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EXTRA-RETINAL SIGNALS INFLUENCE INDUCED MOTION: A NEW KINETIC ILLUSION

K. F. Prazdny* and Mike Brady

ABSTRACT.

When a moving dot, which is tracked by the eyes and enclosed in a moving framework, suddenly stops while the enclosing framework continues its motion, the dot is seen to describe a curved path. This illusion can be explained only by assuming that extra-retinal signals are taken into account in interpreting retinal information. The form of the illusion, and the fact that the phenomenal path cannot be explained on the basis of positional information alone, suggests that the perceived path is computed by integrating (instantaneous) velocity information over time. A vector addition model embodying a number of simplifying assumptions is found to qualitatively fit the experimental data. A number of follow-up studies are suggested.

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* Author's address: Dept. of Computer Science, University of Essex, Colchester, UK.

1. INTRODUCTION

The question of extra-retinal signals combining with retinal information to produce perceptual experiences is still much debated. It seems that such information is primarily of an efferent nature. The afferent signals from the extra-ocular muscles do not seem to contribute very much, if anything, to the body of extra-retinal information influencing perception. (Mack 1975, Mack et. al. 1973, Festinger et. al. 1976).

Induced motion is usually defined as the phenomenal motion of a physically stationary object brought about (or induced) by the motion of a nearby (usually enclosing) moving object (see for example Rock 1975). More generally, the concept of induced motion can be extended to cover cases where the phenomenal motion of physically moving objects depends on both the physical motion of the target object and the motions of nearby objects. Such interactions have been reported frequently in the literature (see for example Gogel 1974).

In this paper, we report a new kinetic illusion involving induced motion and smooth pursuit eye movements. The illusion offers some interesting insights into the relationships between retinal and extra-retinal information as determinants of visual experience. It involves the classical induced motion stimulus, namely a dot inside a moving boundary (see Duncker 1929, Wallach 1959).

Refer to figure 1. When the rectangle R is moved vertically upwards and the dot D obliquely upwards, so that the vertical component of D's velocity is equal to that of R, subjects report the dot D as moving horizontally to the left, sliding along the upper edge of R. If, at a randomly determined point during this sliding motion, the dot D is suddenly stopped and kept stationary while the rectangle maintains its vertical upwards motion, D is seen to move along a curved trajectory (see figure 1b). This illusory motion of the dot D is seen by every observer when the dot is tracked. However, the illusion is crucially dependent on smooth pursuit eye movements tracking the dot. If the dot is not fixated, subjects report the dot as moving along the straight path illustrated in figure 1c, which is a familiar percept predictable from other induced motion studies (Duncker 1929, Wallach 1959, Gogel 1979). It is the form and extent of the curved part of the phenomenal trajectory which is of interest here as a measure of the way in which extra-retinal signals influence, or co-determine, phenomenal motions, and the amount of this influence. Note that in figure 1b the phenomenally downwards motion of the dot is often described by subjects as along a straight line asymptotic to the curved part of the trajectory. The straight line is horizontally displaced with respect to the point where the dot became stationary.

About fifteen different subjects saw the display, and all, without exception, saw the illusory curve depicted in figure 1b. Preliminary observations indicated that a major determinant of the extent of the curved part of the phenomenal trajectory of D was the angle θ' (see figure 1a). The first experiment was designed to evaluate this observation.

2. Experimental set-up

All experiments reported in this paper were carried out using a DEC GT44 graphic visual display terminal controlled by a PDP11/10 single user minicomputer. The stimuli were, strictly speaking, sequences of discrete "snapshots" but due to phi motion, all phenomenal motions were continuous and smooth. The observers were located approximately 1.7 metres in front of the display, which subtended about 20 degrees of arc. The observers were seated with their head fixed by a head restraining apparatus. (The apparatus consisted of several padded clamps preventing rotational as well as vertical head movements. While this way of preventing head movements is superior to a simple head and chin rest, it is probably not as good as using a bite bar.) The experimental room was fully lit and the display was viewed binocularly, as monocular viewing made no difference. Due to the unfavourable refresh time characteristics of our display processor, only two target object (dot) velocities were used, namely one and two degrees of arc per second. Future work should examine a wider range of velocities.

To measure the curved part of the phenomenal trajectory, we measured its width w and height h (refer to figure 2a). This measurement consisted of locating a point on the phenomenal curve, specifically the point where the curve appeared to become a straight line, which we refer to as the asymptote. This point was located using the light pen facilities of the display processor. After the dot crossed the lower boundary of the rectangle R, and disappeared, the observers were presented with the stationary rectangle R, whose horizontal extent was about eight degrees of arc. The end of the horizontal part of the phenomenal trajectory (point E of l_1 in figure 2b) indicated where the dot physically stopped and where its phenomenal trajectory changed abruptly. The task of the experimental subjects was to manipulate the light pen so as to bring the endpoint of the line l_2 into coincidence with the point where, according to their judgement, the path ceased to be curved. To maintain the fixed position of the subject's head, the experimenter manipulated the light pen under verbal instruction from the subject. The display was programmed so that the pen movements manipulating line l_2 were performed outside the rectangular boundary.

There were three experimental conditions corresponding to three different values for the angle θ, namely 120, 140 and 160 degrees. The coordinates of the point E at which the dot objectively stopped and the experimental condition were chosen at random by the program.

The mean length of the line l_1 was six degrees of arc, with a minimum of four. Each experiment consisted of two sessions determined by the velocity v_d of the dot, namely one or two degrees of arc per second. The dot velocity was kept constant throughout each session. The order of presentation of the two sessions was counterbalanced. Each session consisted of sixty measurements, comprising twenty value pairs (h,w) for each of the three values of θ. Before the measurements were taken, the subjects were made familiar with the display, the manner in which responses were to be recorded, and saw approximately ten practice presentations, five at each dot velocity.

3. Experiment one

Four subjects, all with normal vision, participated in this experiment. The values of θ were 120, 140 and 160 degrees of arc. The results are summarised in figure 3. As can be seen, the effect of the slope of the oblique motion completely overshadowed any effect of the speed v_d of the dot. Furthermore, as can be seen from figures 3a and 3b, as h decreased with increasing θ, so w increased. These tendencies are found in every subject. In a previous paper (Prazdny and Brady 1980), we briefly mentioned the illusion and sketched a possible explanation. The refined explanation we propose here is based upon the simultaneous operation of two component processes: the classical induced motion effect, by which the objectively stationary dot is perceived as moving vertically downwards as the enclosing framework moves vertically upwards, and the "induced motion" of the dot due to a consistent under-registration of the extent of smooth pursuit eye motions by the visual system. The explanation is as follows.

