his/her previous (corresponding) extreme position nor to look to a location related to his/her prior SA position. Rather the "halfway" directional requests were framed in terms either of the vertical or horizontal oculomotor range, in keeping with the pattern established for the corresponding "all the way" requests. If the participant's ability to interpret or carry out the preceding "extreme" request precluded him/her from moving the eyes to the true extreme of his/her oculomotor range, then the midposition accuracy calculations contain confounded accuracy data. Despite these limitations, in all cases utilizing relative data, the group of sighted participants produced larger midposition ratios than did the group of participants who were adventitiously blind.

Both of these groups "scaled" close to 0.50 quite consistently, while high variability characterized the group of congenitally blind participants.

Overview of Eye Movement Experiment Results

Considered en masse, the results of the analyses of the experimental data gathered in this research point to an important role of visual experience in human voluntary oculomotor control. Almost without exception, great similarities emerged between the group of sighted participants and the group classified as adventitiously blind; their results furthermore generally contrasted greatly with results obtained for the group of participants classified as congenitally blind. The number of years of visual experience common to participants in each group can hardly be ignored as the most likely basis for the trends observed. This is evidenced further by indications that subpopulations may be discerned within the participants classified as congenitally blind, in relation specifically to number of years of visual experience. To expand upon the evaluation of the analyses presented (thus far made within the context only of the experiment which generated them), what ensues is an effort to consider the results of this research in relation to past relevant work and to possible future research.

DISCUSSION

General Conclusions

This research supports the proposition that ongoing visual experience affects voluntary production of eye movements in adults. The duration of visual experience appears to be most salient through early childhood. In addition only a small amount of degradation of human voluntary oculomotor control apparently takes place after long-term adventitious blindness, that is, in the enduring absence of post-childhood visual experience. These findings, along with past related observations, can be used to estimate the age of onset of blindness beyond which additional visual experience no longer exerts a strong influence upon subsequent production of voluntary eye movements. Data from those who took part lead to the suggestion that vision experienced after approximately ages 8-10 years has a diminishing effect upon later attempts to move the eyes intentionally. This does not negate the possibility that this phenomenon may take place at an earlier age, in that there were few or no participants available with only four, five, six or seven years of visual experience. Other studies have for the most part been limited by the same constraint (e.g., Sherman, 1985; Kompf & Piper, 1987), but generally support the idea that several years of visual experience are prerequisite to subsequent production of identifiable voluntary oculomotor patterns similar to those of sighted "controls".

For purposes of this research, individuals whose blindness occurred at any point before age thirteen were classified as congenitally blind. Striking group differences in voluntary oculomotor ability emerged despite the wide time window encompassed by this classification criterion. Such strong evidence of group effects, regardless of the lack of homogeneity within the group of "congenitally" blind participants, adds weight to the present inferences. That is, in this group, the ages of onset of blindness form a bimodal distribution; had the effect been less pronounced, the influence of visual experience on subsequent oculomotor control might have been obscured due to the skew in the distribution toward a relatively late onset of blindness in childhood (characterizing several individuals included in this group).

Two of the participants, CBG1 and CEL1, who reported having had no visual experience nevertheless appear to have produced voluntary directional responses (see Figure 12), although only three datapoints were available from each individual. There are several ways to explain how these apparent aberrations arose. First, while the self-report method was the best tool available in this study for obtaining vision histories, it is not infallible. With the passage of time, these participants (one of whom was 43 and the other 66 years old at the time of testing), may have failed to recall early visual experience, or may not have remembered others' anecdotes of their having had any vision. In addition, it may be that a small amount of vision existed at an early age but was not discerned as such, or deemed salient, by the examining clinicians when the conditions (ROP and bilateral optic nerve atrophy) were diagnosed. Thus the observed behaviors may be consistent with the preponderance of the experimental data and reflect effects of visual experience not identified upon self-report. Also, there is the not uncontraversial possibility that subcortical visual pathways may have been functional in these individuals early in life, fostering oculomotor control related to "blindsight" (this may be less unlikely in individuals with early rather than post-childhood vision loss, for a discussion see Adams, Bodis-Wollner, Enoch, Jeannerod, & Mitchell, 1990). An argument against this is that it would appear that vision loss in these participants was sufficiently anterior anatomically to preclude such a mechanism.

The lack of uniformity of (post-childhood) visual experience among participants classified as adventitiously blind further supports the present conclusions. Duration of blindness ranged from a few years to several decades. Still, both within-group and in comparison to the group of sighted ("control") participants, the adventitiously blind group was little differentiated, on measures of response variability, magnitude or midposition accuracy.

Comparison with Past Related Research

As expected, the eye movement patterns of all groups bore less resemblance to visual saccades than to the "non-visual saccades" of previous reports (see Introduction sections "Human oculomotor orientation with non-visual stimuli" and "Human oculomotor orientation without visual experience"). Past consideration of oculomotor control in the absence of visual stimuli (e.g., in the dark) and/or visual experience centered on several variables. These include eye position sense, target accuracy, maintenance of gaze fixation and accuracy of re-fixation, as well as saccade number, duration, velocity and amplitude.

The non-visual stimulus conditions used in this study elicited an interesting differential effect upon eye position sense. Unsolicited, sighted and congenitally blind participants tended to remark on their sense of whether and how they had been able to produce eye movements in compliance with the requests. Rarely did this take place when evaluating adventitiously blind individuals. Reasons underlying the comments may differ by group. Congenitally blind participants reported having tried to follow the instructions, but judged that no eye movements had taken place despite their best efforts. Sighted individuals reported having been generally able to follow the instructions, but frequently underestimated the accuracy of their straight ahead responses. This may have arisen from the novelty of having visual feedback unavailable during fixation attempts. By contrast, participants classified as adventitiously blind responded simply and nearly unanimously in the affirmative when asked whether each could follow the instructions about where to move his/her eyes. These individuals perhaps had grown accustomed to no longer being able to depend on visual input for guidance of targeted eye movements, and had over time developed confidence not found among sighted individuals in making such self-judgments.

The relationship of target accuracy to the absence of visual input was not evaluated as such in this study. Past methods for eliciting targeted eye movements made toward specific locations in the dark involved sighted individuals' refixating a remembered visual target (e.g., Merton, 1961; Skavenski & Steinman, 1970; Riggs, et al, 1974; Hung, Ciuffreda, Semmlow, & Horng, 1994). Such a task would not have been possible for the participants in this study who were blind. The inclusion of "extreme" and "halfway" eye movement requests in the present experimental design, however, provided data on the vertical and horizontal oculomotor range and allowed for calculation of an alternative measure of scaling of "midposition accuracy;" this yielded new (albeit somewhat ambiguous) information about the relationship of visual experience to oculomotor control.

One feature of the present research common to much of the past related work was the inclusion of refixation to (simulated) primary position (e.g., Skavenski & Steinman, 1970; Heywood, 1973; Leigh & Zee, 1980; Leigh, et al, 1989. Although participants in this research were not asked to "look straight ahead and fixate," the SA response durations were adequate to consider them in this light. The concordance among the present and past findings supports the conclusion that visual experience influenced the observed group differences in gazeholding, as do a number of additional points. A fundamental aspect of eye position control which operates during visual fixation should be considered at this time and has been identified as follows: "The ability of an observer to maintain steady fixation on a test object is limited by involuntary eye tremor " (Riggs, Armington, & Ratliff, p. 315, 1954). The visual utility of the tremor is to refresh the retinal image, by periodically shifting its location, to preclude habituation of various elements responding in the retina (in turn preventing "disappearance" of the visual image). It is conceivable that in the dark or in an otherwise vision-deprived state an increase in tremor is brought about by the lack of visual input, leading to increase over time of eye instability during attempted fixation. However, possible darkness-induced increase in eye instability over relatively short time periods has been evaluated and was ruled out (Heywood, 1973) based on a lack of either potentiation or attenuation of refixation accuracy with practice in sighted individuals responding under non-visual stimulus conditions. Perhaps the gross eye instability common to congenitally blind individuals therefore arises from chronic visual deprivation an is an as-yet-unexplained pathological manifestation of the tremor phenomenon. Experimental evidence which could refute this possibility is lacking. A very few anecdotal reports exist of individuals gaining or regaining vision after long-term visual deprivation, but these contain little or no mention of oculomotor control(e.g., Von Feuerbach 1833/1966; Sacks, 1995). Regardless of its cause or potential for reversibility, such instability clearly seems incompatible with establishing primary position over a "normal" time course.

Another consideration in evaluating the present findings with regard to eye position control is that non-visual afferents reportedly can affect this variable (e.g., Dichgans, 1975; Steinman, 1975); head stabilization and instructions to the participants precluded this as a possible confound in the present research. Thus the clear group differences in variability of responses to the repeated straight ahead request support the parallel postulates that gazeholding and accuracy of re-fixation are influenced by (immediate) visual input and by visual experience.

The directional response data obtained in this study can be compared, to a limited extent, with results of past reports concerning non-visual saccade characteristics. As noted above, saccade number, duration, velocity and amplitude have in the past been quantified in relation to non-visual stimuli and have been assessed descriptively in relation to visual experience (see Introduction sections "Human oculomotor orientation with non-visual stimuli" and "Human oculomotor orientation without visual experience"). It must be borne in mind also that the present research evaluated entire responses to verbal instructions, rather than evaluating individual saccades. Still, the outcomes of this study are consistent with previous reports of non-visual voluntary eye movements being characterized by long duration (e.g., Riggs, et al, 1974; Koerner, 1975); similarly, they agree with observations relating control of the amplitude of voluntary eye movements to visual experience (e.g., Sherman, 1985). The analyses performed here which approximate the main sequence, however, may be contrasted with main sequence analyses of Hung, et al, (1994), who found that refixations of remembered target positions in the dark fell within main sequence cluster parameters (when plotting peak velocity versus amplitude). This contradiction may indicate that visual experience affects the oculomotor plant whereas non-visual stimulus conditions do not. It serves also as a reminder that the utility of the main sequence approximations attempted here remains to be clarified and perhaps refined.

The present findings agree most closely with indications from the few past studies which have focused on the relationship between visual experience and human oculomotor behavior and are thus most directly related to this work. This is true both for gazeholding, as evidenced by an increase in the variability of the straight ahead responses with decrease in visual experience, and for production of voluntary movements of the eyes, as evidenced in the data charting increase in size of the (appropriate component) of a requested extreme directional eye movement with period of visual experience. In a general sense, comparison of the present results to past related work adds to knowledge of the links between visual experience and the neural underpinnings of saccade production and eye position control.

Neural Mechanisms

The above prompts a revisiting of questions regarding whether and to what extent the neural mechanisms known or hypothesized to be involved in voluntary eye movement are dependent on vision and/or visual experience (for a review of the vision/oculomotor control relationship, see Wurtz, 1996). To recap broadly, the (Helmholtz) "outflow" hypothesis attributed oculomotor control to a direct awareness of (and memory for) internally generated eye movement instructions. The ethologists, including Von Holst, and engineering theory extended this model (see, e.g., Hinde, 1970). The (Sherrington) "inflow" theory held that mechanoreceptors of the extraocular muscles are the source of eye orientation information. It is unclear from either model when and how, during development, such phenomena putatively underlying voluntary oculomotor control might arise. As just presented, however, note that the inflow and outflow hypotheses need not be regarded as mutually exclusive; the following consideration of central nervous system (CNS) and peripheral mechanisms is set forth with this in mind.

The CNS role in eye position and movement information in the dark has been hypothesized to include, for example, feedback coming directly from the oculomotor nuclei or from corollary discharge associated with instructions to the eye movement system (Heywood, 1973). Vision has been set forth unequivocally as being vital to VOR appearance and ongoing production, as controlled by "the neural structures associated with the velocity storage mechanism and or the neural integrator" (Sherman, 1985, p. 1-2). The vertical and horizontal gaze instability associated with nystagmus, and a "wandering null point" of eye position which were observed in one adult who was blind from birth have been hypothesized similarly to have been brought about by an "abnormal neural integrator" (Leigh, et al, 1989). VOR development and adjustment have been described based on other research as depending on visual experience and visuo-vestibular interaction, such that in individuals who are blind throughout life the VOR is abolished over the long-term by progressive degradation of "incompletely matured neural structures" (Kompf & Piper, 1987). That is, it was asserted that in the absence of visual experience, the lack of calibration provided by vision leads to an irretrievable loss of vestibular connections.

More specifically, vestibulo-ocular responses, gazeholding, and saccadic accuracy have been theorized to be monitored and sustained during vision, and adversely affected in the absence thereof. by structures including the dorsal vermis and vestibulo-cerebellum (which receive visual inputs) (Leigh & Zee, 1980). Areas implicated as possibly involved in saccade information processing and storage include the frontal eye fields of the cortex, with some hemispheric exchange facilitated by the corpus callosum (Heywood, 1973). The cortex has been pointed to also as the site of origination of non-visual saccades; consideration of non-visual corrective saccades led to the suggestion furthermore that the latter arise from an extra-striate internal feedback loop which may send afferent, proprioceptive, information from the eye muscles to the cerebellum (Koerner, 1975). Koerner postulated that a lower oculomotor brain stem neuron firing rate must accompany this process. He suggested therefore that a secondary activating pathway leads from the (cortical) frontal eye fields, which under these circumstances inhibits the brain stem. Reduction in saccade velocity when eye movements are directed toward areas of visual field loss has been attributed to oculomotor neurons' failing to receive and act upon hypothesized "visuo-sensory facilitation" from a corticotectal pathway (Koerner, 1975). Based on evaluation of fixational saccades, produced in light versus darkened conditions, Snodderly (1987) implicated a fovea-peripheral retinal input interaction.

Snodderly posited that one role of fixational saccades may be to stimulate pathways originating in the peripheral retina, influencing fixational control systems.

Complementary research has examined eye movements in adults with cerebellar abnormalities and has provided the basis for much implicating the cerebellum and associated structures in studies relating visual experience to gazeholding and production of voluntary human eye movements. For example, Leech, Gresty, Hess and Rudge (1977) found that "Three abnormalities of eye movement in man are described which are indicative of cerebellar system disorder, namely, centripetally beating nystagmus, failure to maintain lateral gaze either in darkness or with eye closure, and slow drifting movements of the eyes in the absence of fixation." (p. 774). Other workers Zee, Yee, Cogan, Robinson, & Engel, 1976) implicated the cerebellum by quantifying the eye movements of five out of twelve individuals from a family affected by late onset hereditary cerebellar ataxia. Eight eye movement abnormalities were identified, including several related to gazeholding. Among the identified eye movement abnormalities was a "saccadic dysmetria, especially downward overshoot" (p. 231). The coincidence of the observed abnormalities led the authors to suggest that the cerebellum "(1) helps maintain eccentric gaze, (2), produces smooth pursuit eye movements, and (3) modulates the amplitude of saccadic eye movement" (p. 231). The (saccadic) overshoots in the downward direction parallel present results interestingly, in that it was in the "down extreme" directional responses only that the group of adventitiously blind participants exhibited larger displacements than did the sighted group. If downward ocular motility is restricted with advancing age as has been reported for upward gaze (Chamberlain, 1971), an interaction between foveal and peripheral retinal elements such as that suggested by Snodderly (1987) might explain the smaller displacements in the downward vertical direction in the sighted compared to the adventitiously blind group. That is, sighted individuals accustomed to depending on this mechanism might experience more restriction in vertical oculomotility than do adventitiously blind individuals not dependent on visual factors. Chamberlain (1971) described a progressive symmetrical limitation in upward gaze taking place as a normal trend with age; the author found that the upward eye rotation range changes from a range of 40 degrees in childhood (5-14 years) to and average of 15 degrees rotation at 75-84 years, and thus likened it to a supranuclear paralysis (characterized by an inability to elevate the globe). Chamberlain hypothesized that this phenomenon arises from reduced use of the eyes in the upper field with advancing years (and recommended that age be considered when evaluating oculomotility in middle aged and elderly participants). The reverse effect having been observed in the present study in upward responses, i.e., the sighted group was characterized by larger displacements, might be explained as follows. A tendency toward "higher" gaze position with advancing age, i.e., the eyes tend to be deviated upward, may exist in adventitiously blind individuals (although this is to date an anecdotal observation). This might confer a greater upward range in this group (and might arise from a chronic imbalance in the strength of the relevant set of opposing extraocular muscles, normally overcome by visual feedback).

No dramatic findings were uncovered by the present research which necessitate the foregoing hypothesized neural mechanisms to be called into question further than has been noted already at appropriate points in the text.

Nature of Effect

When discussing plasticity, it is important to distinguish which role or roles are being associated with the (here, visual) experience during development. Gottlieb (1976) has identified three ways in which experience can play a role in behavioral and neurophysiological development; these include maintenance, facilitation and/or induction. Unless otherwise indicated, the remainder of this section is considered with respect to Gottlieb's treatment of these issues.

A "maintenance" effect is implicated when experience is necessary solely to preserve an already developed state or endpoint (regardless of how the state or endpoint arose initially). Lack of maintenance has been associated with well-defined sensory and motor outcomes; for example, the longterm absence of sensory stimulation, or the short-term prevention of spontaneous but overt motor movements during particular periods in early neonatal or embryonic development (as evidenced using certain animal models) can lead to, in the former, atrophy and disintegration of neural tissue in the deprived sensory system, and in the latter, muscular atrophy and loss of use of the joints of the experimentally manipulated extremities. The "functional validation theory" of Jacobson (whose interest was specificity in the visual system), furthermore, holds that the specificity of neural connections and functions is a consequence of the selective experiential maintenance of endpoints achieved by prior neural maturation processes (for a discussion see Gottlieb, 1976).

Although Jacobson's functional validation theory did not consider motor systems, Gottlieb noted that maintenance may operate in this realm. In considering the results of the present study, ascribing a maintenance function to visual experience would seem to require the assumption that participants "begin" with voluntary oculomotor control abilities like those of adults, and that in the absence of visual experience that capacity deteriorates. While the literature reviewed in the introduction of this thesis presents evidence of directional oculomotor responses in infants as young as two minutes old (Wertheimer, 1961), these behaviors were in most cases not described as adult-like. It is difficult to know how closely the behaviors measured here match those uncovered in infant research, although it should be noted that Aslin and Ciuffreda 1983 have indicated that the optimal performance on oculomotor tasks of preschool children resembles that of untrained adults. This uncertainty leaves open the possibility that visual experience operates according to Gottlieb's maintenance principle.

The term "facilitation" is used to describe a quantitative or regulative effect of experience on the development of behavior and/or the nervous system. Facilitation assists quantitatively in the achievement of certain states or endpoints in development, i.e., these milestones would be reached eventually, to a greater or lesser extent, with or without facilitative experience. Thus it is distinguished importantly from maintenance (which preserves already achieved.states or endpoints). Interestingly, it has been hypothesized that the spontaneously occurring experience of rapid eye movement (REM) sleep has facilitative effects on fetal and newborn neural structural differentiation and growth (i.e., maturation) in the central nervous system; another theory has been that REM provides the intrinsic mechanism necessary for the development of binocular oculomotor control (theorized to be independent of peripheral visual input initially during wakefulness).

To assess whether the observed effects of the lack of visual experience on blind participants' voluntary eye movements in this study were due either to failure of maintenance or an absence of facilitation, the present approach seems reasonable in that it quantified the identified effects of differing experiential time courses in individuals of different ages. To couch the design of this research in a familiar "sensory deprivation paradigm" analogy, it is as if the participants ("animals") were either allowed visual experience ("light reared") or denied visual experience ("dark reared") for various periods of time after birth, then tested at particular ages. Such a research design optimally would include age-matched comparisons, in order to best discern and distinguish between any maintenance or facilitation effects. In this study, the evaluations of years of visual experience as a function of age of available participants approximated such a comparison. Assuming that voluntary directional oculomotor ability (like that exhibited in the "control" group of sighted adults) is not present at birth, results of these analyses would appear to indicate that volitional movement, vertical or horizontal, neither develops nor improves in the total absence of visual experience. Such control is discernible in cases in which vision was experienced, and it "improved" with experiential duration to an apparent limit. This evidence would appear to implicate an "inductive" role (see below). It should be noted that as a group, the responses of the participants classified as adventitiously blind were generally not quite as "appropriate" as those of the controls, suggesting that facilitation may operate also. Even after longterm blindness, there was evidence of only minimal "degradation" in voluntary oculomotor control among these and those "congenitally" blind participants with what may be a threshold duration of visual experience required for adult manifestation of voluntary oculomotor control. This does not speak to facilitation, but would seem to again contradict a maintenance explanation.

"Induction," according to Gottlieb, determines whether or not a given behavioral or neural aspect is present; that is, in the presence or absence of inductive experience (as appropriate), development of susceptible behavior and/or neural structure and function would take a different course, resulting in a different outcome. One criterion for an inductive effect of experience is whether there is a qualitative difference between the behavior of the "appropriately" and "inappropriately" experienced individuals. clear qualitative differences emerged among groups tested here, e.g., duration, size, and directional appropriateness of response. While this may be indicative of an inductive effect, these results do not rule out the possibility that the involved components of the nervous system were somehow modified; this is a drawback noted by Gottlieb with regard to (animal) sensory deprivation studies. That is, the observed results may not bear directly on understanding of normal development, in that these behaviors arose in the absence of the nervous system's being able to generate normal, adaptive, visual function.

This study contributes to knowledge of the nature and extent of the neural plasticity inherent to the relationship between visual experience and voluntary oculomotor control. Its evidence is relevant to appearance and ongoing production/retention of voluntary oculomotor control in the absence of long-term visual input. Evidence from successful use of orthoptic therapy supports the idea also that voluntary oculomotor control retains a degree of plasticity well into childhood, and perhaps even into adulthood. This has been shown, for example, in improvement of monocular function in an eleven year old strabismic amblyope (Hokoda & Ciuffreda, 1986), and in improvement in accommodative accuracy and related visual functions in an adult strabismic, although in the latter study eye deviation was not improved (Schnider, Ciuffreda, & Selenow 1985.

The foregoing indicates, theoretically and perhaps clinically, that oculomotor control adequate to subserve vision might be anticipated in individuals with even a short period of prior visual experience, were it possible to restore function to the other components of the visual system. Particularly hopeful in the present study was the finding that remarkably "normal" response patterns tended to be produced by participants in this research even when the quality of the vision experienced was quite poor (see, e.g., directional data in Figure 12 for CRW1 and CAC1). The observed covarying of response patterns with visual experience may thus be construed as an encouraging outcome.

Areas for Future Study

Although this investigation had to be circumscribed within reasonable bounds to result in the present treatment, the recorded eye movement patterns discussed here merit additional description and evaluation. For example, in considering the directional eye movement experimental data, its similarity to infant targeted eye movement patterns could be examined in a specific revisiting of the classic model of "adult (blind) human" as "(sighted) adult human infant." Other analyses of the observed covarying of response patterns with visual experience might concentrate on recency of vision loss, further quantifying possible degradation or other change in behavior characteristics with duration of post-childhood blindness. Future treatment of these data also which would be desirable include: evaluation of saccades, fixations, drifts and glissades, inclusion of automated procedures to identify particular types of responses; analyses for age effects, evaluation of data from "mixed" participants (including those whose visual history is such that they could be classified as having one "congenitally blind" and one "adventitiously blind" eye, plus the monocularly blind individual), additional univariate statistical analyses, multivariate statistical analyses, and quantitative comparison of absolute data with data from other studies.

The benefit of hindsight suggests that a few modifications to the procedures followed here could improve similar future research. Alterations might be to include more directional requests and a "relax your eyes" request. These were contemplated for this study, but were not used, in part because the taping session was relatively long already (about three uninterrupted minutes). The latter was skipped furthermore to avoid inducing blinks, but would be desirable in that it might be a more valid approach to approximating primary position under non-visual stimulus conditions (assuming that this is a meaningful comparison).

A number of "follow-on" directions are suggested by this work. Rehabilitation-based observations and consideration of several past oculomotor research studies, for example, Steinman, Kowler and Collewijn (1990), prompt the inference that measurements of unrestrained participants' oculomotor behavior (including eye, head and torso) would be desirable in further evaluation of the role of visual experience in human voluntary eye movement. In using such an approach (and in consideration of past research, neuroanatomy and neurophysiology), Steinman, et al (1990) were led to suggest that the oculomotor system uses two subsystems to fixate and track a central representation of objects (in three dimensional space), although in-depth consideration of this and other models is beyond the present scope. Evaluation of "unrestrained" responses in an experiment otherwise similar to that of the present study would allow for investigation of the possible influence of non-visual afferents on human voluntary eye movements as it may relate to visual experience.

Other follow-on work could fruitfully include: testing a more continuous age range of blind participants, including younger individuals (to fill in gaps in existing data), testing sighted individuals who have regained their vision after blindness, performing "on-line" attempts at shaping oculomotor responses, to see whether voluntary control can be improved/gained/regained in adults with varying amounts of visual experience given auditory feedback linked to gaze direction (this could provide a basis for clarifying the relationship between visual experience and the oculomotor plant/practice/attention), evaluating REM in blind participants, adapting sighted individuals to displacing prisms in order to then test them in the dark using methods such as were employed here.

