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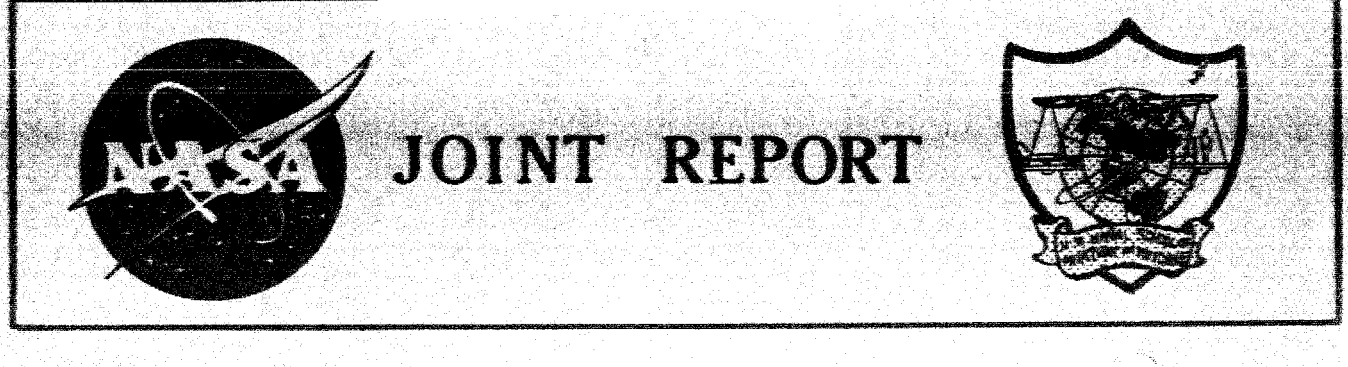

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UNITED STATES NAVAL SCHOOL OF AVIATION MEDICINE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Research Report

THE EFFECT OF CHANGING THE RESULTANT LINEAR ACCELERATION RELATIVE TO THE SUBJECT ON NYSTAGMUS GENERATED BY ANGULAR ACCELERATION*

Martin P. Lansberg, Fred E. Guedry, Jr., and Ashton Graybiel

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U. S. NAVAL SCHOOL OF AVIATION MEDICINE
U. S. NAVAL AVIATION MEDICAL CENTER
PENSACOLA, FLORIDA

SUMMARY PAGE

THE PROBLEM

To estimate the influence of linear acceleration on nystagmus initiated by semicircular canal stimulation.

FINDINGS

Centripetal accelerations between 1 and 2 g-units can change the magnitude, plane, and direction of nystagmus initiated by 10 deg/sec^2 angular accelerations.

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INTRODUCTION

Possible effects of centrifugal force on the cupula response when the head is positioned away from the center of rotation have been investigated theoretically and experimentally (1,5-8, 15, 18,24,25). Ter Braak (2) estimated that only slight differences in relative densities of the cupula and endolymph would be sufficient for centrifugal force to influence the cupula endolymph response; Lorente de No' (16) and Schmaltz (24) both suggested that lack of rigidity of the membranous labyrinth could result in a canalicular response to linear acceleration even with equivalent specific gravity of the cupula and endolymph. In support of these possibilities, Gemandt (6) and Ledoux (15) found changes in central nervous system neural activity, apparently emanating from the ampulla, when centrifugal force was added to the angular acceleration stimulus.

In agreement with a review of the subject by Jongkees and Groen (12) [and also the earlier theoretical analyses by Gaede (5), Mach (18), and Schmaltz (24)], Graybiel, et al. (8) found no difference in duration of the oculogyral illusion as a consequence of adding centrifugal forces of different magnitudes (up to 0.25 g-units) and directions relative to the head. Centrifugal forces greater than 0.25 g-units yielded inconclusive results, apparently because judgments were complicated by the oculogravic illusion. Recently Benson and Whiteside (1) have obtained similar results in regard to sensation duration, but they reported significant suppression of nystagmus by centrifugal forces of 3.1 g-units. Hence a review of theoretical considerations of this problem as well as direct experimentation relevant to this problem leaves a number of issues open to question:

Are the observed changes in results when centrifugal force is added attributable to a) modulation of sensory input from the semicircular canal system by otoliths and other graviceptors; b) an influence of linear acceleration on the mechanical response of the canals; or c) artifacts in methods of recording?

The present experiment investigated the effect of adding centripetal acceleration while the subject was fixed in one of several positions relative to the plane of rotation. In some of these different positions the planes of the semicircular canals remained unchanged relative to the plane of rotation although the otolith system was changed in orientation relative to the tangential and centripetal components of the total acceleration deriving from the rotation. In these cases, the semicircular canals stimulated would be the same, irrespective of the direction of the resultant vector deriving from gravity and the centrifugal force, if the semicircular canal system responds only to change in angular momentum. On the other hand, the otolith system and other somesthetic receptors would be stimulated as though the body were undergoing increasing tilt as the angular velocity of the centrifuge increases.

PROCEDURE

SUBJECTS

Subjects were twenty-six Navy enlisted and officer candidate personnel within the approximate age range of from 18 to 23 years, and one civilian and one officer who were in the age range of 35 to 40 years.

APPARATUS

All of the data were collected in the Pensacola centrifuge which has been described elsewhere in detail (11). For this experiment, special cabs were used which permitted positioning of the body in a variety of attitudes at radial distances of either 17 or 20 feet. In addition, subjects could be tested near the center of rotation at a radial distance of about 2.0 feet. In all situations, the test chambers were darkened to eliminate light sources for visual fixation, and the eyes were kept open throughout nystagmus recordings.

Eye movements were recorded by the corneo-retinal potential method. Electrodes were placed above and below the left eye and at the outer canthus of each eye to detect vertical and horizontal components of eye movements. These signals were amplified by a Sanborn Model 350-1600 preamplifier (time constant 1.5 sec) and recorded on a Sanborn polygraph. This method of recording has several possible sources of error, some of which are described by Lansberg (14).

METHODS

Various positions of the subjects are listed in Table I. Positions of particular interest are illustrated in Figure 1. The number of conditions to which any one subject was exposed varied somewhat randomly. Two subjects were exposed to only one condition, while two other subjects were exposed to nineteen different conditions. Some subjects were brought back for as many as five repeat tests on a given condition; others received only one exposure to a single condition. A total of 315 different trials were run, which means that the average number of trials per subject was eleven; the average number of conditions to which each subject was exposed was ten.

Stimulus Pattern

Angular acceleration of the centrifuge is controlled by clutching the superstructure to a 46-ton flywheel which is driven by a gasoline engine. Manual control of the clutching allows fair repeatability of angular acceleration profiles. Because these profiles did not vary systematically from one experimental condition to the next, it is believed that this source of error did not contribute significantly to the main findings. The average time of angular acceleration was about eight seconds, constant angular velocity was maintained about ninety seconds, and the average stopping time

Table I

Various Body Positions Used in the Experiment and Their Letter Designations

Seated: Head 20 feet from center	Chair Erect	Chair Tilted 45° Inward
" heading forward	D	D+
" heading backward	D_1	D_1+
" heading centripetal	D_2	D_2+
" heading centrifugal	D_3	D_3+
Seated: 4 feet from center*	D'	

Recumbent: Head 17 feet from center	Supine	45°R	R Side	45°L	L Side
head centripetal	A		A_1		A_2
head centrifugal	Z		Z_1		Z_2
head leading	B		B_1	B-	
head trailing	C	C-		C+	C_1
Recumbent: Head 2 feet from center			A'_1		

*Sometimes tested facing inward or outward at 2 or 4 feet radius

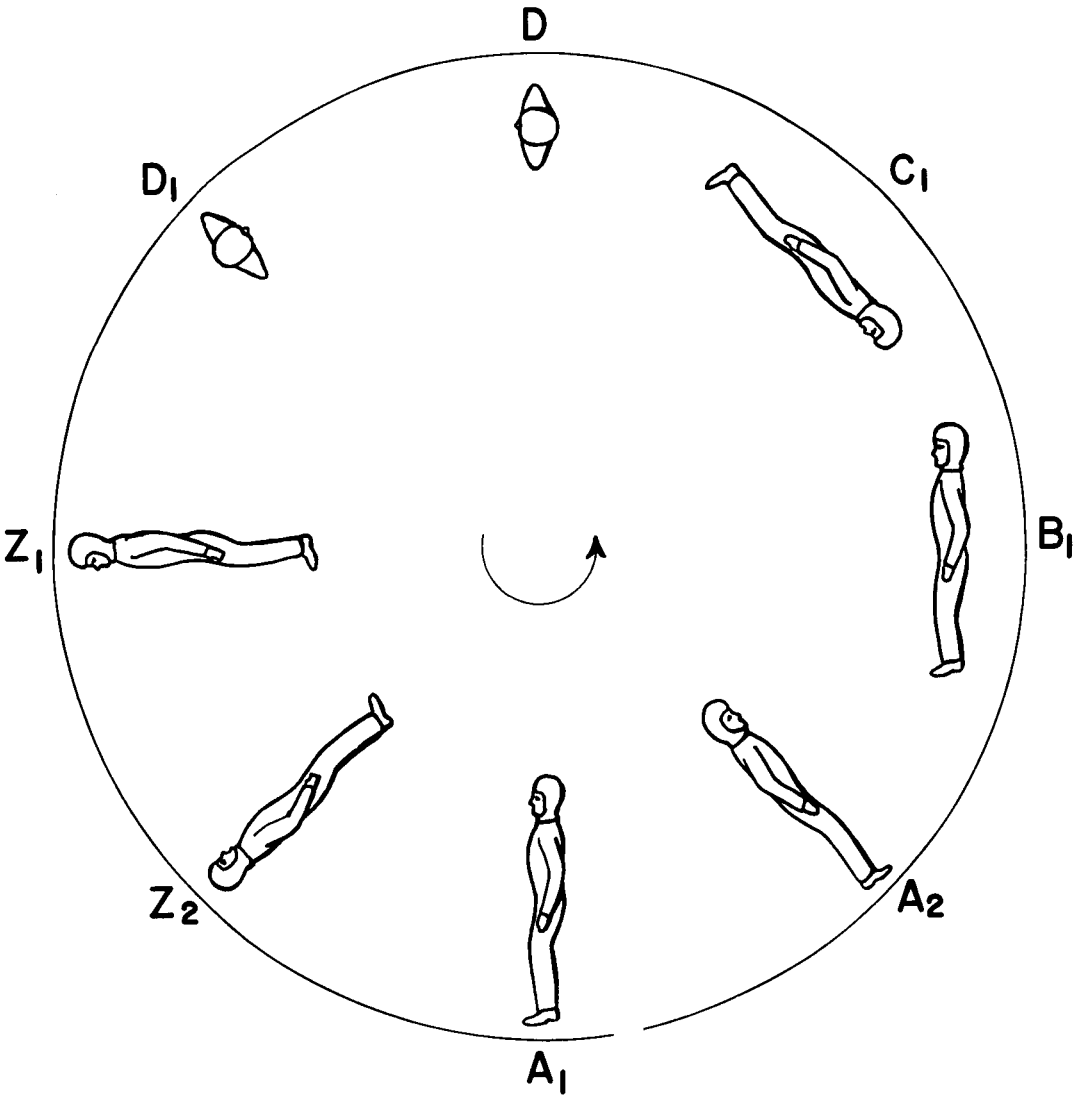

Figure 1

Illustrating Some of the Body Orientations Used in the Experiment. Actual Distances from Center of Rotation to the Head Were 17 and 20 Feet.

was about eight seconds. Constant angular velocity was also varied from one trial to another. The majority of runs in the D and D_1 positions were made either with a maximum angular velocity of 14 or 17 RPM. The various maximum constant angular velocities used along with the centripetal accelerations, and resultant accelerations generated at various radii, are indicated in Table II.

RESULTS

The centripetal acceleration (and hence centrifugal force) increases as the product of the square of the angular velocity times the radius, and this is important to the interpretation of the results. As angular acceleration terminates and maximum constant angular velocity is attained, the cupula, if influenced solely by change in angular momentum, would commence a return movement by virtue of its elasticity at exactly the point in time when the otolith structures and other body organs receive maximum resultant force. During stopping, the reverse is true; i.e., the cupula would return by its elasticity when the resultant force has diminished to normalcy, i.e., the force of gravity. With the assumption that angular acceleration and deceleration were nearly of the same magnitude and duration, responses from these two stimuli for any one condition should have been of the same magnitude, but this was not true as can be seen in Figure 2.

Perhaps the most striking differences produced by the various conditions were results yielded by the D and D_1 body positions. These are two positions in which planes of the canal system retain the same orientation relative to the plane of rotation whilst the otolith structures have different orientations relative to tangential and centripetal components of acceleration. Consequently, records of those subjects who experienced both the D and D_1 positions at the same angular velocity (14 RPM) were scored as follows: The records were divided into two-second intervals, and separate averages for the horizontal and vertical components of eye movements were obtained for each interval. Vectorial resolution of these two components then provided a single vector representing the magnitude and direction (relative to the skull) of the average response for each two-second interval throughout the course of the reaction. Figure 2 presents the results of this method of data reduction from eight subjects who were run at 14 RPM under both D and D_1 conditions. The direction of the fast phase of nystagmus relative to the skull is indicated by the direction of each arrow (an arrow to the reader's left designates nystagmus with fast phase to subject's left), and the magnitude of the response is indicated by height above the x-axis, i.e., by the ordinate of the arrow. It is clear that the D and D_1 positions yield different responses during angular acceleration and also during constant angular velocity, when the cupula would be expected to recover its position of static equilibrium by classical concepts of cupula mechanics. The per-rotary response in the D_1 position does not reach its anticipated magnitude and appears to change in both plane and direction. The per-rotary response in the D position may be of greater magnitude and duration than the usual response without the added centrifugal force (compare acceleration response with the deceleration response) but is otherwise essentially of the expected direction and plane.