In interpreting retinal movements, the visual system takes the movements of the eyes into account (see for example Rock and Ebenholtz 1962, Mack 1975, Festinger and Holtzmann 1976, Mack and Herman 1973). At the moment the dot stops, the eyes overshoot it. Because the visual system registers only a portion of the actual eye movements, say p(v), where v is the retinal velocity, (Mack 1975, 1978, Festinger et. al. 1976) the rest, (1-p(v)), of the retinal motion of the dot will be unaccounted for and will thus be regarded by the visual system as due to the target (dot) motion. The visual system then detects the overshoot and applies a corrective force, similar to braking in a dynamical system. This means that the speed of eye movements decrease with time and with it the proportion of the eye movement unaccounted for. Qualitatively, the exact structure of the function p(v) is not important for this argument, even though it is quantitatively. Various possible forms for p have appeared in the literature, for example Festinger et. al. (1976) suggest that it is a fixed velocity, while Mack (1975) suggests a fixed proportion of the actual eye velocity.

The two components of classical induced motion and under-registration add as vectors to produce the instantaneous velocity vector of the target D. The decreasing component due to the overshoot of the eye then accounts for the shape of the phenomenal path (see figure 4). Qualitatively, the simplifying assumptions used in the derivation of figure 4 generates curves which were judged by all observers to resemble very closely the path they perceived.

To ascertain the validity of the simple vector addition model proposed above for the phenomenal path of the dot, we performed a second experiment. Consider figure 5. When the wedge shaped region R is moved vertically upwards and the dot moves obliquely upwards as shown, observers again report that the dot travels along the upper sloping edge of R. The speed at which it slides along the edge is slower than in the case of the horizontal boundary discussed in experiment one by a factor $\cos(\theta-\beta)/\cos(\theta)$. This time the motion of the wedge is changed so that, at the moment the dot stops, it is moved to the right with the same speed v_v as it had when moving vertically upwards. It is possible to predict the phenomenal path of the dot from the additive model (see figure 6). As can be seen from figures 6b and 6c, the value of w is predicted to decrease monotonically with θ, while the value of h first increases and then decreases. In figure 6c, we illustrate the increase and subsequent decrease in more detail. Positive values of the function indicate that h increases to about 130 degrees of arc when u is seven. Negative values indicate decreasing h.

Experiment two was designed to test these predictions.

4. Experiment two

Experiment two was equivalent to experiment one except for the shape of the enclosing framework and its motion (see figure 5). The graphics display was programmed so that at the moment the dot stopped, the enclosing framework moved to the right with a speed equal to its vertical speed prior to the change. The relationship between the speed of the dot and of the framework is easily found by resolving both normal to the sloping boundary, namely

$$v_v = v_d \sin(\theta-\beta)/\cos \beta,$$

where β is the slope of the upper boundary. Again, w and h were measured in the same way as in experiment one (see figure 5b). The results of experiment two are summarised in figure 7. The general shape of the phenomenal path is judged to be very similar to that predicted, and, as can clearly be seen, the general trends for w and h predicted by our model closely matches the results obtained. The quantitative match is not very close, but this is to be expected given our simplifying assumptions. In reality the braking force and consequent deceleration of the eye is probably a complex nonlinear function, not only of the instantaneous velocity of the eye, but also of such factors as the mismatch between the target and the fovea and, possibly, the direction of tracking movements, since there seems to be an asymmetry in the effect of the direction of pursuit eye movements at least when horizontal eye movements are used.

4. Discussion

We wish to stress two major findings of the investigation reported here. Firstly, our experiments strongly suggest that the phenomenal path of a tracked object is computed on the basis of integrating the instantaneous velocity information over time. The curved portion of the path cannot possibly be explained by assuming that the computation of the path is based solely on positional information. The discrepancy between the positional and velocity information is in a sense reflected in the parameter w of the illusory curve, and as we pointed out earlier, w is a monotonic function of θ. As such, our experiments provide unexpected support for the notion of separate processing channels for motion and positional (or pattern) information (see for example: Tolhurst 1973, Frisby and Clatworthy 1974, Sekular and Levinson 1977).

Secondly, if our additive model is at least conceptually correct, the effect of the postulated under-registration of smooth pursuit eye movements and the overshoot of the target by the eyes is localised to the target to be tracked! This localisation may be mediated by attentional or spatial factors, but in any case it is essential. If the effect of the overshoot was **not** localised to the target, it would also apply to the enclosing framework, and one could not possible obtain the curved path which characterises the illusion reported here.

Our illusion seems to be related to the "rebound illusion" reported by Mack et. al. (1973). There, when a horizontally moving dot, which is tracked by the eyes, stops suddenly, it is seen to rebound sharply backwards. Mack et. al. (1975) suggested that this rebound is due to the unmonitored overshoot of the target by the eyes. We note that this sort of explanation could also account for the perceptions described here if a further assumption was made. One would need to assume that at the moment the visual system detects the target/fovea discrepancy and "decides" to take corrective action, the detection and decision are taken somewhere on a peripheral level and that until the eye is stationary **no** information about eye movements is available to the retinal motions / extra-retinal signal comparator. As a result of these peripheral corrective activities, the speed of the eye motion would decrease with time and the additive model would predict qualitatively equivalent paths. We feel however that this latter assumption is too over-constrained and that the explanation is consequently implausible.

References

Duncker K. 1929 "Ueber Induzierte Bewegung", Psych. Forsch., 12, 180-259.

Festinger L., Sedgewick H. A., and Holtzmann J. D. 1974 "Visual perception during smooth eye movements", Vis. Res., 16, 1377-1386.

Frisby J. P. and Catworthy J. L. 1974 "Evidence for separate movement and form channels in the human visual system", Perception, 3, 87-96.

Gogel W. C. 1979 "Induced motion as a function of the speed of the inducing object measured by means of two methods", Perception, 8, 255-262.

Mack A. 1975 "Perception during pursuit eye movements", Psychologia, 18, 31-62.

Mack A., Fendrick R., and Sirigatti S. 1973 "A rebound illusion in visual tracking", Am. J. Psych., 86, 425-433.

Mack A. and Herman E. 1973 "Position constancy during pursuit eye movements", Q. J. Exp. Psych., 25, 71-84.

Prazdny K. F. and Mike Brady 1980 "Illusory motion of a dot in a three object display", submitted to: Perception.

Rock I. 1975 *An introduction to perception*, MacMillan, New York.

Rock I. and Ebenholtz S. 1962 "Stroboscopic movement based on change of phenomenal rather than retinal location", Am. J. Psych., 75, 193-207.

Sekuler R. and Levinson E. 1977 "The perception of moving targets", Sci. Am., 236(1), 60-73.

Tolhurst D. J. 1973 "Separate channels for the analysis of the shape and the movement of a moving visual stimulus", J. Physiol. (London), 231, 385-402.

