INFORMATION AVAILABLE FROM NATURAL CUES DURING FINAL APPROACH AND LANDING

M. Dean Havron

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SUMMARY

This report further develops HSR work for the Federal Aviation Agency on airport and heliport marking and lighting. The purpose of this report is to evaluate the effectiveness of guidance the pilot may obtain from his viewing the apparent expansion pattern of the earth. Formulae are presented which describe the apparent speeds of movement of ground objects during final approach. Next, human factors data are brought together to estimate perceptual thresholds for movement. Speeds of movement expressed as iso-velocity curves are then compared with perceptual thresholds of motion to evaluate the effectiveness of guidance that the apparent expansion pattern of earth can provide for touchdown point, heading and flare-out.

Results must be considered tentative because human factors data available for estimation of thresholds were collected under laboratory rather than field conditions. Further, quantitative values of thresholds for perception of movement vary widely among reports in the literature.

Major findings are as follows:

1. In final approach, the area of no perceptible movement is not just the point of impact or the so-called x-spot. For 3 degree glide slopes it is seen as a thin inverted horseshoe. For steep V-STOL approaches (15 to 30 degrees) the opening of the "shoe" may be closed so the area looks like an ellipse. In both cases, most of this area perceived as not moving is on the far side of the x-spot.
2. The expanding pattern of vectors surrounding the area of no perceptible movement should provide better guidance for steep approaches

than for shallow approaches. Of the three types of guidance, directional guidance is believed to be best, guidance for optional point of touchdown next best, guidance for flare-out poorest.

3. We suggest that during approach pilots use the non-moving area and expansion pattern for steering by visually back-tracking from those expanding vectors that are perceptible to locate their projected point of impact by triangulation. They then place this point of impact slightly forward of their intended touchdown point to allow for flare.

4. A better understanding of extra-cockpit cues available and how pilots can best use them should have import for pilot training, for better understanding of conditions conducive to false guidance and optical illusions, for better and more economical design of AML systems and for flight safety.

I. INTRODUCTION AND BACKGROUND

The purpose of this report is to describe quantitatively the movement[1] of extra-cockpit phenomena during final approach and landing and the information this movement can provide to pilots. This work extends prior Human Sciences Research, Inc. research (9) and certain work of Gibson (5, 6) and Calvert (1, 2). In the referenced HSR report we examined the concept of the x-spot and the expansion pattern of the panorama of earth about it. It was pointed out that with good visibility, the value of the guidance provided by the x-spot depends on the radial rates of movement of earth objects about it, and upon the ability of pilots to perceive this movement[2].

But precise information as to the actual speeds of movement was lacking and time did not permit a careful review of human factors literature concerned with the movement threshold. Hence, a more definitive study of actual rates of movement and ability of the human to perceive it was recommended.

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[1] The term "apparent movement" might have been used throughout the paper. However, in psychological literature "apparent movement" denotes illusions in which fixed objects are perceived as moving. We take an aircraft-oriented viewpoint and consider the earth surface as moving.

[2] For an aircraft gliding or diving, the x-spot is its point of impact on the ground if it maintains the same (straight) course. This point does not move as does the ground around it. But our initial report (9) pointed out that because of human inability to detect small movements, the pilot sees not only the spot as not moving but an area of some size about it. Our initial report attempted a first approximation of the size of this area. It was stated that when the plane flying 150 mph is 4,000 feet from touchdown on a 3^{o} glide slope intersecting the runway 1,000 feet from threshold, the so-called x-spot is a large cigar-shaped area symmetrical to the runway center line. This lane of no perceptible movement about the actual x-spot was estimated to be approximately 150 feet in width, and some 1,100 feet in length.

This study implements these recommendations. Specifically, we

1. develop formulae that describe the quantitative characteristics of movement of the earth panorama for different angles and speeds of approach,
2. estimate the capability of the human to perceive this movement under day and night conditions,
3. compare movement characteristics of earth stimuli with evidence as to human perceptual capabilities to evaluate the extent to which the pilot can use movement cues for information.

We consider landing by visual cues in both fixed and rotary wing aircraft. However, it should be noted that

1. we consider only extra-cockpit stimuli and their interpretation; we do not consider pilot response times, aircraft pitch and roll rates, inertia of aerodynamic response--all links in the feedback system required to fly an aircraft.
2. effects of vibration, turbulence, windshield distortion and reduced visibility on visual thresholds are not treated.

Need for better Understanding of Visual Cues

While better landing systems and more sophisticated means of guidance are being developed, more aviation accidents still occur during final approach and landing than during any other flight phase. Hence, any additional means that can provide effective pilot guidance promises further reduction of today's already small probability of accident during final approach and landing. Natural cues cost nothing and if they can be clearly discriminated and used they provide an additional bonus for flight safety.

We examine a "natural" situation. Natural in that during childhood and since we have learned to construct a three dimensional world from the two-dimensional images that fall on our retinas. It is manifest that living organisms can use cues about them to steer their movement in three dimensions. Full-grown birds land on small twigs without difficulty or tutoring, and pilots successfully flew gliders before the advent of powered flight. However, it is not immediately apparent just which stimuli and changes therein are providing useful flight information. This paper applies a quantitative approach to determine the extent to which certain stimulus classes can be more specifically defined and utilized.

A better understanding of how pilots use extra-cockpit cues can be of value to the FAA in several respects. First, in concept, such understanding can provide a basis for training pilots in more effective sampling of extra-cockpit cues. (Some programs of training helicopter pilots give explicit attention to instruction in extra-cockpit scanning patterns at present.) Second, this knowledge might contribute to an appreciation of optical illusions and misinformation derived from airport and other lights. Allegedly this misreading of stimuli caused several commercial accidents in the last decade and possibly contributed to other accidents the causes of which remain somewhat conjectural. Finally, basic knowledge as to how pilots do use optical information can help to design landing systems that provide better man-made marks and lights for pilot guidance.

Available Arrays of Light and Their Use in Aircraft Guidance

The problem of determining the information available to the pilot from natural cues is both physical and phenomenological. From a physical viewpoint, as the aircraft moves over the earth surface, the pattern of light rays reflecting to the cockpit is continually changing. Perceptually, these changes may be used as information to establish and monitor a future flight path.

But before consideration of availability and use of external cues, it is well to distinguish between what a completely accurate mechanism might perceive and compare, and what the human with his limitations can actually see and do. To preserve this distinction in the discussion that follows, we introduce, in concept, an hypothetical perfect perceiver-comparator-computer (PCC). In piloting the aircraft our PCC can perceive any external motion however small. He can interpret the direction and rate of motion of external objects against his pre-established comparator program which tells what these rates should be. He can realign his flight path so that he nulls errors or departures from this program. Inclusion of the computer concept allows the PCC to place the x-spot properly on the runway at the proper time. The computer also carries a variety of subroutines which allow PCC to sample both intra- and extra-cockpit displays at differential rates as a function of phase and flight (8). Characteristics of the light rays reflected from the earth to PCC are treated next.

Observed objects on the earth have both variant and invariant properties (9). The variant properties are those light rays that undergo continuous changes which are precisely determined by the translational movement of the aircraft in x, y and z dimensions. These light rays move at differential speeds as a function of heading, altitude and speed of the aircraft. This continuous transformation specifies the movement of the PCC and can be used by him to determine and maintain his flight path.[3] It is immediately apparent that the light rays available from the entire surface of the earth provide more cues than are needed.

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[3] The invariant property of earth stimuli can provide still further information. If the exact dimensions of specific objects such as runway, control tower, etc. are programmed into PCC, then, when in their presence, range from the object can be computed precisely by comparing actual mil area against known size translated into mil area.

Let us examine the pattern of rays seen by PCC during final approach. At what would be the point of impact of the aircraft if it maintained its present course, earth objects exhibit no movement. This point of impact is a point of no optical velocity, the center of an expansion pattern. During approach, objects on the earth plane appear to expand radially away from this point in a melon-shaped pattern of optical velocities, and the vectors of all velocities in the field point exactly away from the point of impact. At some points in the visual field these vector velocities reach a maximum. Beyond these maxima, vector rates of movement continually decrease all the way to the horizon.

Guidance for Landing from X-spot and Light Rays

The point of impact has been referred to as the x-spot. For the PCC the x-spot and light rays that radiate from it can be used for guidance as follows.

1. Maintenance of proper glide slope. On turning into final approach, PCC locates the x-spot. He maintains pitch and power adjustment so that the x-spot and his spot of intended landing coincide[4]. The x-spot moving toward him warns that the approach path will overshoot so power and/or pitch correction is made. If the x-spot moves away, undershoot is indicated so that PCC increases power and/or decreases glide angle.

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[4] This is roughly true. The extended landing gear must be allowed for as well as glide during flare-out, two factors that work in opposition to each other. The approximation is sufficiently accurate for present purposes.

2. Azimuth. If the x-spot moves to the right or left, drift or an incorrect heading is indicated. PCC changes heading to center the x-spot on the runway.