Table II

Various Acceleration Conditions Used in the Experiment

RPM	17-Foot Radius Centripetal Acceleration	Resultant G	20-Foot Radius Centripetal Acceleration	Resultant G
12	26.8 ft/sec^2	1.30	31.6 ft/sec^2	1.40
14	36.7 ft/sec^2	1.51	43.2 ft/sec^2	1.67
17	53.9 ft/sec^2	1.95	63.4 ft/sec^2	2.21
18	60.0 ft/sec^2	2.11	70.6 ft/sec^2	2.41

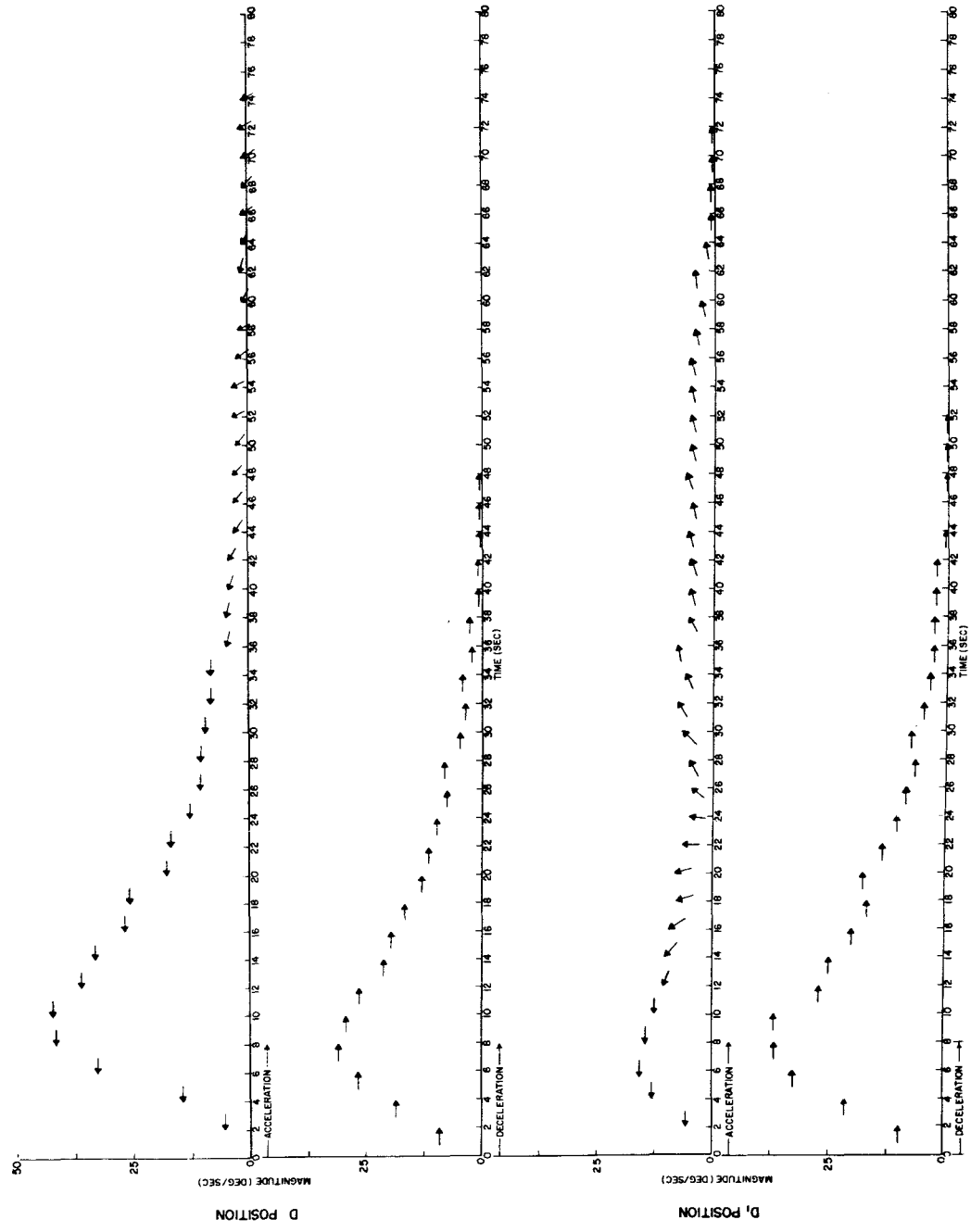

Figure 2

Vectorial Presentation of Nystagmus. An Arrow to the Reader's Left Designates Nystagmus to the Subject's Left. Response Magnitude is Indicated by Height above the x-axis.

The data for all other conditions were scored by selecting "representative" beats for measurement at various points in time in the individual records. From these estimates, curves were plotted separately for horizontal and vertical components of eye movements for each subject. Curves for each position were then traced onto a master plot, and these families of curves for the various positions are shown in Appendix A. It should be noted that some of these families of curves include runs at different peak centripetal accelerations and that the principal justification for combining these curves was the body position rather than commonality of rotation characteristics.

For conditions A_1, A_2, C_1, B_1, Z_1, and Z_2, all shown in Figure 1, "average" curves were drawn through these families of curves by visual inspection. From "average curves" for the horizontal and vertical components, resultant vectors were derived. These are presented in Figure 3. It should be noted that different numbers of subjects contributed to the data represented under the different letter designations. Eight subjects contributed the results depicted under Z_1 and Z_2 in Figure 3, and five of these joined nine other subjects who contributed results labeled A_1. Of these nine, two were run with centripetal acceleration of 53.9 ft/sec^2 and the remainder with a centripetal acceleration of 36.7 ft/sec^2. For these reasons care should be taken in interpreting differences between conditions illustrated in Figure 3, particularly in regard to response magnitudes. However, the prolongation and change of plane and direction of per-rotary nystagmus in conditions A_1 and B_1 are probably not attributable to individual differences among the subjects and seem to represent an effect attributable to the added centrifugal force on the nystagmus. A_1 and A_2 results were obtained from essentially the same subjects.

DISCUSSION

The most significant aspect of the results was that in certain comparisons, e.g., D with D_1, A_1 with Z_1, and A_2 with Z_2, different nystagmus responses were obtained even though the orientations of the canal system relative to the plane of rotation in each of these comparisons were the same. In A_1, B_1, and D_1, nystagmus commenced in the direction anticipated from Ewald's first law, then almost stopped, and then gradually changed plane and direction. In each case, A_1, B_1, and D_1, nystagmus did not reach its anticipated magnitude as compared with the deceleration response or the acceleration responses in other conditions. Noteworthy also is the point at which the response reached a minimum before changing planes. This point was approximately where the responses under the other conditions terminated. This might lead to the suspicion that these reversed responses are simply the onset of prominent secondary reactions, and they might be, but the reduced magnitude during the angular acceleration leads to the suspicion that this "secondary" response is a manifestation of some counteracting process which commenced before the primary reaction had been in progress for more than a few seconds. It is also important to note that the reversal of response was absent in A_2, C_1, Z_1, Z_2, and D, and in all of these strong primary responses to the angular acceleration were given.

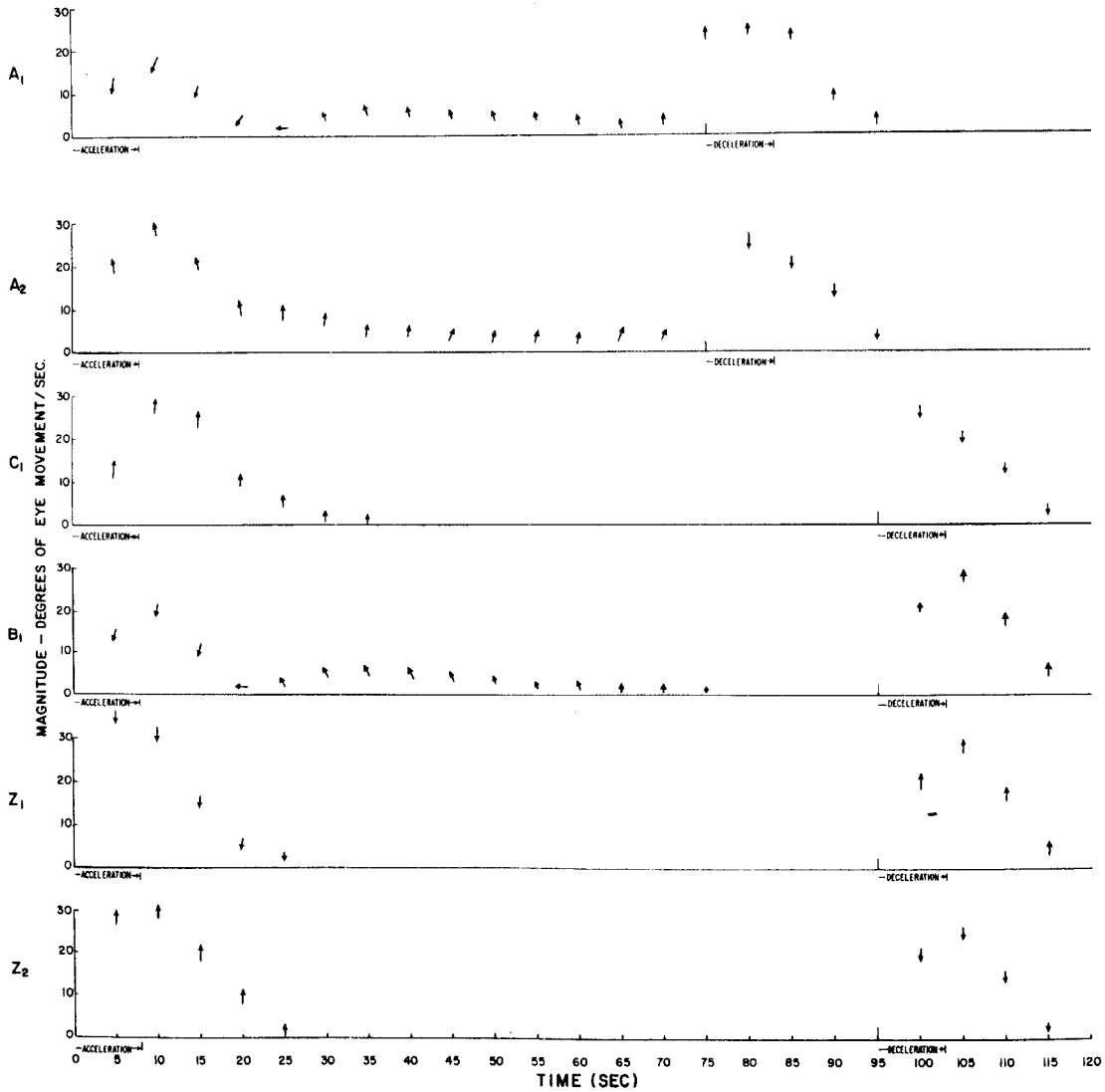

Figure 3

Vectorial Presentation of Nystagmus Secured by Method of Selected Beats

As indicated earlier, it is possible that the apparent suppression of nystagmus in some conditions may be an artifact of the recording method. Change in gaze may change the ocular bioelectric field to an unfavorable orientation relative to the recording electrodes. Lansberg (14) has indicated that a large shift in gaze without a change in plane of nystagmus relative to the skull can produce significant changes in recordings of nystagmus, presumably without real change in intensity of nystagmus. However, it is unlikely that the changes in plane and direction of nystagmus noted under certain conditions herein are attributable to such artifacts; e.g., the nystagmus reversal in D1 could not be produced by such mechanisms, but final conclusions must await verification by other methods of recording.

Assuming that the major findings were free of such artifacts, the question may be considered as to whether the present results are attributable to 1) an effect of linear acceleration on the cupula response or 2) an interaction between canalicular input and input from other organs, e.g., the otoliths. On the basis of structure (4,26), it seems unlikely that the cupula is an efficient detector of linear accelerations which do not induce a change in angular momentum whereas the structure of the otolith organs would appear adequate to serve this function. However, the cupula could be an insensitive detector of linear accelerations, and it is possible that the utricular organs are insensitive detectors of angular acceleration (17, p. 118).

Albeit, the modulation of ampullar input by otolith and proprioceptor systems is also a distinct possibility. Rotation about a horizontal axis at constant angular velocity, such that the horizontal canals are in the plane of rotation, yields a continuous nystagmus which persists long after the theoretical end of nystagmus (3,9). Since individuals apparently without vestibular function did not show similar nystagmic responses (9), it appears likely that the persistence of nystagmus in this situation is attributable to the continual reorientation of the otolith structures relative to gravity. In this situation the cupula would be alternately aided and hindered by gravity in its return to the position of static equilibrium if it were influenced by gravity, and this presumably could not account for the prolonged unidirectional response observed.

From these experiments and other recent reports (10, 13, 20-23), it is tentatively concluded that nystagmus initiated by canalicular stimulation can be modulated by otolithic stimulation.