Appendix A Sample Acuity Scoring Form

DATE: ____________________ **Subject's Code:** ____________________

BETTER EYE (circle): **L** **R** **CHART # 1**

LEFT EYE [ ]

Row Number	Meters	Conversion to Snellen Equivalent	I	II	III	IV	V	LogMAR
1	40	200	N	C	K	Z	O	1.0
2	32	160	R	H	S	D	K	0.9
3	25	125	D	O	V	H	R	0.8
4	20	100	C	Z	R	H	S	0.7
5	16	80	O	N	H	R	C	0.6
6	12	63	D	K	S	N	V	0.5
7	10	50	Z	S	O	K	N	0.4
8	8	40	C	K	D	N	R	0.3
9	6	32	S	R	Z	K	D	0.2
10	5	25	H	Z	O	V	C	0.1
11	4	20	N	V	D	O	K	0.0
12	3	16	V	H	C	N	O	-0.1
13	2.5	12.5	S	V	H	C	Z	-0.2
14	2	10	O	Z	D	V	K	-0.3

RIGHT EYE [ ]

Row Number	Meters	Conversion to Snellen Equivalent	I	II	III	IV	V	LogMAR
1	40	200	N	C	K	Z	O	1.0
2	32	160	R	H	S	D	K	0.9
3	25	125	D	O	V	H	R	0.8
4	20	100	C	Z	R	H	S	0.7
5	16	80	O	N	H	R	C	0.6
6	12	63	D	K	S	N	V	0.5
7	10	50	Z	S	O	K	N	0.4
8	8	40	C	K	D	N	R	0.3
9	6	32	S	R	Z	K	D	0.2
10	5	25	H	Z	O	V	C	0.1
11	4	20	N	V	D	O	K	0.0
12	3	16	V	H	C	N	O	-0.1
13	2.5	12.5	S	V	H	C	Z	-0.2
14	2	10	O	Z	D	V	K	-0.3

Testing technician: ____________________

TECHNICIAN:

1. Indicate the order in which eyes were tested by placing 1 or 2 in the corresponding brackets above. **REMEMBER: The WORSE eye must be tested FIRST!**
2. Indicate correct answers by placing a check mark [✓] in the cell with the letter. Indicate incorrect answers by the [X] mark. Do **NOT** leave any cell unmarked!

Appendix B

Sample Instruction Set

Please wait to hear each complete instruction before beginning to move your eyes.

When you hear the beep look straight ahead.
When you hear the beep look down as far as you can.
When you hear the beep look straight ahead.
When you hear the beep look halfway down.
When you hear the beep look straight ahead.
When you hear the beep look up as far as you can.
When you hear the beep look straight ahead.
When you hear the beep look halfway up.
When you hear the beep look straight ahead.
When you hear the beep look as far to the right as you can.
When you hear the beep look straight ahead.
When you hear the beep look halfway to the right.
When you hear the beep look straight ahead.
When you hear the beep look as far to the left as you can.
When you hear the beep look straight ahead.
When you hear the beep look halfway to the left.
When you hear the beep look straight ahead.
When you hear the beep pretend to look at the spot between your eyes.
When you hear the beep look straight ahead.
When you hear the beep pretend to look at the spot halfway between your eyes.
When you hear the beep look straight ahead.
The end, thank you.

Appendix C

Sample Participant Questionnaire

Date

Participant Code

Instruction Set #

Date of birth

Are you male or female, please specify?

Visual acuity: Right Eye

Left Eye

Are you blind (yes/no)?

[If yes] What caused your blindness (right eye, left eye)?

When did you lose your vision (right eye, left eye)?

Have you ever had any problems or surgery involving the eyes, face, head, neck or back? Please explain what and when.

[The space below was used for any comments made by the participant after the eye movement recording.]

Could you follow the instructions about where to move your eyes?

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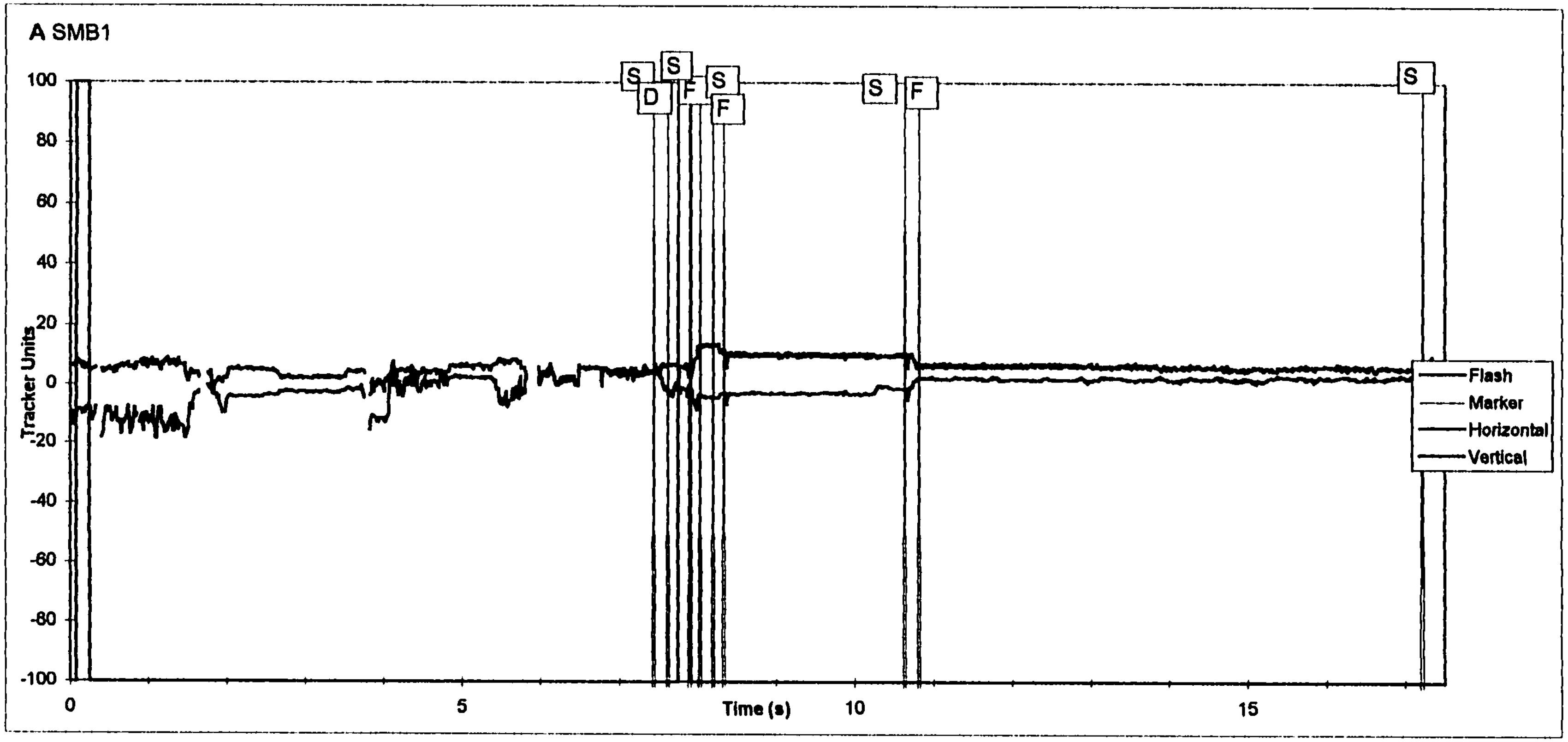

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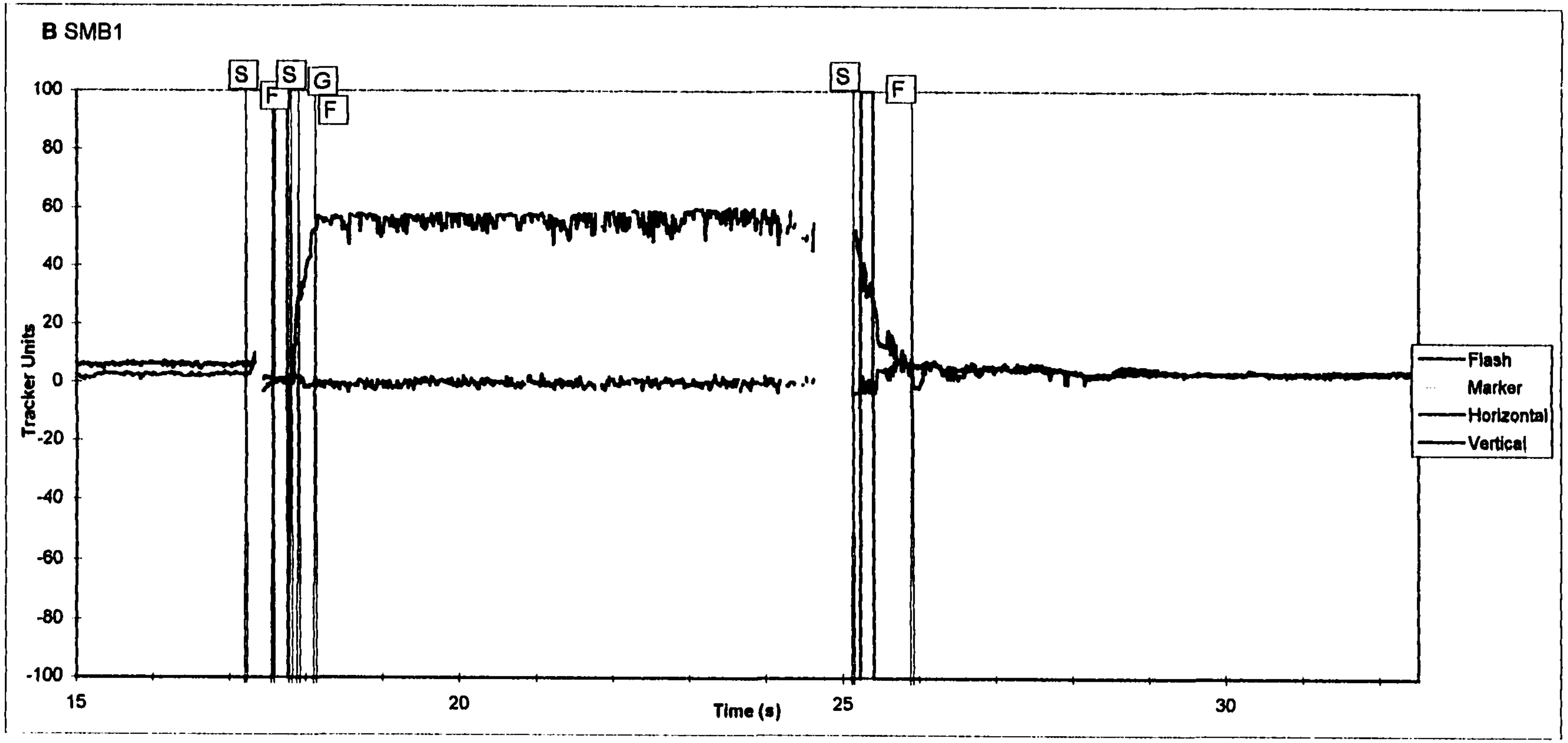

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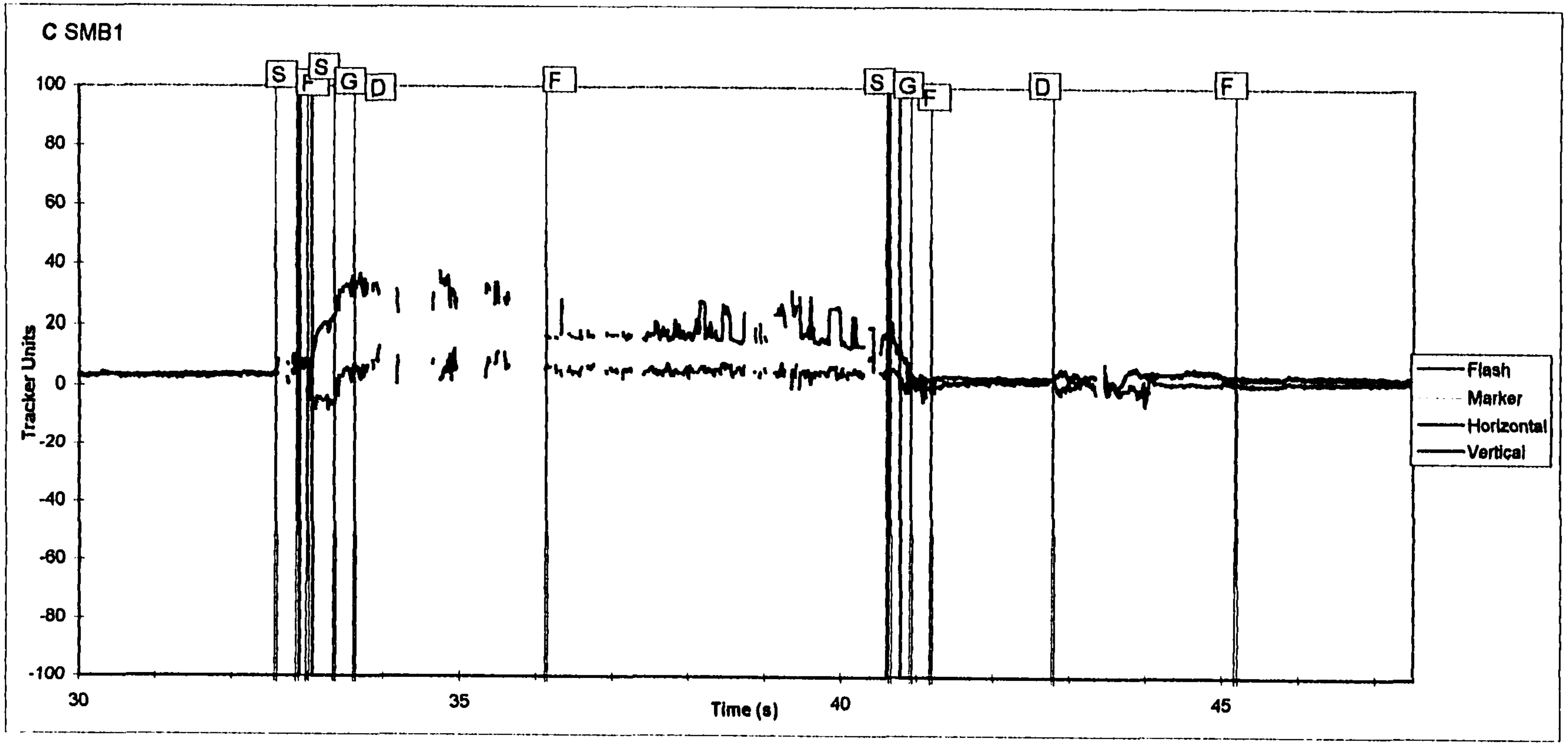

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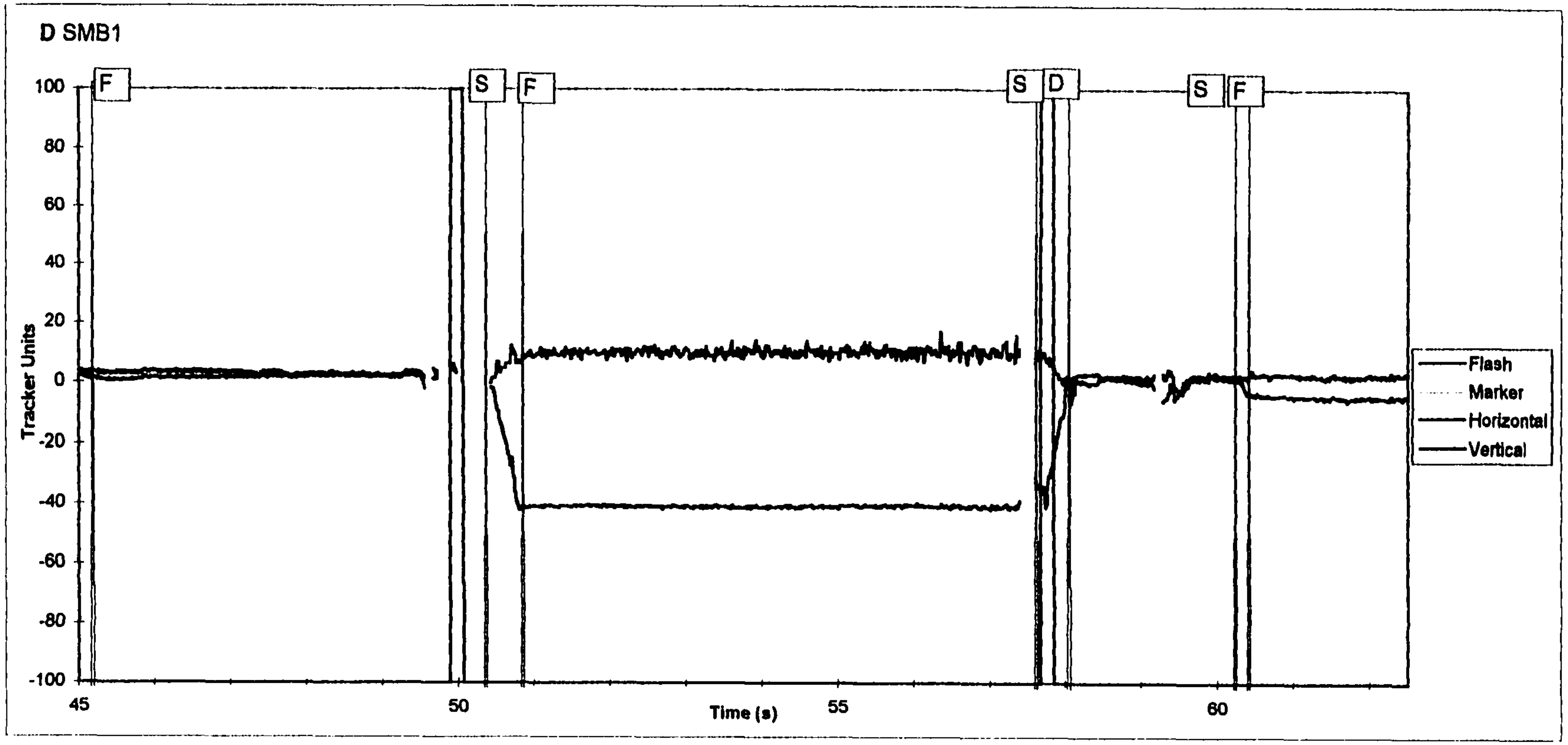

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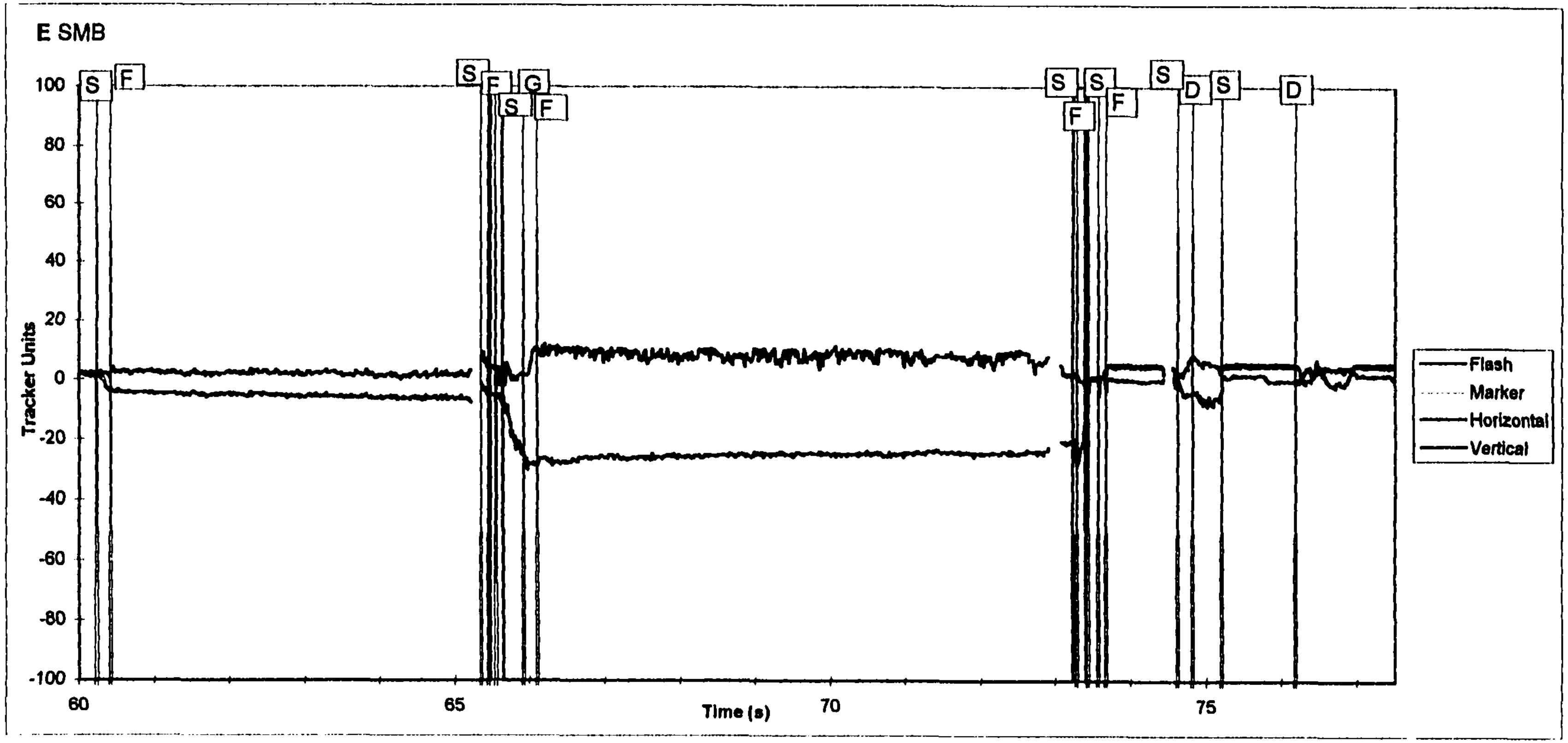

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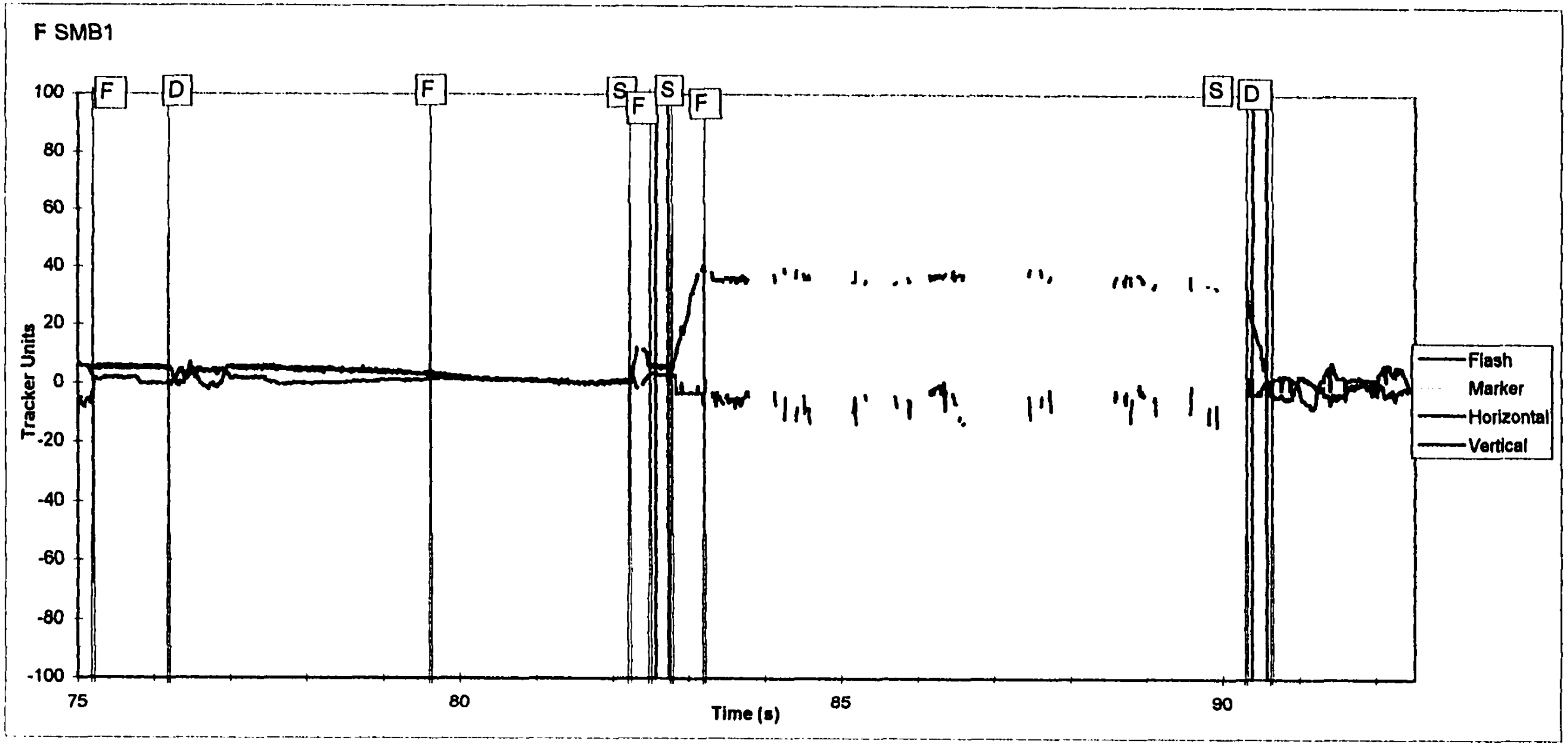