3. Rate of Closure. For a specified altitude and flight trajectory, ground speed, hence rate of closure, can be ascertained by PCC by comparing perceived rates of flow of the streamer pattern moving past him (1) with known rates for the ground speed and distance from threshold and/or x-spot.

4. Flare. If PCC intends to flare prior to landing, when streamer rates at appropriate points in the visual field reach a pre-programmed velocity, he increases angle of attack and reduces power.

These are ways in which our hypothetical PCC can use patterns of light arrays for guidance in landing. Calvert suggests other ways in which the expanding cue pattern can provide guidance (1). Conceptually, the pilot can use the same cues as PCC. The key question is concerned with the extent to which the pilot has this capability. This question must be answered by first determining the requisite rates of flow of the objects on the ground in terms of mathematical equations, then comparing these rates with his ability as a perceiver. Equations describing rate of flow are considered next and their derivation is developed in Appendix A.

II. QUANTITATIVE DETERMINATION OF THE RATES OF MOVEMENT OF LIGHT RAYS REFLECTED FROM THE GROUND

Consider an aircraft on final approach. It is assumed to be traveling along a straight line which intersects the ground at the point at which it will touch down unless it changes course. This point of touch-down or x-spot has no apparent motion. Every other point on the earth's surface appears to be moving directly away from this x-spot. At any given moment during the approach, different points on the earth will, as the pilot sees them, have differing apparent angular velocities. Our problem is to devise a mathematical description of angular velocities of the points on the earth's surface. In addition to being an accurate portrayal of the physical situation, this mathematical description should allow us to discover significant aspects of the pattern of the velocities, and to compute their values as required.

In order to accomplish these goals, the earth's surface was considered to be a flat x, y plane with the x-spot as the origin.

The ground track of the aircraft was considered to be the y axis with its plus direction in the forward direction of the aircraft, i.e., the aircraft is over the negative part of the y axis during final approach.

There remain three parameters to specify. Let:

α = the angle the glide path makes with the negative y axis

V = the linear velocity of the aircraft

D = the distance from x-spot to the aircraft

Then, letting K stand for the apparent angular velocity of any point on the plane with coordinates x, y we find that

$$(1) \qquad K = \frac{v\sqrt{x^2 + y^2 \sin^2\alpha}}{x^2 + y^2 + D^2 + 2Dy\cos\alpha}$$

The development of this formula is treated in detail in Appendix A. This formula exhibits some of the more obvious facts that one could deduce from physical experience and/or a qualitative consideration of the situation. For example, when (x, y) = (o, o) then K = o. As either x or y become very large in relation to v, K approaches zero. Starting out from the x-spot as a point of origin and considering points on the x, y plane, we can see that their associated K values increase to a maximum and then eventually decrease out to the horizon. Furthermore, since this function is continuous everywhere, the increase and decrease is gradual and without any discontinuities.

In order to examine the behavior of the function when it is not zero (x-spot) and not essentially zero (horizon), it is most effective to transform (1) from rectangular (x, y) coordinates to polar[5] (r, θ) coordinates. This transformation yields

$$(2) \qquad K = \frac{v\,r\sqrt{1-\sin^2\theta\,\cos^2\alpha}}{r^2 + D^2 + 2Dr\sin\theta\cos\alpha}$$

This is still the same function of the points in the plane as (1) is and it will give the same values. However, a given point must now be expressed in terms of values of r and θ, rather than as x and y.

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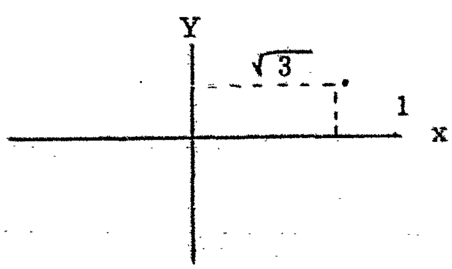
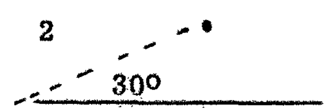
[5] If we consider the point known as $x = \sqrt{3}$, y = 1 in rectangular coordinates, this <u>same point</u> would be expressed as r = 2, $\theta = 30^\circ$ in polar coordinates.





If we differentiate (2) with respect to r we can observe a very interesting set of facts.

$$(3) \quad \frac{\partial K}{\partial r} = \frac{v\sqrt{1-\sin^2\theta\cos^2\alpha}\ (D^2-r^2)}{(r^2+D^2+2Dr\sin\theta\cos\alpha)^2}$$

This partial derivative is seen to be zero (within the physical context) when and only when D = r.

What this tells us is that if we consider values of K along any given straight line in the plane from x-spot to horizon, these values increase monotonically from 0 at the x-spot, reaching a maximum at distance D from the x-spot, then decreasing monotonically and approaching zero. If we then consider this function (1) as a surface in 3-dimensional space with a standard x, y, K representation, it corresponds roughly to a volcanic crater, a perfect circle, whose ridgeline is a constant distance D from the vertical K axis or x-spot . From consideration of the landing situation, we know that the fastest speeds of rays of lights from the ground are going to be approximately under the aircraft. The slower speeds are beyond the x-spot. The maximum speeds around the lips of the crater are equal only when the aircraft dives directly at a 90° angle at the earth. Hence, the ridgeline or sides of the volcano crater are tipped so that the high side is under the aircraft, the low side beyond the x-spot. This we can confirm in a qualitative way from actual flight.

To determine quantitatively the speed at the top of the ridgeline itself, we first substitute r = D in (2) obtaining

$$(4) \quad K = \frac{v\sqrt{1-\sin^2\theta\ \cos^2\alpha}}{2D\ (1+\sin\theta\ \cos\alpha)}$$

This expresses K as a function of the single variable Θ , and considers only those points which are on the ridgeline. Differentiating (4) we get

$$(5) \qquad \frac{dK}{d\Theta} = \frac{-v \cos\Theta \cos\alpha}{2D\,(1+\sin\Theta \cos\alpha)\sqrt{1-\sin^2\Theta \cos^2\alpha}}$$

We can see that (5) is zero (within the physical context) when, and only when, $\Theta = \pm \frac{\pi}{2}$ ($\pm 90^\circ$). This would indicate the function reaches a maximum at one of these values and a minimum (for the ridgeline) at the other.[6] A qualitative consideration of the situation selects $\theta = -\frac{\pi}{2}$ (or x=0, y=-D) as the one which is the absolute maximum of the function, the peak of the lip of the crater. Actually we can see these facts directly in (5). For $-\frac{\pi}{2} < \theta < \frac{\pi}{2}$ the derivative is everywhere negative, indicating monotonically decreasing values of K as we glance around the ridgeline from (x,y) = (0,-D) to (x,y) = (0,+D). Thus, the low point is the point on the ridgeline directly beyond the x-spot. Similarly, the values increase as we continue around the other side on the way back to the point of absolute maximum.

There are several implications of this configuration of values of K to assist a pilot during landing to pick up visual cues from the expansion pattern. The maximum value occurs almost directly under him. This value occurs at a point on the ground which is the same distance (measured along the ground) from the x-spot as the aircraft (measured along the glide angle). If the pilot were physically able to observe this point by looking almost directly downward, and slightly to the rear the angle back to this point would be exactly 1/2 glide angle (α) from the vertical.

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[6] If we leave the restricted domain of the ridgeline, the "minimum" is actually a saddle point.

If he wishes to observe points to his right or left which are maxima then he should direct his attention out from the vertical by an amount such that he is looking at the points on the ridgeline just abreast of him. If we let β stand for this amount of angle out from the vertical, we find that β is dependent only on α . The relationship is described by

$$(6) \qquad \tan\beta = \sin\alpha$$

As α ranges from 0° to 90°, β decreases monotonically from 100% α to 50% α . The angle out to the ridgeline points, which are abreast of the x-spot, is independent of all parameters and is a constant 45°.

The x-spot itself is obviously at an angle below the horizontal of exactly α. The ridgeline point directly beyond the x-spot splits this angle in two and is exactly $\alpha/2$ below the horizontal.

For the following four points on the ridgeline, (x,y) = (0, +D), (0, -D), (+D, 0), (-D, 0), the main formula, (1), may be considerably simplified. This then enables us to calculate K for these four points very easily.

The point (0, -D) is the point where K reaches its absolute maximum value

$$(7) \qquad K_{max} = \frac{v \sin\alpha}{2D\,(1-\cos\alpha)}$$

The ridgeline minimum occurs at (0, +D). For the particular point

$$(8) \qquad K = \frac{v \sin\alpha}{2D\,(1+\cos\alpha)}$$

When we consider the points at which the ridgeline intersects the x-axis, <u>viz.</u> $(\pm D, 0)$

$$(9) \qquad K = \frac{v}{2D}$$

The value of K at this point, interestingly, is independent of the glide angle, α.