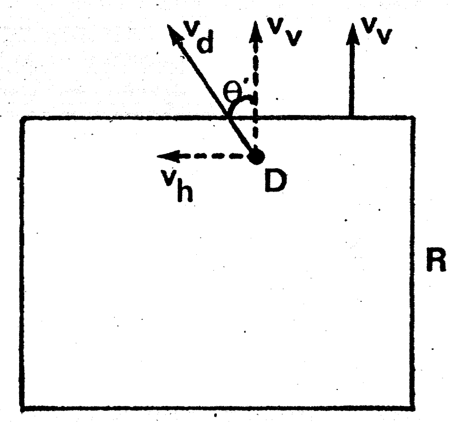
Wallach H. 1959 "The perception of motion", Sci. Am., 56-60.

Legend to figure 1.

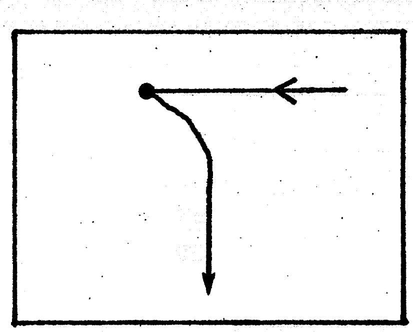
a. The dot D moves obliquely upwards and to the left with velocity v_d. Its motion can be resolved into its horizontal (v_h) and vertical (v_v) components. When the enclosing rectangle R moves vertically upwards with velocity v_v, the dot is seen to slide leftwards along the upper horizontal boundary of R. The angle between the actual path of the dot and the vertical is denoted by θ', and $\theta'+\pi/2$ by θ.

b. The dot D is stopped while the rectangle continues to move upwards as in (a). Immediately, the phenomenal path commences to trace the curve shown and finally merges into a vertically downward motion. At the moment that the dot objectively stops, its speed is seen to increase sharply and then to decrease slowly until it moves with unchanging speed.

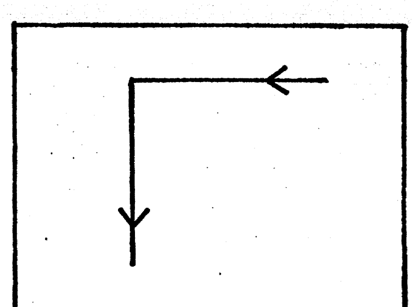
c. When the dot D is not tracked but some other part of the display is fixated, the phenomenal path is not curved. Instead, it moves as predicted by classical induced motion studies.



1a.



1b.

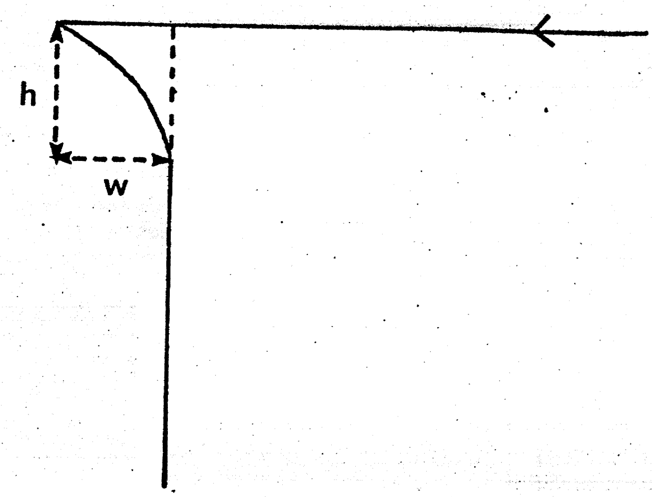


1c.

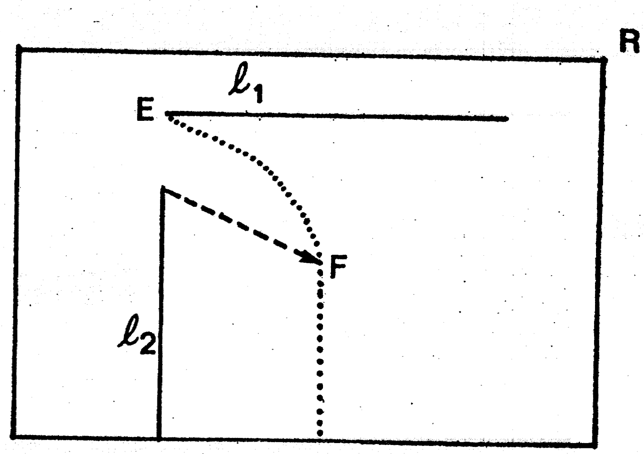
Legend to figure 2.

a. the principal parameters of the phenomenal path measured in the experiments, w and h, effectively measure the phenomenal separation of two points E and F. E is the point where the dot is seen to change its motion abruptly, that is the point at which it actually stops moving. F is the point where it phenomenally leaves the curved part of its trajectory and begins to move vertically downwards.

b. To measure the position of the point F, the observers manipulated a movable line l_2 which could change its position as well as its length, so that its endpoint coincided with F. The point E corresponds to the endpoint of the line l_1, which was displayed throughout. All measures of w and h were thus relative to E. The dotted path illustrates the phenomenal trajectory of the dot D. The dashed path π illustrates the observer's manipulation of the endpoint of l_2 to the point F. In each case the coordinates of the point F were recorded.



2a.