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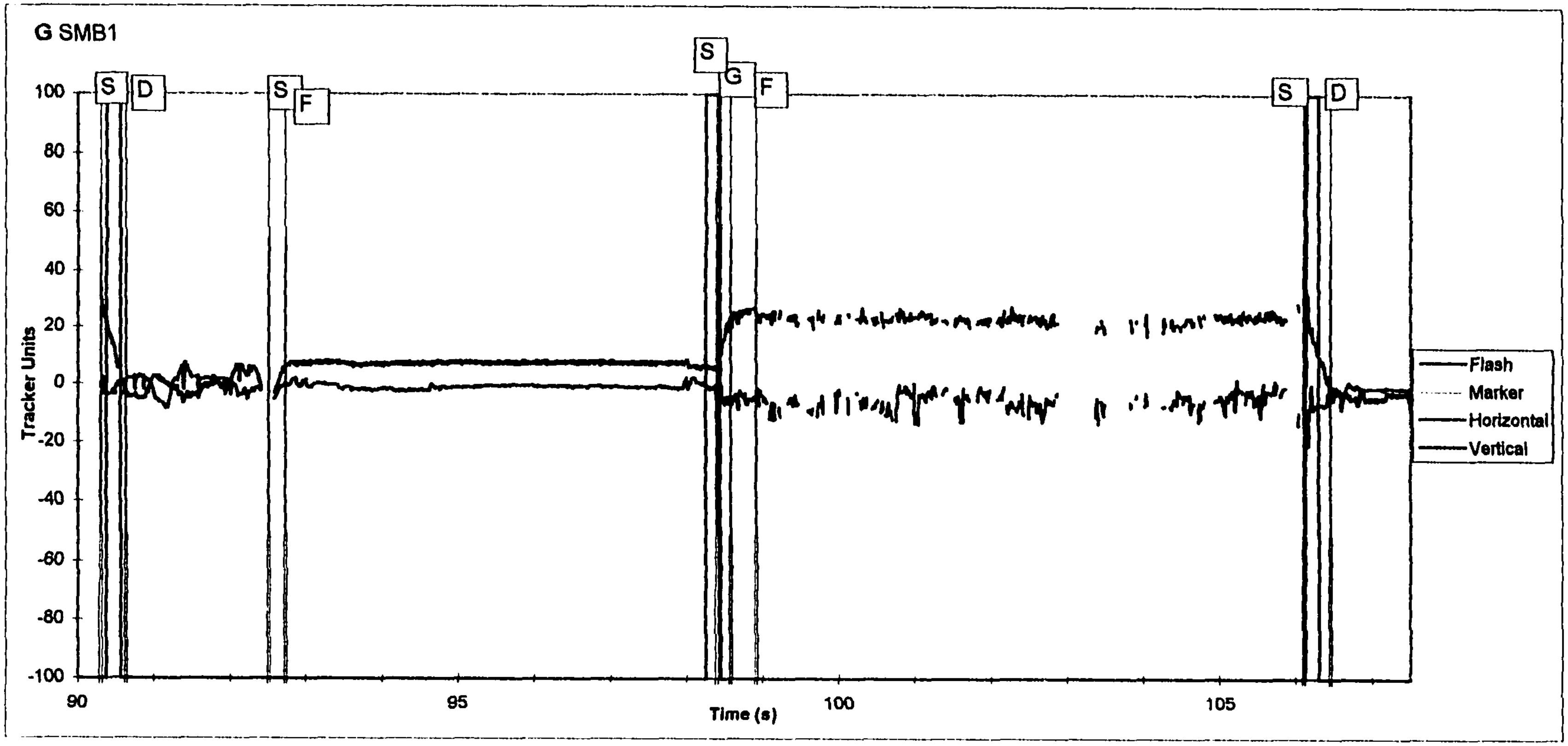

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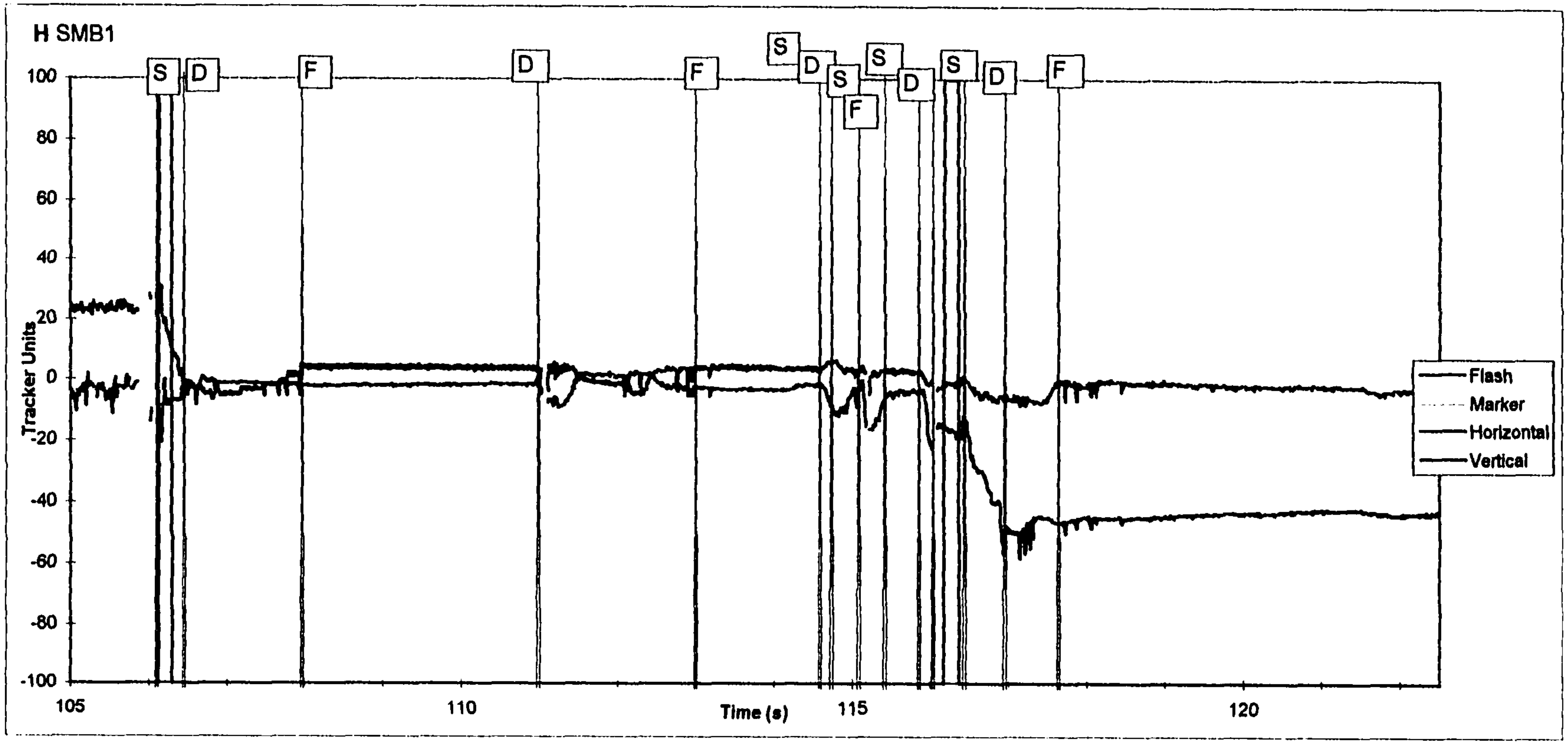

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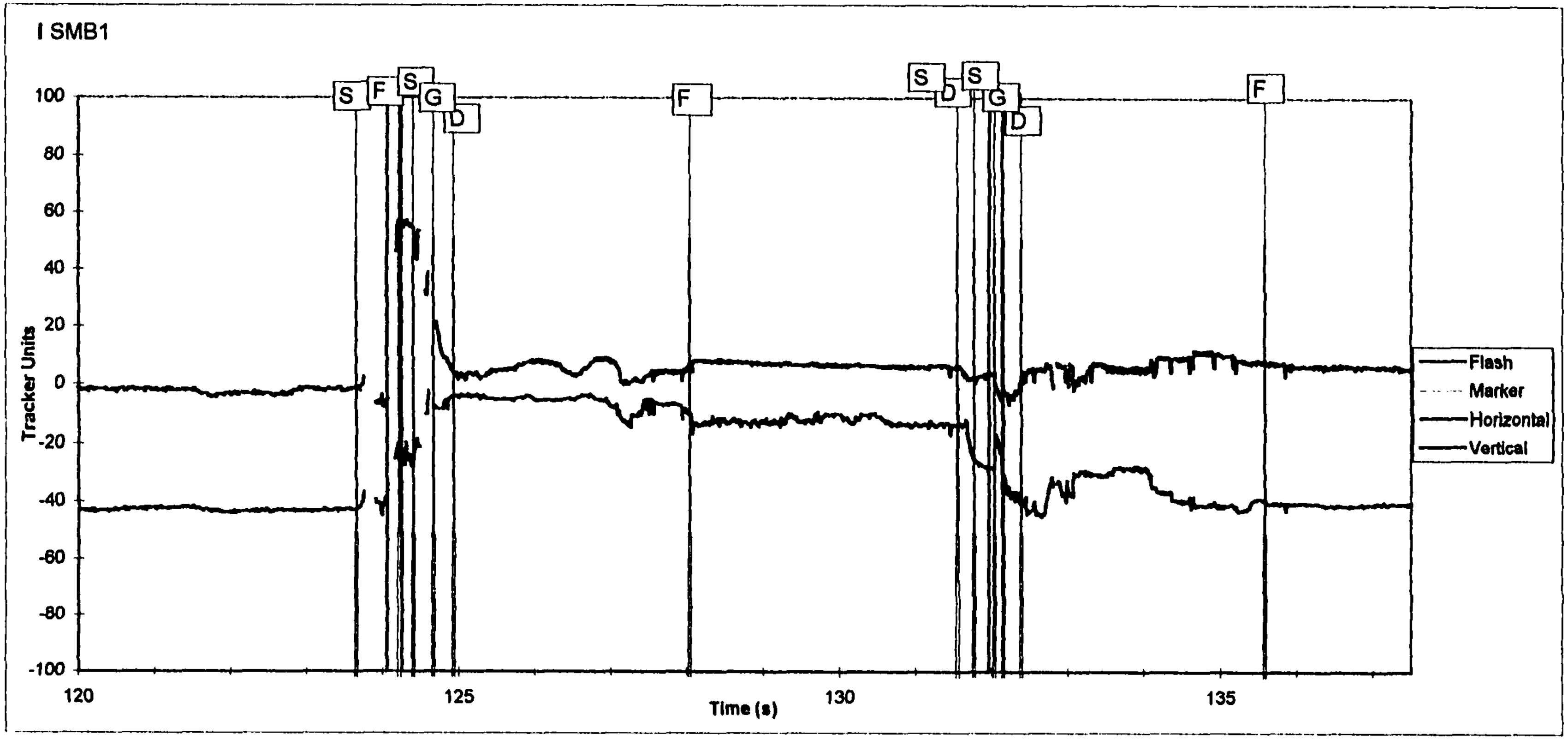

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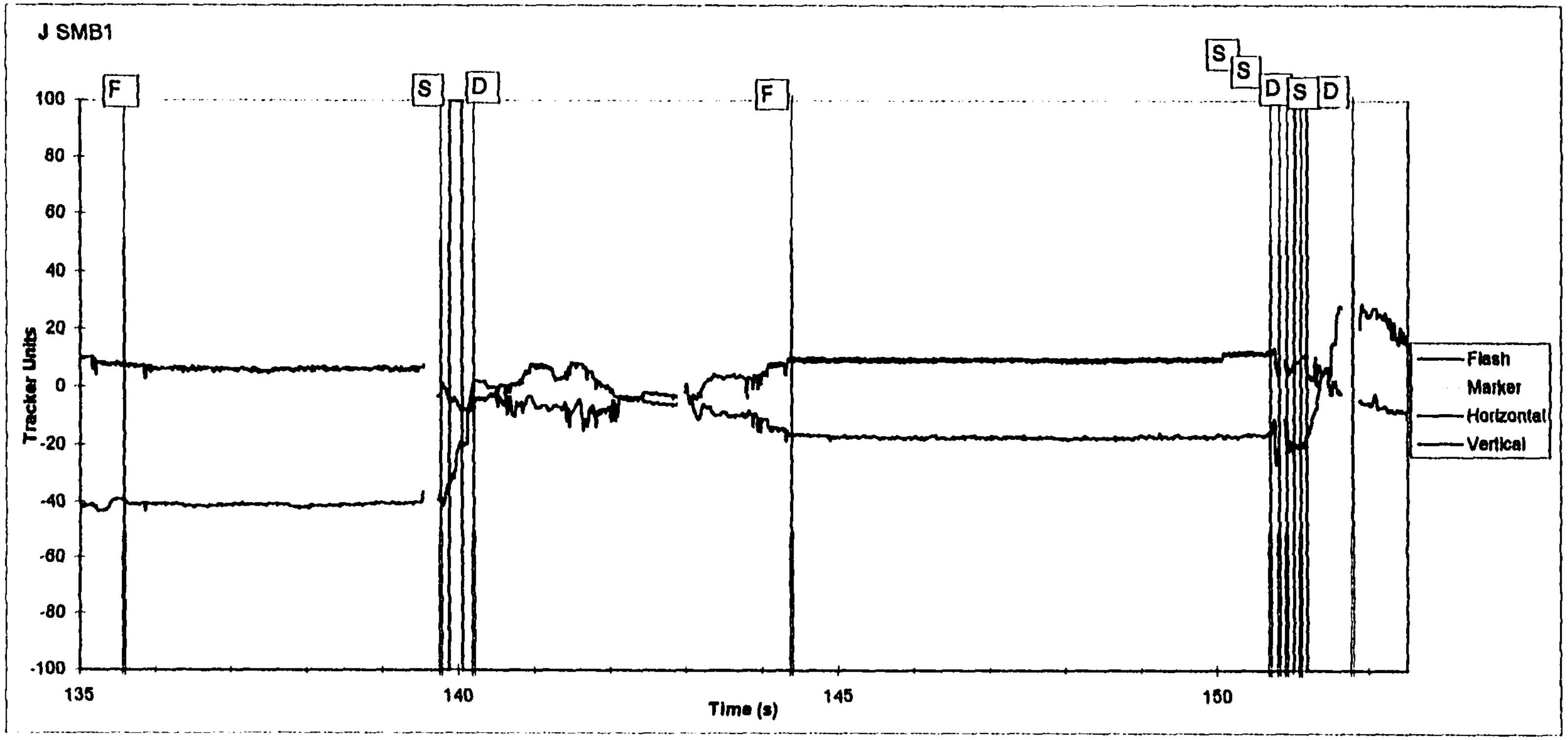

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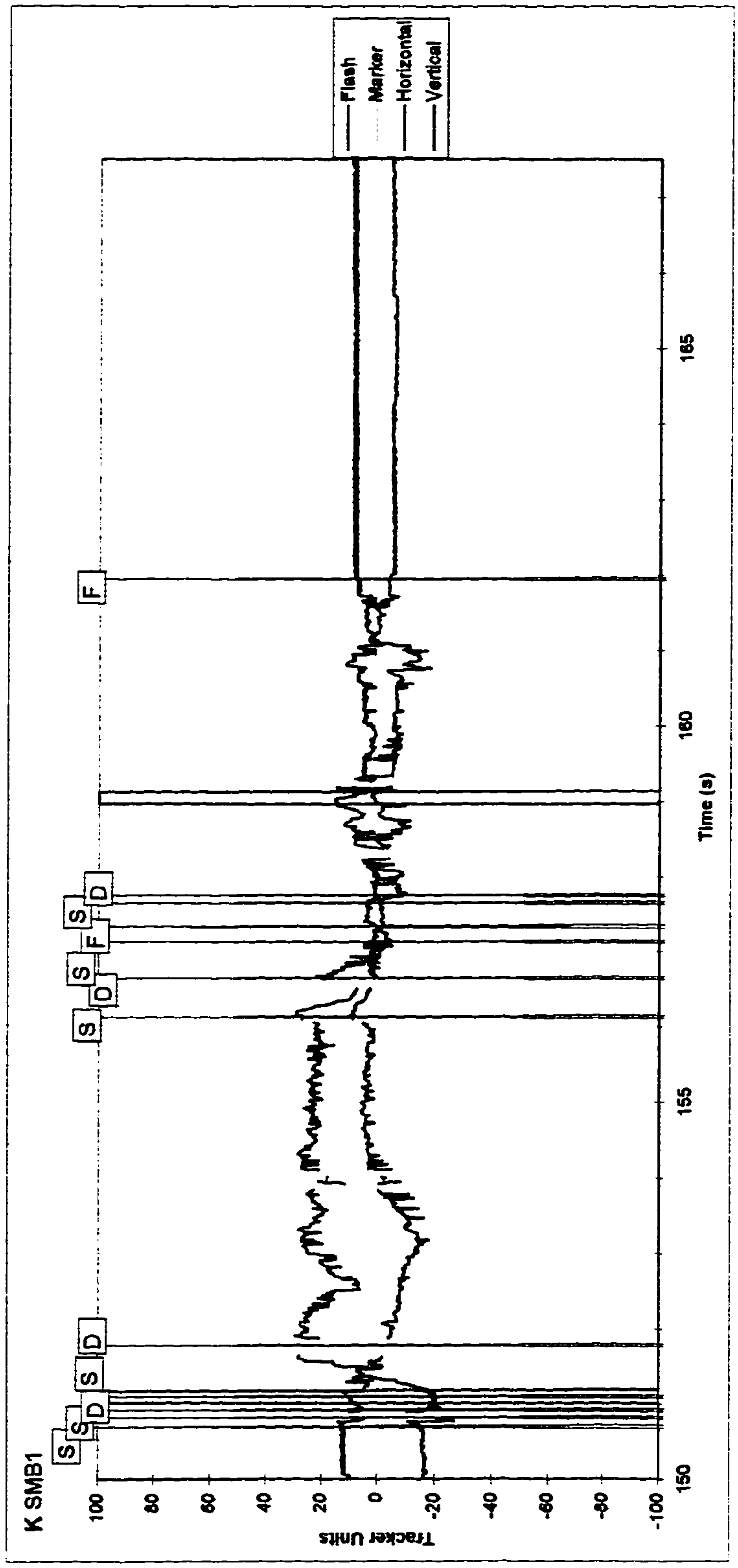

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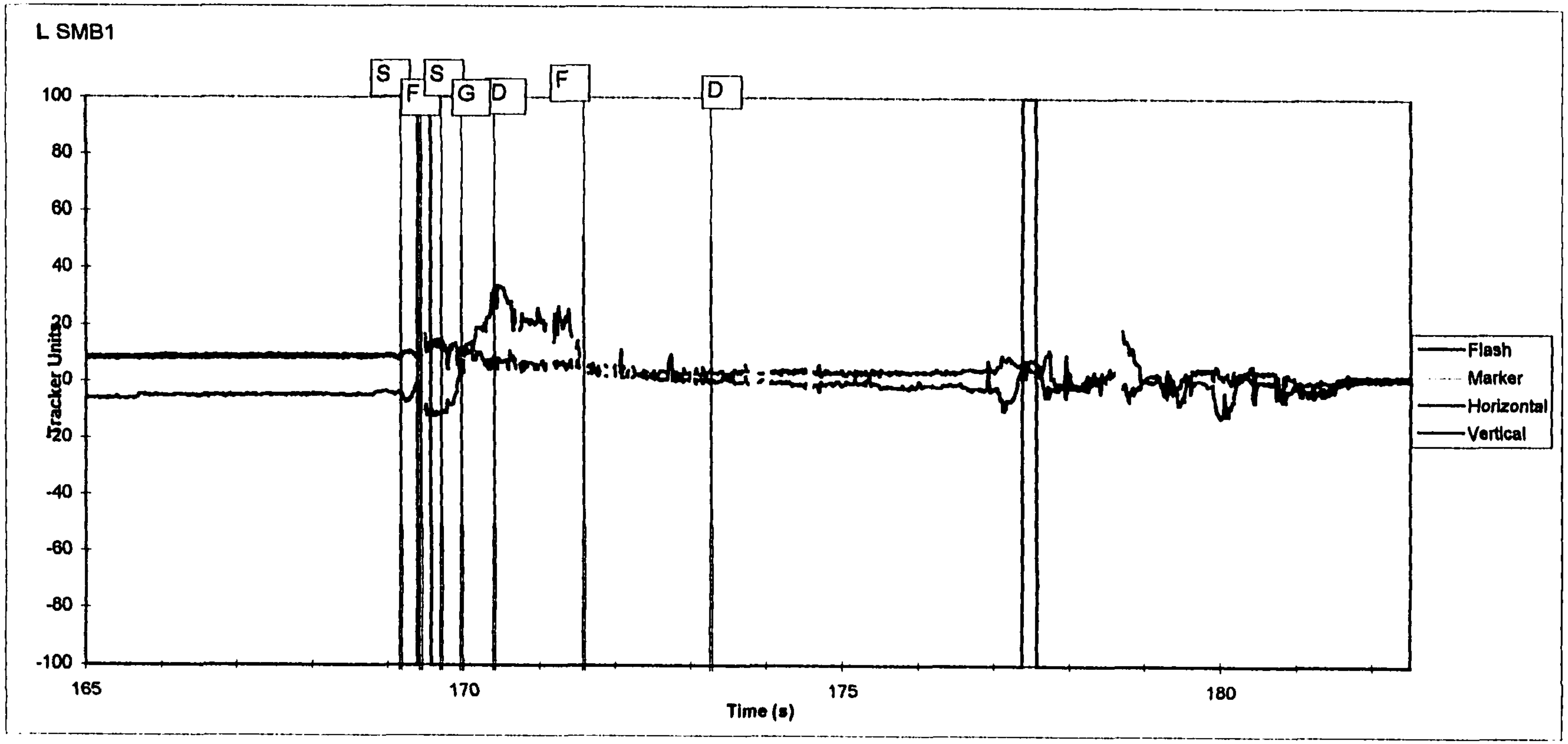

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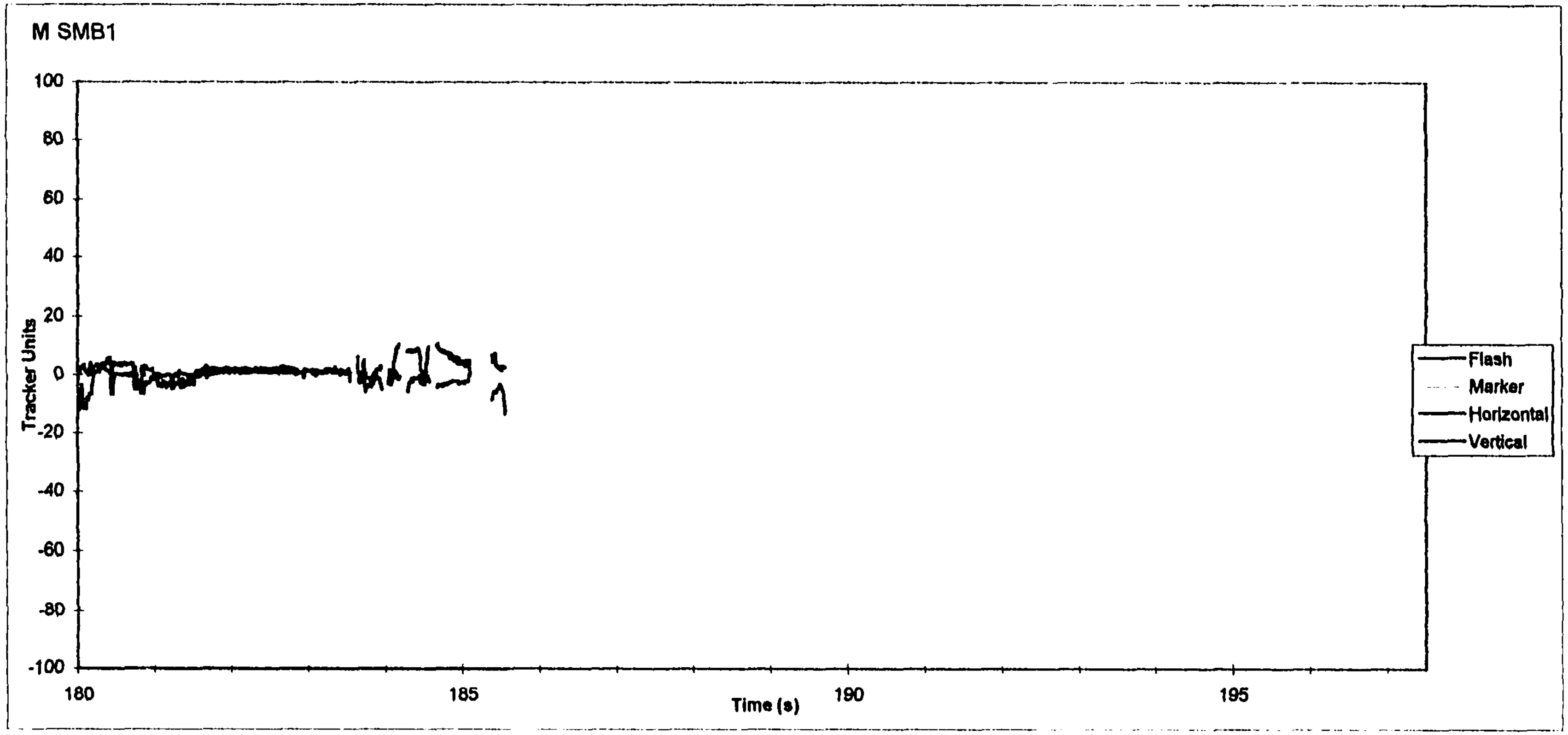