Angular Velocities of Expansion Patterns

To better examine the nature of expansion patterns, we have calculated angular velocities for a number of values of D, v and α at four points along the circular ridgeline: $x=0$, $y=-D$; $x=0$, $y=+D$; $x=\pm D$, $y=0$. Values of v and α are intended to be typical for approaches in fixed-wing and rotary wing aircraft. The 30° angle of approach in rotary wing aircraft is not now recommended but such steep approaches may be required in the future for landings on downtown rooftop heliports. Values are shown in Table 1.

From the data presented in Table 1 it is apparent that rates of angular movement increase rapidly with glide angle, decrease with an increase in D, and increases with an increase in velocity. Guidance for steep approaches by observation of the expansion pattern of light rays should be more precise than guidance for shallow approaches, even though steep approaches commonly require slower airspeeds.

Angular velocities can be depicted as iso-velocity curves. Each iso-velocity curve connects points of the plane which all have the same angular velocity for a plane on final approach under a particular set of values of D, v and α.

Table 1

Values of K in Minutes of Arc Per Second of Time for Combinations of D, α and V in Final Approach

Fixed-Wing Aircraft

D = 1,500; $\alpha = 3^{\circ}$	V = 100 kts	150 kts
x = 0, y = -1,500, K =	7,394	11,091
x = 0, y = +1,500, K =	5	8
x = ± 1,500, y=0, K =	194	290

D = 7,500; $\alpha = 3^{\circ}$	V = 100 kts	150 kts
x = 0, y = -7,500, K =	1,479	2,218
x = 0, y = +7,500, K =	1(+)	2(-)
x = ± 7,500 y=0, K =	39	58

V-STOL

D = 300 V= 30 kts	α = 15°	30°
x = 0, y = -300, K =	2,205	1,083
x = 0, y = +300, K =	38	77
x = ± 300, y = 0, K =	290	290

D = 300 V = 90 kts	α = 15°	30°
x = 0, y = -300 K =	6,616	3,251
x = 0, y = +300 K =	115	233
x = ± 300, y = 0 K =	870	870

Further examination reveals that there are exactly three types of iso-velocity curves, designated here as Types I, II and III. Figure 1 shows the ridgeline and one Type I curve, two Type II curves and one Type III curve. The Type I curve and the two Type II curves were drawn from calculated points. The Type III curve is an estimate. Ground speed is 100 knots, D is 1,500 feet from touchdown point and the glide angle is 3 degrees.

Under this set of conditions the maximum value of K is at x=0, y=-1,500 feet. This value is 7,390 minutes of arc per second of time. Values of K decrease very sharply near this point. On the far side of the ridgeline, directly beyond the x-spot K is slightly greater than 5 minutes of arc per second of time. Inside the ridgeline values of K decrease to zero at the origin or x-spot. Beyond the ridgeline they decrease also, and approach 0 at the horizon.

Type I curves are a family of very thin and elongated curves which look like ellipses[7]. All Type I curves have the x-spot in their interior and all are contained within the ridgeline. There is a Type I curve for every value of K greater than zero and less than or equal to the value that K assumes when x=0 and y=D. A maximum Type I curve is shown in Figure 1.

Type II curves are shown in Figure 1, one for K=739 minutes per second and K=73.9 minutes per second respectively. These velocities are 10% and 1% of the absolute maximum value of K. Type II curves all contain the point of absolute maximum in their interior, and they all cut the ridgeline in precisely two points. There is a Type II curve for every value of K less than the absolute maximum and greater than the minimum K on the ridgeline.

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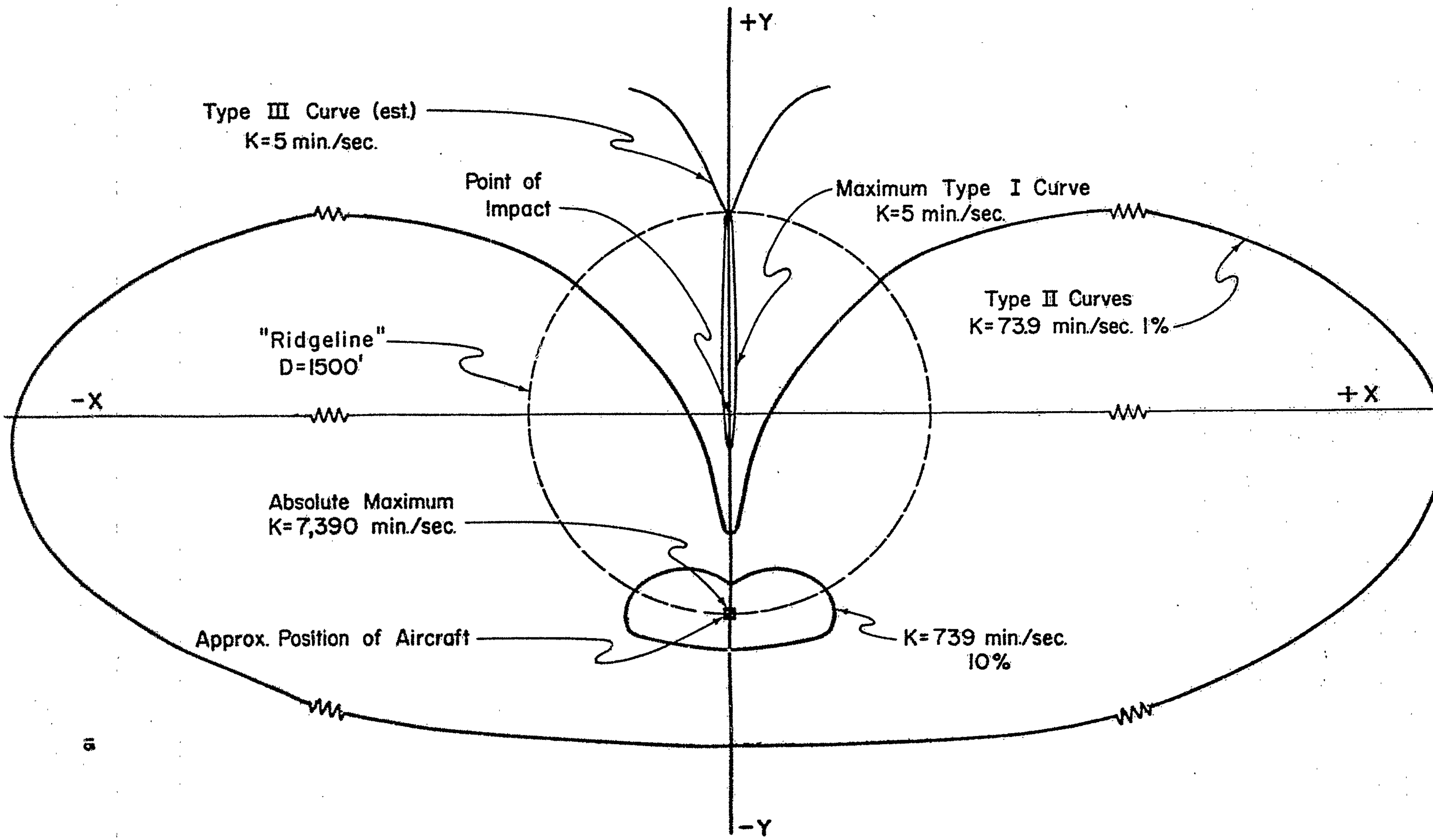
[7] We did not determine whether they actually are ellipses.

FIGURE 1

Ridgeline And Isovelocity Curves

NOTE: V = 100 KTS, α = 3°, D = 1500'

PLAN VIEW



An approximation of a Type III curve is shown in Figure 1. For every Type I curve in the interior of the ridgeline, there is a corresponding Type III curve (of the same K value) completely enclosing the ridgeline in its interior. The maximum Type III curve would start just beyond the far ridgeline x=0, y=1,500 feet and fan out toward the horizon. Iso-velocity curves greater than the value of K at x = 0, y = 1,500 feet will consist of Type II curves.

The next section explores the available reports on the ability of the human to detect these speeds of movement and, after that, the apparent value of these movement cues for aircraft guidance during final approach and landing.

III. HUMAN CAPACITY FOR MOVEMENT AND RATE JUDGMENTS

Having established the relative rates of movement of ground objects, the next problem is to determine pilot thresholds for detection of movement and for making comparative rate judgments[8]. The detection of absolute threshold involves the judgment that the stimulus is moving or that it is not. Rate judgments introduce the comparator function wherein the pilot compares a perceived rate or rates of movement with remembered rates.

Data relevant to determination of thresholds are presented in Appendix B. Additional information may be obtained from (11) Part III, Chapter II, Section VII, pages 4-5 and from treatment of movement thresholds in (10). Two generalizations may be drawn from these data.

1. Data were collected under laboratory conditions generally with the eye or eyes fixated on one source of light rather than a sheath of light rays, and the source is usually relatively near (3-6 feet) the eye(s). Further, subjects are not in motion.