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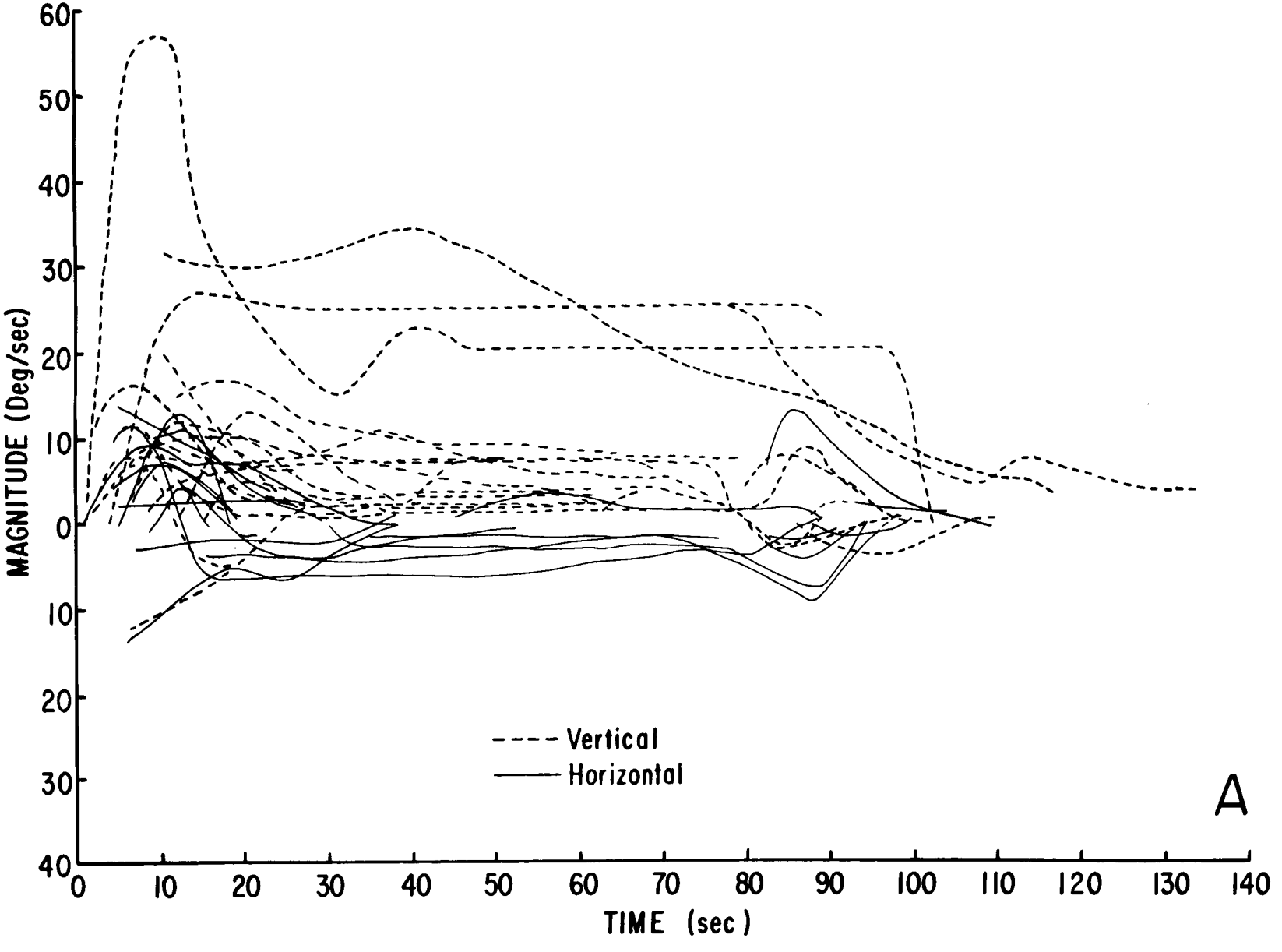
APPENDIX A