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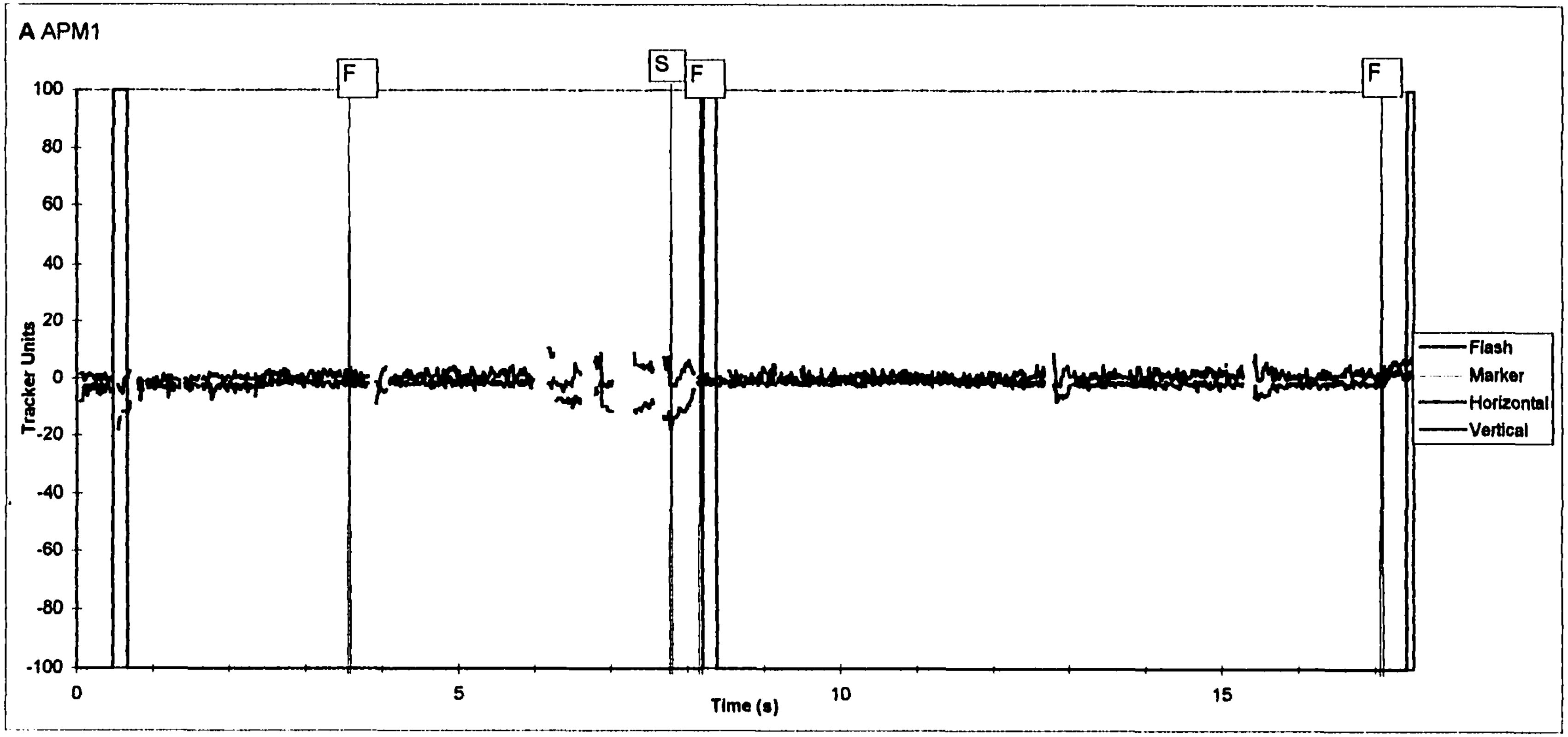

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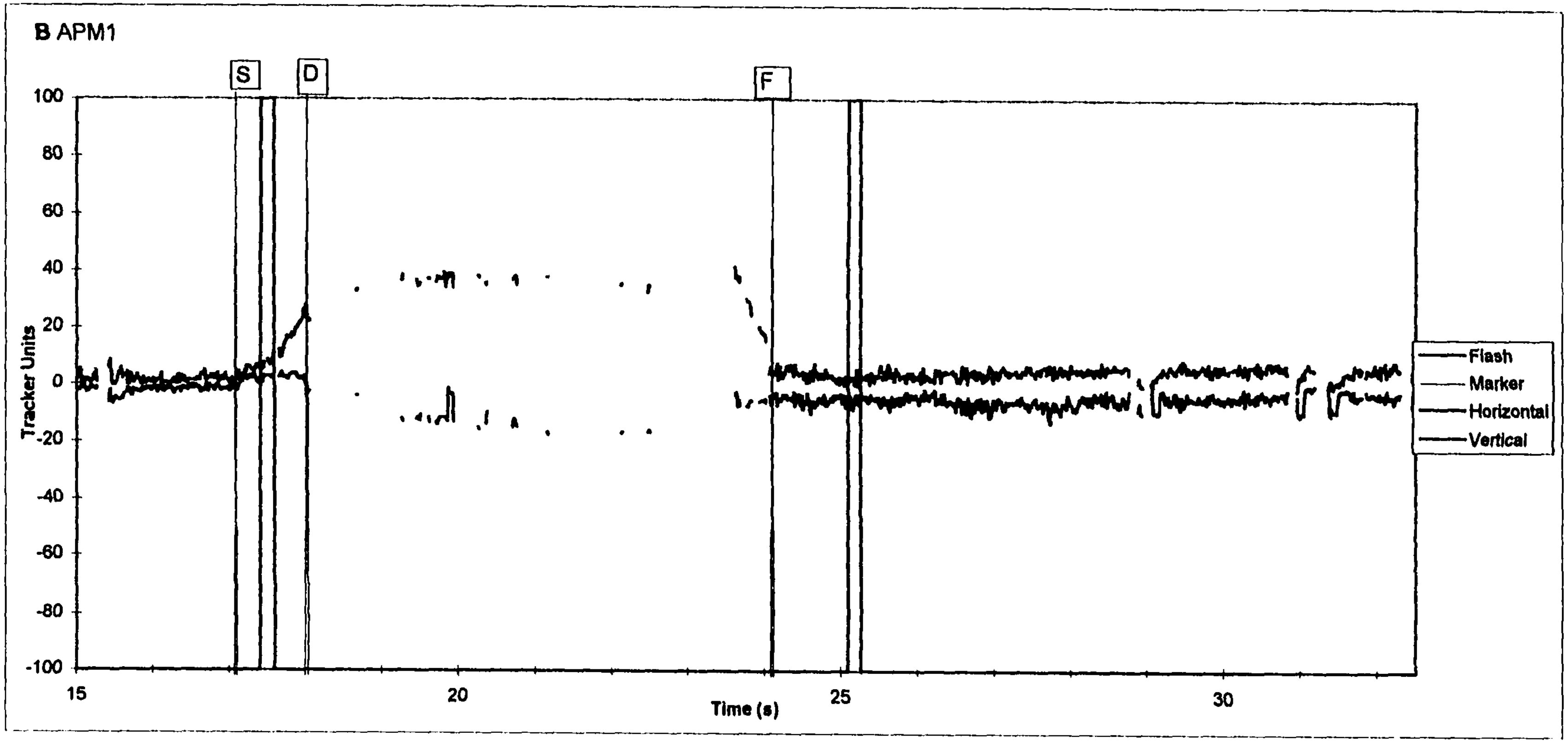

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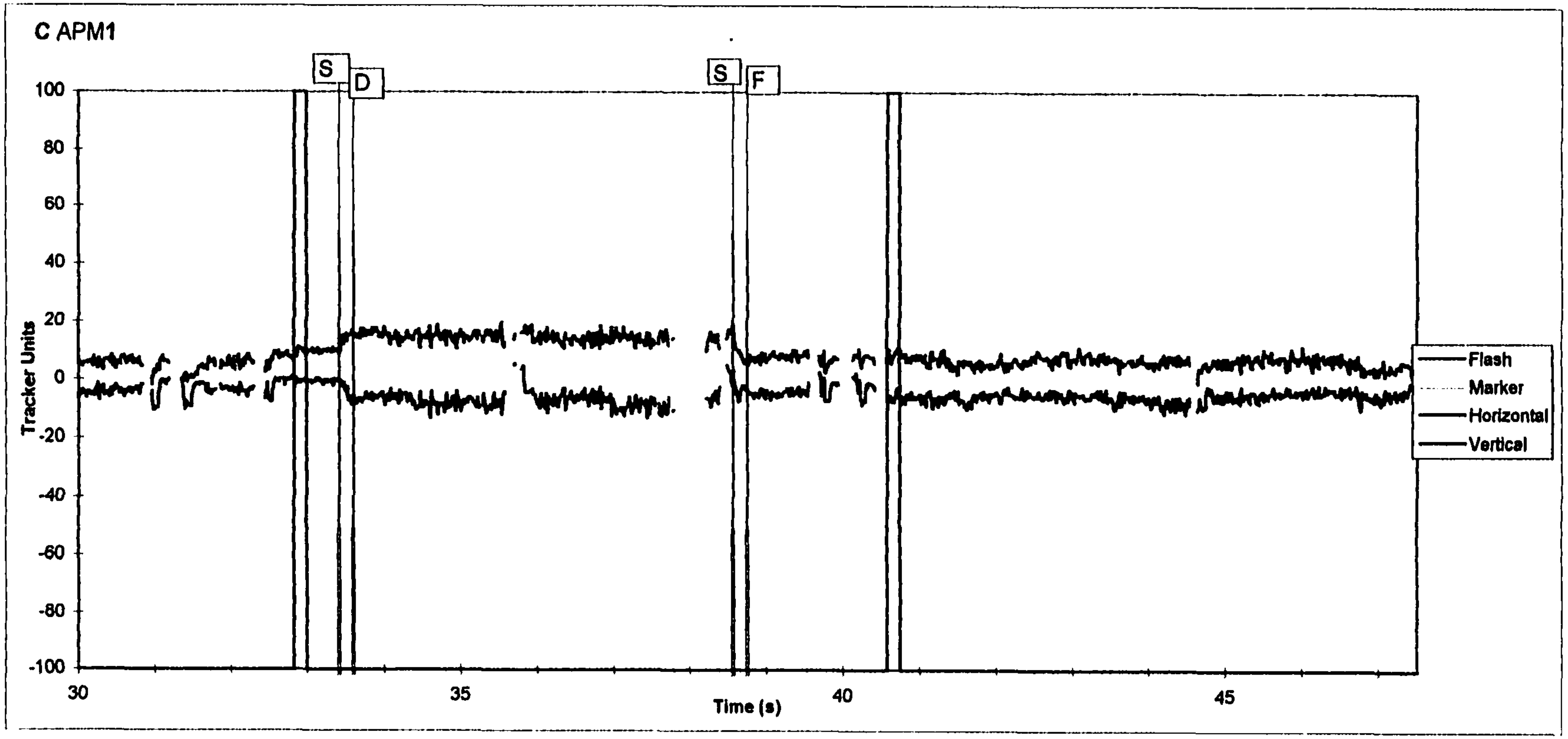

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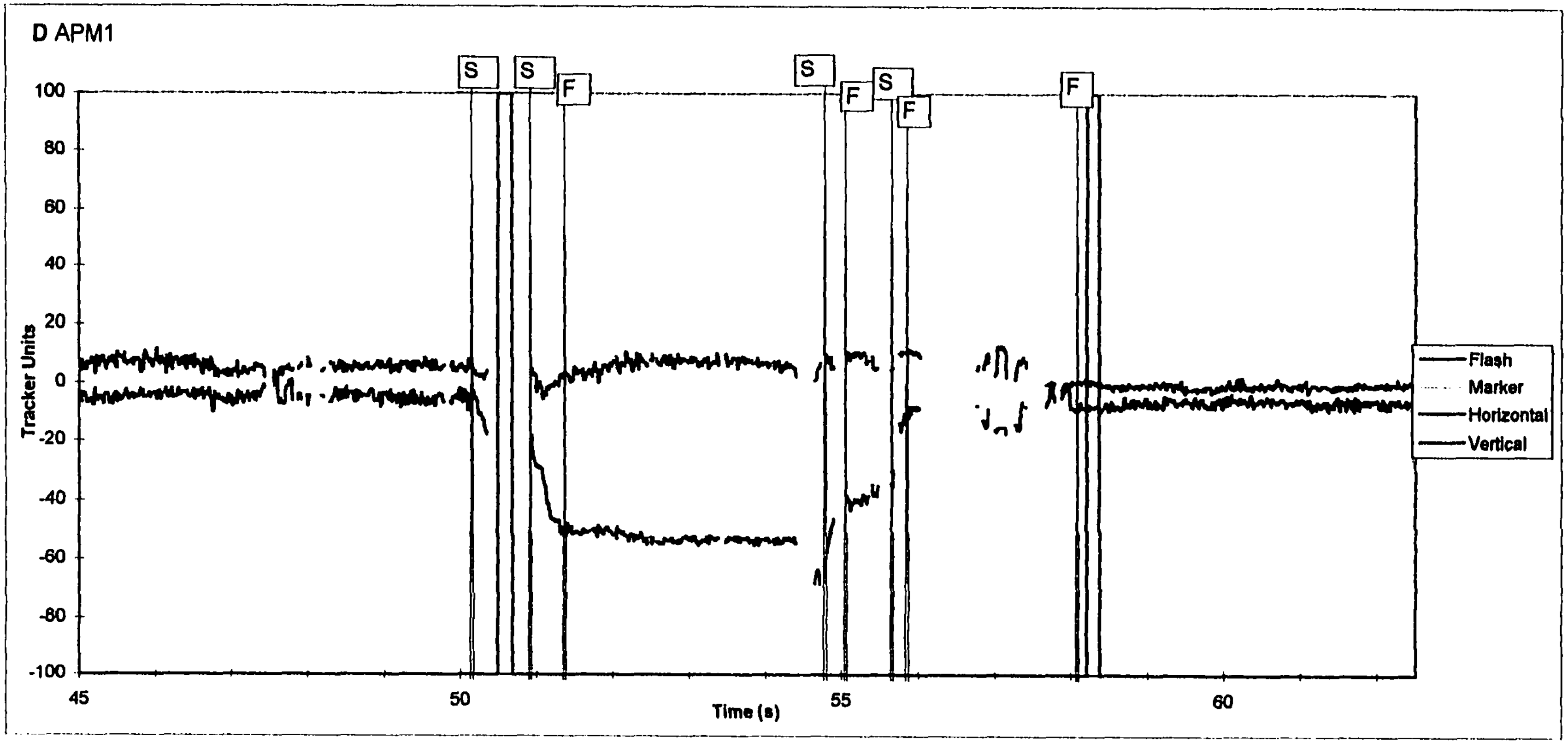

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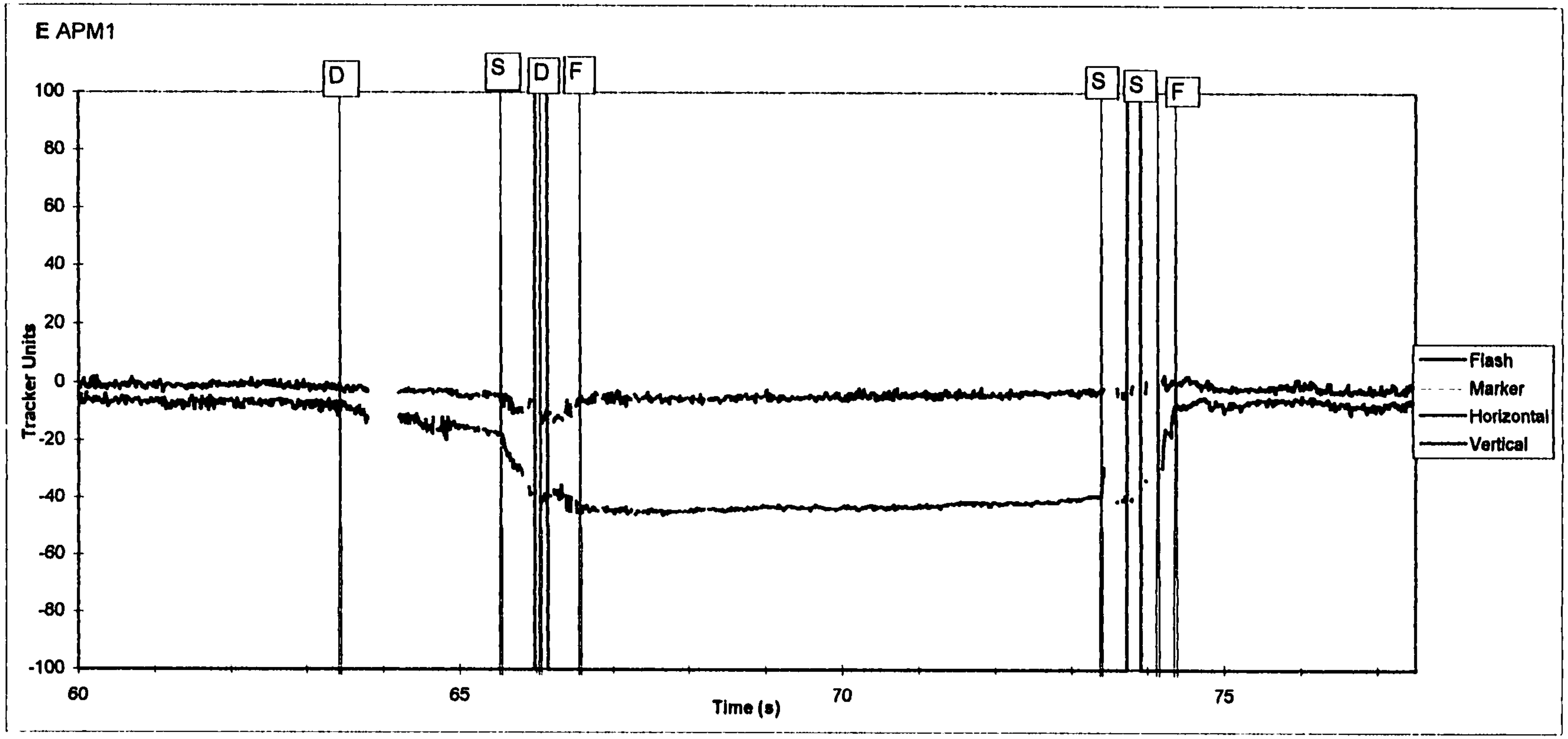

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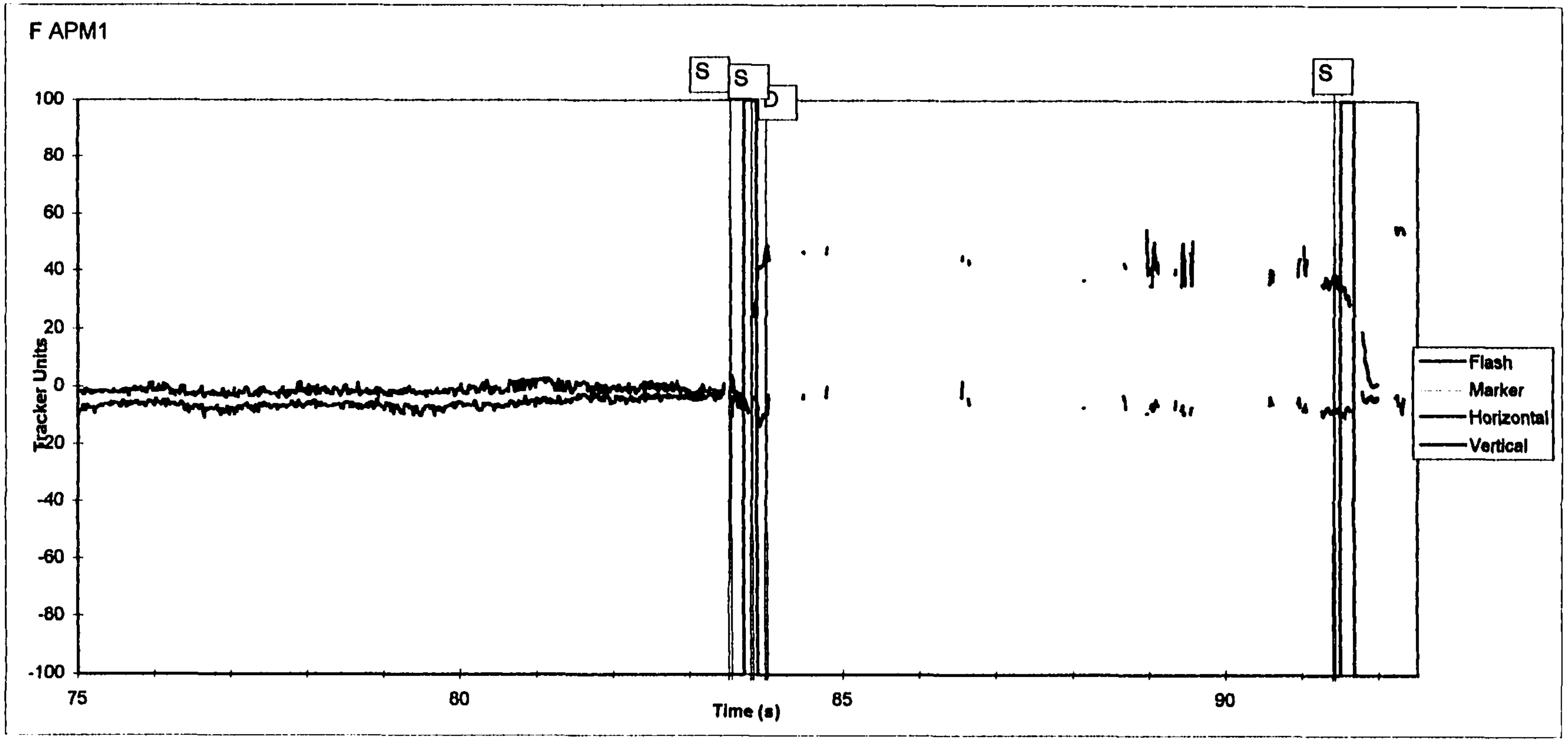

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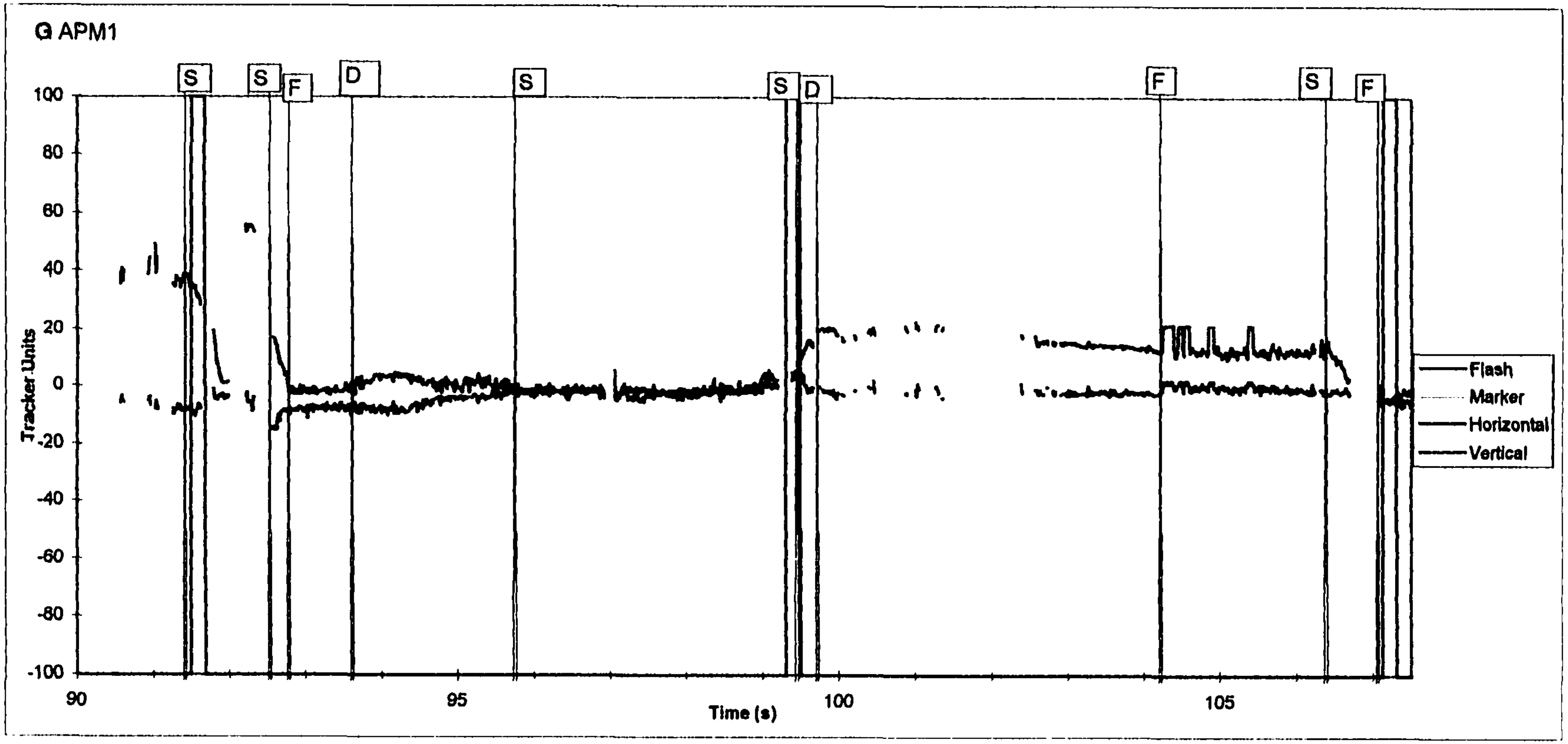