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[8] The absolute threshold for movement divides the continuum of visual stimuli into two classes; those which the human can detect as moving, and those which he does not detect as moving (11). Thresholds for differential rates of movement are referred to by psychologists as difference thresholds. They may be further subdivided into two classes--those obtained when the subject judges two rates that may be seen simultaneously, and those involving comparison of a perceived rate of movement with remembered rate(s). In the landing situation we are concerned with both: the relative speeds of light rays or streamers to the right and left of the cockpit, and the ability of pilots to compare a perceived rate of movement with a remembered rate, i.e. the comparator type function.

2. Under such controlled conditions, many variables influence threshold for velocity. Those pertinent to our problem include level of illumination, whether photopic or scotopic vision, duration of observation, size of field, and the retinal area stimulated. Sizeable individual differences are present.

Photopic and Scotopic Visual Thresholds

Evidence cited above was sorted to determine which experimental contexts and conditions were roughly similar to perceptual problems of landing of aircraft, and which of these influence threshold values. This task is difficult because data collected under apparently similar conditions sometimes vary by factor of 3 or 4 times. The following is an excerpt from the Handbook of Experimental Psychology (10).

> "...our knowledge of the relevant parameters is at an elementary stage of analysis. Complete functional descriptions of the relevant relations are badly needed, as are careful considerations of variables."

These qualifications noted, two conditions which consistently influence absolute movement thresholds are daylight and night conditions calling for photopic and scotopic vision respectively, and the retinal area stimulated.

Photopic Thresholds

Under optimal conditions, i.e. high level illumination, high target-ground contrast, direct foveal vision, sufficient duration of target exposure and so forth, thresholds of less than 1 minute of arc/second have been reported but the most commonly given values are 2 minutes per second of arc or thereabouts. However, thresholds as great as 6 minutes of arc/second have also been found. This extreme variation in thresholds evidently reflects differences in experimental conditions (see Appendix B.). Threshold values are at a minimum when the center of the fovea is stimulated. They increase rather rapidly for retinal stimulation within 2 to 5 degrees from the center of focus presumably because the cones in the retina are more sensitive to stimulation than the rods. Values continue to increase but at a much slower rate out to the periphery of the visual field.

Scotopic Threshold

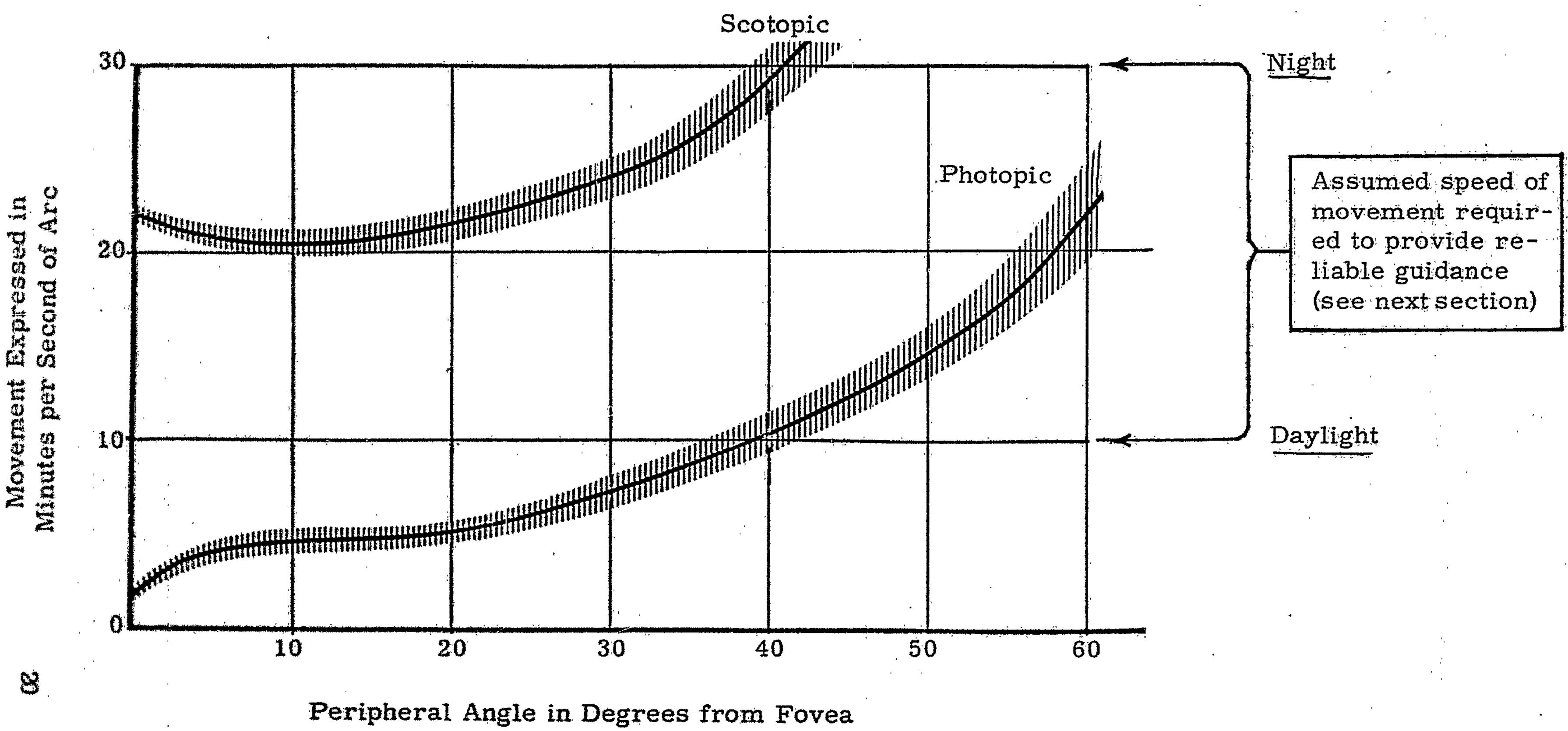
Studies of photopic thresholds predominate, so fewer supporting data are available on scotopic thresholds. Our primary reference is Tufts Handbook of Human Engineering Data (11), Part III, Chapter II, Section VIII, page 7, a summary of studies by C. J. Warden, H. C. Brown, and S. Ross. The photopic threshold for movement decreases very slightly from the fovea to a point in the periphery of the retina, about 7 to 10^{o} from the fovea, then starts increasing at a gradually accelerating rate.

Approximations of Absolute Thresholds

The information reported above for photopic and scotopic vision is brought together to estimate thresholds for perception of movement for day and night vision from the fovea to the periphery of the visual field. The variance in the data indicate clearly that there is no single perceptual threshold. Estimates of thresholds are shown in Figure 2.

Figure 2

Estimated Photopic and Scotopic Thresholds
from Fovea to Periphery of Retina



Approximation of Difference Thresholds

Several sources provide information as to ability to judge rates of movement or difference thresholds (10, 11). However, here again differences in experimental conditions and widely varying results make an estimate at best an educated guess. Thresholds for rate discrimination vary with the rate of movement and are reported as being between 30 and 100 seconds of arc per second (10). From (10), Aubert's and Gibson's data reported in Appendix B and other data on human capabilities, it is suggested that well trained pilots can probably make judgments of difference rates of movement during landing with an accuracy of 5 to 12 percent of the true value.

These data were obtained under daylight conditions. No evidence was found concerning ability to make comparator type judgments when eyes are dark adapted. The next section fits these human factors data to iso-velocity curves established in the prior section.

IV. EARTH VELOCITIES AND HUMAN CAPACITIES COMBINED

Section II developed formulae for radial rates of movement of objects at various distances from the x-spot as a function of aircraft distances from touchdown point, speed and angle of approach. Section III summarized data from laboratory studies of visual perceptual thresholds. These two sources are combined to investigate the situations under which movement of external stimuli is sufficient to provide guidance for approach and landing.

Problems of Combining Data

Angular rates of movement of earth objects have been shown in Table 1 for a fixed-wing aircraft at two speeds in normal approach and for a helicopter in steep and very steep approaches. Figure 2 provided an estimate of visual threshold for photopic and scotopic vision. Combining these data to evaluate the conditions under which the pilot can use rates of movement of extra-cockpit cues for guidance raises a number of questions.

1. The implications of the definition of the threshold should be pointed out. As a rough definition it is the stimulus speed at which movement is noted in approximately 50% of the observations[9]. If we were to translate this concept into a framework for pilot guidance, this would be the isovelocity curve at which the pilot can detect movement half the time. For reliable steering, it is highly desirable that movement be detectable in all cases; or, if this cannot be accomplished, that it be detectable in the great preponderance of instances. As rough estimates, and to provide an even figure, we take 10 min/sec. as a super threshold value for daylight conditions

[9] Assuming the median and mean are at approximately the same point.

and 30 minute/seconds as a sufficient value to permit detection of movement at night. It is assumed that pilots can reliably detect movement of these rates under most conditions encountered in contact flight.[10]

2. Next, because thresholds increase toward the periphery of the field of view, we need to know whether to assume that the pilot looks straight ahead or that he focuses on moving objects some distance from the x-spot. An increasing function specifies angular rate of movement of stimuli (as far as the ridgeline), but if he only looks at the x-spot, his ability to detect this movement continues to decrease. It is assumed that the pilot does not have to look directly ahead during approach and landing although it appears that for the most part he does so (2). He can turn his head and/or eyes so as to look at objects moving at super-threshold velocities with the most sensitive area of the retina.