Families of Curves for Various Positions. Dotted Lines Designate the Vertical Component of Nystagmus. Solid Lines Designate the Horizontal Component of Nystagmus.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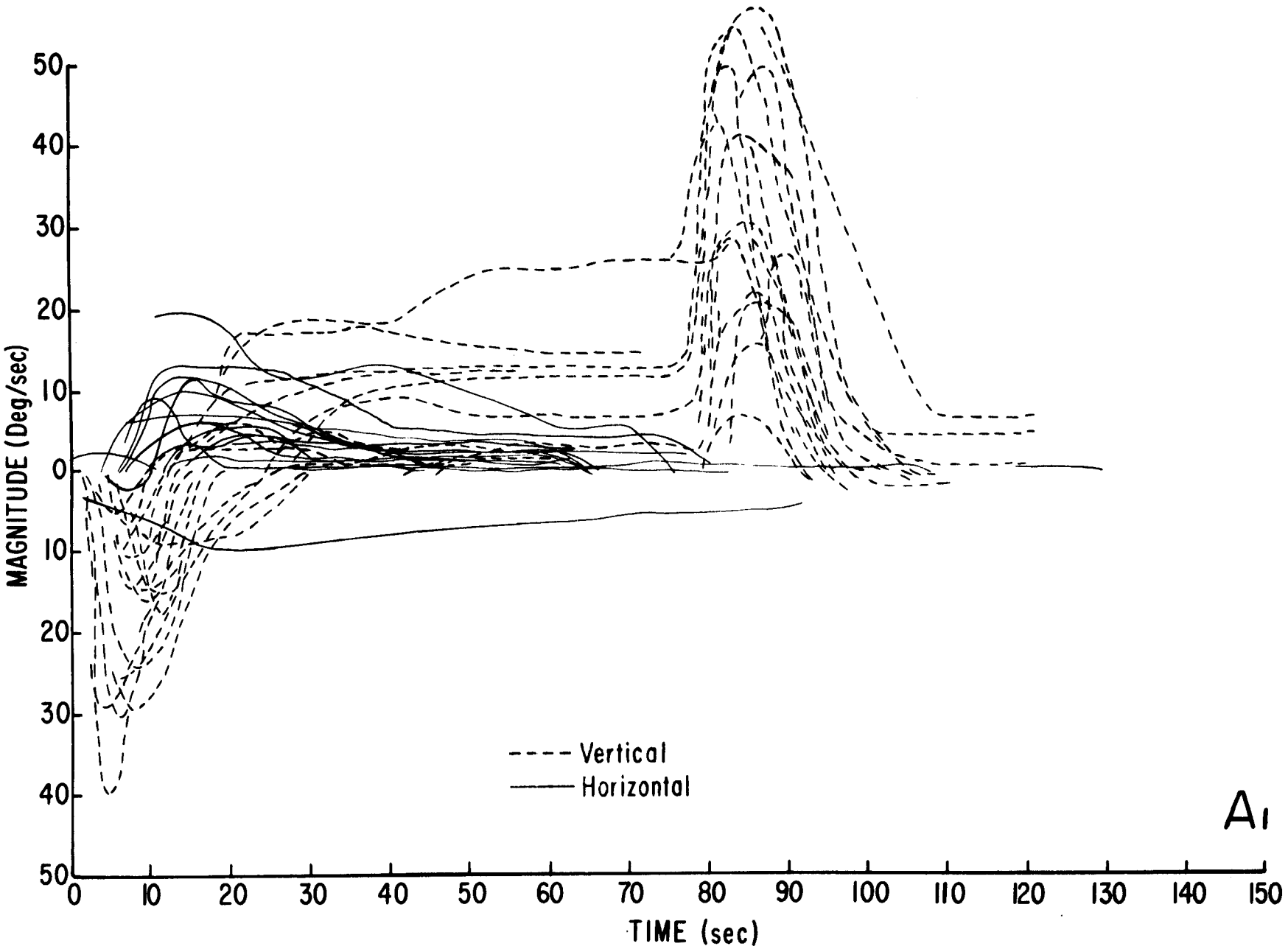
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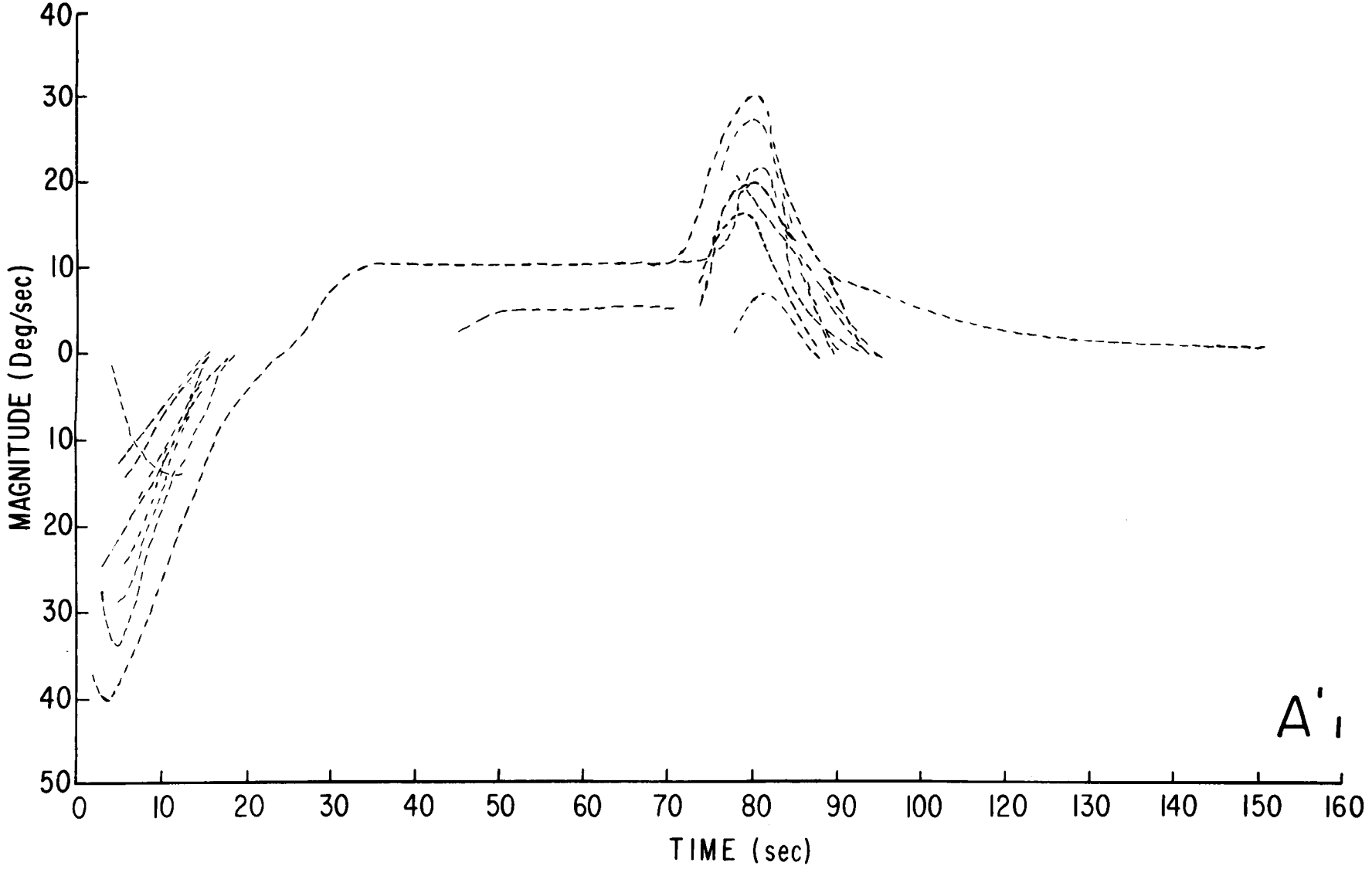
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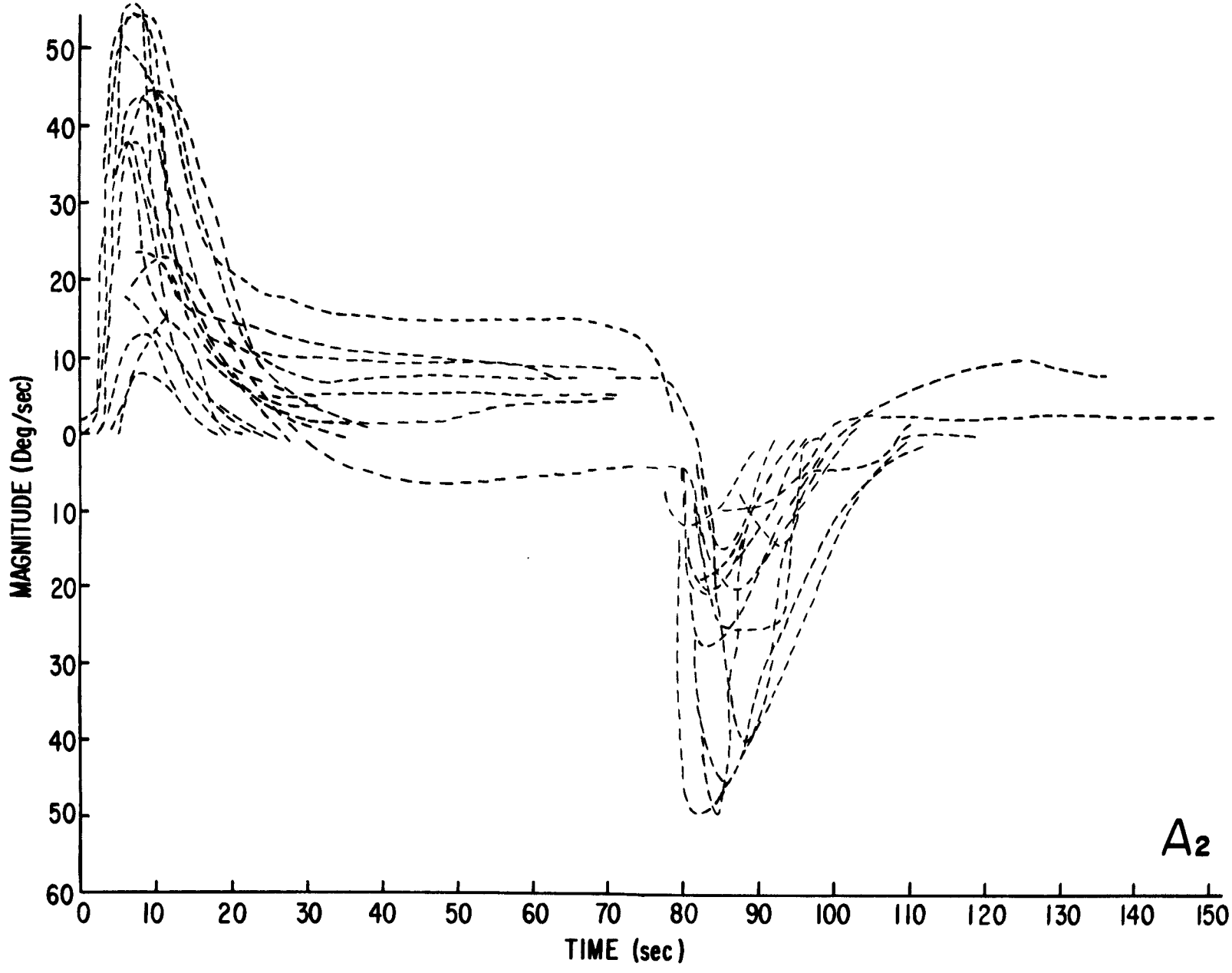
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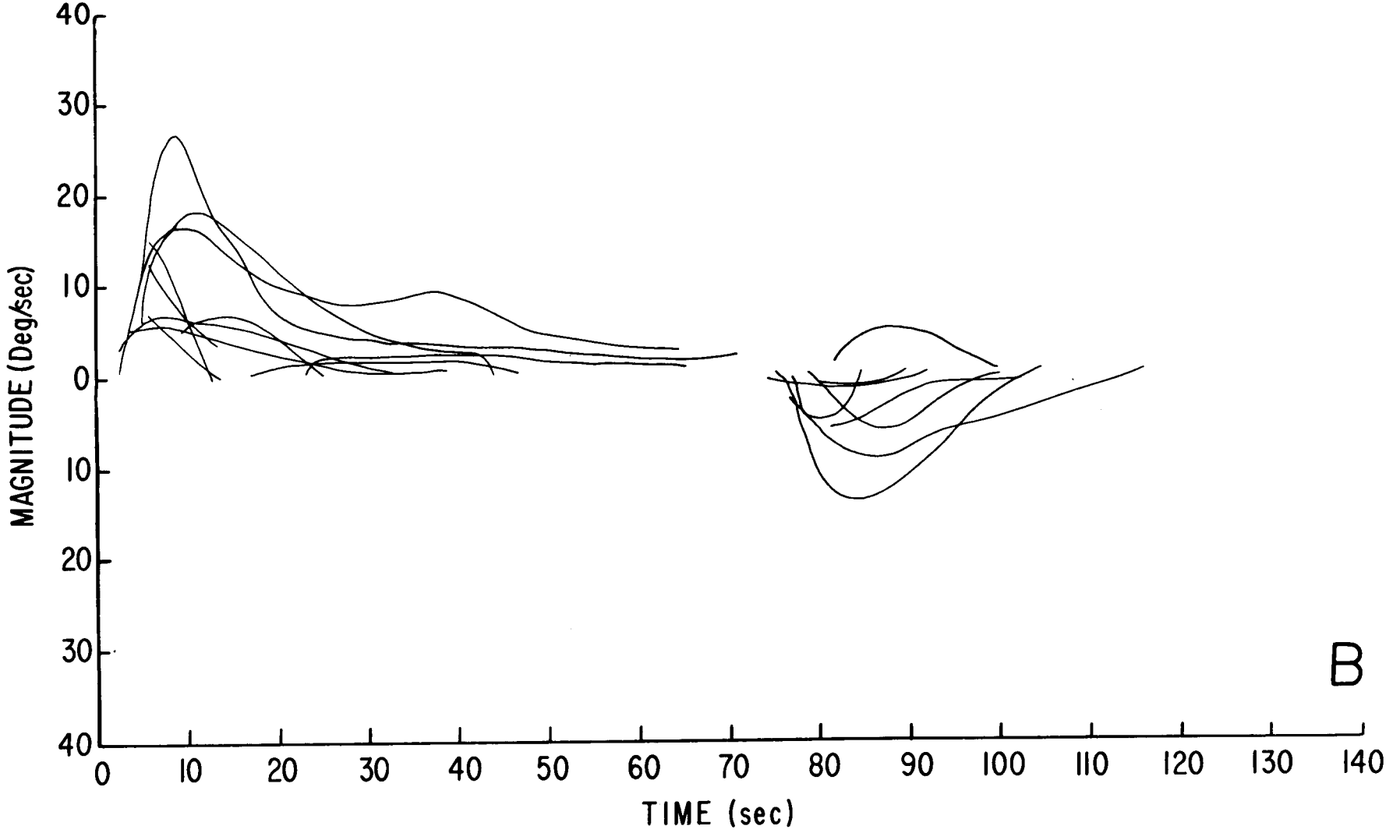
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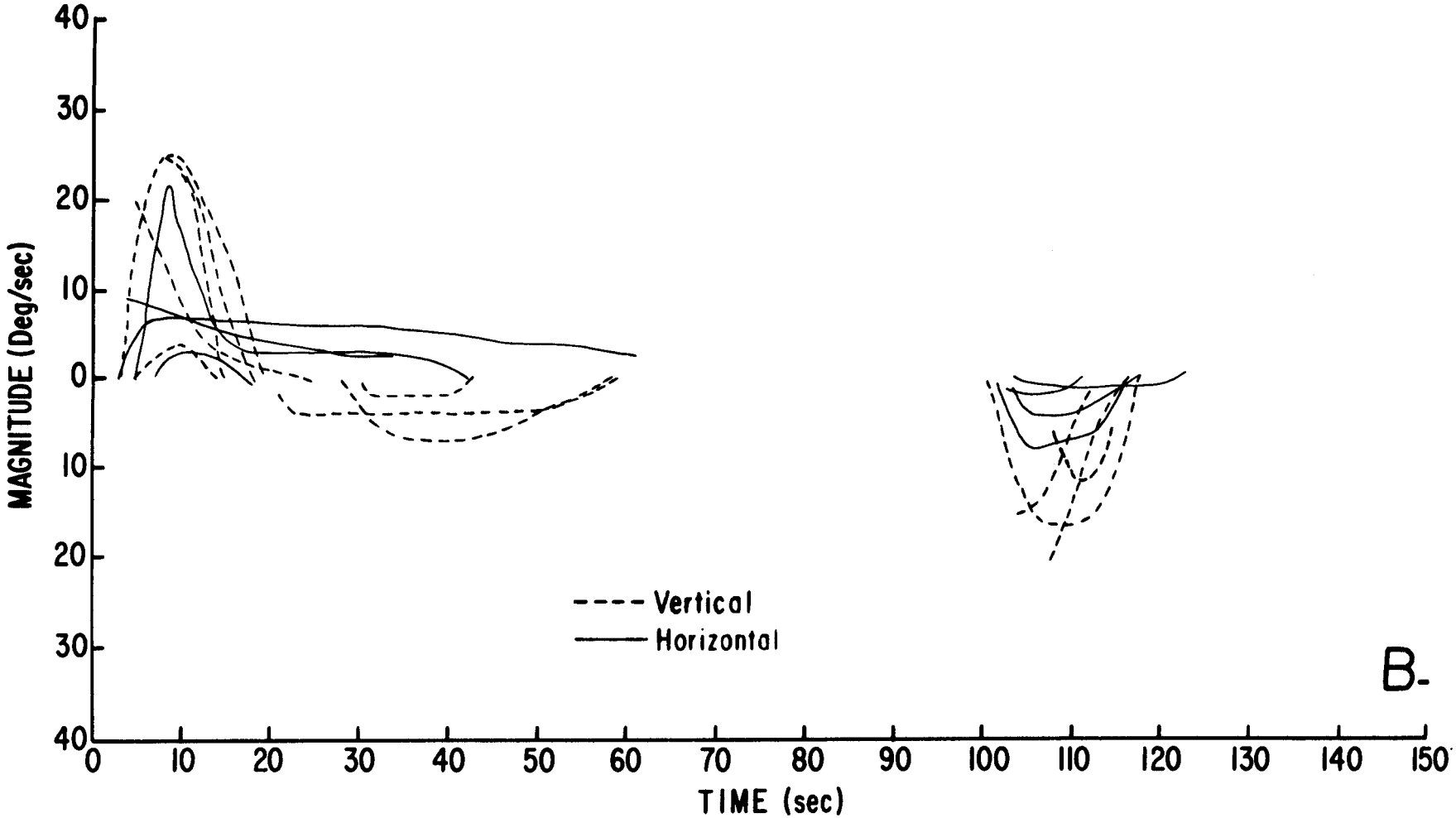