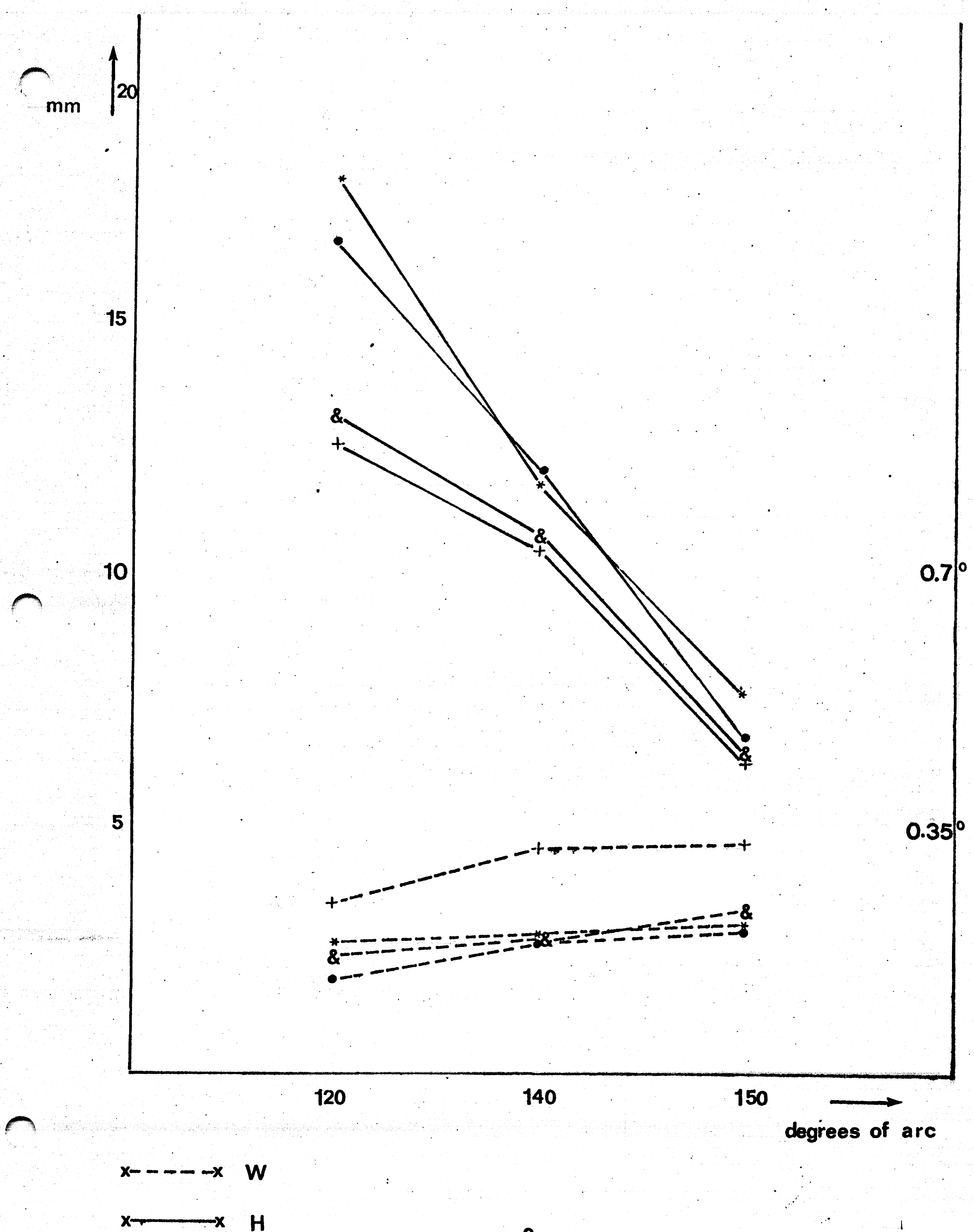


2b.

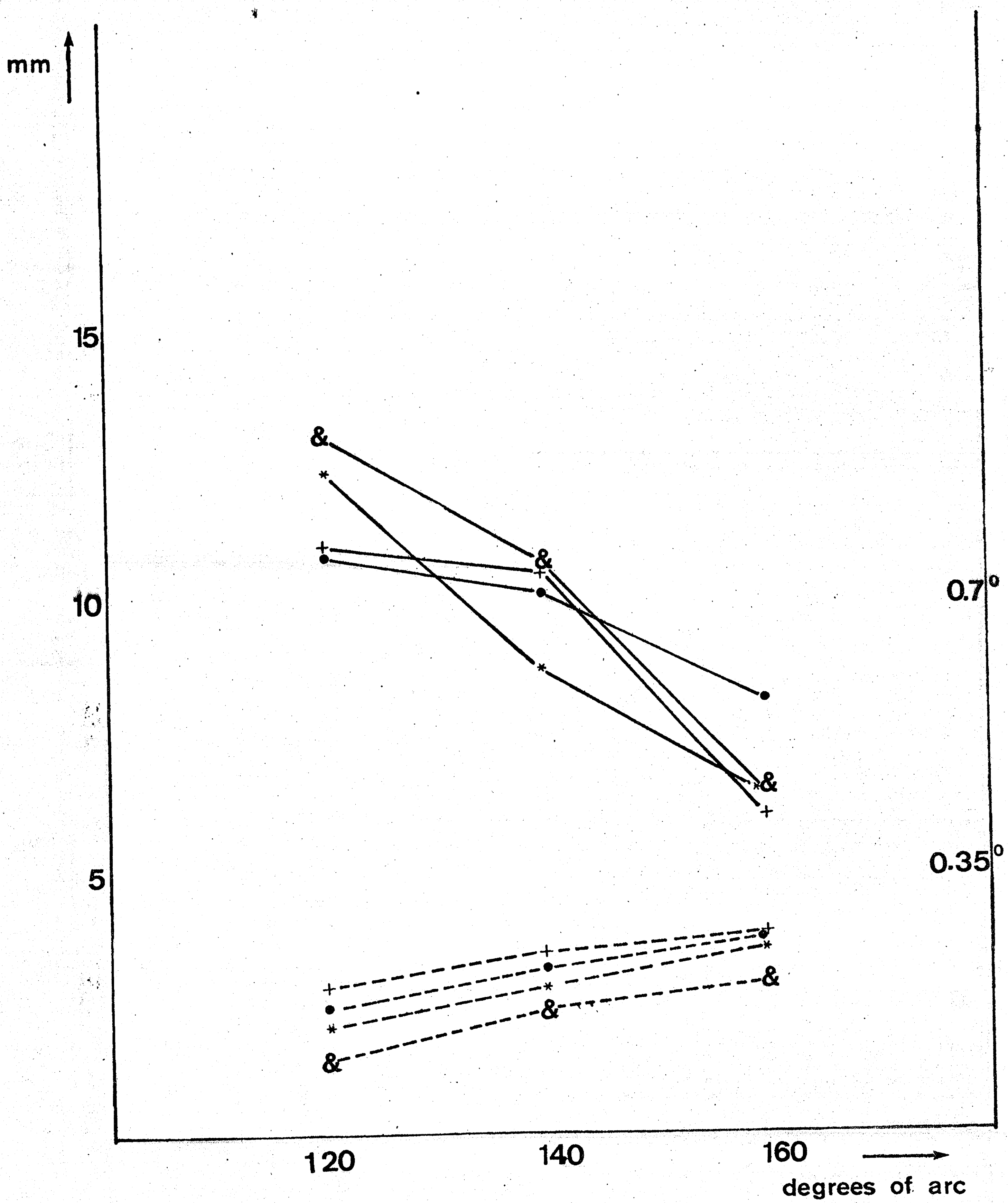
Legend to figure 3.

a. Experimental results for the four observers participating in experiment one. The speed v_d of the dot was 2 degrees of arc per second. Each data point is the mean of 20 observations. The observers' (*,+,@,&) average estimation of the parameters w and h for each of the three values of θ used are shown.

b. Further experimental results for experiment one. The speed v_d of the dot was one degree of arc per second. The notation is the same as in figure 3a.



3a.



3b.

Legend to figure 4.