3. Assuming that the pilot, by head and eye movements, does sample the parts of the environment he perceives as moving, where does he look and what computations do we assume he makes? The answer will, of course, depend on type of aircraft, and canopy shape. Within the constraints placed on his field of view by the windscreen frame, we suspect that he should first identify this threshold for movement for the particular flight. This threshold will appear as a narrow horseshoe pointing away from him. By looking at rays moving away from the x-spot he traces back the vectors to estimate the position of the x-spot for that moment in flight.

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[10] Effects of turbulance, vibration, windscreen distortion are not considered.

Adequacy of Movement Cues for Visual Guidance

We now combine data developed earlier. Figure 3 superimposes the assumed super-threshold values of 10 and 30 minutes per second of arc in red on the iso-velocity curves. For this particular figure, D=1500 feet, v=100 knots, and angle of approach $=3^{\circ}$. The boundary of the inner curve indicates the daylight vision super-threshold value assumed here. The earth can be perceived as moving at any place outward of this line. The area to the right and left of the boundary of the outer red curve is the area that could be seen as moving with scotopic vision.

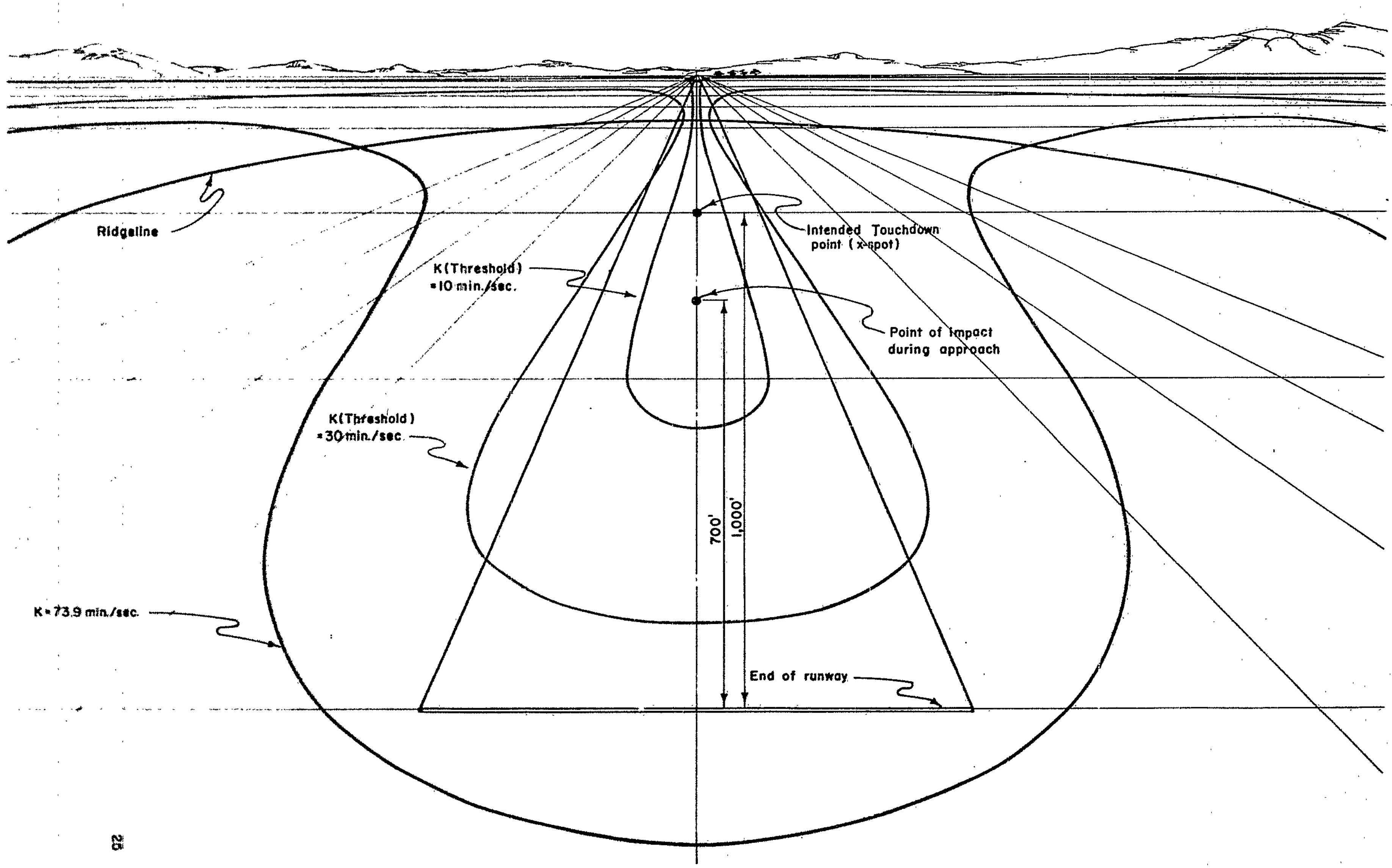
With regard to the precision with which a pilot might use these non-moving areas for guidance, we are plainly in the realm of speculation. However, let us make conjectures, considering control of the craft in final approach. In final approach, the pilot maintains glide angle. He commonly carries more than enough power to make the field, reducing power when he sees he has the runway made. If approach power is maintained too long the aircraft will land too fast and/or overshoot. The position of impact point or x-spot is controlled by the pilot by changes in pitch and power which change angle of approach. Prior to landing, pitch is increased to effect flare-out after which the aircraft may glide several hundred feet. Therefore, it would seem reasonable that prior to flare, the point of impact or x-spot would be positioned closer to the near end of the runway than the point of intended landing. However, we must allow for the fact that the gear is some 15 feet below the pilot's eyes, and hence below the glide angle from the pilot's head to the point of touchdown. This means that for a glide slope of 3°, his wheels would touch some 285 feet ($15 \times \cot 3^{\circ}$) before he reaches the precise point of impact projected from his eyes.

Assumed post flare-out glide distance and an allowance for the projection of gear can be added to determine the desired position of the

FIGURE 3

PILOT'S EYE VIEW OF ISOVELOCITY CURVES

NOTE: V = 100 KTS, GLIDE SLOPE = 3°, D = 1500' FROM POINT OF IMPACT



x-spot along the runway. Assume that the pilot wishes to touchdown at precisely 1000 feet beyond the near end of the runway. Assume that he expects to glide some 600 feet after flare-out and that his gear will touch some 300 feet before the eye, projected along the glide slope, would have reached the point of impact. Under these assumptions, during approach the x-spot projected from the cockpit should be placed at 1000-600+300, or 700 feet beyond the near end of the runway.

There is an area of no perceptible movement which extends back toward the aircraft from this x-spot. If we assume a motion threshold value of 10 minutes of arc per second of time, the area of no perceptible movement will begin at some 400 feet in front of the x-spot. If a motion threshold value of 30 minutes per second of arc is assumed, the area seen as not moving will begin at almost 700 feet back from the point of impact. We assumed above that the point of impact used for guidance during approach is 300 feet back from the point of intended touchdown. Thus, for an assumed visual threshold of 10 minutes of arc, the area of no perceptible movement begins some 300 feet beyond the near end of the runway. For an assumed visual threshold of 30 minutes of arc, the area of no perceptible movement starts right at the runway threshold. The reader is reminded that these specific values are for a D of 1500 feet, speed of 100 knots, a glide angle of 3 degrees, an intended touchdown point 1000 feet beyond threshold, and motion thresholds of 10 and 30 minutes. The exact position at which the area of no perceptible movement begins will change with changes in these assumed values.

Guidance for Optional Point of Touchdown

The x-spot is inside and just beyond a stationary appearing area that extends forward all the way to the horizon. In concept, the task of adjusting glide angle to properly place the x-spot could be solved in two ways. Coming back from the stationary area is a horseshoe shaped line at which stimuli appear to start moving back toward the pilot. If this line can be detected with some accuracy, it may possibly be used to assist in determination of glide slope. This line remains at a constant angle from the x-spot if angle of approach is constant. However, the line at which movement can just be detected moves forward as the aircraft does. Hence, it cannot be anchored on any object on the ground. Another possible method is to sample rays to the right and left. The pilot mentally back-tracks along the vectors and approximates the position of the x-spot by triangulation. Lacking empirical evidence, we would classify these possible solutions as marginal.