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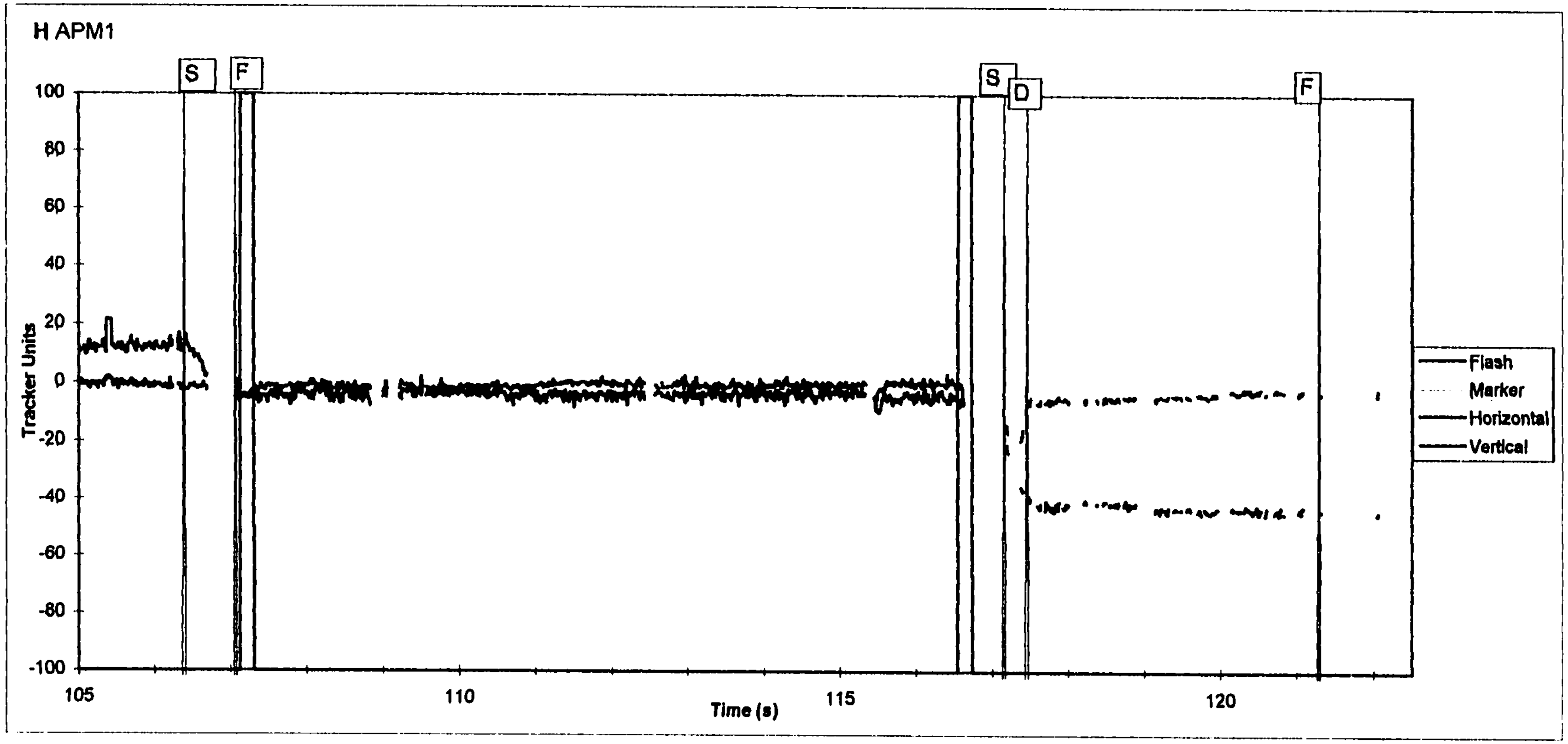

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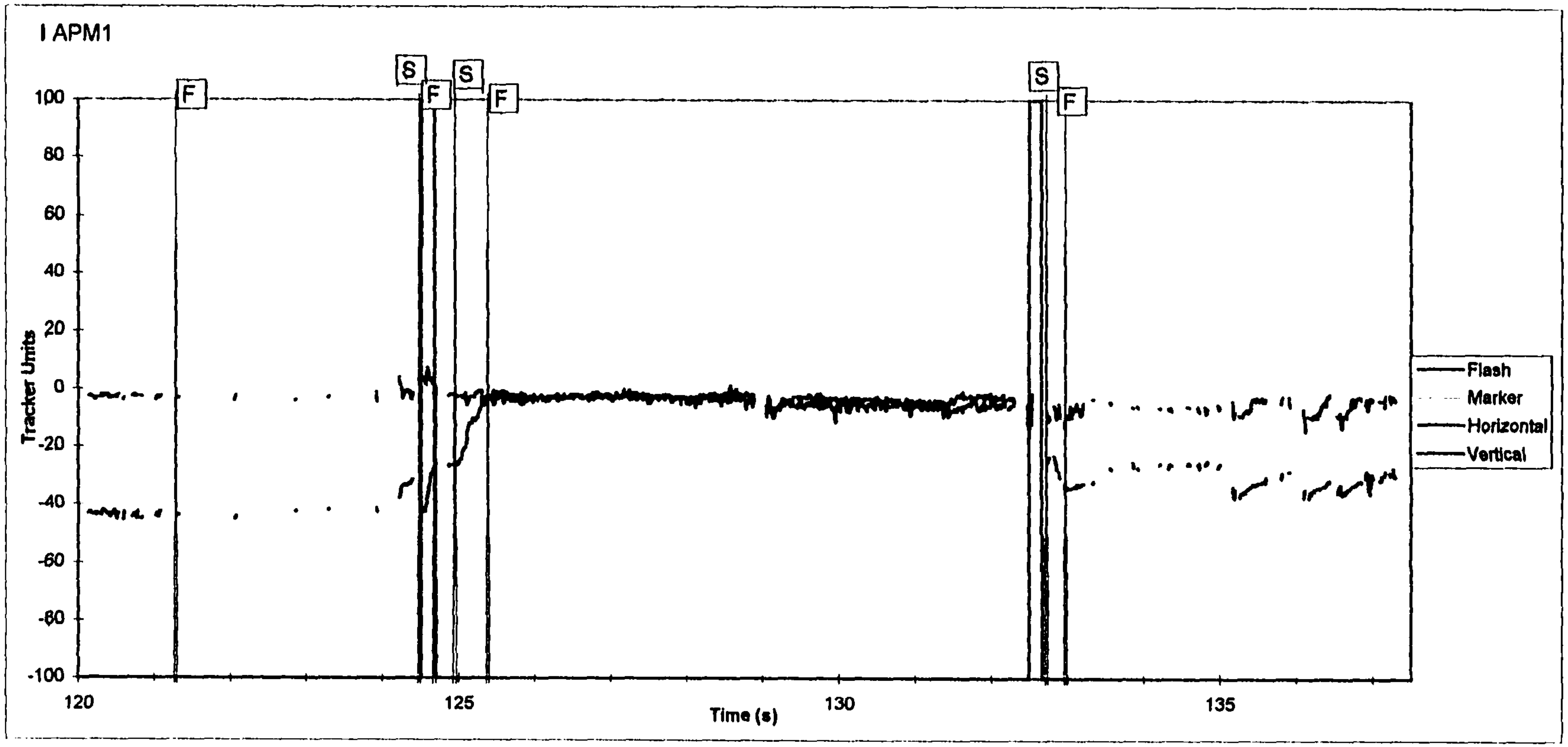

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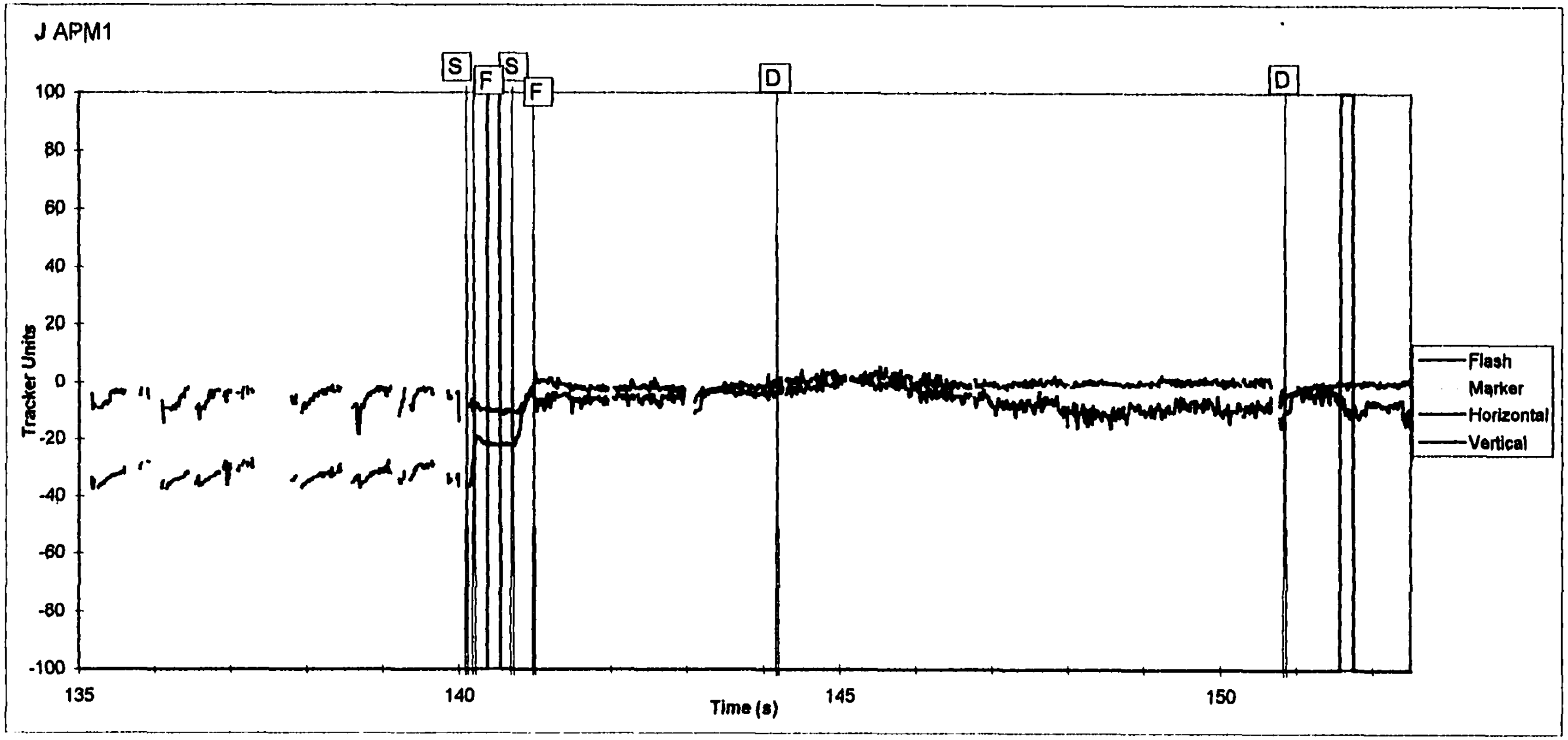

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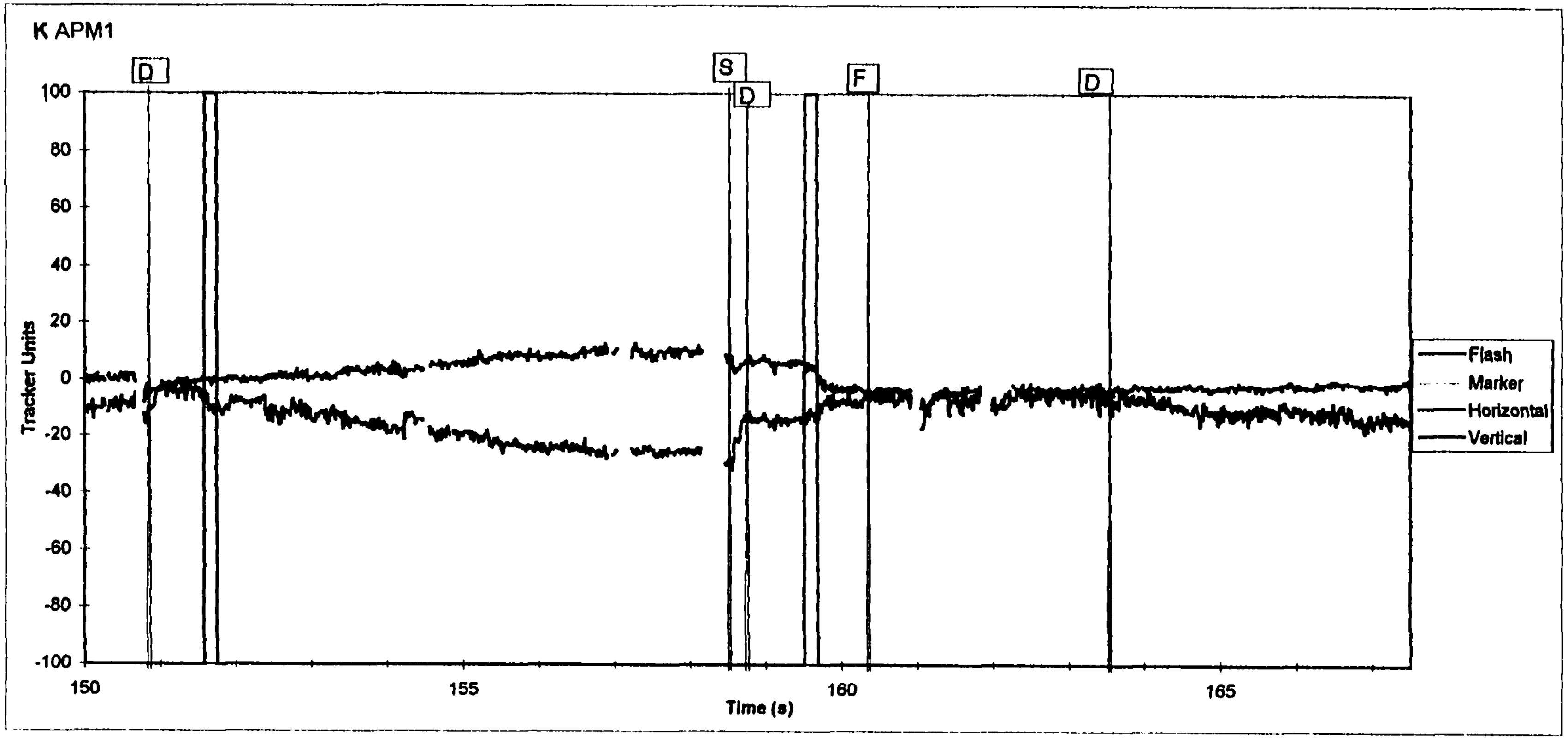

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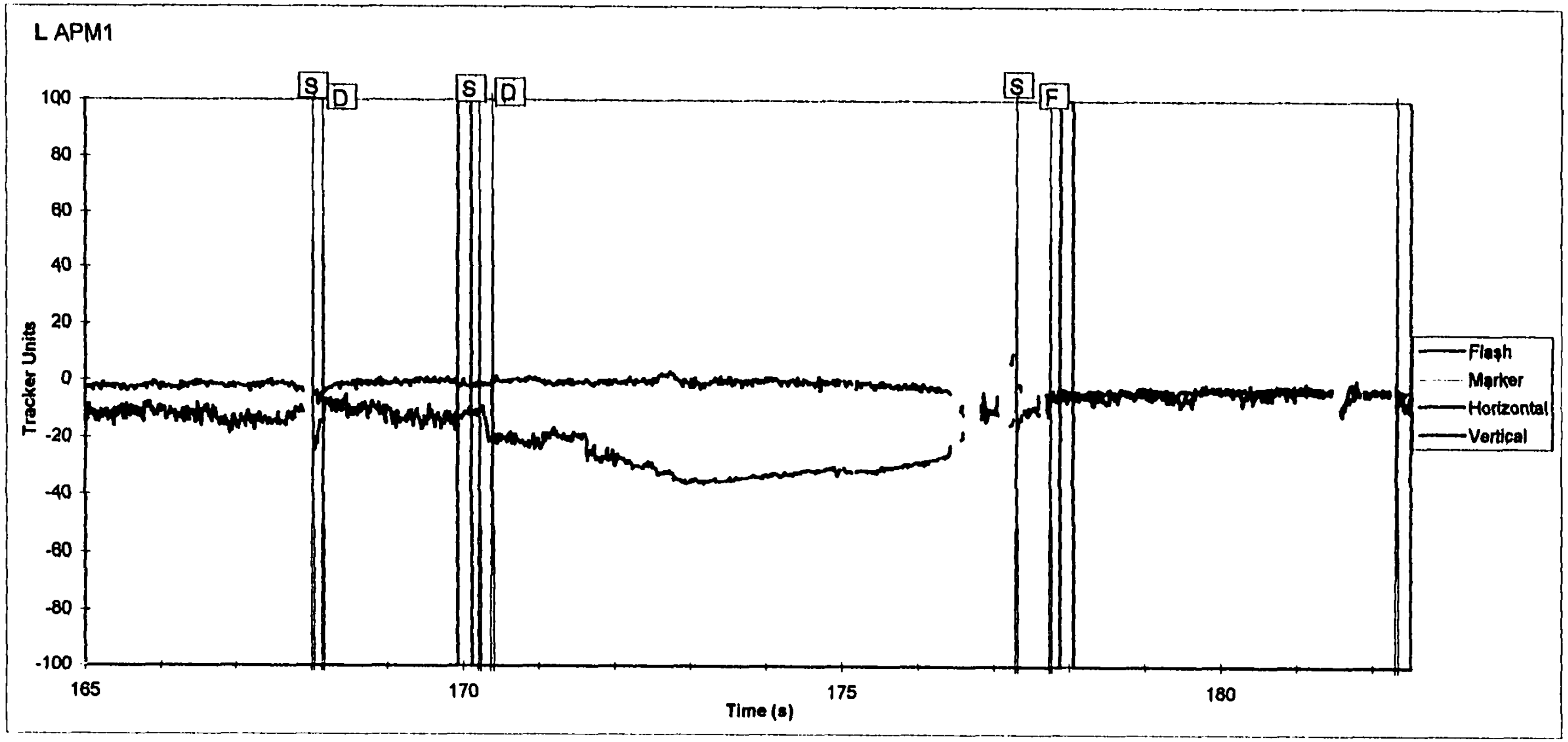

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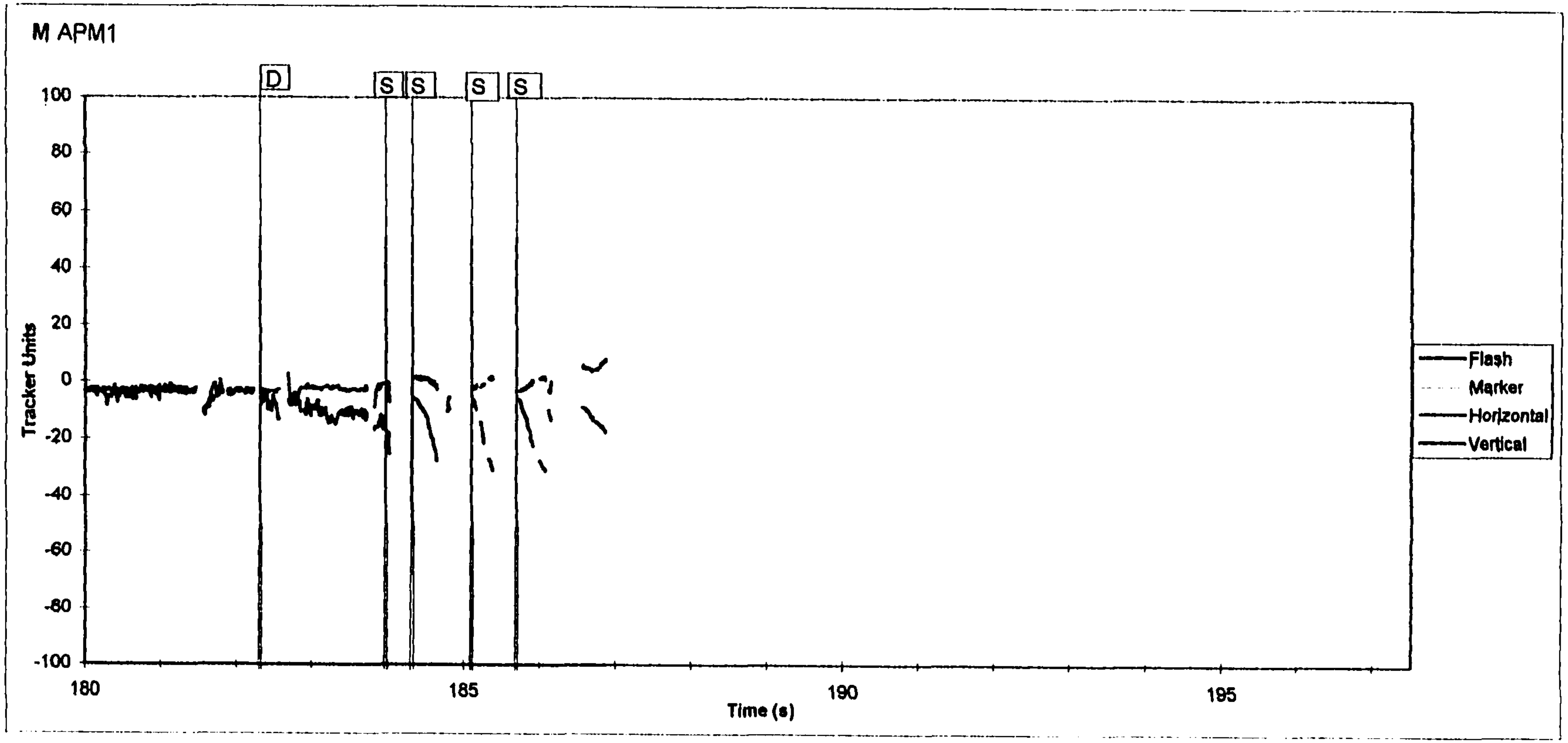

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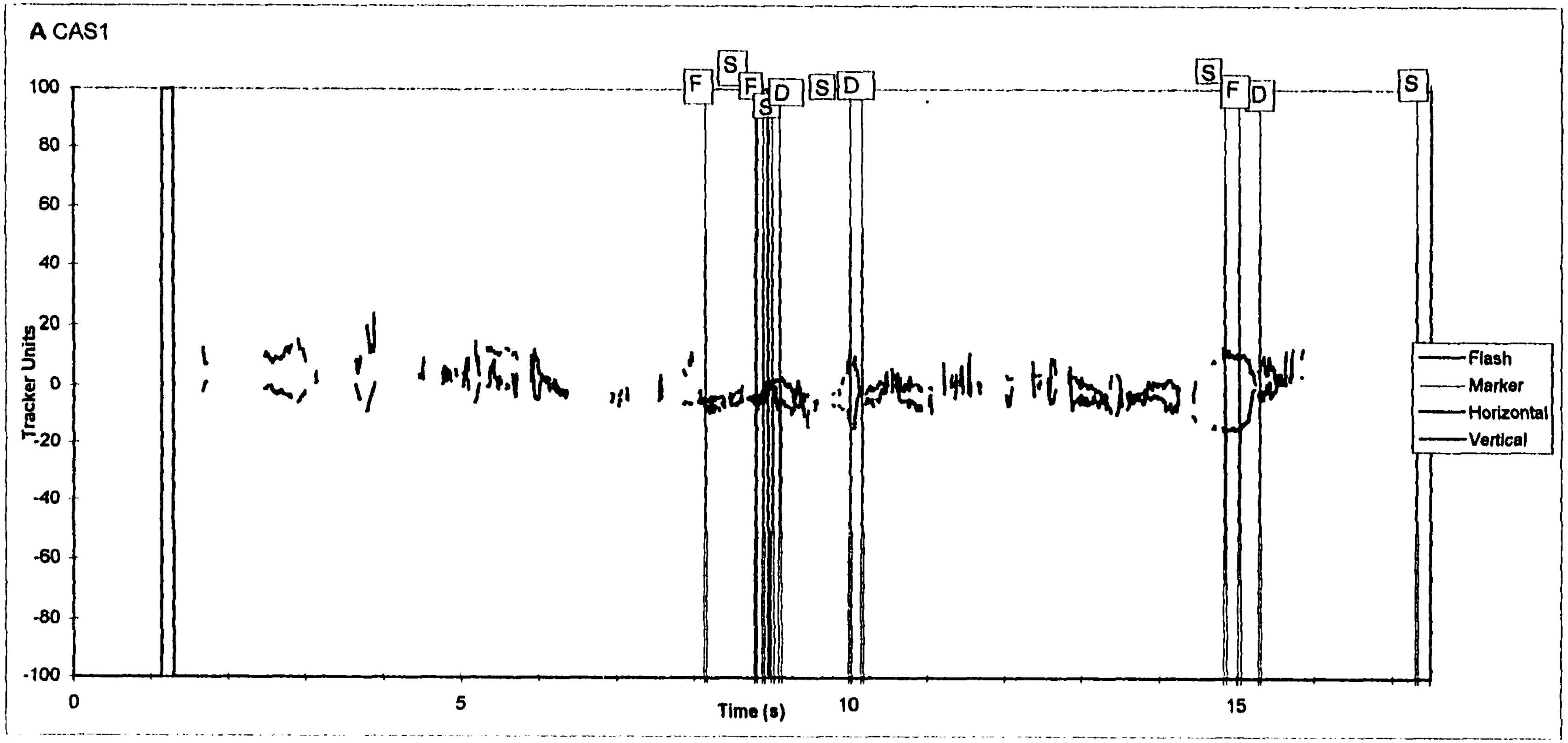