The phenomenal path of the dot under the simplifying assumption that the braking force is proportional to eye speed. The instantaneous velocity vector of D is

$$\underline{v}(t) = (0, v_V) + \underline{w}(t),$$

where $\underline{w}(t)$ results from the braking force applied to the velocity vector $\underline{u}$, which represents the portion of the dot's motion which is unaccounted for by the visual system. By assumption,

$$d\underline{w}(t)/dt = -k\ \underline{w}(t)$$

and $\underline{w}(0) = (-u \cos \theta,\ u \sin \theta)$,

so that

$$\underline{w}(t) = (-u \cos \theta,\ u \sin \theta)\ e^{-kt}.$$

It follows that

$$\underline{v}(t) = (-u \cos \theta\ e^{-kt}\ ,\ v_V + u \sin\theta\ e^{-kt}).$$

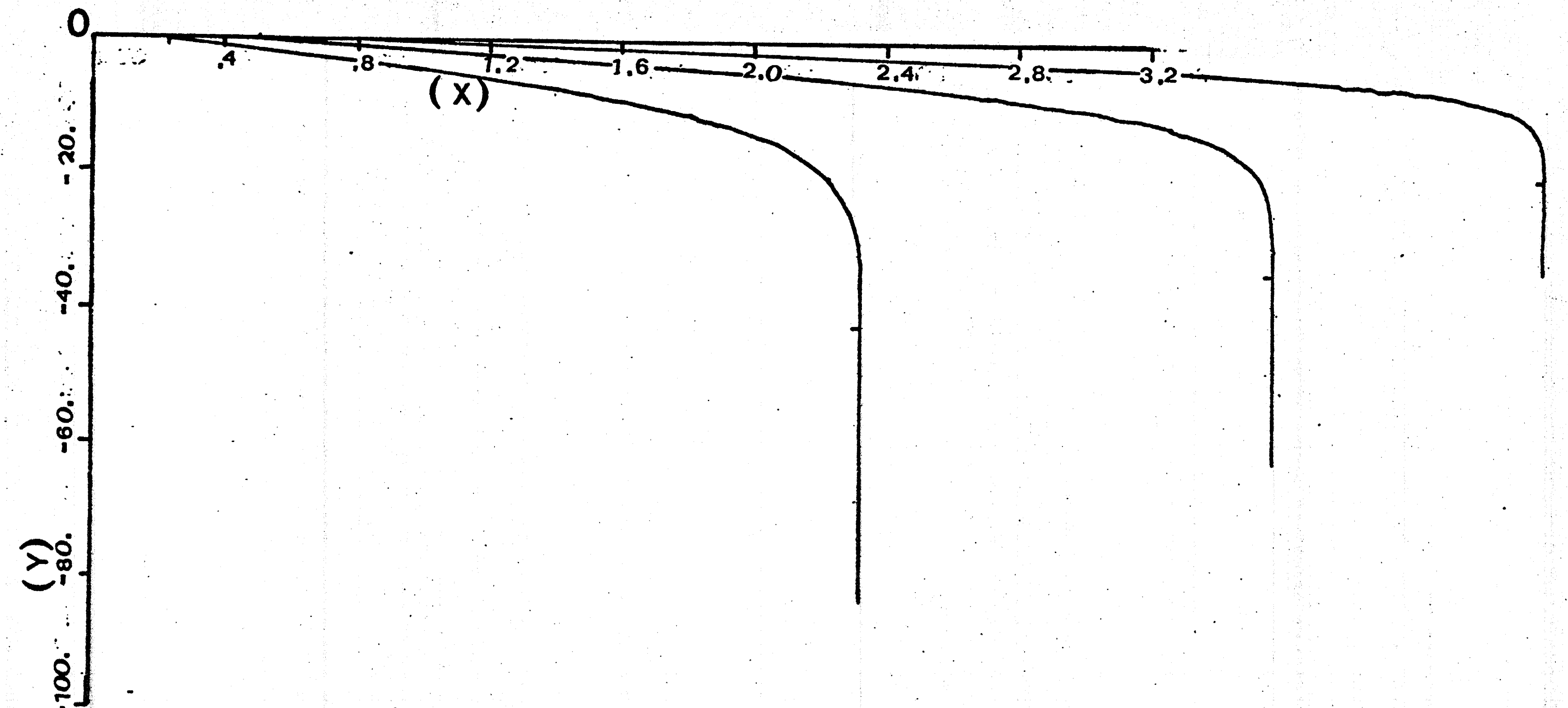
Integrating, we find that

$$x(t) = u \cos\theta \, (e^{-kt}-1)/k$$

and

$$y(t) = v_v t - u \sin\theta \, (e^{-kt}-1)/k.$$

We experimentally determined a value of k which gave results close to those obtained in our experiments and by varying time, plotted x(t) and y(t) for θ = 120, 140, and 160 (reading from left to right). The ticks on the three curves indicate the approximate points where the phenomenal path reaches its asymptote, to within some small error ϵ (that is, where abs(x(t)-x'(t)) is less than or equal to ϵ and x'(t) is the asymptote function). Note that the curve with greatest curvature corresponds to the case θ = 160. On the plot, nine units of the x- or y-scale is equal to two millimeters.



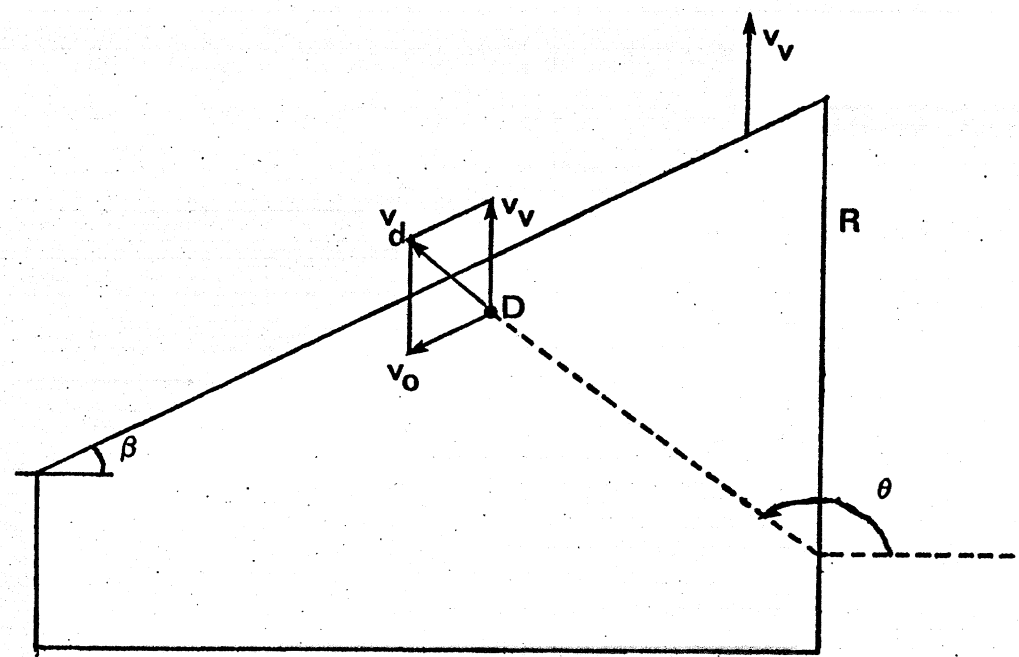
$[V_V = 9 : U = 7]$

4.