Lateral Guidance

The pilot needs to maintain a track straight down the landing path, veering neither right nor left. What aspects of the expansion pattern should he look at to do this, and what do they promise by way of information? The area of no perceptible movement extends roughly along the sides of the runway. It should be possible for the pilot to infer the position of the x-spot by viewing vectors to the left and right. He might then trace moving vectors to the right and left backward, locating the x-spot by a rough triangulation procedure. Another possibility for directional guidance is to note the direction of the "streamers" (1) with respect to the nose. If they cut across the nose of the plane at a slight angle rather than coming directly down the nose, then the aircraft is either drifting or heading is slightly off. The solution by triangulation may be marginal for fixed-wing aircraft; because of the super-threshold speeds of streamers, the latter hypothesis seems more appealing. Perhaps a more obvious solution, assuming that runway edges are distinguishable, is this: the pilot sights down the runway edges. When the left and right edges visualized as projected back through his position fall to his left and right respectively, then--drift not considered--if he maintains heading he will set his wheels on the runway.

Experimental evidence would have to be obtained to determine which of these cue classes provide best lateral guidance.

Rate of Closure and Flare-out

The perceptual-comparator problems are essentially the same for judgment of rate of closure and selection of the point at which to flare-out. Here, the pilot's problem is not merely one of detecting motion. He compares sensed speeds of motion of objects with remembered speeds so as to adjust power, attitude, flaps, etc., to make actual speeds correspond to remembered (proper) speeds. However, here again there are complications.

First, in fixed-wing aircraft, because the velocity of the air mass and its direction with respect to landing is variable (from, say 0 to 30 knots), the pilot does not hold constant ground speed for all landings. Air speed is the more crucial parameter to monitor and control. Because of air mass movement, airspeed and ground speed are not equivalent. Consequently, if we assume that remembered rates of streamers are used as a control parameter for comparison with perceived rates, it is apparent that the (proper) value on the control parameter must be varied as a function of wind velocity. Hence we have a variable control parameter. Further, to establish the phenomenal value of this parameter for any particular landing, the pilot needs instant information as to wind speed and direction with respect to the duty runway.

Second, on comparing pilot capability for judgment of absolute velocity rates with airspeed control requirements, it would appear that at approximately the runway threshold at which flare judgments must be made, pilot ability in fixed wing aircraft is marginal. For steep approaches in helicopters, it is probable that the pilot can utilize both the area of no perceptible movement and streamers to better advantage. He places his sight picture and the area of no perceptible movement on the intended landing area. He holds apparent ground speed constant thus reducing actual groundspeed by maintaining a constant rate of flow of streamers past his cockpit. Our data suggest that optical information available will permit him to do this in relatively steep approaches . That pilots do use such information in rotary wing aircraft is confirmed by existing approach practices (3).

Summary: Adequacy of Information about Movement from Extra-Cockpit Cues

Our main source of uncertainty in attempting to match calculated angular velocities with pilot thresholds is our lack of confidence in the threshold values selected here or, for that matter, any motion threshold values that might be selected on the basis of available experimental evidence. For this reason, conclusions suggested below must be regarded as conjectural, pending further empirical studies.

Under the assumptions made here, it is apparent that the pilot can obtain considerable guidance by using the expansion pattern for steering. However, the data leave open the question as to whether this guidance is sufficiently precise for touchdown within 200 feet or so of the intended touchdown point, a capability which well-trained pilots show. Thus, pilots appear to make landings more precisely than they might be expected to from the use of expansion patterns. This appears to be true for fixed-wing aircraft, less true for helicopters, especially when making steep approaches. Guidance for flare-out would appear to be marginal. Because of the nature of the pattern of angular velocities, directional guidance would appear to be better than guidance for touchdown point and flare-out guidance.

V. TOWARD A BETTER UNDERSTANDING OF INTERPRETATION AND RESPONSE TO EXTRA-COCKPIT CUES

As pointed out in the introduction, pilots and birds obviously use optical information for guidance and they do so with a great deal of confidence and reliability. The preceding summary indicates that, on the basis of data presently available, the hypothesis that pilot can obtain sufficiently precise steering information from x-spot and the radial expansion pattern of light rays must be regarded as not proven, even under good visibility conditions and in smooth air. This is surely true for fixed wing aircraft and for relatively shallow angles of approach generally. How, then, do pilots do it? We do not know, but we can speculate. Discussed below briefly are concepts of spatial and temporal summation of stimuli and the use of the windscreen frame along with external cues to facilitate judgment.

Spatial Summation

Reported experiments on movement thresholds commonly involve the subject responding to only one stimulus in the visual field. In landing an aircraft, the entire panorama of earth is moving. Consequently, the pilot has vastly more than sufficient cues potentially available. A substantial number of light rays taken together should reinforce and confirm the information obtained from any one ray. This (spatial summation) has been shown to be true in studies of sensory thresholds and it should be true in our situation, summation being both sensory and perceptual. The result would be to lower the threshold for movement.

Temporal Summation
Sampling Rates

Summation of cues is undoubtedly temporal as well as spatial. In the studies of motion thresholds reported, stimulus presentation times vary from a fraction of a second to several seconds. Perceptual thresholds for motion are commonly reduced with longer stimulus presentation times.

Now the question arises, "What are--or might be--the extra-cockpit sampling rates of pilots for relevant objects in their visual field?" With regard to time-sharing between extra- and intra-cockpit cues: after breakout on final approach, the fixed wing pilot looks at his instruments--air speed primarily--approximately 44% of the time (12, see page 259). Fifty-six percent of his time is spent in extra-cockpit viewing. By remembering the position of the stimulus in the visual field the last time he looked out, or at times before that, the pilot can summate stimulus movement over time to estimate his change in position. This is obviously what he does in navigation by extra-cockpit cues. Whether he is able to do this with sufficient precision to lower his threshold for motion during landing is an issue that can only be answered by further experimental studies.

Use of the Windscreen to Facilitate Judgment

Interacting with temporal summation as a basis for more accurate judgments is undoubtedly the guidance provided by the windscreen frame and its orientation with respect to the horizon. While the screen is presumed to be clear, the pilot should be able to note change in position of objects due to their change in location on the screen. He does not usually place a marker on the object, but the screen frame likely improves his judgment of movement. Experimental evidence on human perception strongly supports this assertion. Movement thresholds are much lower when the background against which the object moves is marked and when the size of the visual field is reduced (10). It may be argued that the windscreen frame cannot properly be compared with a fixed pointer since it moves with the rotation of the aircraft. This is true but if we assumed that the pilot can utilize the (external) horizon to fix attitude, then the canopy frame can be held in a relatively constant position. Hence, the horizon picture may substantially increase the accuracy with which he can judge the motion of external objects.

Summary

This study is a further extension of FAA work to better determine specifically how pilots glean information from extra-cockpit viewing. We have developed a formula giving a quantitative definition of the speed with which all visible stimuli move as a function of variables that describe flight path. We have matched human capabilities to iso-velocity curves derived from the formula to estimate the accuracy with which the pilot can use optical information in important landing tasks. These estimates and records of pilot performance suggest that the pilot may be doing a better job of guiding his aircraft than one would predict by superimposing laboratory information as to his perceptual abilities upon iso-velocity curves and comparing results with actual records of distributions of touchdown points during carefully controlled landings.

Our clarification of the potential and limitations of movement cues makes it possible to formulate further hypotheses as to how pilots use visual cues for steering guidance. Examination of the validity of alternative hypotheses would substantially increase our understanding as to precisely how optical information is used in landing, as well as the capabilities and limitations of pilots in using such information. A better understanding of the crucial details of flight tasks should make it possible to design AML systems that are least equivocal in interpretation, hence to still further improve flight safety.