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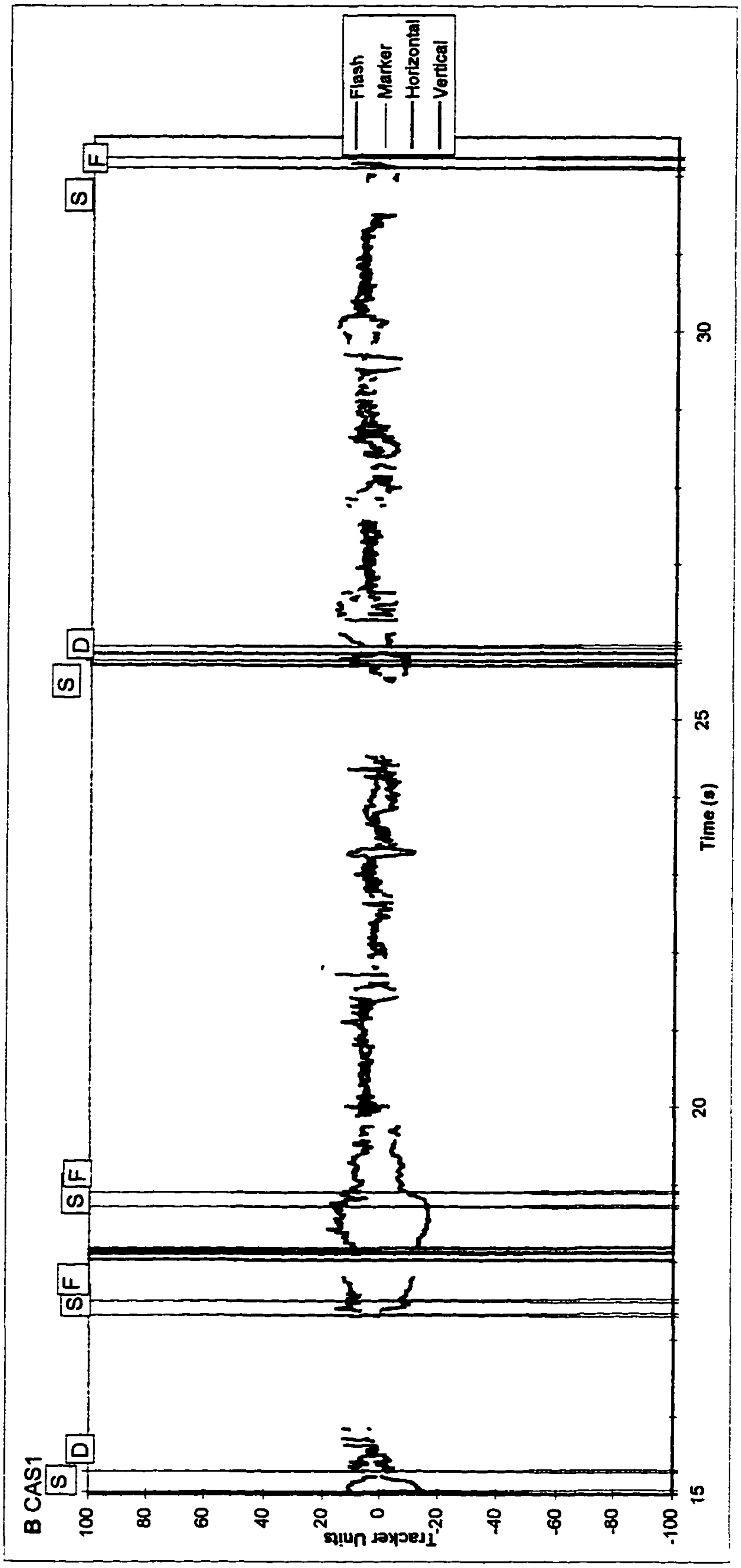

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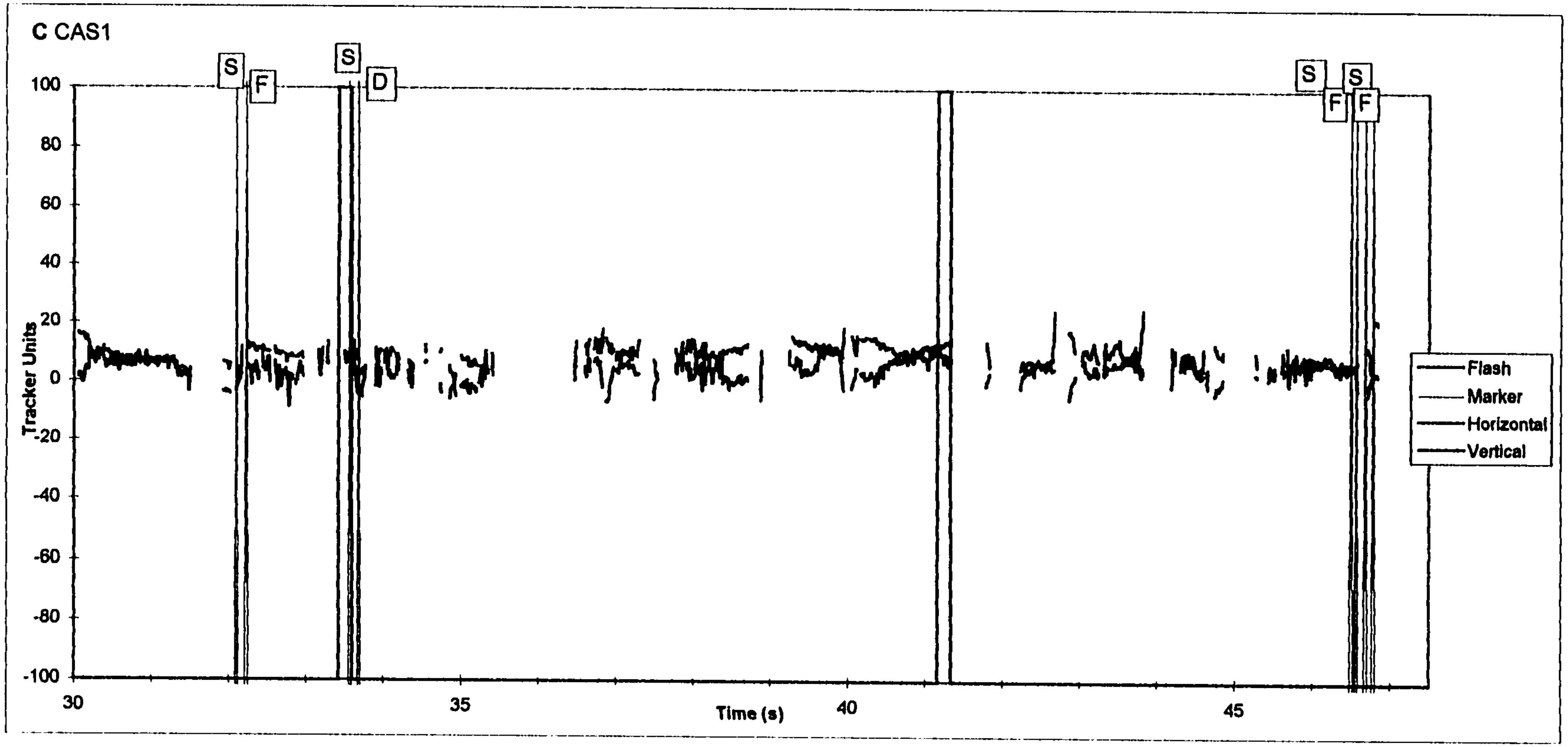
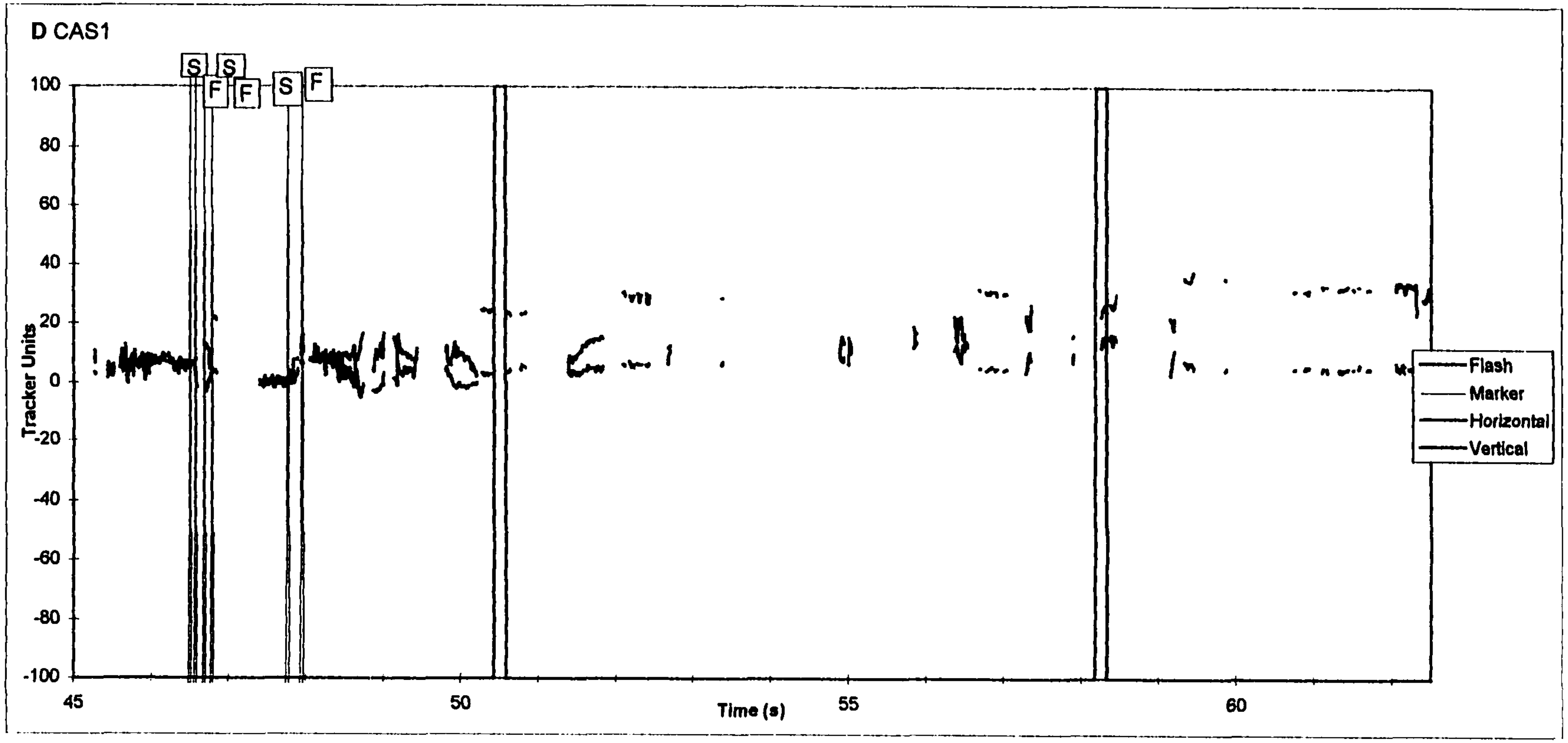
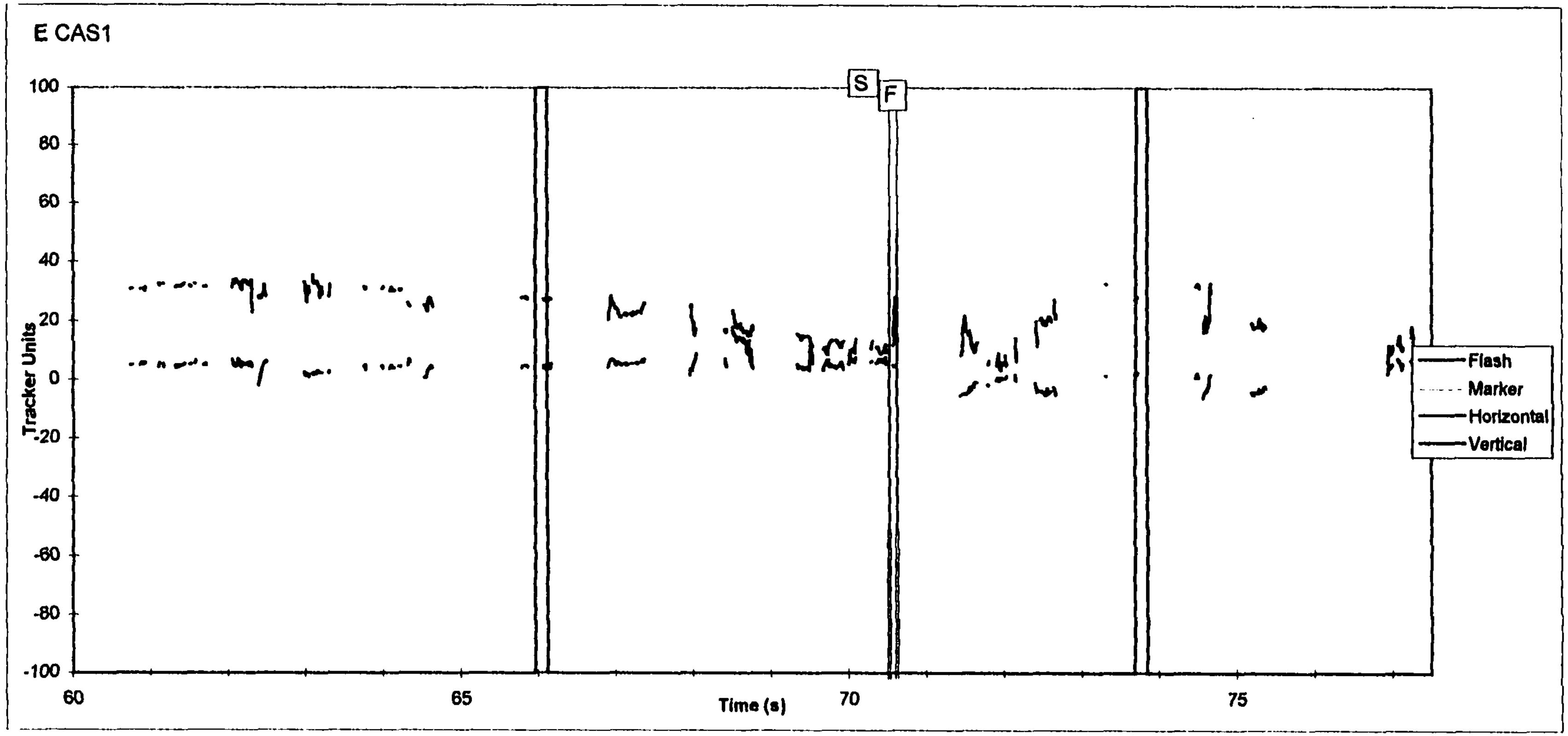


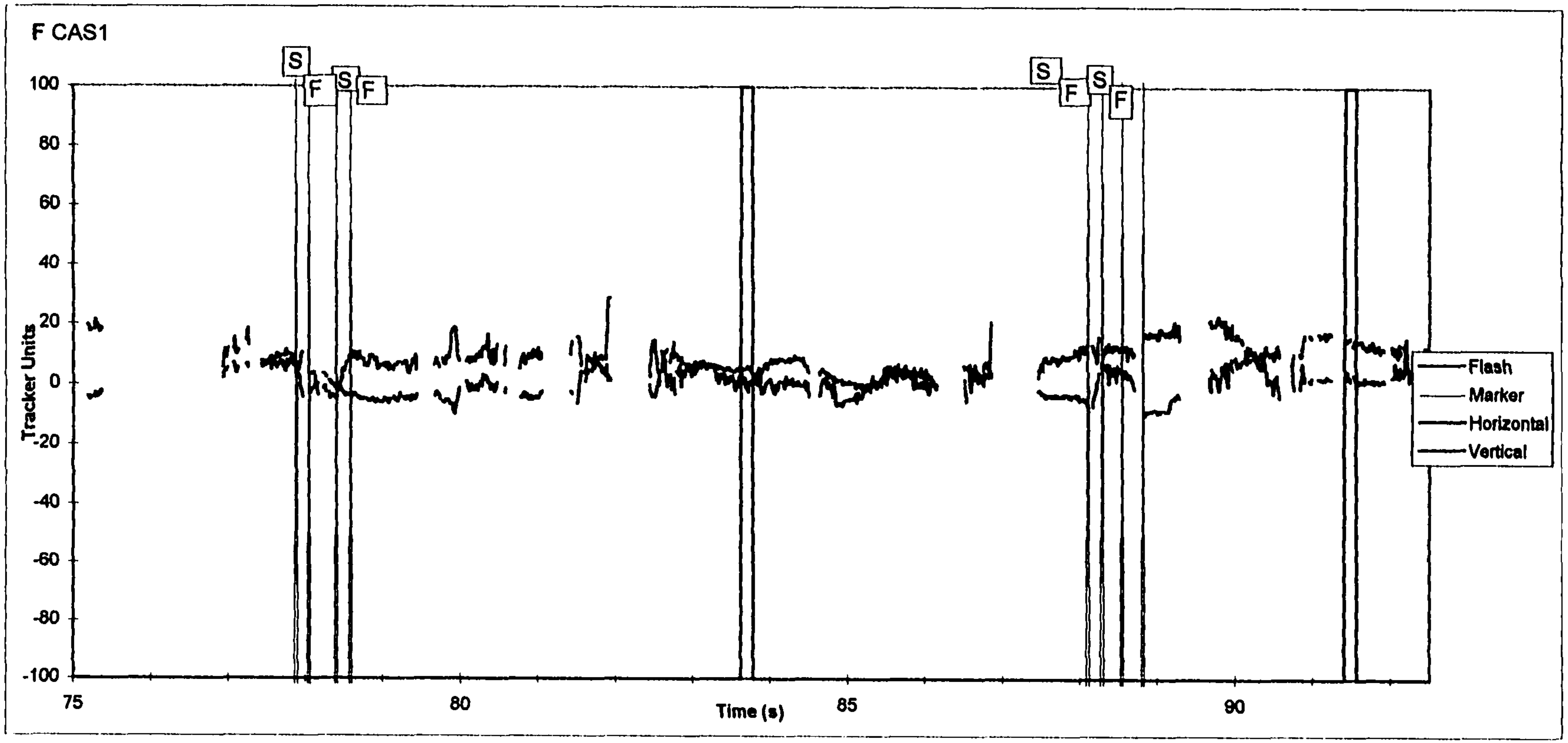
Appendix D3 Graphed and Labeled Tracker Data



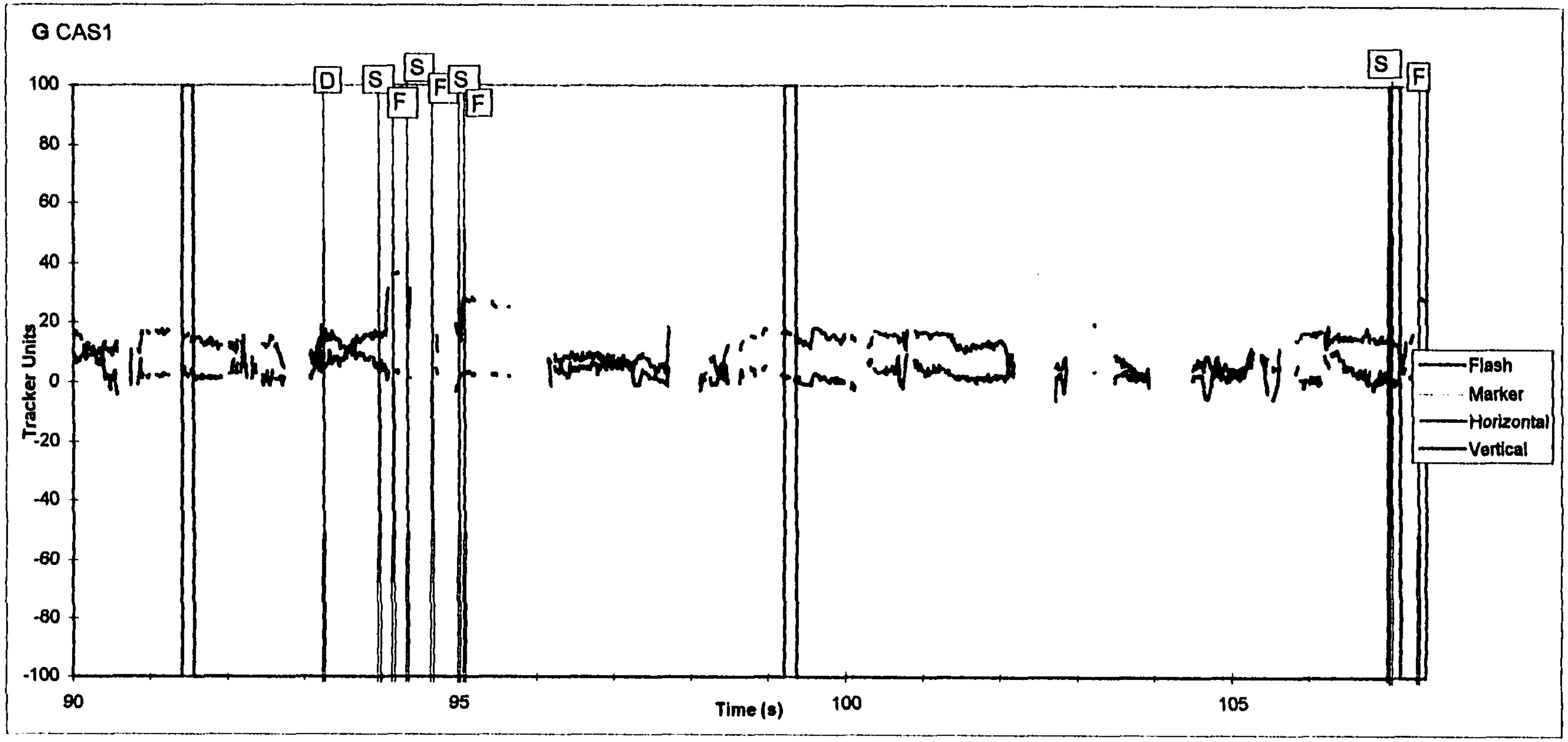
Appendix D3 Graphed and Labeled Tracker Data



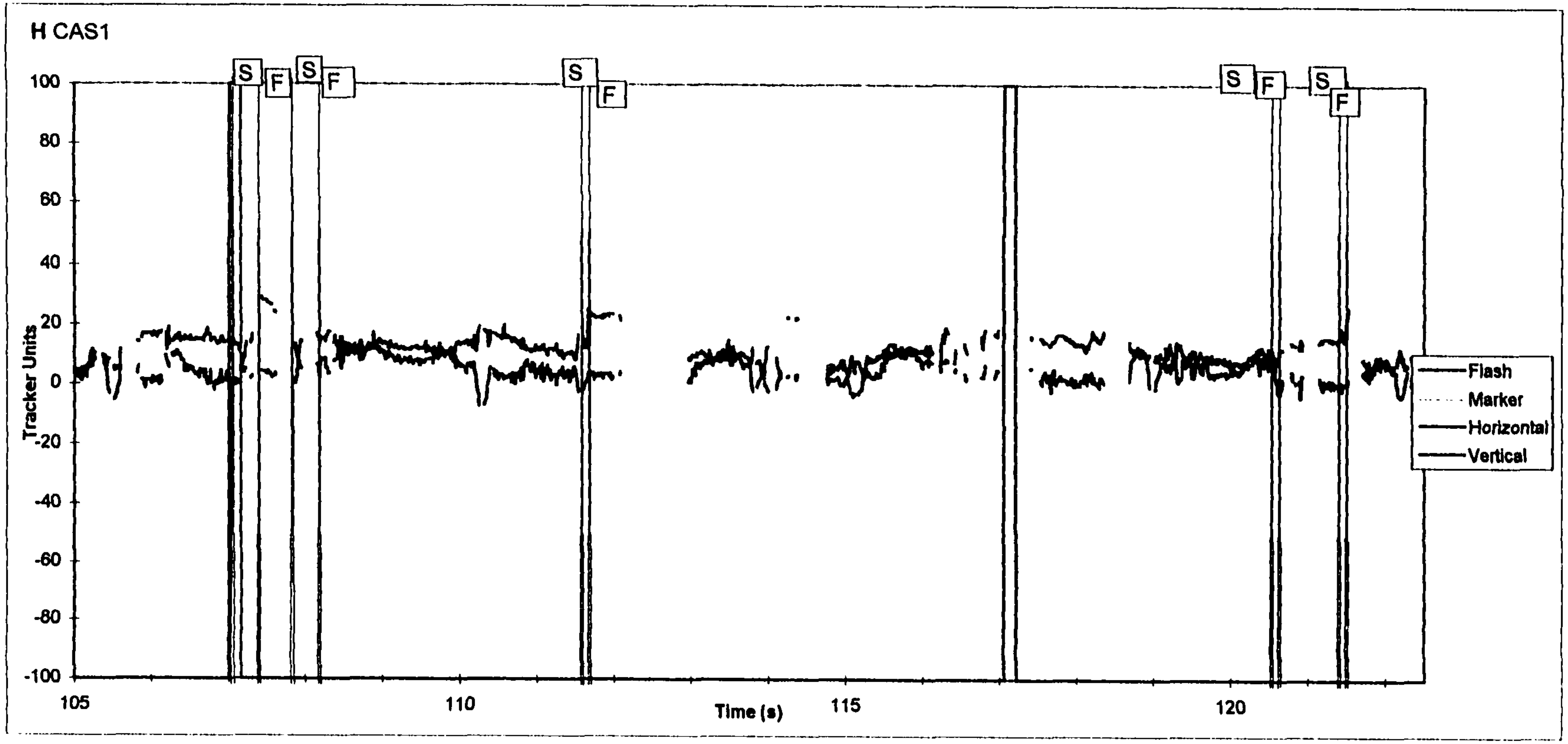
Appendix D3 Graphed and Labeled Tracker Data