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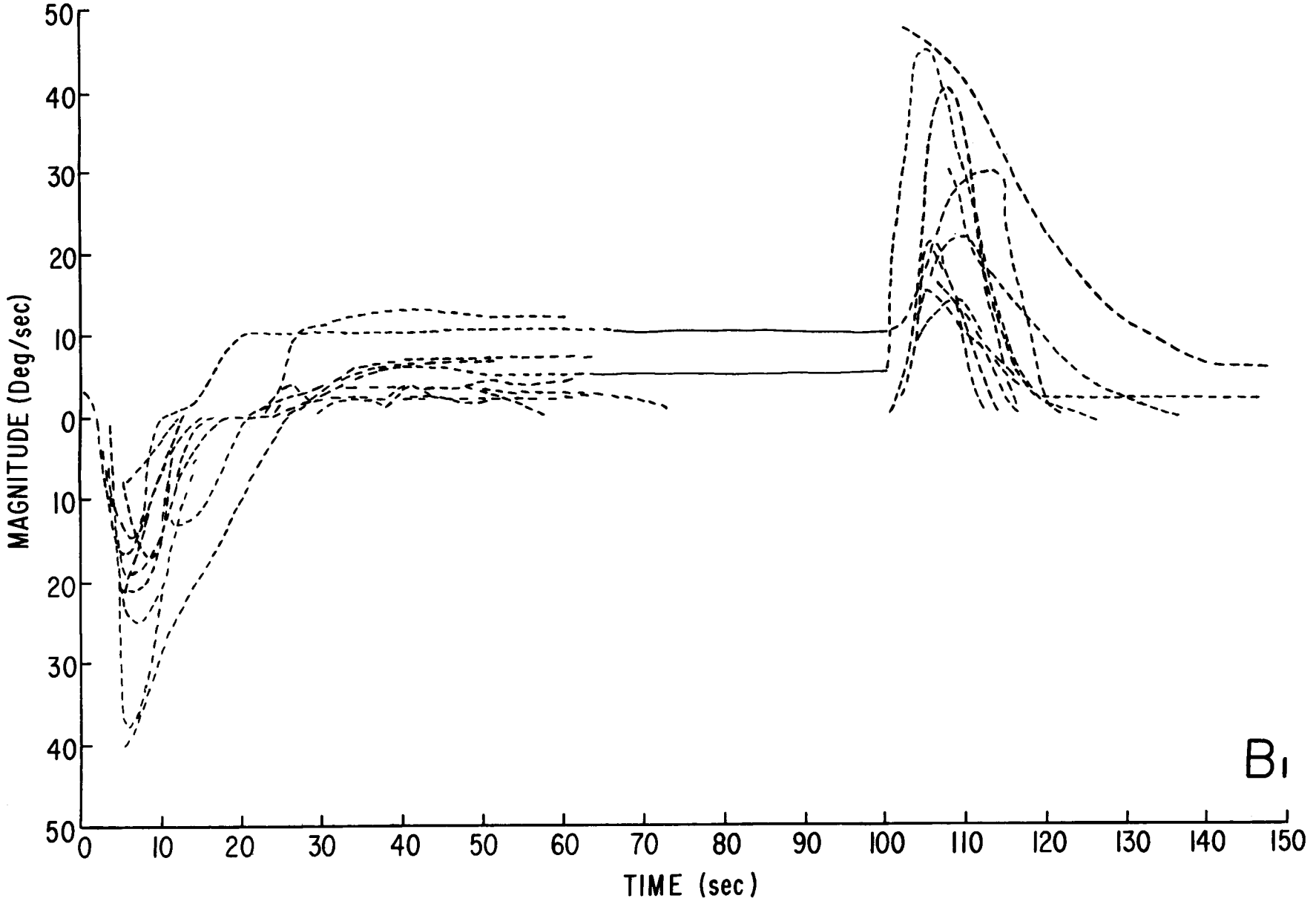
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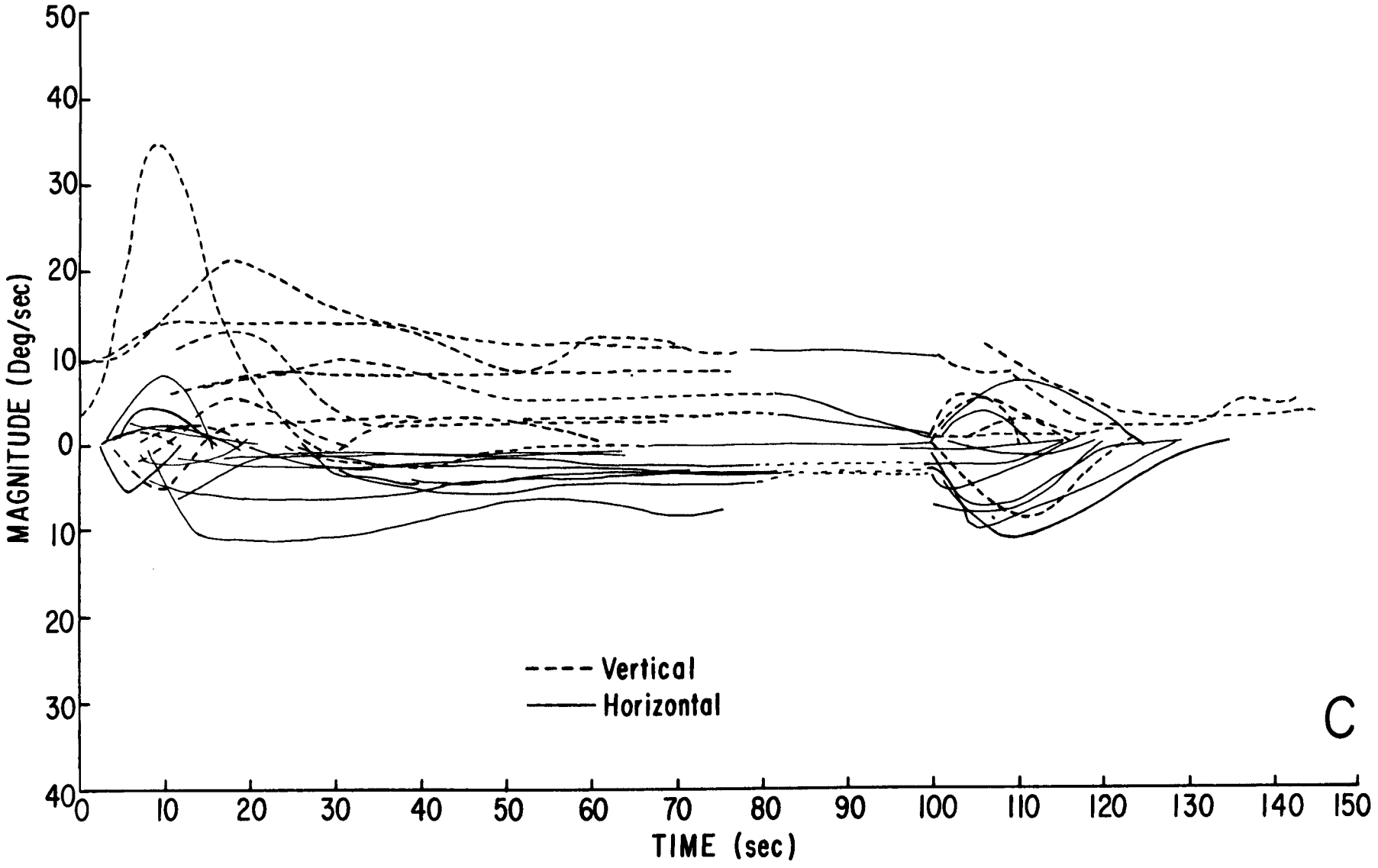
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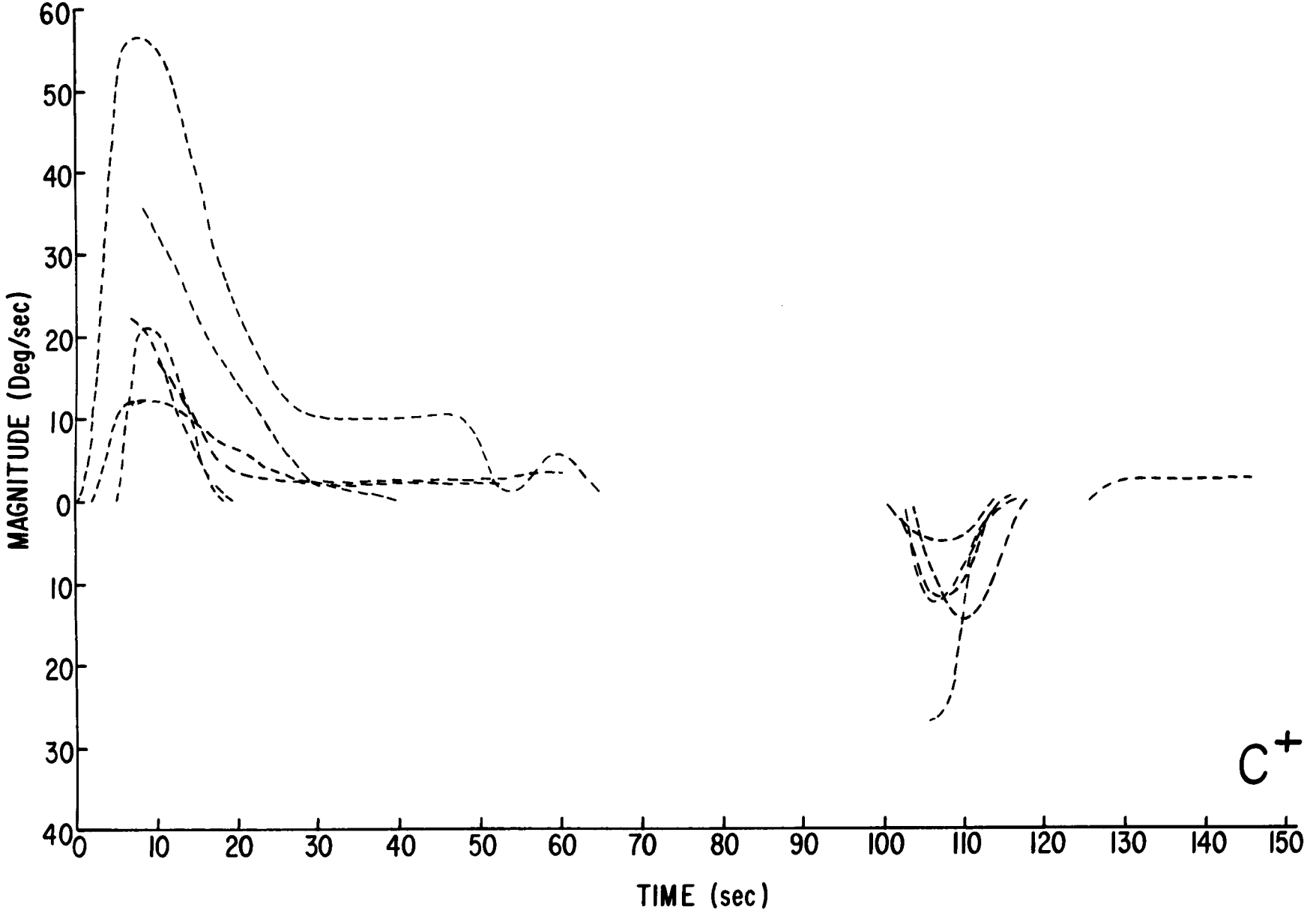
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MAGNITUDE (Deg/sec)
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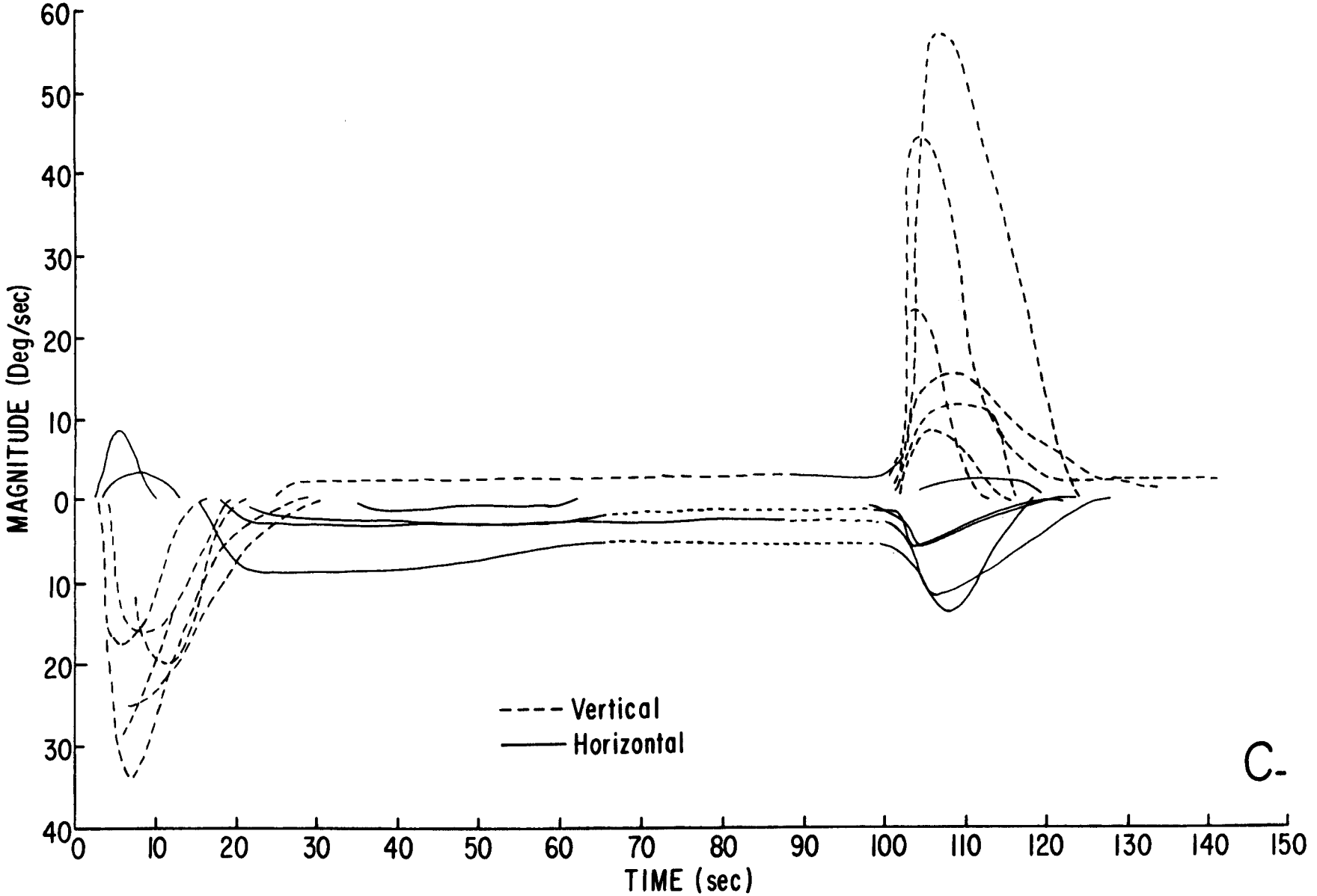
TIME (sec)
C+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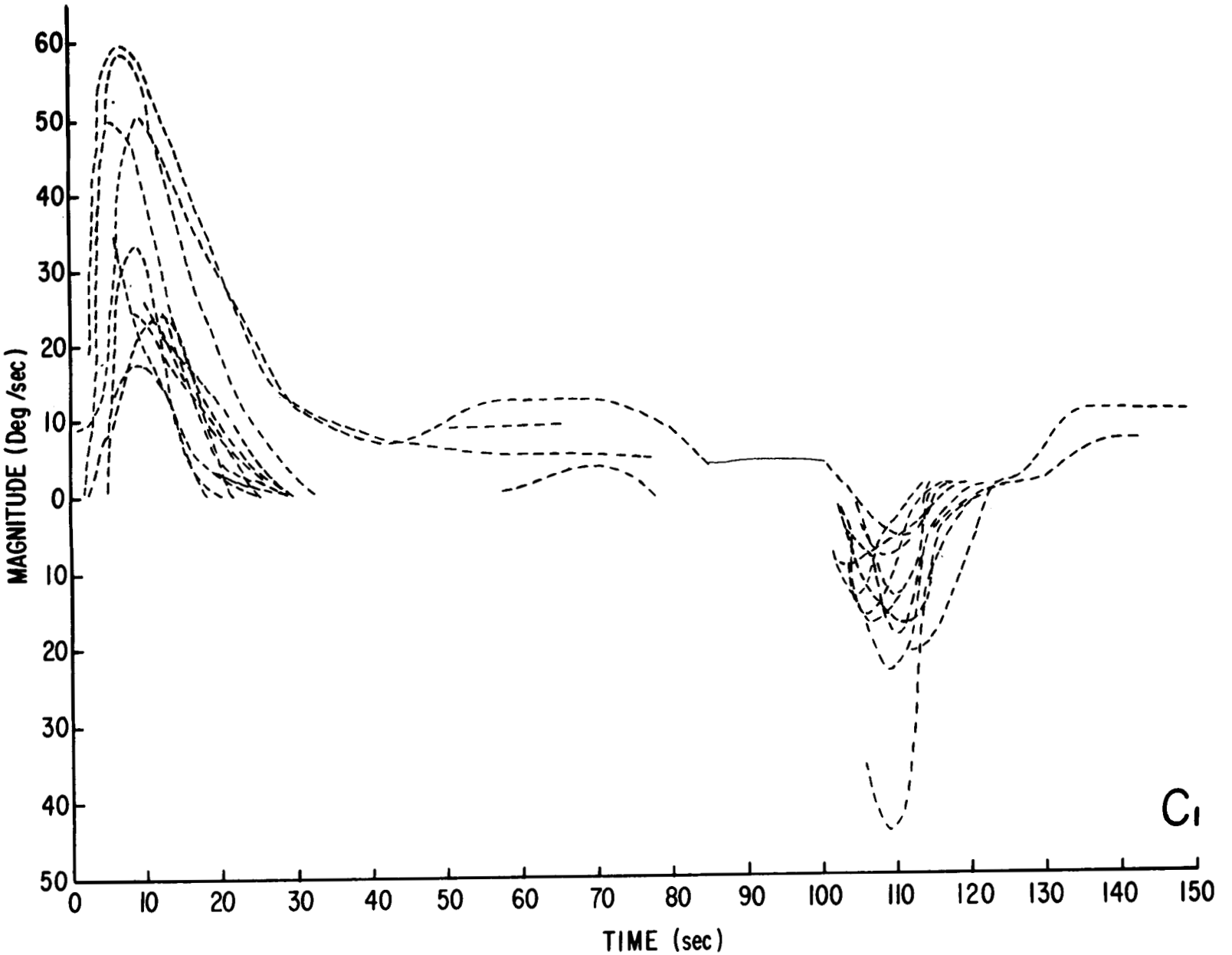
TIME (sec)
Vertical
Horizontal
C-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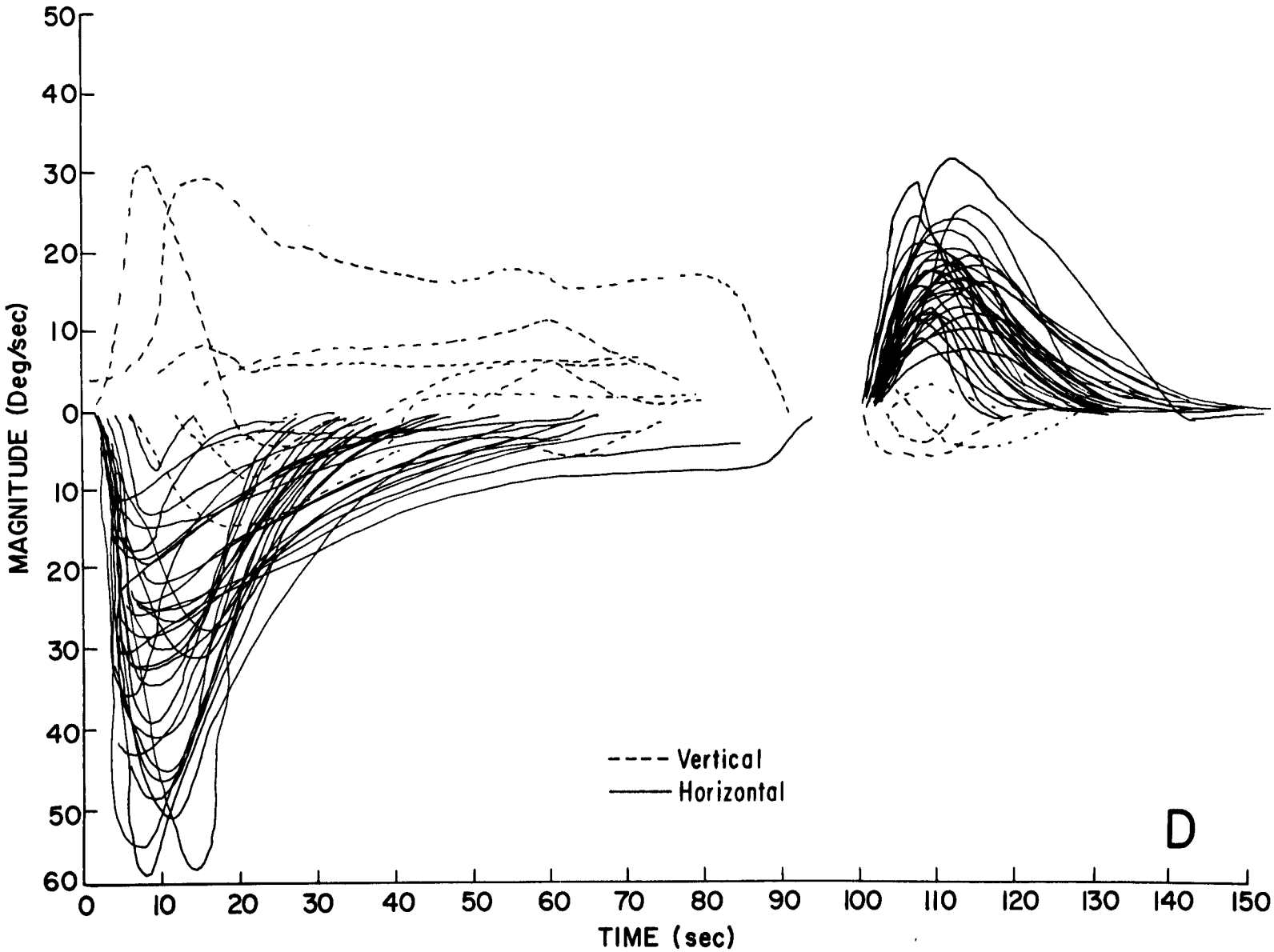