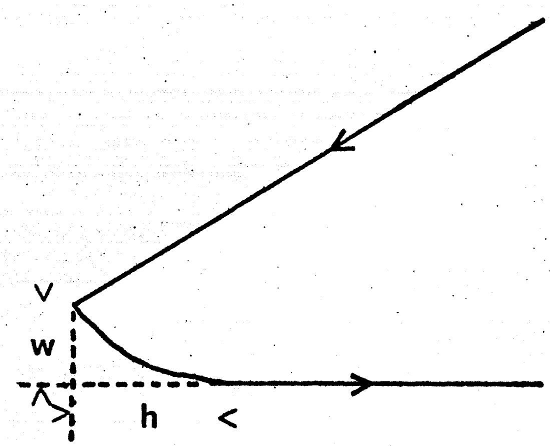
Legend to figure 5.

a. The two-dimensional objects used in experiment two are illustrated. The velocity of the dot can be resolved into its vertical component v_v and its component v_o along the oblique upper boundary of the enclosing framework whose slope is β. When the framework is moved upwards with velocity v_v, observers see the dot as moving along the upper boundary as in experiment one.

b. The parameters w and h of the perceived motion of the dot are defined analogously to experiment one, see figure 2.



5a.



5b.

Legend to figure 6.

a. The vectors involved in the additive model for the phenomenal curved path of the dot D in experiment two. The vector $\underline{v}_h$ in the horizontal direction is due to the rightward motion of the framework. For simplicity of analysis we set $v_h = v_v$, but not equal to u. See text for more details.

b. Assuming as before that the speed of the tracking eye movements decreases exponentially over time after the dot stops, the predicted phenomenal path of the dot can be obtained by integrating its velocity vector.

$$\underline{v}(t) = (v_v - u \cos\theta \, e^{-kt} \, , -u \sin\theta \, e^{-kt}).$$

The x and y coordinates of the points on the curve are then

$$x(t) = v_v t - (u \cos\theta \, / \, k)(1-e^{-kt}),$$

and

$$y(t) = (-u \sin\theta \, / \, k)(1-e^{-kt}).$$

The vertical marks on the three curves indicate the approximate points where the curved path reaches its asymptote. Analogous to figure 4, this is where abs(x(t)-x'(t)) is less than or equal to ϵ. The scale is as before.

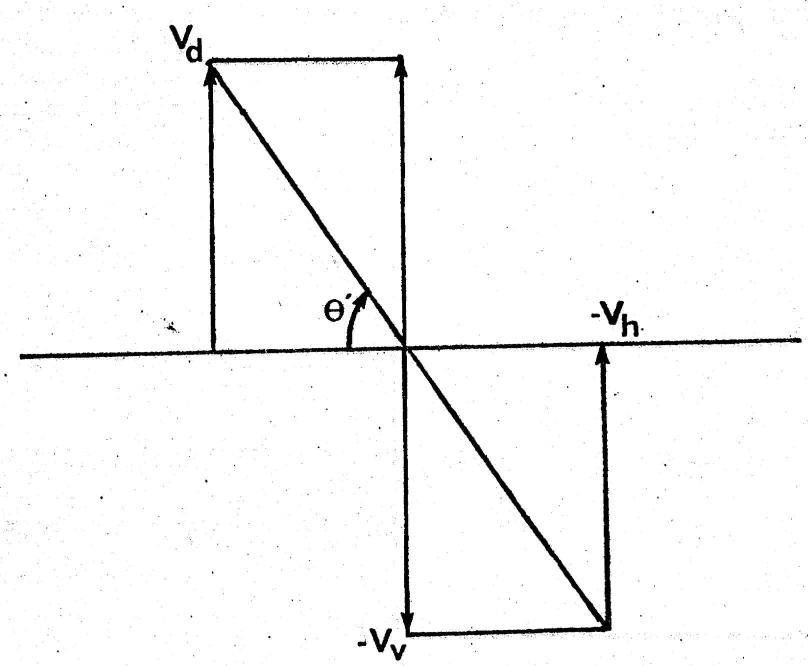
c. To find out how h and w vary with θ, we consider the signs of $\partial h/\partial\theta$ and $\partial w/\partial\theta$. It is easy to show that

$$\partial w/\partial\theta = -u \cos \theta$$

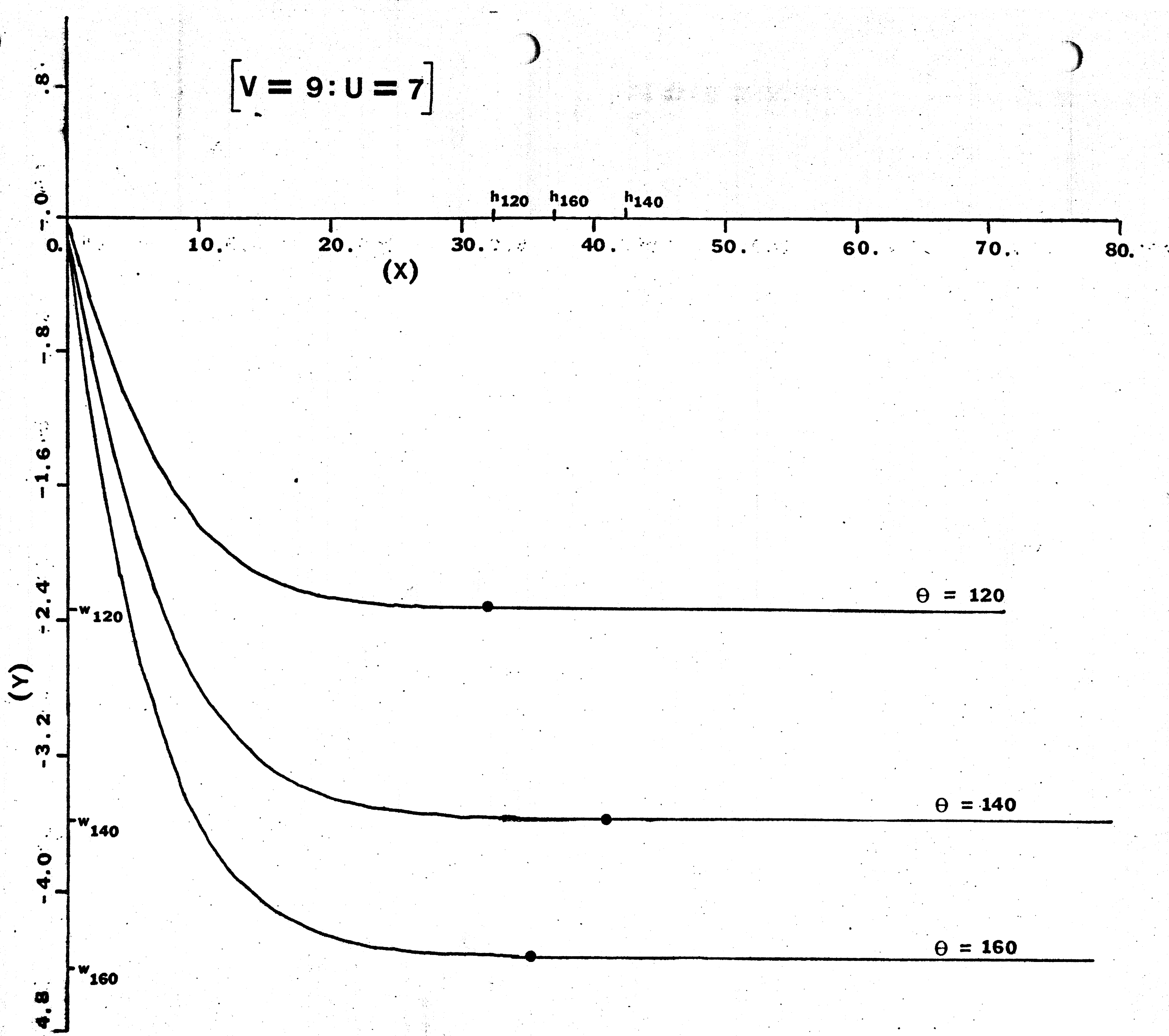
which is greater or equal to zero for the range of θ used here. Recalling that $v_v = v_d \sin(\theta-\beta)/\cos$, it is easy to show that the sign of $\partial h/\partial\theta$ is equal to the sign of