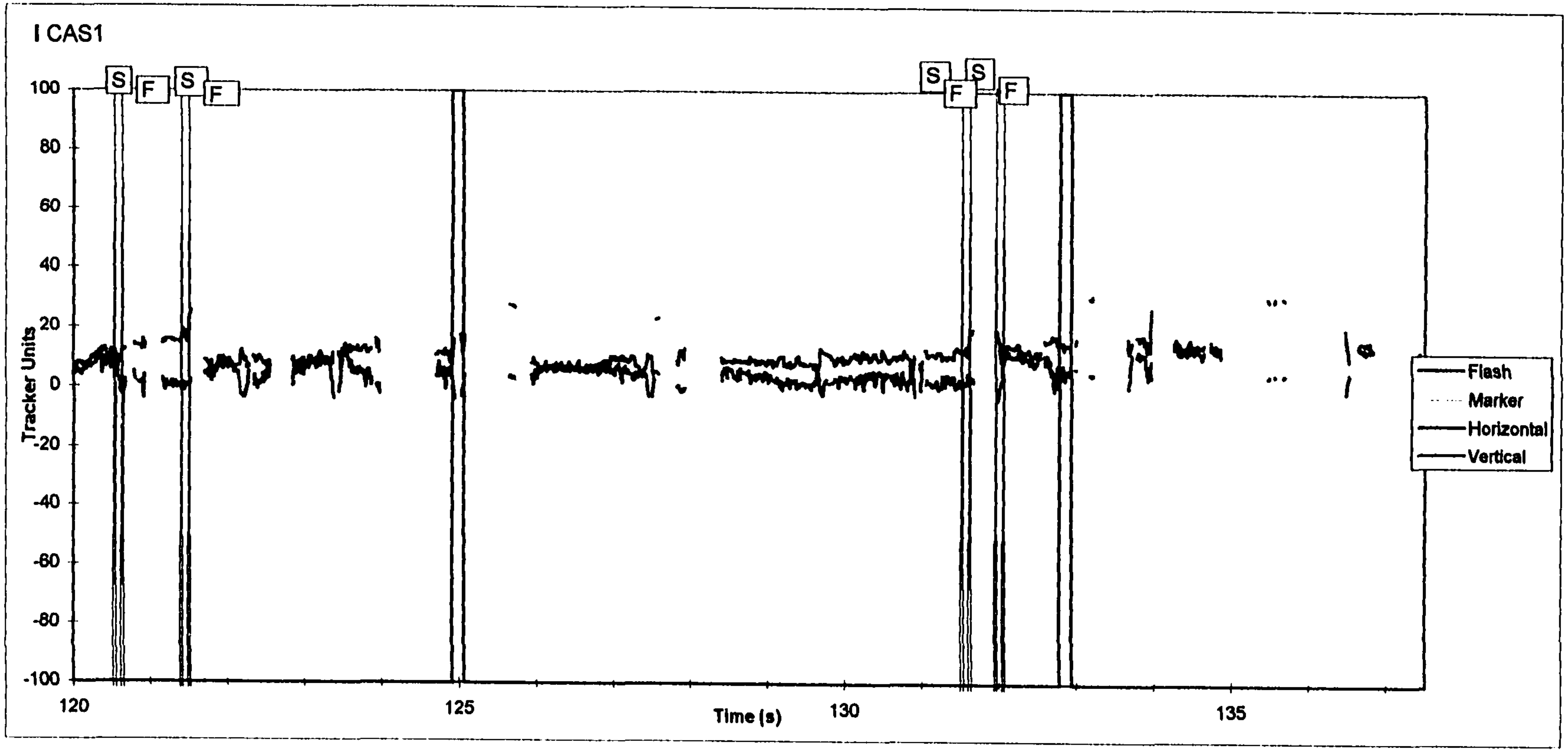
Appendix D3 Graphed and Labeled Tracker Data



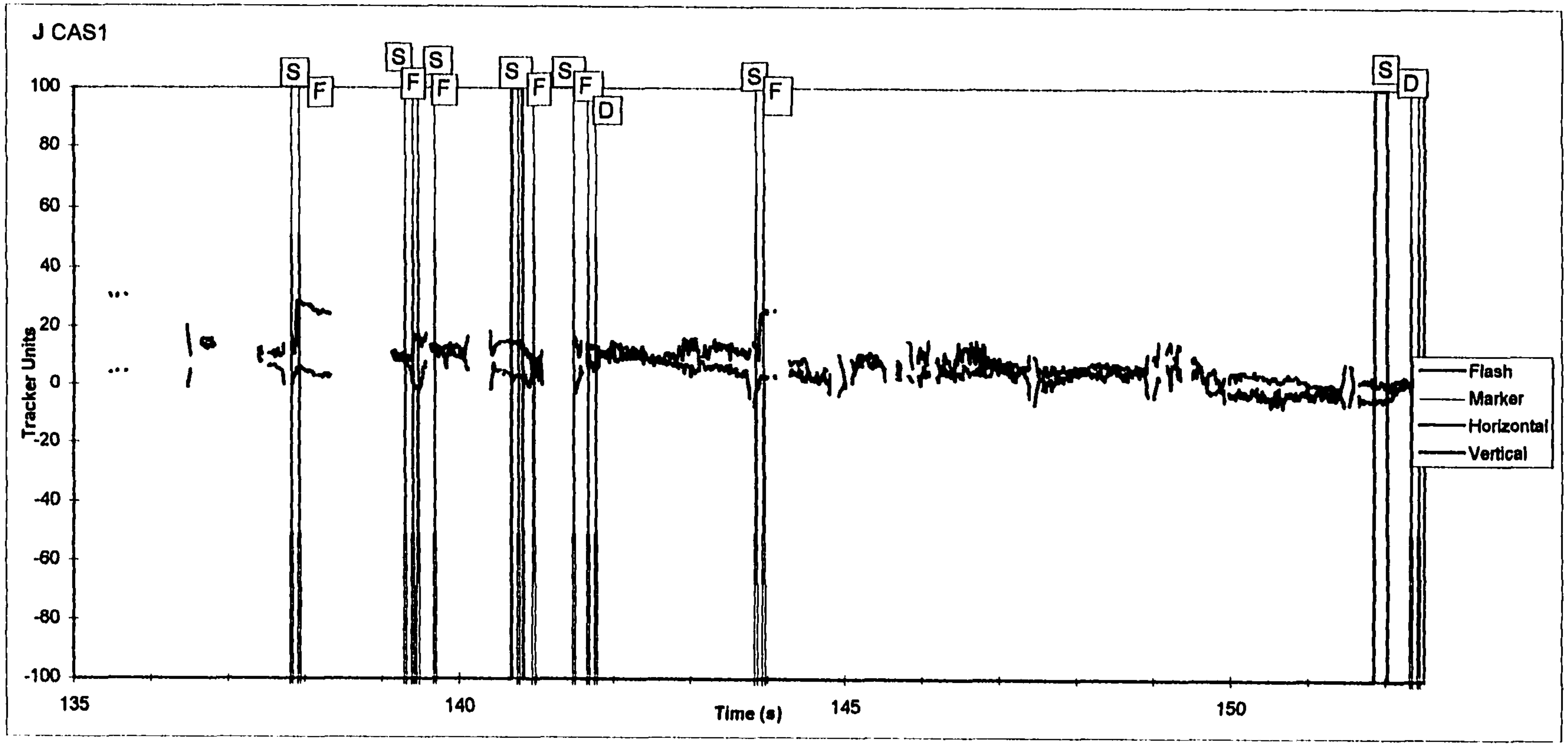
Appendix D3 Graphed and Labeled Tracker Data



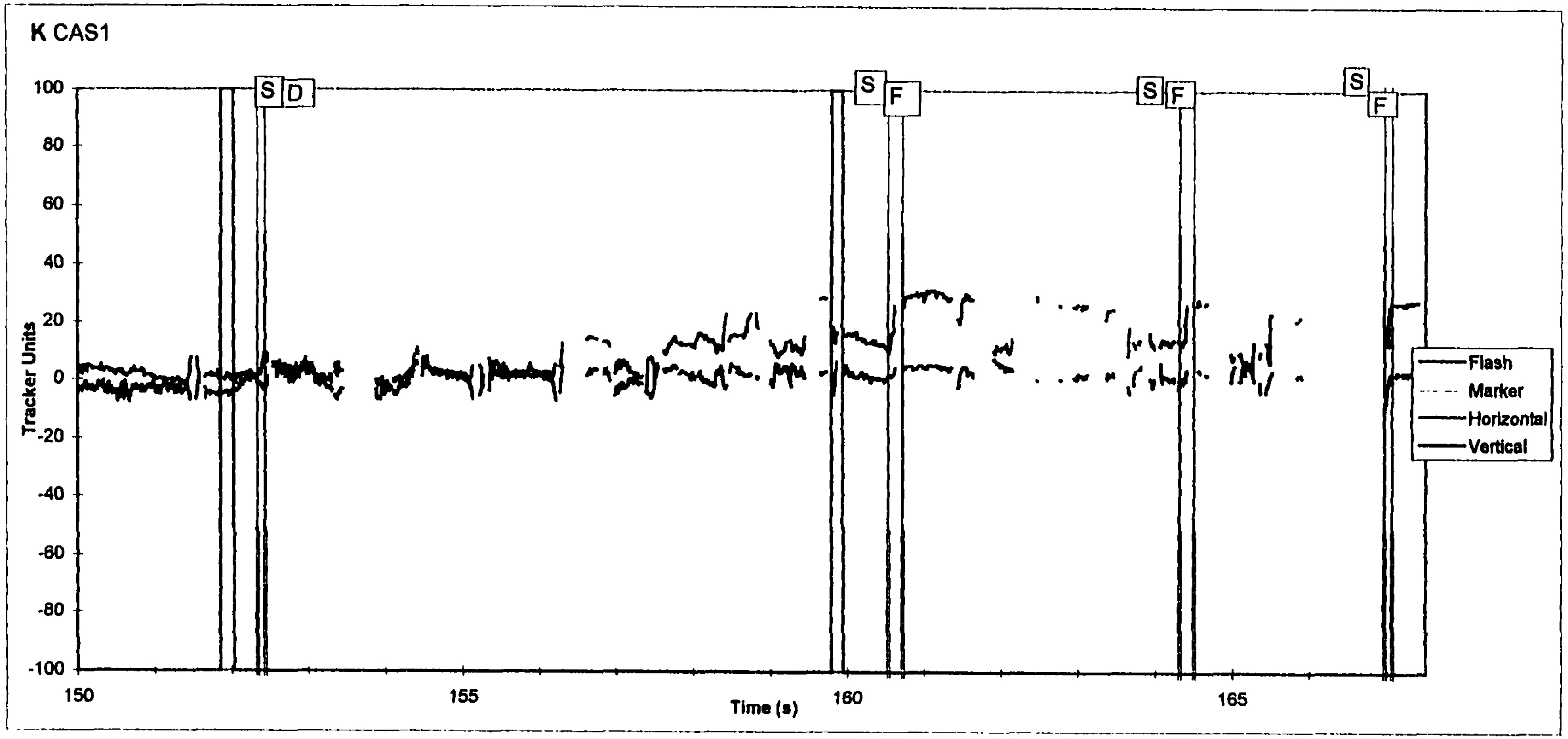
Appendix D3 Graphed and Labeled Tracker Data



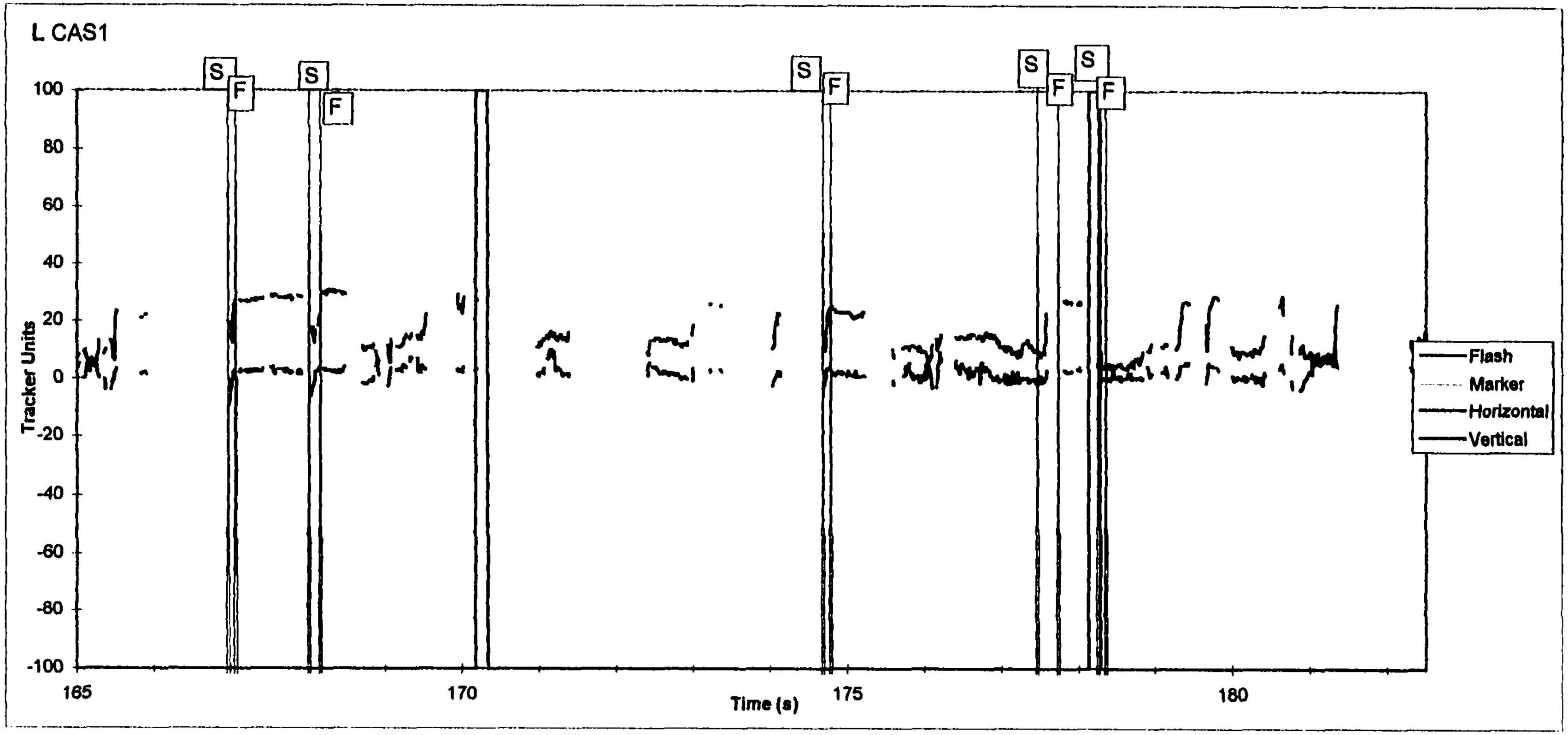
Appendix D3 Graphed and Labeled Tracker Data



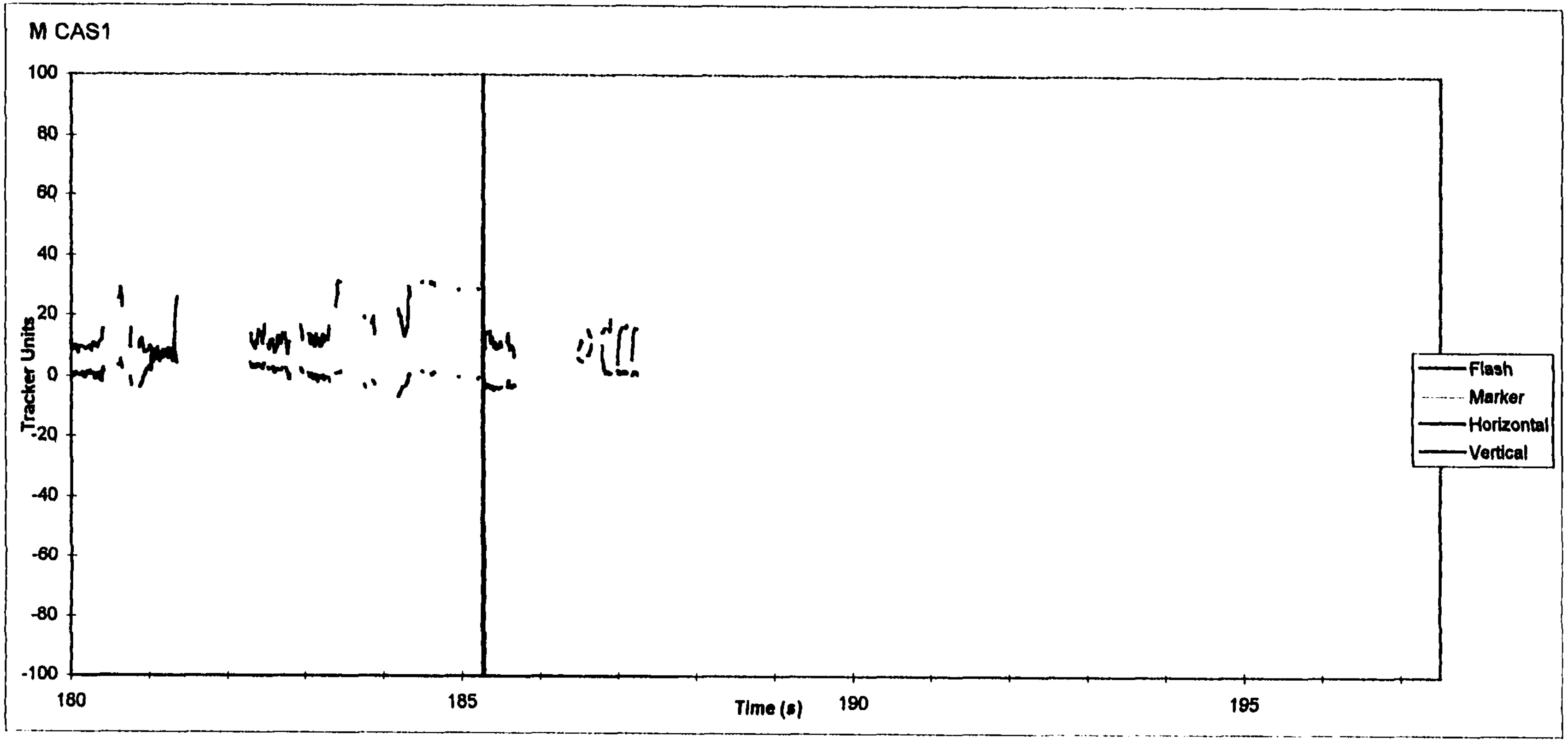
Appendix D3 Graphed and Labeled Tracker Data



Appendix D3 Graphed and Labeled Tracker Data



Appendix D3 Graphed and Labeled Tracker Data



Appendix E1: Summary of Down Extreme Eye Displacement and Velocity Values, Relative and Absolute Data

Participant	Years Vision	Years Blind	Relative Horizontal Displacement (degrees visual angle)	Relative Vertical Displacement (degrees visual angle)	Relative Average Velocity (degrees visual angle/sec)	Relative Amplitude (degrees visual angle)	Relative Direction (degrees rotation)	Absolute Horizontal Displacement (degrees visual angle)	Absolute Vertical Displacement (degrees visual angle)
SKD1R	20.00	0.00							
SGP1R	33.00	0.00	-1.61	-41.24	137.57	41.27	267.76	-6.44	-41.00
SPB1R	34.00	0.00							
SRS1R	33.00	0.00							
SGW1R	25.00	0.00	-1.20	-41.84	66.09	41.86	268.35	8.83	-40.22
SKB1R	25.00	0.00							
SRP1R	48.00	0.00	-4.30	-22.64	62.85	23.04	259.25	3.80	-51.68
SAV1R	27.00	0.00	1.44	-39.00	63.29	39.03	272.12	5.78	-48.09
SMB1R	45.00	0.00	1.31	-50.44	112.13	50.46	271.48	9.62	-55.17
ACC1R	65.00	11.00							
ABR1R	47.00	2.00	1.31	-43.28	123.72	43.30	271.73	-1.91	-43.66
ADS1R	15.00	19.00	29.70	-55.44	209.65	62.89	298.18	18.57	-55.05
AYK1R	19.00	23.00	-15.61	-8.32	12.63	17.69	208.06	-8.08	-13.46
APM1R	25.00	15.00							
AOR1R	28.00	10.00	13.07	-70.12	83.92	71.33	280.56	15.58	-73.33
AWW1R	13.00	45.00							
ABH1R	39.00	19.00	9.11	-67.44	38.52	68.05	277.69	6.24	-73.02
ARC1R	54.00	9.00	19.73	-60.20	211.17	63.35	288.15	13.44	-59.41
ABC1R	21.00	17.00							
CBG1R	0.00	43.00							
CAC1R	18.00	24.00							
CMV1R	0.00	57.00							
CJD2R	10.00	47.00	3.20	-21.68	54.78	21.91	278.39	12.60	-28.70
CPA1R	0.00	39.00	8.83	4.48	59.43	9.91	26.89	30.85	-27.71
CEB1R	0.00	71.00							
CWM1R	0.00	41.00	-13.10	30.40	86.35	33.10	113.31	24.97	-38.44
CPD1R	0.00	44.00							
CAS1R	0.00	43.00	8.90	-14.00	10.59	16.59	302.46	-5.91	-13.67
CWM2R	8.00	34.00	-24.68	33.92	27.36	41.95	-4.49	9.33	
CEL1R	0.00	66.00							
CPL1R	0.00	47.00							
CKG1R	3.00	45.00	22.41	5.40	138.32	23.05	13.55	-16.62	
CRW1R	11.00	25.00	17.36	-64.08	137.36	66.39	285.16	-10.06	-51.92
CJD1R	9.00	19.00	-2.78	20.28	9.30	20.47	97.82	-3.00	8.99
CJC1R	0.00	53.00	5.19	-36.96	62.20	37.32	277.99	-18.32	-4.52

Appendix E2: Summary of Down Midposition Eye Displacement and Velocity Values, Relative and Absolute Data

Participant	Years Vision	Years Blind	Relative Horizontal Displacement (degrees visual angle)	Relative Vertical Displacement (degrees visual angle)	Relative Average Velocity (degrees visual angle/sec)	Relative Accuracy (mid/ extreme)	Relative Amplitude (degrees visual angle)	Relative Direction (degrees rotation)	Absolute Horizontal Displacement (degrees visual angle)	Absolute Vertical Displacement (degrees visual angle)
SKD1R	20.00	0.00	6.12	-30.04	91.97		30.66	281.51	12.72	-34.41
SGP1R	33.00	0.00	-1.03	-16.64	28.58	-0.19	16.67	266.46	-3.38	-15.52
SPB1R	34.00	0.00								
SRS1R	33.00	0.00								
SGW1R	25.00	0.00	-0.83	-2.52	39.78	-0.87	2.65	251.87	3.16	-3.66
SKB1R	25.00	0.00								
SRP1R	48.00	0.00	-14.58	-40.96	74.53	2.77	43.48	250.41	-6.20	-47.36
SAV1R	27.00	0.00								
SMB1R	45.00	0.00	1.51	-34.40	48.05	0.36	34.43	272.52	13.40	-37.21
ACC1R	65.00	11.00	19.53	-24.32	45.64		31.19	308.76	10.65	-34.34
ABR1R	47.00	2.00	4.57	-12.16	70.86	-0.40	12.99	290.60	0.15	-20.90
ADS1R	15.00	19.00	9.52	-17.16	98.12	-0.38	19.62	299.03	9.25	-9.05
AYK1R	19.00	23.00	2.96	-0.64	45.36	-0.66	3.02	347.78	-0.69	-10.34
APM1R	25.00	15.00								
AOR1R	28.00	10.00	6.19	-64.72	76.48	0.82	65.01	275.47	5.44	-70.64
AWW1R	13.00	45.00					0.00			
ABH1R	39.00	19.00	0.72	-55.12	44.10	0.62	55.12	270.75	-3.90	-56.86
ARC1R	54.00	9.00								
ABC1R	21.00	17.00								
CBG1R	0.00	43.00								
CAC1R	18.00	24.00								
CMV1R	0.00	57.00	-7.46	-9.68	15.60		12.22	232.38	-4.79	-12.46
CJD2R	10.00	47.00	-0.28	-9.48	4.25	-0.13	9.48	268.34	8.55	-25.34
CPA1R	0.00	39.00								
CEB1R	0.00	71.00								
CWM1R	0.00	41.00								
CPD1R	0.00	44.00								
CAS1R	0.00	43.00	6.53	2.28	4.46	0.14	6.92	19.24	-6.91	-3.39
CWM2R	8.00	34.00								
CEL1R	0.00	66.00								
CPL1R	0.00	47.00	4.98	-6.24	4.99		7.99	308.62	-6.32	-2.60
CKG1R	3.00	45.00								
CRW1R	11.00	25.00	-0.79	-26.52	6.24	-0.20	26.53	268.29	10.29	-38.04
CJD1R	9.00	19.00	1.14	14.56	2.20	0.43	14.60	85.54	9.52	9.99
CJC1R	0.00	53.00	-26.37	-11.72	38.47	0.55	28.85	203.97	-22.41	-14.52

Appendix E3: Summary of Up Extreme Eye Displacement and Velocity Values, Relative and Absolute Data

Participant	Years Vision	Years Blind	Relative Horizontal Displacement (degrees visual angle)	Relative Vertical Displacement (degrees visual angle)	Relative Average Velocity (degrees visual angle/sec)	Relative Amplitude (degrees visual angle)	Relative Direction (degrees rotation)	Absolute Horizontal Displacement (degrees visual angle)	Absolute Vertical Displacement (degrees visual angle)
SKD1R	20.00	0.00							
SGP1R	20.00	0.00	1.00	35.36	40.05	35.37	88.38	-0.80	33.36
SPB1R	34.00	0.00	-14.06	-29.56	89.27	32.73	244.56	-3.67	-0.71
SRS1R	33.00	0.00	-3.78	56.28	69.07	56.41	93.84	-4.03	54.80
SGW1R	25.00	0.00	-18.01	44.52	32.02	48.03	112.03	-11.38	44.58
SKB1R	25.00	0.00							
SRP1R	48.00	0.00	-11.07	56.24	56.38	57.32	101.13	-13.15	53.12
SAV1R	27.00	0.00	-14.61	41.12	56.92	43.64	109.56	-11.89	37.67
SMB1R	45.00	0.00	-10.90	43.84	108.42	45.17	103.96	-6.26	50.31
ACC1R	65.00	11.00	-20.76	51.68	64.26	55.69	111.89	-21.32	42.62
ABR1R	47.00	2.00							
ADS1R	15.00	19.00	14.68	32.56	164.84	35.72	65.73	6.85	39.35
AYK1R	19.00	23.00							
APM1R	25.00	15.00	1.31	34.32	38.16	34.35	87.82	7.56	33.90
AOR1R	28.00	10.00	-4.40	14.56	152.10	15.21	106.81	-13.34	24.35
AWW1R	13.00	45.00							
ABH1R	39.00	19.00	-5.16	-1.96	33.09	5.52	200.81	-4.97	-3.90
ARC1R	54.00	9.00	4.88	30.16	40.74	30.55	80.81	-8.28	42.67
ABC1R	21.00	17.00							
CBG1R	0.00	43.00	-5.81	-2.24	93.39	6.23	201.09	-2.10	17.61
CAC1R	18.00	24.00	-3.06	33.32	401.52	33.46	95.25	3.38	47.71
CMV1R	0.00	57.00	7.98	16.52	122.29	18.34	64.23	16.73	12.18
CJD2R	10.00	47.00	-18.18	68.68	77.50	71.05	104.83	-8.81	50.66
CPA1R	0.00	39.00	4.54	-2.40	77.00	5.13	332.12	7.44	2.89
CEB1R	0.00	71.00	-7.08	9.68	18.94	11.99	126.19	7.49	19.44
CWM1R	0.00	41.00							
CPD1R	0.00	44.00							
CAS1R	0.00	43.00	2.82	1.96	2.39	3.43	34.81	-8.22	6.21
CWM2R	8.00	34.00	20.87	2.68	16.18	21.04	7.32	37.07	17.61
CEL1R	0.00	66.00	-4.71	5.92	16.21	7.57	128.49	-1.07	5.56
CPL1R	0.00	47.00	15.88	-6.16	170.34	17.03	338.80	-14.88	19.00
CKG1R	3.00	45.00	-21.28	3.60	6.29	21.58	170.40	-17.46	18.02
CRW1R	11.00	25.00	-1.79	80.44	30.95	80.46	91.27	7.05	77.08
CJD1R	9.00	19.00	-4.23	-7.12	4.28	8.28	239.30	6.01	0.79
CJC1R	0.00	53.00	32.79	24.72	164.27	41.07	37.01	13.03	10.20