TIME (sec)
C1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MAGNITUDE (Deg/sec)
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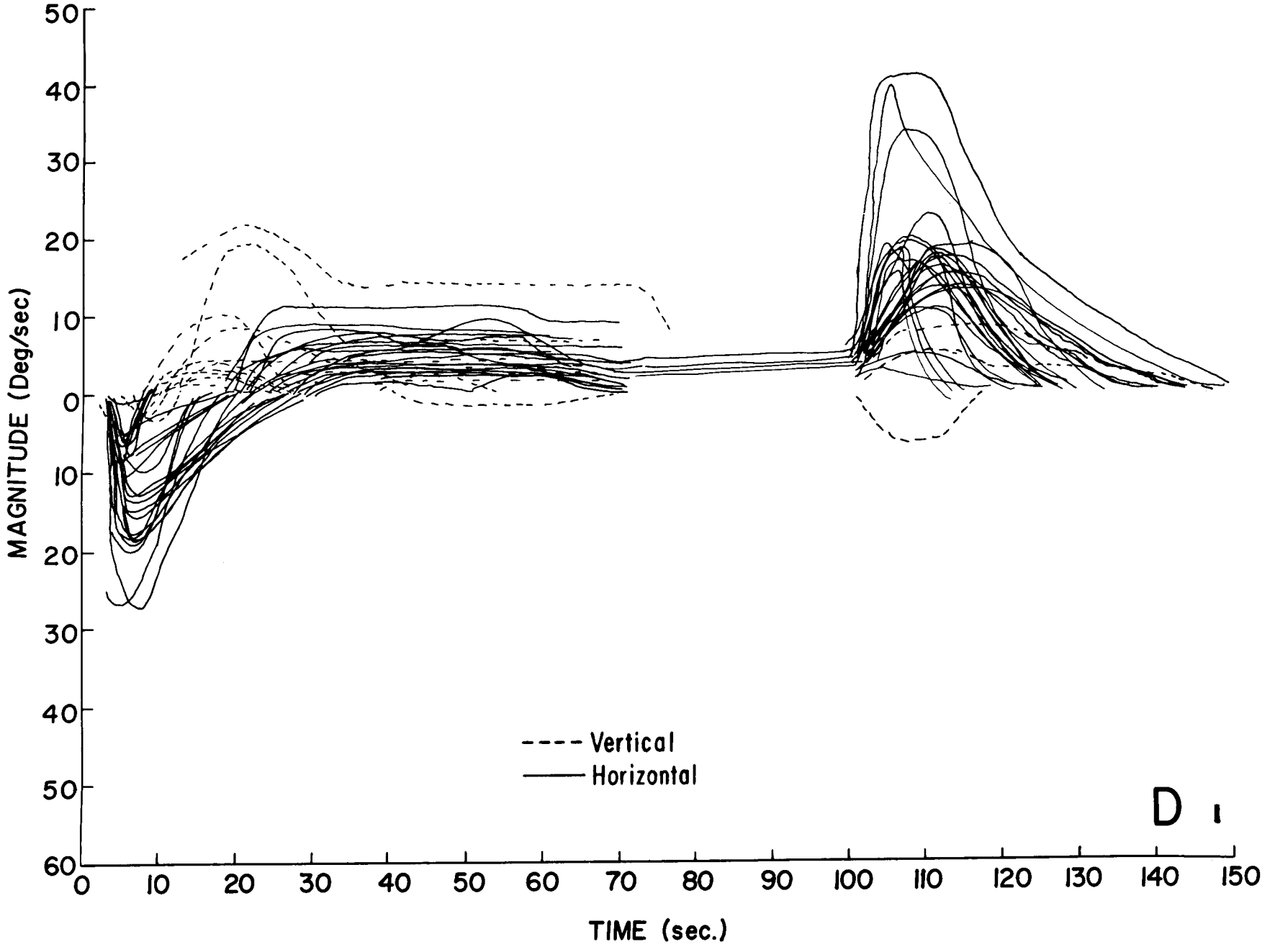
TIME (sec)
---- Vertical
—— Horizontal
D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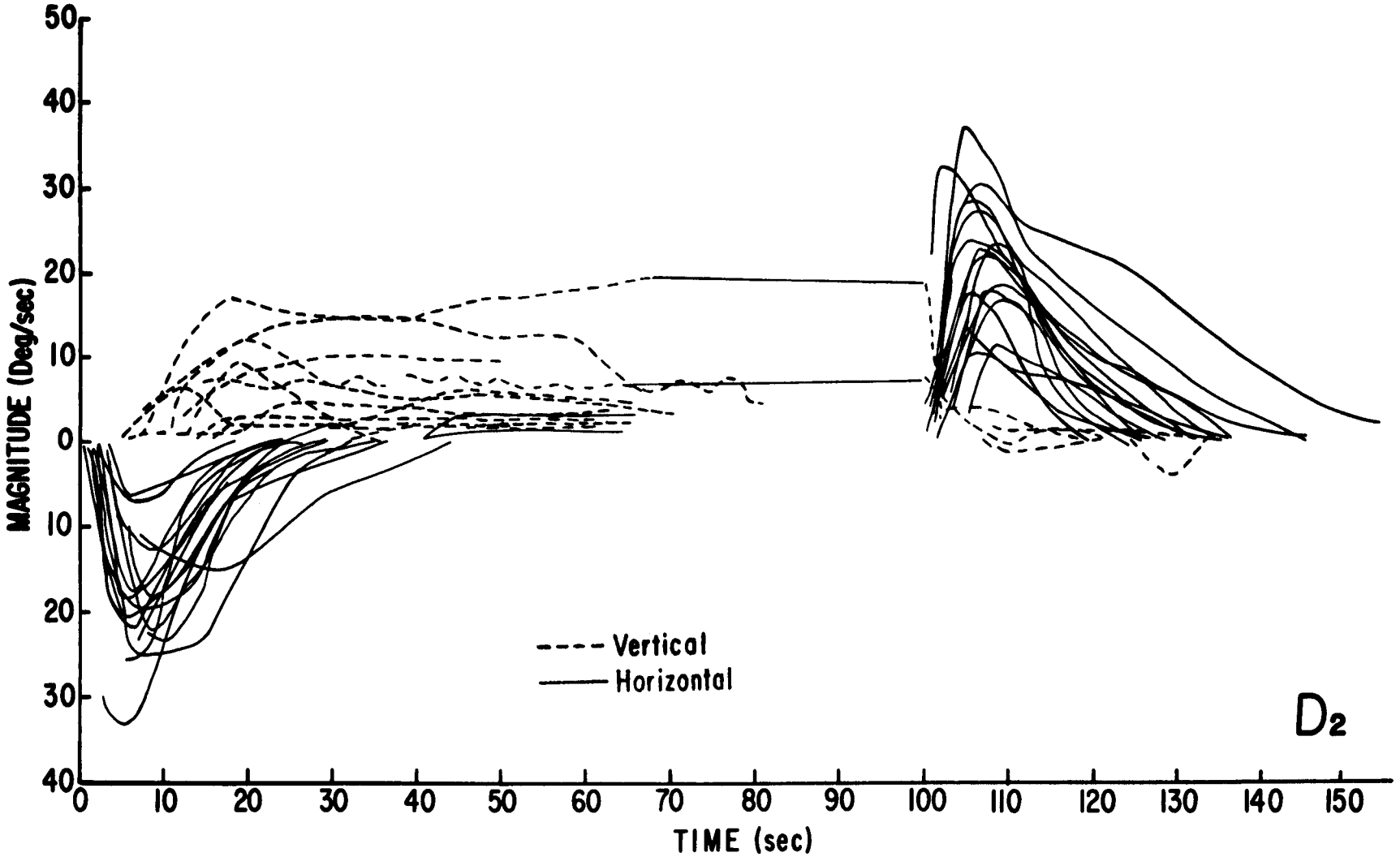
TIME (sec.)
---- Vertical
—— Horizontal
D 1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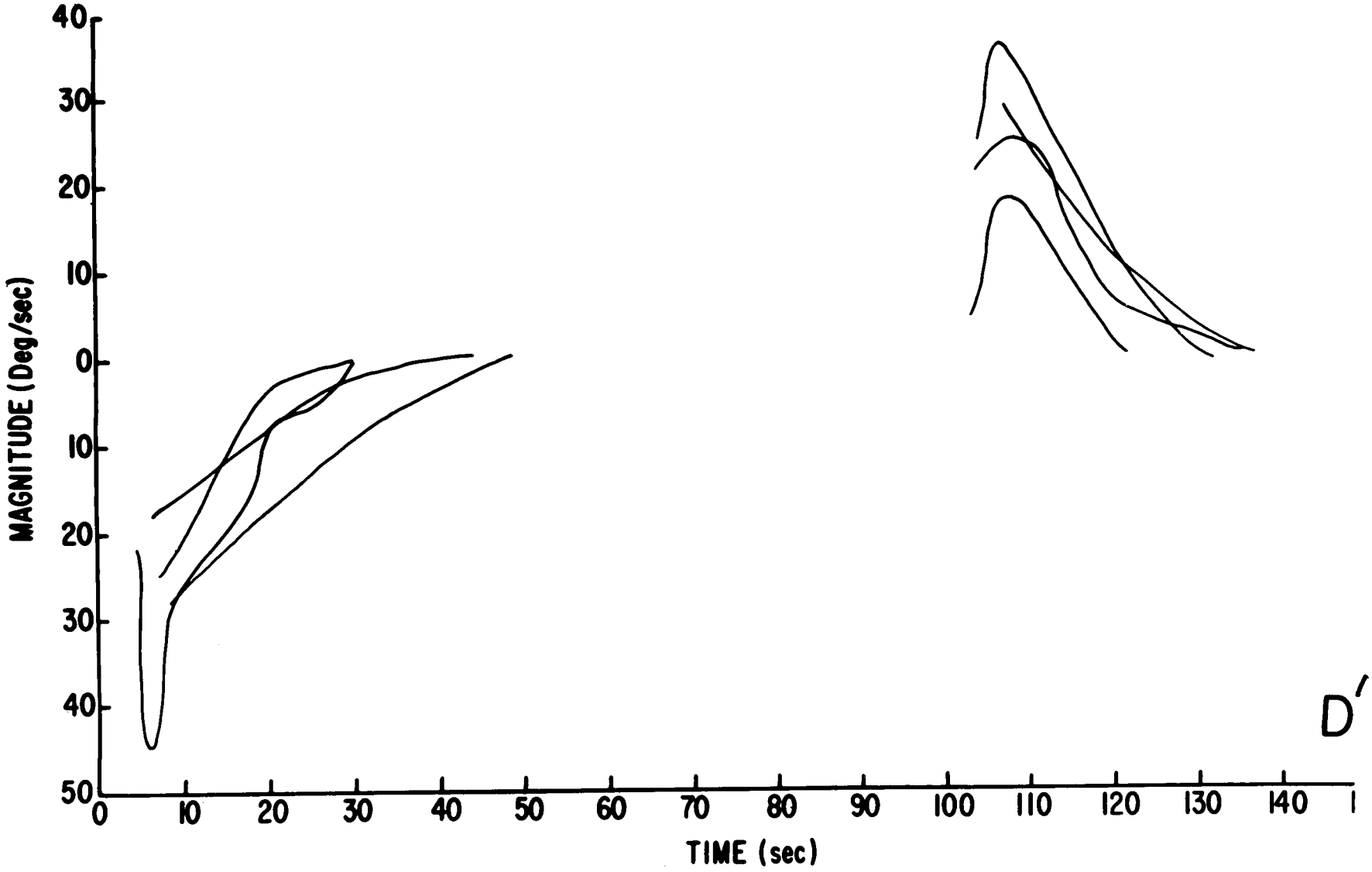
TIME (sec)
Vertical
Horizontal
D2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TIME (sec)
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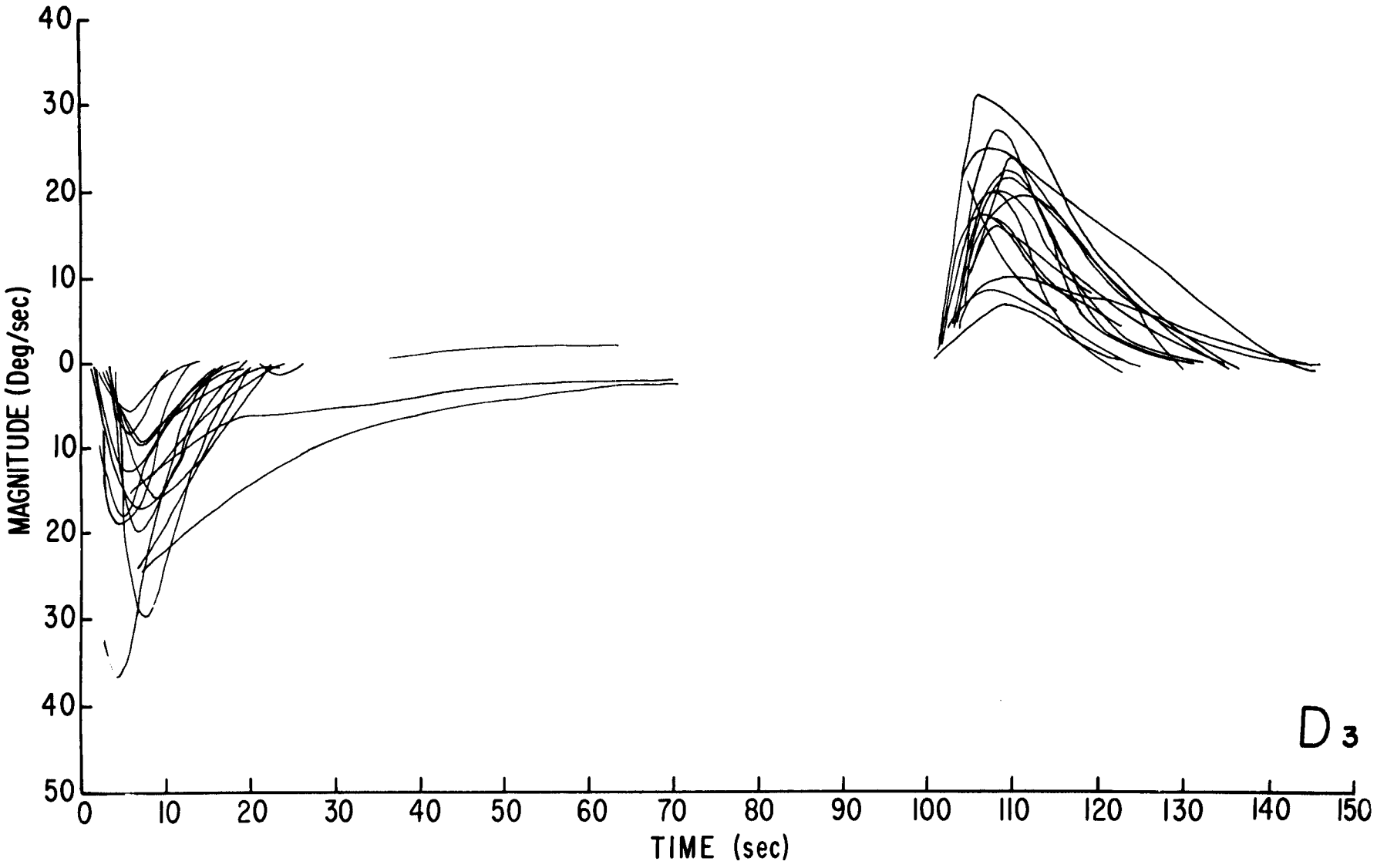