APPENDIX A

DERIVATION OF APPARENT ANGULAR VELOCITY OF POINTS ON THE SURFACE AS A FUNCTION OF X, Y COORDINATES

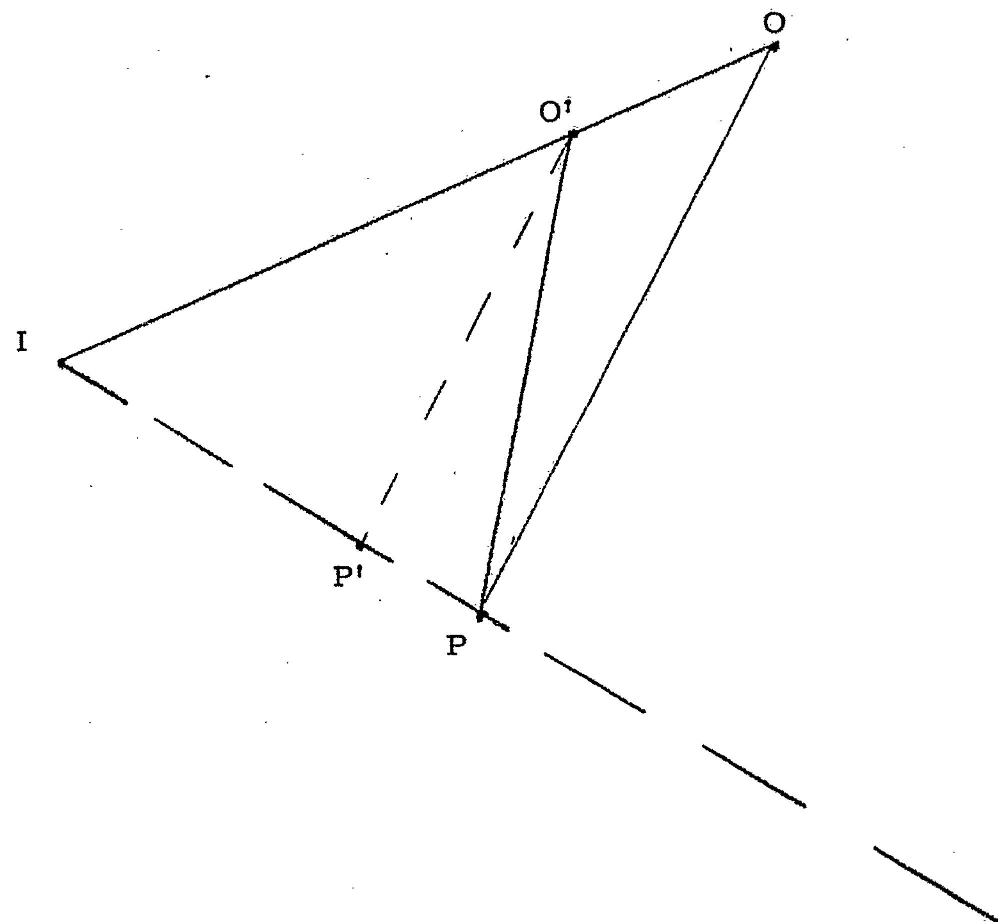
Consider the following problem: An aircraft pilot is approaching the runway in preparation for landing. He is proceeding to a point of impact along a straight line and at a given velocity. To an observer in the aircraft this point appears to be stationary while all other points on the earth's surface seem to be moving directly away from the stationary point. This can be appreciated by examining Figure 4, where,

- I represents the point on the earth's surface intersected by what would be the point of impact of the aircraft if it maintained its present course.
- O and O' represent successive positions of the aircraft through time.
- P represents any point on the earth's surface distinct from I
- P' represents the point on line I P such that P' O' is parallel to P O.

If an observer, watching P, proceeded from O to O', he would have to turn head or eyes to increase the angle of the line along which he was directing his attention from IOP to IO'P in order to keep point P under scrutiny. If he kept looking out at the same angle he would be observing P' rather than P. This increment back along IP is what we are here considering as the increment in the angular position of P as aircraft goes from O to O'. When we speak of the apparent angular velocity of point P, we mean the rate of change of the angle IOP with respect to time.

Figure 4

Angular Velocity Geometry



The problem which we solve here is that of finding a formula which will give use this apparent angular velocity of a point on the earth's surface as a function of the point itself.[11]

Formally, we make the assumptions that the earth's surface is a plane and that the aircraft and observer are reduced to a point. Where Δt is the time required to proceed from O to O', our problem becomes that of finding

$$\lim_{\Delta t \to O} \frac{\text{angle } P'O'P}{\Delta t}$$

The first step in the derivation is to note that from the geometry of figure 4, P'O'P = O'PO. For a given time interval, then, the change in angle IOP is of the same magnitude as the change in IPO, but of opposite sign. In other words, the apparent angular velocity of a point on the ground is of the same magnitude as the angular velocity of the aircraft when observed from that point on the ground.

Let

α = the glide angle of the aircraft

D = the distance from x to O

v = the linear velocity of the aircraft

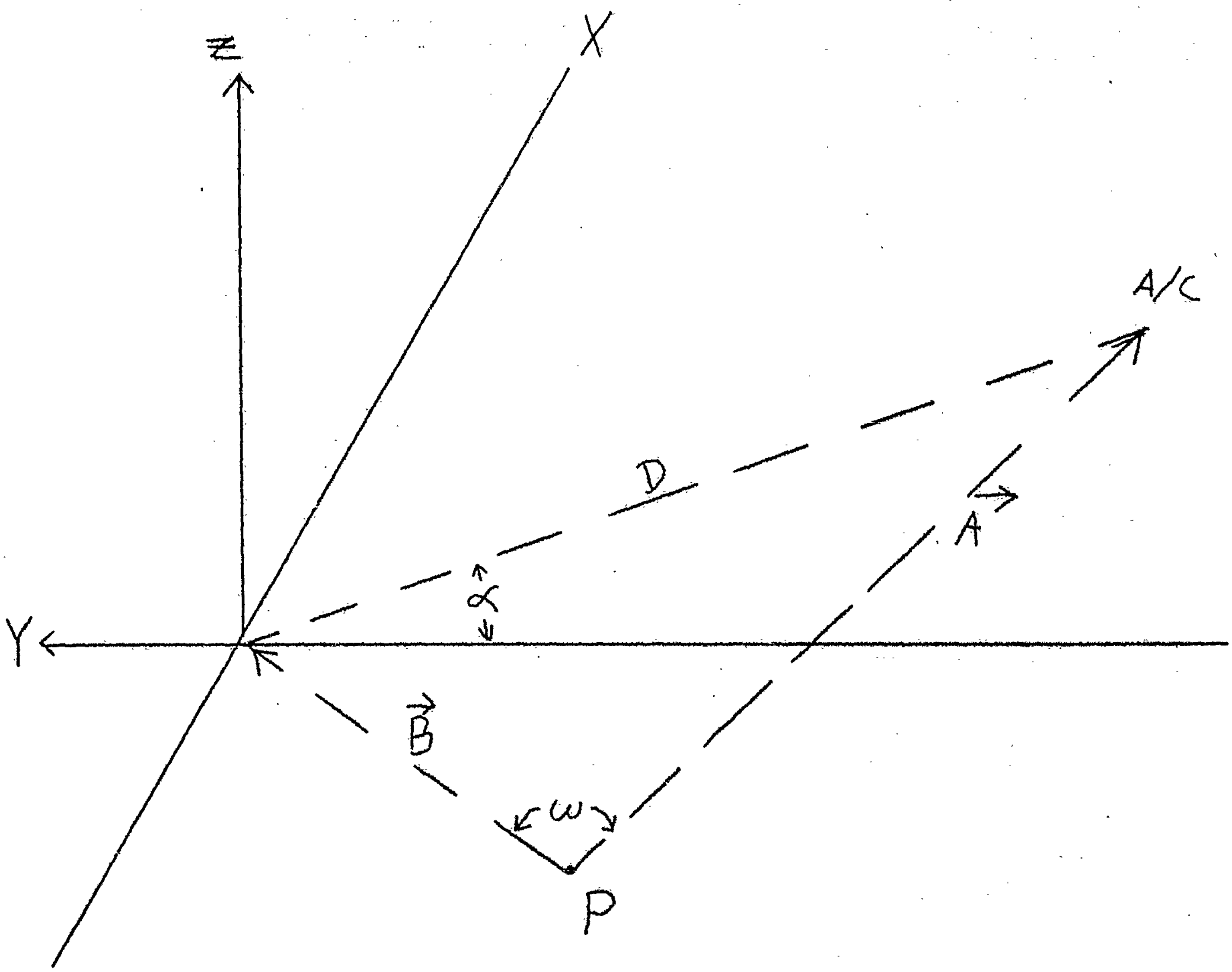
K = the apparent angular velocity (radians/second) of the point in question.

We assume $O^{o} < \alpha < 90^{o}$ and we set up a standard x, y, z coordinate system such that the point that the aircraft is heading toward is the origin, his ground track is the y axis and he is flying in a positive direction. Such a system may be seen in Figure 5, with two vectors added, viz. $\vec{A}$ from P to aircraft, and $\vec{B}$ from P to origin.

[11] A very similar problem has already been solved cf. Gibson, 1955(6). Instead of locating the point P in x, y coordinates as we shall do here, they locate the point in terms of two angles. One of these angles is the angle we have called IOP and the other does not appear in our derivation nor in our final result. We solved in terms of velocities as a function of x-y coordinates of points on the plane.