Appendix E4: Summary of Up Midposition Eye Displacement and Velocity Values, Relative and Absolute Data

Participant	Years Vision	Years Blind	Relative Horizontal Displacement (degrees visual angle)	Relative Vertical Displacement (degrees visual angle)	Relative Average Velocity (degrees visual angle/sec)	Relative Accuracy (mid/ extreme)	Relative Amplitude (degrees visual angle)	Relative Direction (degrees rotation)	Absolute Horizontal Displacement (degrees visual angle)	Absolute Vertical Displacement (degrees visual angle)
SKD1R	20.00	0.00								
SGP1R	20.00	0.00	6.26	15.84	30.05	-0.04	17.03	68.45	0.12	19.20
SPB1R	34.00	0.00	-5.33	20.56	49.02	0.30	21.24	104.53	-11.20	32.73
SRS1R	33.00	0.00								
SGW1R	25.00	0.00								
SKB1R	25.00	0.00								
SRP1R	48.00	0.00	3.47	15.68	24.71	-0.44	16.06	77.52	0.19	9.88
SAV1R	27.00	0.00	-12.17	15.76	34.13	-0.09	19.91	127.67	-8.10	18.63
SMB1R	45.00	0.00	0.96	28.84	57.71	0.28	28.86	88.09	-3.17	33.03
ACC1R	65.00	11.00	-2.10	14.68	26.17	-0.47	14.83	98.13	-5.50	25.30
ABR1R	47.00	2.00	0.45	15.68	72.40		15.69	88.37	0.32	23.14
ADS1R	15.00	19.00	-3.88	10.68	136.38	-0.36	11.36	109.98	-4.91	9.95
AYK1R	19.00	23.00	7.32	22.16	41.19		23.34	71.71	12.95	17.94
APM1R	25.00	15.00	-8.94	8.68	83.06	-0.27	12.46	135.83	-5.05	20.30
AOR1R	28.00	10.00	-5.74	8.76	125.69	0.38	10.47	123.24	-8.39	13.19
AWW1R	13.00	45.00								
ABH1R	39.00	19.00	-2.30	-4.28	48.60	0.76	4.86	241.73	-11.57	5.66
ARC1R	54.00	9.00	-6.57	22.44	28.63	0.53	23.38	106.31	-6.56	17.47
ABC1R	21.00	17.00	9.08	-18.04	86.55		20.19	296.70	21.92	36.67
CBG1R	0.00	43.00								
CAC1R	18.00	24.00								
CMV1R	0.00	57.00	-9.76	18.88	-2.39	1.32	21.25	117.34	-20.26	-3.50
CJD2R	10.00	47.00	-10.18	27.76	42.24	-0.17	29.57	110.13	-8.74	14.02
CPA1R	0.00	39.00								
CEB1R	0.00	71.00	-1.38	3.28	23.71	-0.41	3.56	112.74	5.46	9.60
CWM1R	0.00	41.00	3.13	84.48	51.24		84.54	87.88	21.19	44.68
CPD1R	0.00	44.00	12.75	14.20	60.27		19.09	48.07	6.45	4.68
CAS1R	0.00	43.00	17.88	-0.84	1073.68	9.43	17.89	357.31	12.48	3.57
CWM2R	8.00	34.00								
CEL1R	0.00	66.00								
CPL1R	0.00	47.00	4.71	-7.36	1.28	0.03	8.74	302.61	-4.53	6.36
CKG1R	3.00	45.00								
CRW1R	11.00	25.00	3.03	30.76	35.66	-0.23	30.91	84.38	-11.68	63.80
CJD1R	9.00	19.00	5.23	7.40	2.35	1.19	9.06	54.77	4.46	3.47
CJC1R	0.00	53.00	-9.63	-19.44	2.80	0.06	21.69	243.66	4.95	-16.44

Appendix E5: Summary of Right Extreme Eye Displacement and Velocity Values, Relative and Absolute Data

Participant	Years Vision	Years Blind	Relative Horizontal Displacement (degrees visual angle)	Relative Vertical Displacement (degrees visual angle)	Relative Average Velocity (degrees visual angle/sec)	Relative Amplitude (degrees visual angle)	Relative Direction (degrees rotation)	Absolute Horizontal Displacement (degrees visual angle)	Absolute Vertical Displacement (degrees visual angle)
SKD1R	20.00	0.00	-49.09	-9.80	120.13	50.06	191.29	-39.80	-0.85
SGP1R	20.00	0.00	-41.73	-29.16	16.88	50.91	214.94	-45.18	-32.16
SPB1R	34.00	0.00							
SRS1R	33.00	0.00	-57.10	-4.68	118.53	57.29	184.69	-57.65	-2.16
SGW1R	25.00	0.00							
SKB1R	25.00	0.00	-49.60	5.04	28.76	49.86	174.20	-53.86	9.60
SRP1R	48.00	0.00							
SAV1R	27.00	0.00	-53.42	-7.32	82.95	53.92	187.80	-49.49	2.95
SMB1R	45.00	0.00	-58.78	-11.12	55.22	59.82	190.71	-60.33	-9.81
ACC1R	65.00	11.00	-49.57	2.92	26.84	49.66	176.63	-47.82	5.42
ABR1R	47.00	2.00	-45.44	-9.76	32.05	46.48	192.12	-50.45	-10.94
ADS1R	15.00	19.00							
AYK1R	19.00	23.00	-21.21	-0.24	42.42	21.21	180.65	-25.17	-1.78
APM1R	25.00	15.00	-49.64	-4.56	42.12	49.85	185.25	-49.71	2.70
AOR1R	28.00	10.00	-55.21	-2.96	94.78	55.29	183.07	-57.51	-19.97
AWW1R	13.00	45.00	-21.73	-8.12	35.68	23.19	200.49	-21.39	-2.52
ABH1R	39.00	19.00	-48.19	-11.48	32.67	49.54	193.40	-45.19	-7.66
ARC1R	54.00	9.00	-45.34	4.52	49.71	45.57	174.31	-46.68	-4.01
ABC1R	21.00	17.00	-38.71	-9.52	88.58	39.86	193.82	-38.37	11.11
CBG1R	0.00	43.00							
CAC1R	18.00	24.00	-45.62	-15.68	68.91	48.24	198.97	-36.50	5.67
CMV1R	0.00	57.00	-10.21	2.92	91.01	10.62	164.04	-33.98	-2.02
CJD2R	10.00	47.00	-30.87	4.92	27.18	31.26	170.95	-29.37	-5.10
CPA1R	0.00	39.00	-7.08	-7.92	-1.65	10.62	228.20	3.31	-1.43
CEB1R	0.00	71.00	3.16	14.00	15.66	14.35	77.27	0.92	5.60
CWM1R	0.00	41.00							
CPD1R	0.00	44.00	-1.31	-60.92	110.79	60.93	268.77	-8.36	-16.80
CAS1R	0.00	43.00	1.65	2.32	4.27	2.85	54.59	-1.27	-9.03
CWM2R	8.00	34.00	-17.33	22.00	98.84	28.00	128.22	-14.32	4.81
CEL1R	0.00	66.00	-11.24	-1.76	25.28	11.38	188.90	-14.71	-5.24
CPL1R	0.00	47.00							
CKG1R	3.00	45.00							
CRW1R	11.00	25.00	-90.06	-9.88	45.68	90.60	186.26	-83.56	-11.00
CJD1R	9.00	19.00							
CJC1R	0.00	53.00	-36.51	-9.84	63.01	37.81	195.08	-31.93	1.00

Appendix E6: Summary of Right Midposition Eye Displacement and Velocity Values, Relative and Absolute Data

Participant	Years Vision	Years Blind	Relative Horizontal Displacement (degrees visual angle)	Relative Vertical Displacement (degrees visual angle)	Relative Average Velocity (degrees visual angle/sec)	Relative Accuracy (mid/ extreme)	Relative Amplitude (degrees visual angle)	Relative Direction (degrees rotation)	Absolute Horizontal Displacement (degrees visual angle)	Absolute Vertical Displacement (degrees visual angle)
SKD1R	20.00	0.00	-32.28	1.04	49.68	0.29	32.30	178.16	-32.89	2.79
SGP1R	20.00	0.00	-49.98	-1.44	23.44	0.96	50.00	181.65	-49.44	-3.08
SPB1R	34.00	0.00	-27.91	-5.44	56.88		28.44	191.03	-31.59	-16.52
SRS1R	33.00	0.00	-30.42	9.68	23.65	0.11	31.93	162.35	-38.74	8.20
SGW1R	25.00	0.00	-33.93	-4.72	48.94		34.26	187.92	-42.18	-4.94
SKB1R	25.00	0.00	-18.60	9.56	12.67	-0.16	20.91	152.79	-17.97	9.96
SRP1R	48.00	0.00	-40.25	-7.08	38.92		40.87	189.98	-41.50	-7.08
SAV1R	27.00	0.00	-49.84	-0.36	90.63	0.85	49.84	180.41	-47.43	-0.73
SMB1R	45.00	0.00	-12.75	-4.60	40.67	-0.55	13.56	199.83	-42.53	-0.65
ACC1R	65.00	11.00	-23.27	-7.60	11.75	-0.01	24.48	198.08	-33.90	0.18
ABR1R	47.00	2.00	-30.32	-3.24	79.54	0.31	30.49	186.10	-40.04	-11.66
ADS1R	15.00	19.00	-17.19	-1.08	43.05		17.22	183.59	-13.54	-11.05
AYK1R	19.00	23.00	-25.30	12.80	25.78	1.67	28.35	153.16	-32.59	7.70
APM1R	25.00	15.00	-21.97	0.24	54.92	-0.12	21.97	179.38	-37.71	-7.74
AOR1R	28.00	10.00	38.53	4.68	194.08	0.40	38.82	6.92	-60.37	-15.61
AWW1R	13.00	45.00								
ABH1R	39.00	19.00	-75.52	-15.72	125.09	2.11	77.14	191.76	-83.10	-14.26
ARC1R	54.00	9.00	-33.89	4.44	62.15	0.50	34.18	172.54	-47.19	0.67
ABC1R	21.00	17.00	-30.25	-25.12	90.74	0.97	39.32	219.71	-27.17	-4.97
CBG1R	0.00	43.00								
CAC1R	18.00	24.00	-13.44	-8.12	19.23	-0.35	15.70	211.14	-25.53	5.99
CMV1R	0.00	57.00								
CJD2R	10.00	47.00	-12.03	-3.68	3.25	-0.20	12.58	197.01	-8.09	-9.18
CPA1R	0.00	39.00	-16.43	4.24	92.56	2.19	16.97	165.53	-52.14	-4.27
CEB1R	0.00	71.00								
CWM1R	0.00	41.00								
CPD1R	0.00	44.00								
CAS1R	0.00	43.00	8.39	-0.12	7.86	4.89	8.39	359.18	7.91	2.17
CWM2R	8.00	34.00	-22.65	-4.32	69.18	0.65	23.06	190.80	-9.81	-16.59
CEL1R	0.00	66.00								
CPL1R	0.00	47.00	-0.62	7.12	15.88		7.15	94.97	-4.05	-9.56
CKG1R	3.00	45.00								
CRW1R	11.00	25.00	-59.23	-33.00	64.57	0.50	67.80	209.13	-54.61	-22.12
CJD1R	9.00	19.00	13.85	3.76	18.72		14.35	15.18	12.99	12.95
CJC1R	0.00	53.00	5.12	6.48	23.60	-0.56	8.26	51.68	-5.36	0.80

Appendix E7: Summary of Left Extreme Eye Displacement and Velocity Values, Relative and Absolute Data

Participant	Years Vision	Years Blind	Relative Horizontal Displacement (degrees visual angle)	Relative Vertical Displacement (degrees visual angle)	Relative Average Velocity (degrees visual angle/sec)	Relative Amplitude (degrees visual angle)	Relative Direction (degrees rotation)	Absolute Horizontal Displacement (degrees visual angle)	Absolute Vertical Displacement (degrees visual angle)
SKD1R	20.00	0.00	43.18	2.52	55.21	43.25	3.34	43.21	0.23
SGP1R	20.00	0.00	54.69	-1.36	72.94	54.71	358.57	56.88	-6.48
SPB1R	34.00	0.00	54.04	-1.88	49.91	54.07	358.01	54.93	-19.08
SRS1R	33.00	0.00							
SGW1R	25.00	0.00							
SKB1R	25.00	0.00	39.88	1.64	239.45	39.91	2.35	44.93	6.00
SRP1R	48.00	0.00							
SAV1R	27.00	0.00	43.07	4.72	68.42	43.33	6.25	43.90	8.71
SMB1R	45.00	0.00	57.37	2.40	181.33	57.42	2.40	59.36	0.39
ACC1R	65.00	11.00	51.91	14.16	12.71	53.80	15.26	52.93	17.02
ABR1R	47.00	2.00	69.99	-10.40	176.89	70.76	351.55	56.56	0.34
ADS1R	15.00	19.00	76.18	-10.32	384.35	76.87	352.28	67.79	-9.01
AYK1R	19.00	23.00	48.50	2.16	171.35	48.55	2.55	60.08	4.22
APM1R	25.00	15.00							
AOR1R	28.00	10.00	49.74	-3.16	44.63	49.84	356.37	50.23	-16.65
AWW1R	13.00	45.00	46.71	-14.12	146.41	48.80	343.18	46.30	-12.80
ABH1R	39.00	19.00	52.01	-10.16	64.89	52.99	348.95	63.68	-14.26
ARC1R	54.00	9.00							
ABC1R	21.00	17.00	35.99	1.20	74.51	36.01	1.91	36.39	6.67
CBG1R	0.00	43.00							
CAC1R	18.00	24.00	24.20	6.60	65.44	25.08	15.26	33.97	8.63
CMV1R	0.00	57.00	9.83	20.24	14.36	22.50	64.09	-15.86	-1.90
CJD2R	10.00	47.00	33.31	20.80	26.18	39.27	31.98	43.20	10.18
CPA1R	0.00	39.00							
CEB1R	0.00	71.00						-1.86	1.88
CWM1R	0.00	41.00	6.77	17.72	189.69	18.97	69.08	28.06	33.92
CPD1R	0.00	44.00	22.79	17.92	23.19	28.99	38.18	10.95	0.64
CAS1R	0.00	43.00	9.59	-14.00	18.18	16.97	304.41	-2.06	-0.95
CWM2R	8.00	34.00	7.29	4.60	14.77	8.62	32.26	27.48	9.49
CEL1R	0.00	66.00	5.81	-2.92	10.54	6.50	333.32	12.86	-6.72
CPL1R	0.00	47.00							
CKG1R	3.00	45.00	-8.70	12.84	103.38	15.51	124.11	-6.01	16.94
CRW1R	11.00	25.00	27.74	-4.00	168.17	28.03	351.79	34.79	-1.00
CJD1R	9.00	19.00							
CJC1R	0.00	53.00	19.01	-11.88	30.57	22.42	328.00	14.40	3.96

Appendix E8: Summary of Left Midposition Eye Displacement and Velocity Values, Relative and Absolute Data

Participant	Years Vision	Years Blind	Relative Horizontal Displacement (degrees visual angle)	Relative Vertical Displacement (degrees visual angle)	Relative Average Velocity (degrees visual angle/sec)	Relative Accuracy (mid/ extreme)	Relative Amplitude (degrees visual angle)	Relative Direction (degrees rotation)	Absolute Horizontal Displacement (degrees visual angle)	Absolute Vertical Displacement (degrees visual angle)
SKD1R	20.00	0.00	49.50	-7.44	130.58	1.31	50.06	351.45	22.04	-3.85
SGP1R	20.00	0.00	54.28	5.84	48.17	1.00	54.59	6.14	56.29	-0.16
SPB1R	34.00	0.00	55.89	2.12	197.42	1.07	55.93	2.17	60.68	-20.52
SRS1R	33.00	0.00								
SGW1R	25.00	0.00	29.60	3.16	55.81		29.77	6.09	36.71	-3.46
SKB1R	25.00	0.00								
SRP1R	48.00	0.00								
SAV1R	27.00	0.00	21.31	1.28	116.46	-0.01	21.35	3.44	24.21	0.71
SMB1R	45.00	0.00	29.46	0.96	49.13	0.03	29.48	1.87	39.22	7.43
ACC1R	65.00	11.00	51.80	0.52	48.57	0.93	51.80	0.57	27.57	-3.86
ABR1R	47.00	2.00	28.94	-0.44	82.71	-0.18	28.95	359.13	48.82	-3.22
ADS1R	15.00	19.00								
AYK1R	19.00	23.00	25.03	-0.96	166.96	0.03	25.04	357.80	40.97	-8.38
APM1R	25.00	15.00	9.69	-4.32	48.98		10.61	335.98	19.52	0.10
AOR1R	28.00	10.00	-22.48	-14.60	107.24	0.08	26.81	213.00	43.18	-16.85
AWW1R	13.00	45.00	2.13	-2.48	19.62	-0.87	3.27	310.66	5.97	0.40
ABH1R	39.00	19.00	59.50	0.56	38.81	1.25	59.50	0.54	57.29	1.34
ARC1R	54.00	9.00	23.55	-3.52	17.42		23.81	351.50	40.12	-1.37
ABC1R	21.00	17.00								
CBG1R	0.00	43.00	9.76	12.32	157.19		15.72	51.61	12.86	-5.15
CAC1R	18.00	24.00	13.61	4.60	95.79	0.15	14.37	18.67	22.42	6.27
CMV1R	0.00	57.00	4.33	14.80	14.46	0.37	15.42	73.69	0.98	-0.38
CJD2R	10.00	47.00								
CPA1R	0.00	39.00	-32.11	18.44	63.47		37.03	150.13	8.50	8.93
CEB1R	0.00	71.00								
CWM1R	0.00	41.00								
CPD1R	0.00	44.00								
CAS1R	0.00	43.00	1.55	8.84	17.37	0.06	8.97	80.08	-2.92	6.97
CWM2R	8.00	34.00	-21.35	-15.92	93.99	5.18	26.63	216.71	-1.74	-7.15
CEL1R	0.00	66.00								
CPL1R	0.00	47.00								
CKG1R	3.00	45.00								
CRW1R	11.00	25.00	71.33	2.04	107.04	4.09	71.36	1.64	54.04	2.12
CJD1R	9.00	19.00	-8.46	18.28	57.55		20.14	114.82	-10.53	13.95
CJC1R	0.00	53.00	21.73	0.20	65.18	0.94	21.73	0.53	24.47	0.60

Appendix E9: Summary of Convergence Extreme Eye Displacement and Velocity Values, Relative and Absolute Data

Participant	Years Vision	Years Blind	Relative Horizontal Displacement (degrees visual angle)	Relative Vertical Displacement (degrees visual angle)	Relative Amplitude (degrees visual angle)	Relative Direction (degrees rotation)	Absolute Horizontal Displacement (degrees visual angle)	Absolute Vertical Displacement (degrees visual angle)
SKD1R	20.00	0.00	26.78	-21.00	34.03	321.90	14.27	-22.57
SGP1R	20.00	0.00	15.74	-27.04	31.29	300.21	20.65	-30.16
SPB1R	34.00	0.00						
SRS1R	33.00	0.00	-0.34	-12.24	12.24	268.39	9.72	-6.04
SGW1R	25.00	0.00	6.08	13.80	15.08	66.21	2.92	11.74
SKB1R	25.00	0.00	-0.72	-17.96	17.97	267.70	1.66	-18.48
SRP1R	48.00	0.00						
SAV1R	27.00	0.00	14.85	-34.88	37.91	293.06	17.95	-41.25
SMB1R	45.00	0.00	52.28	-15.88	54.64	343.11	32.10	-3.81
ACC1R	65.00	11.00	42.14	-23.36	48.19	331.00	13.88	-21.54
ABR1R	47.00	2.00						
ADS1R	15.00	19.00	24.85	-5.64	25.49	347.22	14.07	-36.97
AYK1R	19.00	23.00						
APM1R	25.00	15.00						
AOR1R	28.00	10.00	1.99	-24.68	24.76	274.61	0.83	-30.57
AWW1R	13.00	45.00						
ABH1R	39.00	19.00	-0.83	-3.08	3.19	255.01	-7.41	-3.46
ARC1R	54.00	9.00	30.66	-11.32	32.69	339.74	10.38	-22.53
ABC1R	21.00	17.00						
CBG1R	0.00	43.00						
CAC1R	18.00	24.00						
CMV1R	0.00	57.00	20.32	8.24	21.92	22.08	-0.70	-11.22
CJD2R	10.00	47.00	13.72	-17.44	22.19	308.18	17.73	-11.42
CPA1R	0.00	39.00						
CEB1R	0.00	71.00	-9.59	-3.04	10.06	197.59	-12.28	-5.04
CWM1R	0.00	41.00	12.51	-0.56	12.52	357.44	13.49	-26.68
CPD1R	0.00	44.00	9.56	-16.20	18.81	300.54	5.94	-17.12
CAS1R	0.00	43.00	29.49	6.08	30.11	11.65	13.58	1.85
CWM2R	8.00	34.00	14.68	11.60	18.71	38.32	40.85	12.13
CEL1R	0.00	66.00						
CPL1R	0.00	47.00	22.83	-2.56	22.97	353.60	-9.21	3.16
CKG1R	3.00	45.00	-23.27	3.00	23.46	172.66	-12.02	-13.70
CRW1R	11.00	25.00						
CJD1R	9.00	19.00	3.99	-7.20	8.23	298.98	1.88	-1.25
CJC1R	0.00	53.00	-3.88	18.20	18.61	102.05	-0.89	18.88

Appendix E10: Summary of Convergence Midposition Eye Displacement and Velocity Values, Relative and Absolute Data

Participant	Years Vision	Years Blind	Relative Horizontal Displacement (degrees visual angle)	Relative Vertical Displacement (degrees visual angle)	Relative Accuracy (mid/ extreme)	Relative Amplitude (degrees visual angle)	Relative Direction (degrees rotation)	Absolute Horizontal Displacement (degrees visual angle)	Absolute Vertical Displacement (degrees visual angle)
SKD1R	20.00	0.00	4.23	-12.88		13.56	288.17	2.34	-19.29
SGP1R	20.00	0.00							
SPB1R	34.00	0.00	-10.24	6.64		12.21	147.04	5.64	-5.48
SRS1R	33.00	0.00	-3.85	1.44		4.11	159.49	-0.11	0.04
SGW1R	25.00	0.00							
SKB1R	25.00	0.00	6.29	-15.32		16.56	292.32	11.14	-12.12
SRP1R	48.00	0.00							
SAV1R	27.00	0.00	-3.64	-18.32		18.68	258.75	-3.15	-30.73
SMB1R	45.00	0.00	45.58	-2.44		45.65	356.94	35.47	10.11
ACC1R	65.00	11.00	5.33	1.04		5.43	11.05	3.85	-15.30
ABR1R	47.00	2.00	8.56	-31.00		32.16	285.43	9.43	-43.54
ADS1R	15.00	19.00							
AYK1R	19.00	23.00							
APM1R	25.00	15.00	-10.42	0.28		10.42	178.46	-18.01	-0.74
AOR1R	28.00	10.00	3.17	-0.88		3.29	344.47	4.89	-16.57
AWW1R	13.00	45.00							
ABH1R	39.00	19.00	-0.58	-1.60		1.70	249.94	-15.00	-3.54
ARC1R	54.00	9.00							
ABC1R	21.00	17.00							
CBG1R	0.00	43.00	-13.23	14.96		19.97	131.50	-25.61	-8.03
CAC1R	18.00	24.00							
CMV1R	0.00	57.00	14.71	-5.64		15.76	339.03	5.59	-12.18
CJD2R	10.00	47.00	2.61	-21.36		21.52	276.97	14.19	-6.22
CPA1R	0.00	39.00	-3.64	12.92		13.42	105.75	-7.83	-6.03
CEB1R	0.00	71.00							
CWM1R	0.00	41.00							
CPD1R	0.00	44.00							
CAS1R	0.00	43.00	2.27	17.32		17.47	82.54	5.67	3.13
CWM2R	8.00	34.00							
CEL1R	0.00	66.00							
CPL1R	0.00	47.00	20.21	8.36		21.87	22.47	0.28	-4.12
CKG1R	3.00	45.00							
CRW1R	11.00	25.00	-0.38	8.80		8.81	92.46	14.31	11.72
CJD1R	9.00	19.00	-1.13	19.00		19.03	93.42	-2.41	11.99
CJC1R	0.00	53.00	-41.01	5.20		41.34	172.77	-42.73	2.96

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