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TIME (sec)
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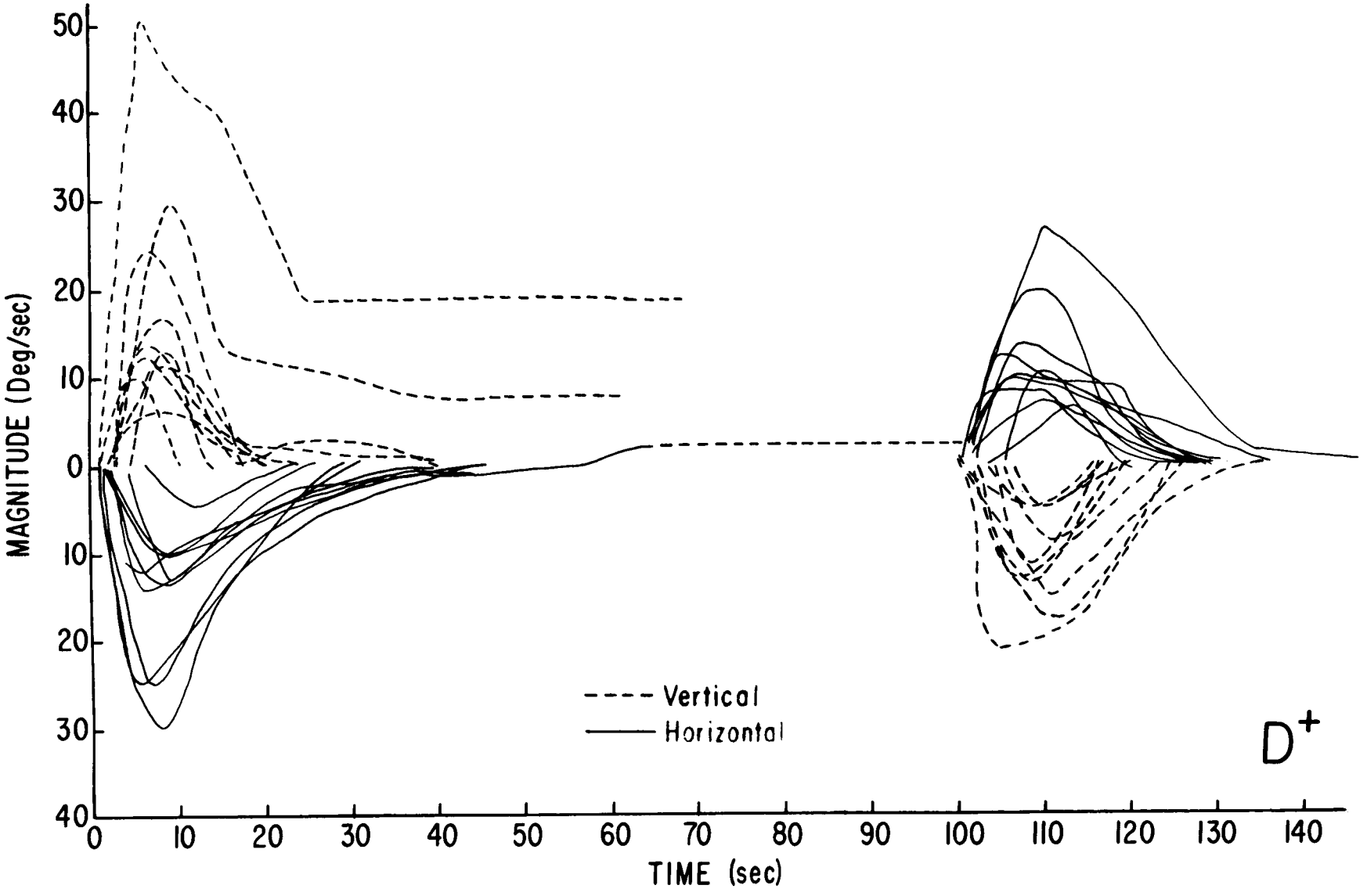
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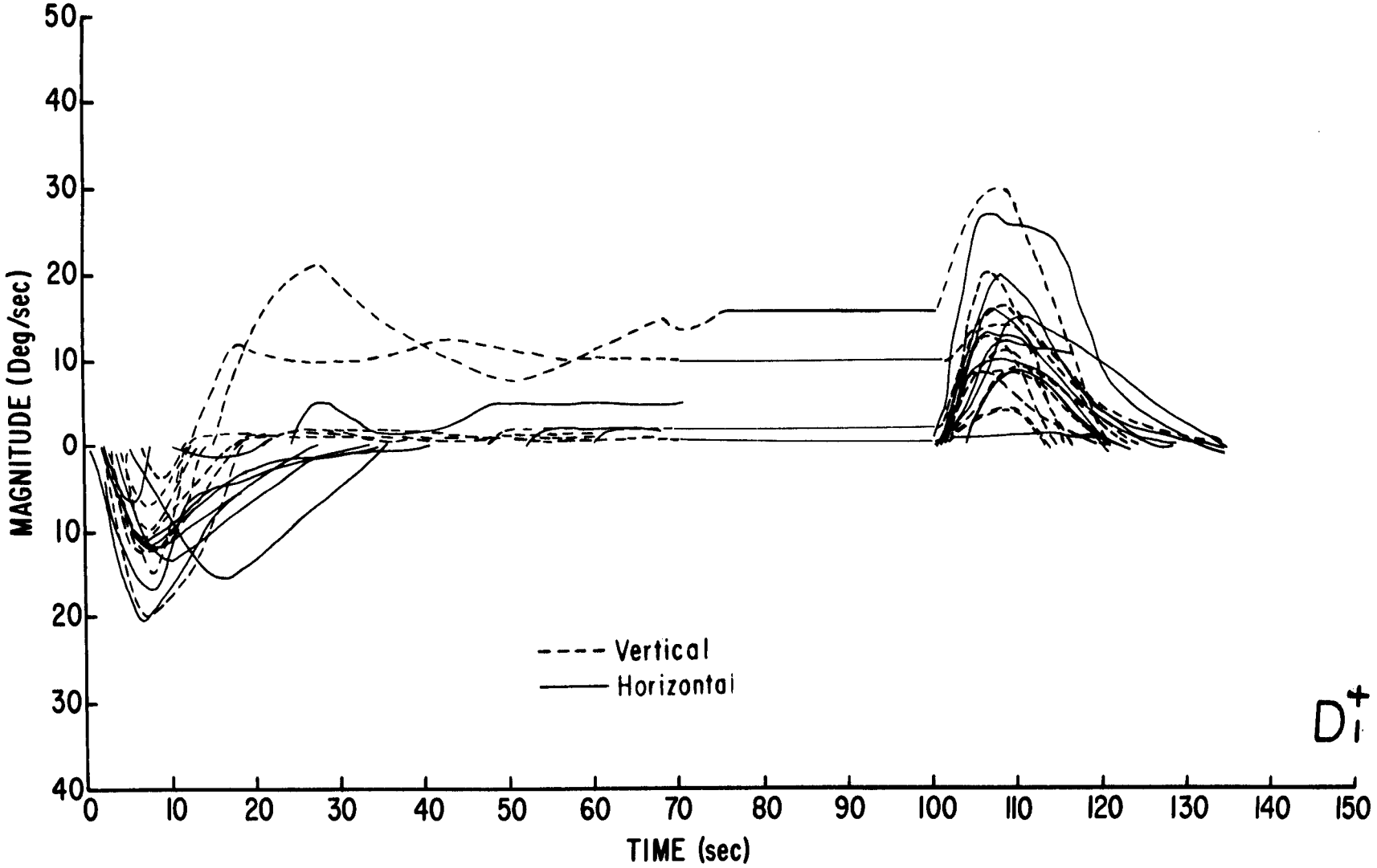
TIME (sec)
Vertical
Horizontal
D+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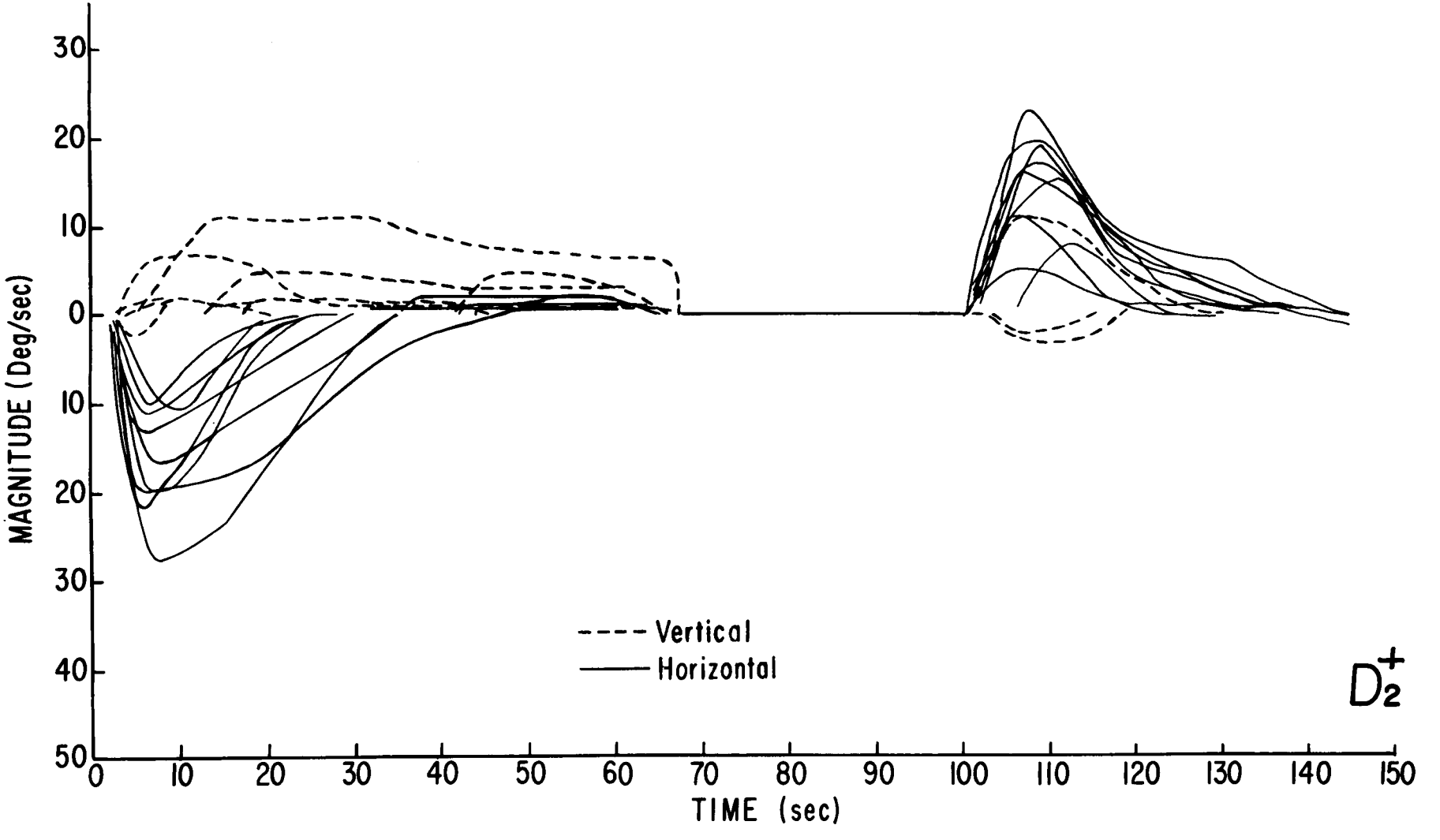
TIME (sec)
Vertical
Horizontal
D1+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MAGNITUDE (Deg/sec)
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Vertical
Horizontal
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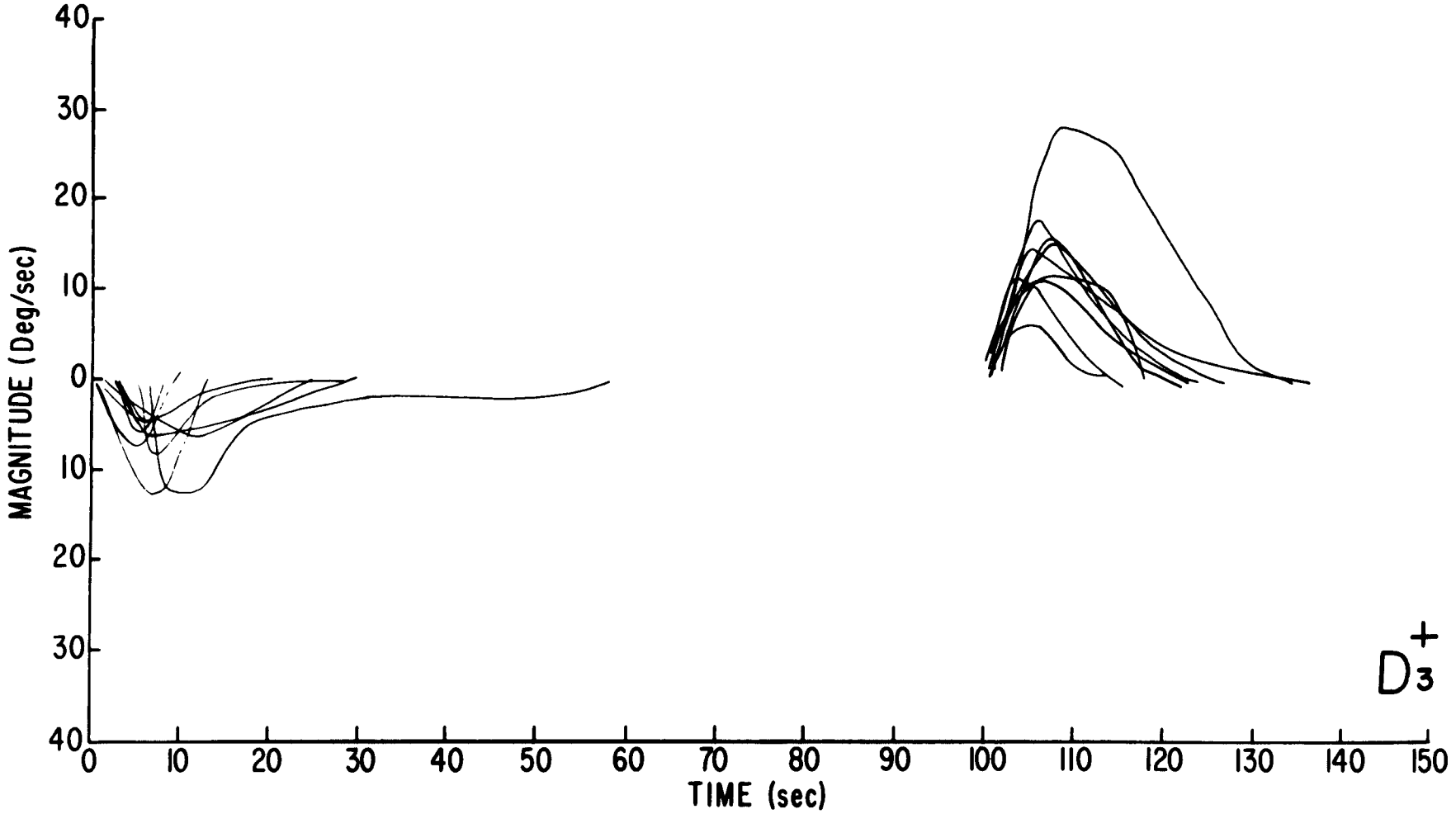