$$\sin^2\theta(u \sin\theta + v_d \sin(\theta-\beta))-dy_\epsilon/dt,$$

where dy_ϵ/dt is some arbitrarily small velocity.



6a.


[V = 9 : U = 7]
.8
-.0
-.8
-1.6
-2.4
-3.2
-4.0
-4.8
(Y)
0.
10.
20.
30.
40.
50.
60.
70.
80.
(X)
h_{120}
h_{160}
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w_{140}
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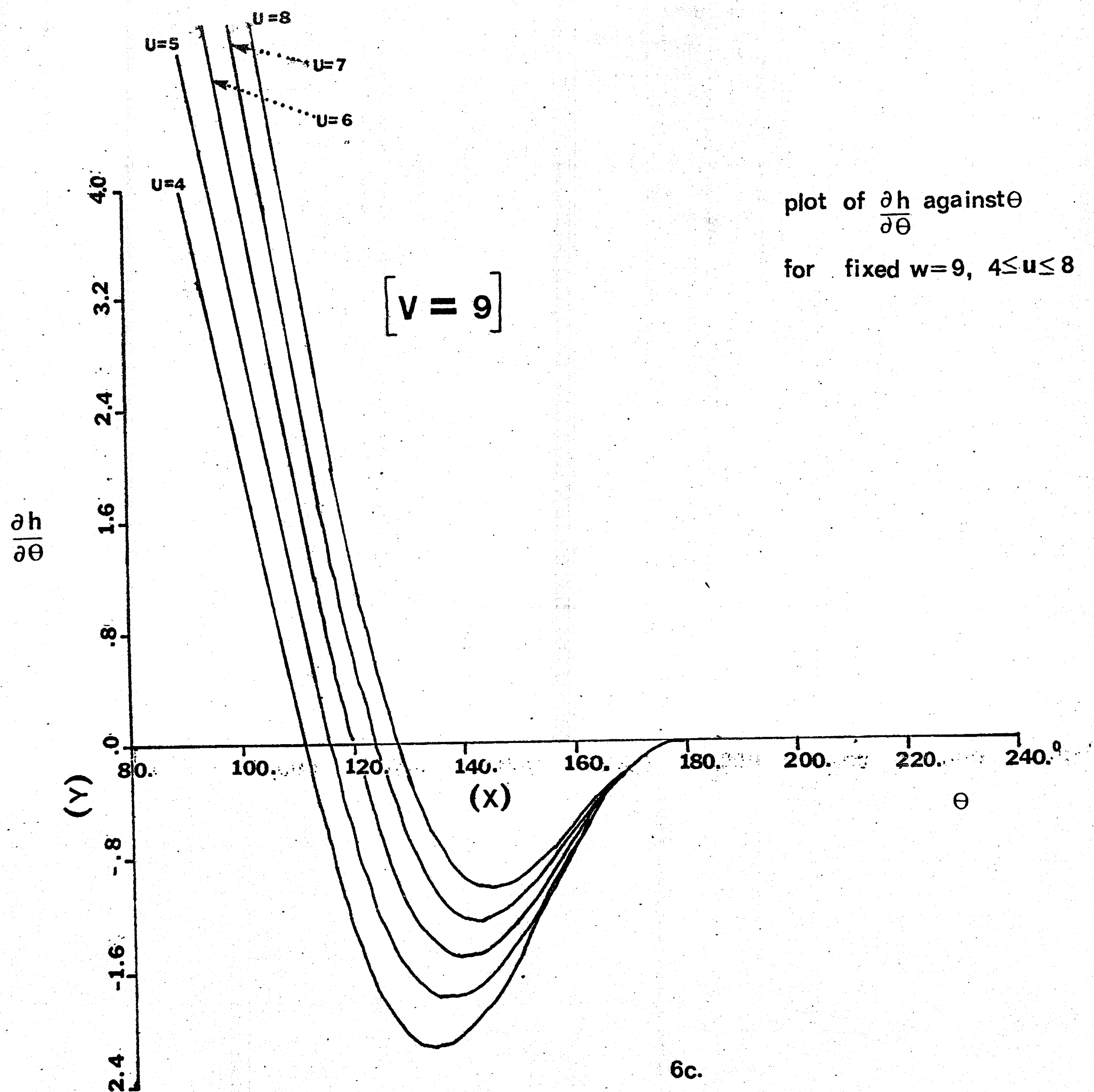
θ = 120
θ = 140
θ = 160

6b.