Figure 5

Angular Velocity Geometry-
Plane of the Earth



Let

A, B	=	magnitude of $\vec{A}$, $\vec{B}$
i, j, k	=	unit vectors in directions x, y, z
$a_1 a_2 a_3$	=	the magnitude of the i, j, k components of $\vec{A}$
$b_1 b_2 b_3$	=	the magnitude of the i, j, k components of $\vec{B}$
x, y	=	the coordinates of P

Then

(1) $$\vec{A} \cdot \vec{B} = A\, B \cos w = a_1\, b_1 + a_2\, b_2 + a_3\, b_3$$

We also have from Figure 5

(2)
$$\begin{aligned}
A^2 &= x^2 + (y + D \cos \alpha)^2 + D^2 \sin^2 \alpha \\
&= x^2 + y^2 + D^2 + 2Dy \cos \alpha \\
B^2 &= x^2 + y^2 \\
a_1 &= -x \\
a_2 &= -y - D \cos \alpha \\
a_3 &= D \sin \alpha \\
b_1 &= -x \\
b_2 &= -y \\
b_3 &= 0
\end{aligned}$$

by equating the second and third members of (1), and substituting the values from the eight relationships of (2) we find that

(3) $$\cos w = \frac{(x^2 + y^2 + Dy \cos \alpha)}{\sqrt{(x^2 + y^2 + D^2 + 2Dy \cos \alpha)\ (x^2 + y^2)}}$$

We differentiate (3) with respect to time and simplify the result and we find that

(4) $$\frac{dw}{dt} = \frac{D(x^2 + y^2 \sin^2\alpha)}{(x^2 + y^2 + D^2 + 2Dy\cos\alpha)^{3/2}\,(x^2 + y^2)^{1/2}\,\sin w} \cdot \left(\frac{dD}{dt}\right)$$

By consulting the definitions we see that

(5) $$-\frac{dD}{dt} = v$$

(6) $$-\frac{dw}{dt} = K$$

We next consider the well-known trigonometric identity

(7) $$\sin\theta = \sqrt{1 - \cos^2\theta}$$

We can utilize (7) to find sin w

(8) $$\sin w = D\sqrt{\frac{x^2 + y^2 \sin^2\alpha}{(x^2 + y^2 + D^2 + 2Dy\cos\alpha)(x^2 + y^2)}}$$

By substituting (5), (6) and (8) into (4) we achieve our principal result

(9) $$K = \frac{v\sqrt{x^2 + y^2 \sin^2\alpha}}{x^2 + y^2 + D^2 + 2Dy\cos\alpha}$$

APPENDIX B

SUMMARY OF LITERATURE ON PERCEPTUAL THRESHOLDS FOR MOVEMENTS

Data from thirteen studies on motion thresholds are summarized in this appendix. We have not attempted to duplicate studies reported in the Handbook of Human Engineering Data (2nd Edition) (11). Also recommended for further information is C. H. Granham's chapter on Visual Perception (7).

LABORATORY DATA ON THRESHOLDS FOR PERCEPTION OF MOTION

Ss=subjects
E = experimenter

Experimenter	Reference	Experimental Conditions	Estimate of Detectible Mean Radial Rate	Comments
Aubert, H.	Die Bewegungsempfindung. Arch. ges. Physiol., 1886, 39, 347-370	Ss estimated movement of a long line, fixated target in a structural field	Threshold for movement: 1 to 2 minutes of arc/sec.	
Aubert, H.	Die Bewegungsempfindung. Arch. ges. Physiol., 1886, 39, 347-370.	Movement perceived at 9^{o} from fixation point.	Threshold for movement: 18 minutes of arc/sec.	
Aubert, H.	Die Bewegungsempfindung. Arch. ges. Physiol., 1886, 39, 347-370.	Ss viewed certain (not specified) moving targets near the fixation point.	Threshold differences for rate of movement: 1 to 2 minutes of arc/sec.	
Brown, J. F.	Thresholds, for visual movement Psych. Forsch., 1931, 14, 249-268.	Ss viewed a moving square target with increasing physical velocity from 0 to 200 cm/sec.	Threshold of just perceptible movement: 2 to 6 minutes of arc/sec.	

Experimenter	Reference	Experimental Conditions	Estimate of Detectible Mean Radial Rate	Comments
Cowper, M. C.	An investigation into the perception of movement. Cambridge: Flying Personnel Research Committee, The Psychological Laboratory, 1947. (Report No. 683)	Ss discriminated motion in four spatial directions: up, down, left, and right. Stimuli were presented tachistoscopically.	Horizontal motion threshold 1 min. of arc sec; vertical motion threshold above 1 min. 30 sec. of arc/sec.	Considerable individual differences. Number of subjects: 10.
Gibson, J. J.	The relative accuracy of visual perception of motion during fixation and pursuit. Amer. J. Psychol. 1957, 70, 64-68.	Ss matched velocities of two moving surfaces at 4.9^{o}/sec. of angular velocity, using two modes of observation, fixation and pursuit, in two directions, right and left.	No significant difference between two modes of observation. The mean of average errors on 20 judgments was 1.21 ft./min. on right and 1.17 ft./min. on left side.	
Goldstein, A. G.	Judgments of visual velocity as a function of length of observation time. Fort Knox, Ky.: Army Medical Research Laboratory, Psychology Department, 1956. (Report No. 239)	Ss judged speed of moving visual stimuli of durations from 2 to 60 sec; physical velocities from 2.4 to 14.3 cm/sec.	2 to 8 sec. - little changes in velocity judgments. 8 to 30 sec. - maximum decline in velocity judgment. 30 to 60 sec. - no change or a slight increase of velocity judgment.	

Experimenter	Reference	Experimental Conditions	Estimate of Detectible Mean Radial Rate	Comments
Grindley, G. C.	Notes on the perception of movement in relation to the problem of landing an aeroplane. Cambridge: The Flying Personnel Research Committee, 1941. (Report No. 426)	Ss viewed a drum covered with inky blots 1/10 inch diameter and 5 per square inch monocularly with 6° field of view. Accelerated range of drums was from $.4^{\circ}$/sec. to 40.5°/sec.	Ease and accuracy of estimating velocities were greatest when velocity was well above that corresponding to "threshold of movement". (Ss disliked the lowest standard velocity of $.4^{\circ}$/sec. and they all liked the highest one of 40.5°/sec.)	Significant individual differences in estimating absolute velocity and learning to estimate velocities. Ss' mean errors varied from 8.4 to 18.1% on the first set of trials; from 6.1 to 12.4% on the second set. Improved performance on second set indicated practice effect.
Johannson, G., et al.	Studies on motion thresholds I. University of Uppsala, Sweden: The Psychological Laboratory, 1957. (Report No. 1)	Ss judged the shortest length of motion track of a visual stimulus	Threshold - about .20 min./sec. of visual angle for angular velocities between .58 and 2.31 min/sec.	

Experimenter	Reference	Experimental Conditions	Estimate of Detectible Mean Radial Rate	Comments
Leibowitz, H. W., & Lomont, J. F.	The effect of grid lines in the field of view upon perception of motion. Wright-Patterson Air Force Base, Ohio: Wright Air Development Center, 1954. (Technical Report No. 54-201)	Ss viewed monocularly circular 2 display of 3.2° of arc from a 90 inch distance, upon which white square targets, each subtending 15 min. of arc, were spaced 45 min. of arc, and discriminated movement under luminance levels from .016 to 500 millilamberts and exposure time from 1/8 to 16 sec.	Threshold velocity decreased with increased luminance rapidly (from 55.70 to 2.40 min. of arc) for 1/8 and 1/4 of sec. of exposure time. At 16 sec., luminance did not have significant effect upon threshold velocities.	Individual differences during initial testing, later significantly reduced with practice.
Miller, J. W., & Ludvigh, E.	The results of testing the dynamic visual acuity of 1000 Naval Aviation cadets. Pensacola, Fla.: U.S. Naval School of Aviation Medicine, 1956. (Report No. 10, Project No. NM 001 110 501)	Ss viewed targets of 20°/sec. and 110°/sec. velocity for critical details at 25 ft. candle illumination and from 4 meter distance.	Average threshold of visual acuity for 110°/sec. velocity was 6.096 min. of arc and for 20°/sec. velocity, 1.927 min. of arc.	Individual differences noted.
Pollock, W. T.	The visibility of a target as a function of its speed of movement. J. exp. Psychol., 1953, 45(6), 449-454.	Ss tried to detect a moving spot of white light at speeds from 50°/sec. to 2000°/sec. of angular velocity in directions left, right, up, and down.	Threshold luminance of target varied from .20 log millimicrolamberts at 50°/sec. to 3.5 log millimicrolamberts at 1600°/sec. Vertical target movements yielded lower threshold than horizontal.	

Experimenter	Reference	Experimental Conditions	Estimate of Detectible Mean Radial Rate	Comments
Steedman, W. C. & Baker, C. A.	Target size and visual recognition. Hum. Factors, 1960 2(3), 120-127.	Ss were shown a standard pattern and problem displays in the form of partly filled-in matrix cells, varying the degree of blur or resolution. They were asked to locate and indicate the form on the display that most closely resembled the standard pattern. Four resolution conditions ranging from .00 to .08 inches were investigated. The size of the problem displays varied from 1.95 to 7.8 inches. Both standard and experimental patterns were manipulated by rotating them by 90° steps through 360°. The errors and time needed to identify the correct pattern were recorded.	Twelve min. of visual angle was the lower limit for target location. At least 20 min./arc for an operational environment is recommended. Targets less than 12 min./arc contributed 98% of errors under laboratory conditions.	Practice effects: search time was reduced from about 20 to 15 sec; individual differences not reported.

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