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MAGNITUDE (Deg/sec)
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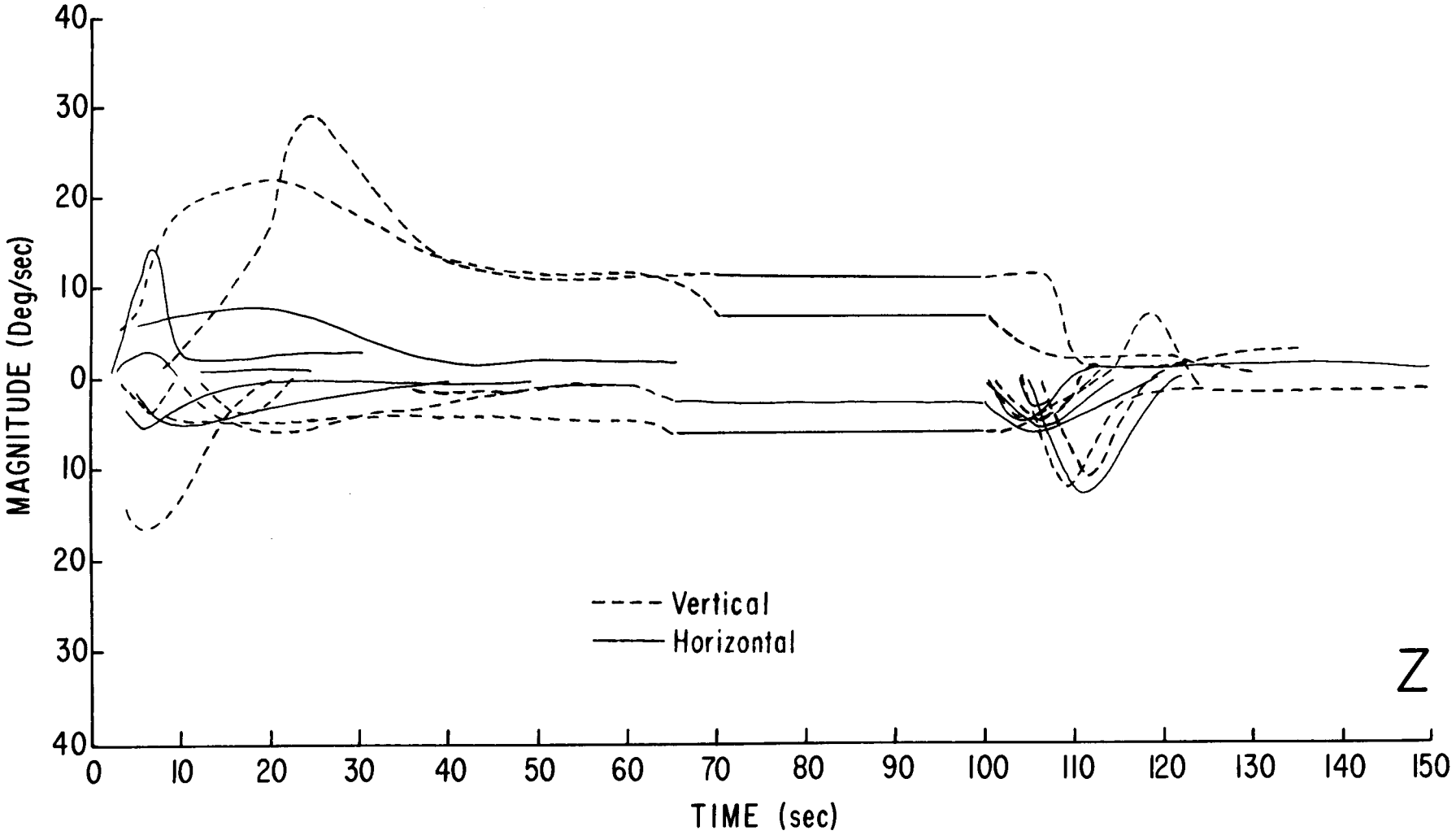
TIME (sec)
D3+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MAGNITUDE (Deg/sec)
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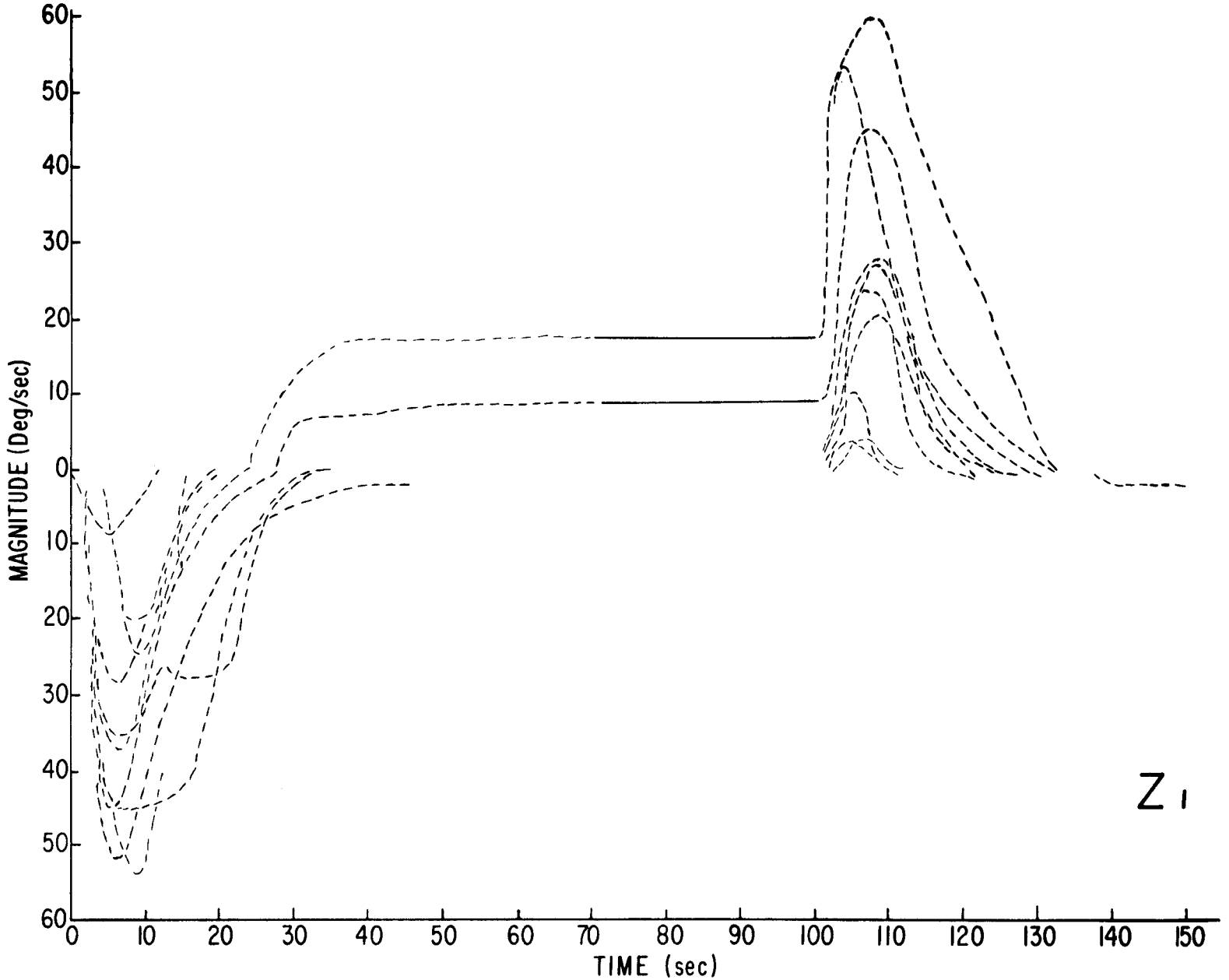
TIME (sec)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MAGNITUDE (Deg/sec)
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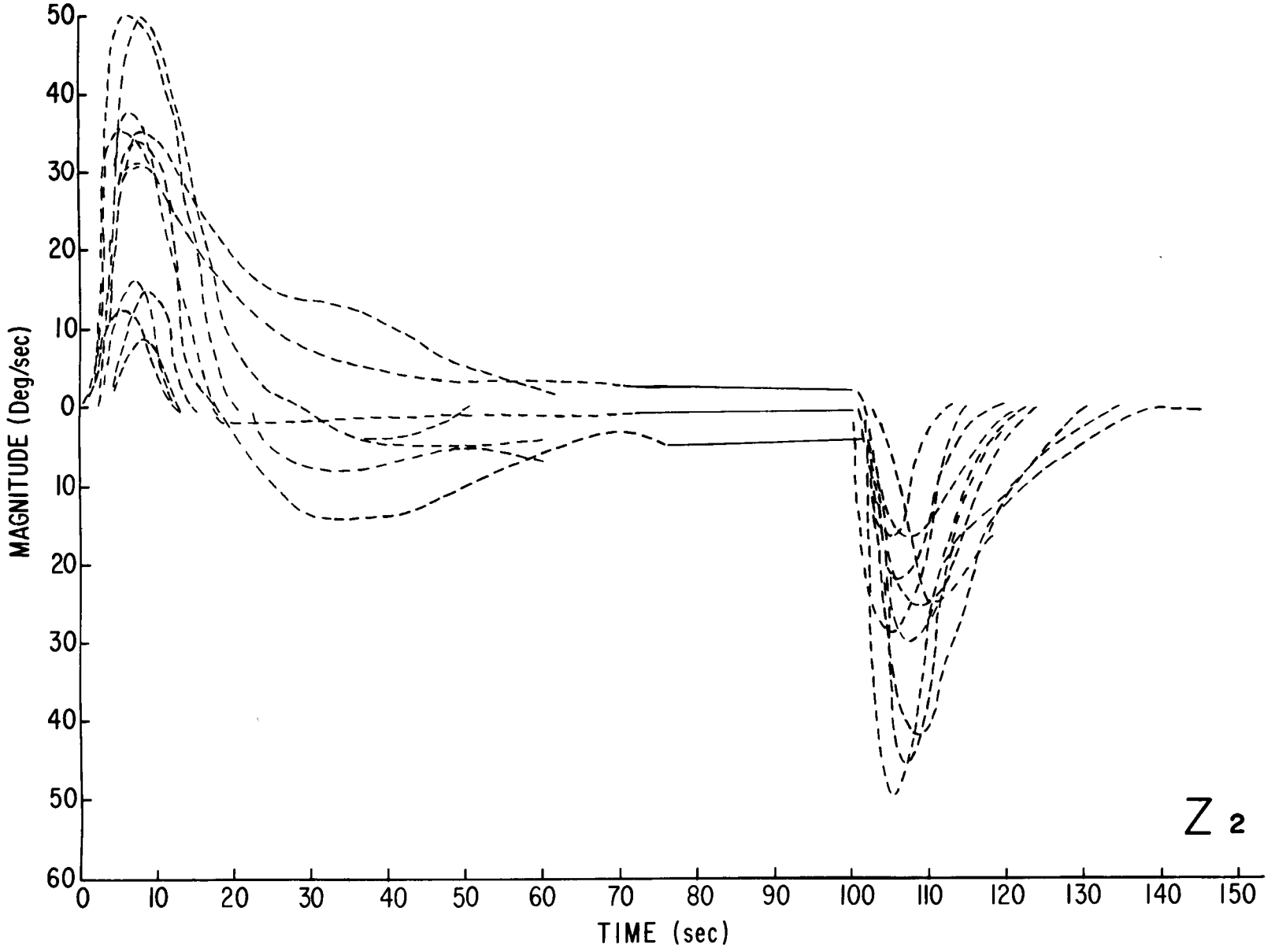
MAGNITUDE (Deg/sec)
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TIME (sec)
Z 2