plot of $\frac{\partial h}{\partial \Theta}$ against Θ

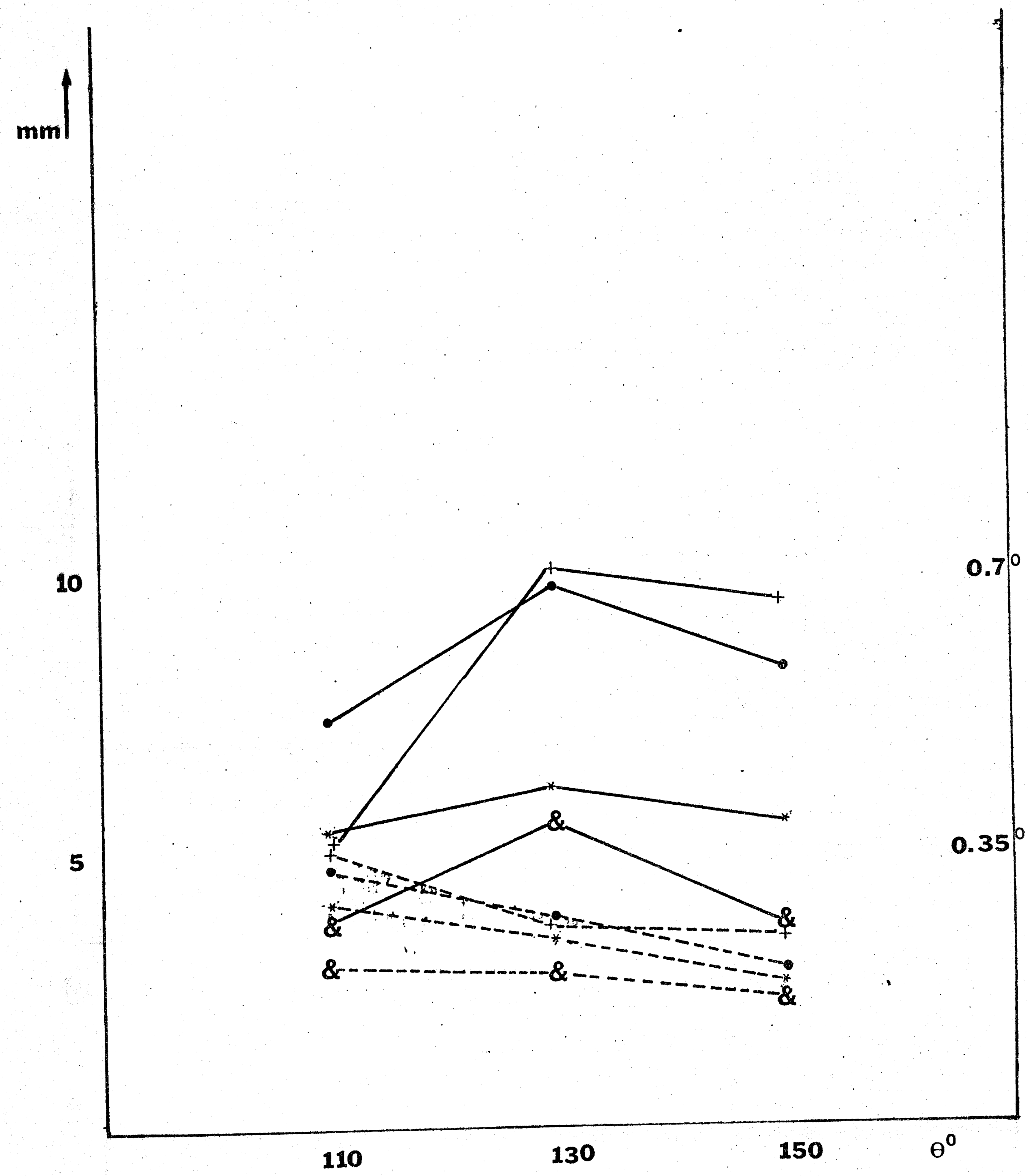
for fixed $w=9$, $4 \leq u \leq 8$

6c.

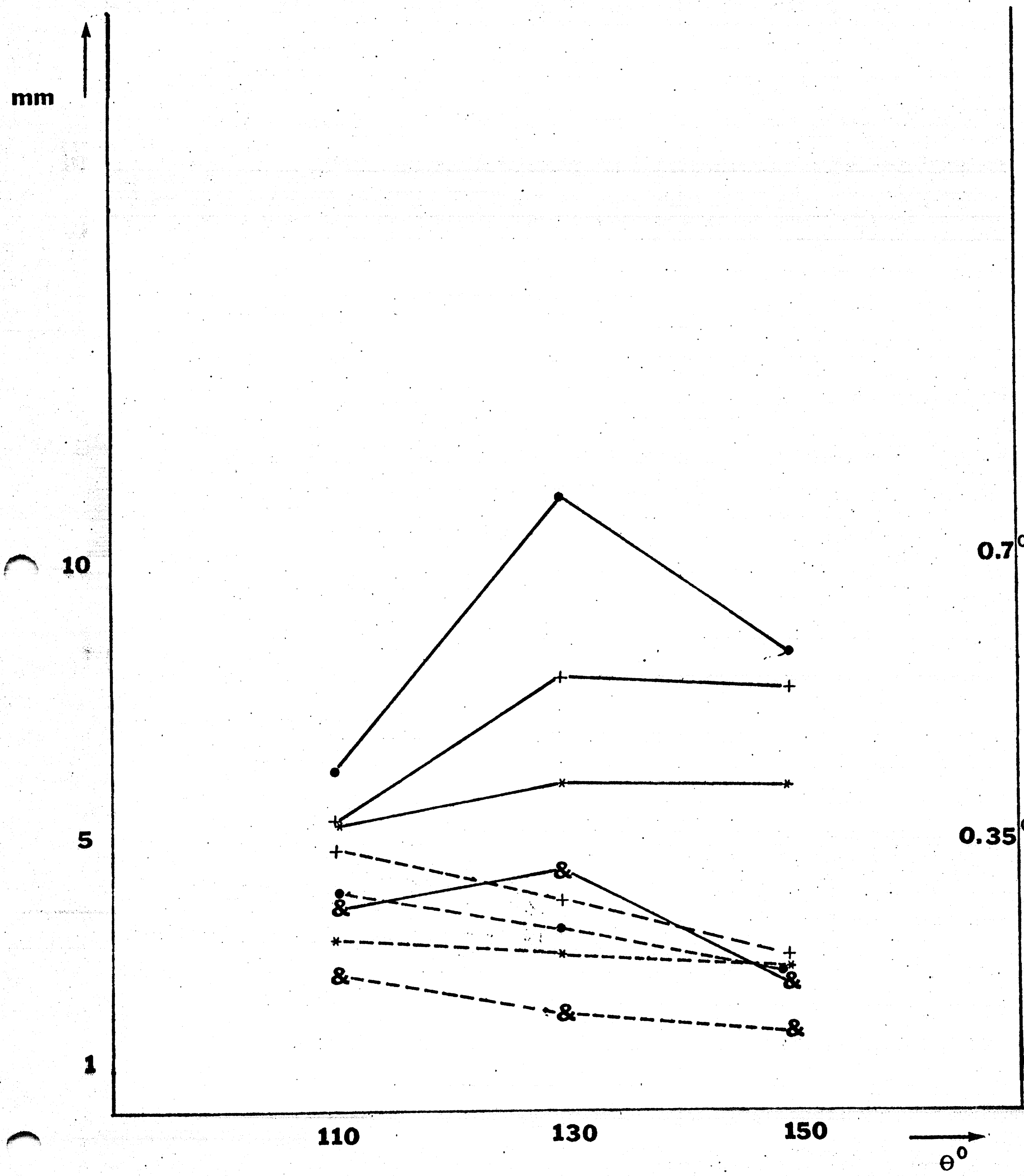
Legend to figure 7.

a. Results from experiment two. The velocity of the dot was two degrees of arc per second. Each data point is the mean of 20 observations as in figure 3.

b. Results from experiment two when the velocity is one degree of arc per second. Again, each data point is the mean of 20 observations.



7a.



7b.