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Stereoscopic Depth Perception

The distance to the perceptual model from the observer turns out to be close to the observer's usual reading distance.

ABSTRACT: *The properties of real space that are correctly perceived in normal binocular vision are investigated, and the results are applied to stereovision in photogrammetry and photointerpretation. Present geometrical theories of stereovision are criticized and it is shown that differential depth, not absolute depth, can be correctly perceived in the absence of perspective or other context. A theorem concerning normal vision is proven and is then applied to optically-assisted stereovision. Depth exaggeration is measured experimentally and is used to establish a metric for perceptual space.*

Introduction

When a photogrammetrist uses a stereoscopic pair of airphotos, two kinds of space model come into being. One is the geometrical space model which may be constructed optically, mechanically, or analytically. It is a precise representation at constant scale of the terrain. The other is the visual space model which is created in the mind of the observer. In spite of the many ingenious efforts to describe it, it has remained up to the present a mystery with respect to its size, location, and geometrical nature. The only connection between the two types of model occurs when a floating mark is brought into coincidence with a point of the visual model, thus carrying out an image correlation and locating a point of the geometric model.

The methods that have been used to investigate the visual model will be discussed in some detail below. They usually have involved geometrical constructions of the rays entering the eyes, and always end up avoiding the question of what is actually perceived by the mind. In this paper, the fundamental nature of the visual model as a mental construct will be central to the theory. Some simple and indisputable facts of normal stereovision will be stated, and other less obvious facts will be derived from them. The perceptual distance to the visual model will be clearly separated from the physical distance that determines the angular subtense of images at the eyes.

Stereoscopic exaggeration of depth, the phenomenon that has created most of the interest in this subject among photogrammetrists, has received many faulty explanations. In this work it will not be 'explained' but will be taken as the natural result of normal stereovision. It will then be treated as a measurable quantity that provides a metric for visual space. The immediate result is a method for determining the perceptual distance from the observer to the visual space model, which is found to vary with the observer and with convergence, but is also found to be about equal to a normal reading distance. This perceptual distance in turn may be used to quantify the three dimensions of the perceptual stereomodel.

The Geometric View of Perceptual Space

The earliest experiments with stereopairs of drawings were made by Wheatstone, who in 1838 gave a simple explanation of stereopsis based on the geometry of the rays entering the eyes. This has been called a "projection" theory and was accepted as a valid explanation for nearly 100 years. It has since been made clear by many workers that the perceived position or shape of a body is not determined by such simple geometry. Von Freitag Drabbe (1951) gave an understanding of the clear distinction between physical and perceptual space models. After such papers, it should

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not be necessary to show that perceptual space is not linked to the geometry of rays entering the eyes in any manner that could be expressed by an analytical transformation of spatial coordinates. Analytical correspondence is also ruled out by modern knowledge of information transfer in the visual neural system (Hubel and Wiesel, 1979). The example of Figure 1 will be given, however, to show just one case where the correspondence obviously breaks down.

The two photographic images of a chimney, *ab* and *a′b′*, are viewed under a simple stereoscope, and the principal rays to the eyes intersect, when produced backward, at *A* and *B*. The simple projection theory assumes that the chimney is seen at *AB* in perceptual space and that the distance, *L*, is an actual distance in that space. The fallacy of the construction has been exposed in many ways, Figure 2 representing one of the simplest. In this figure, the two photographs have been placed at a greater separation so that *A* recedes to infinity while *B* remains at a finite distance. In reality, this experiment does not create the impression that the chimney is infinitely tall, or even that its base is very far away. The case can be made even stronger by further increase of the separation until the points *A* and *B* both are located behind the observer's head. This is still possible with a moderate amount of exophoria or "wall-eyeing".

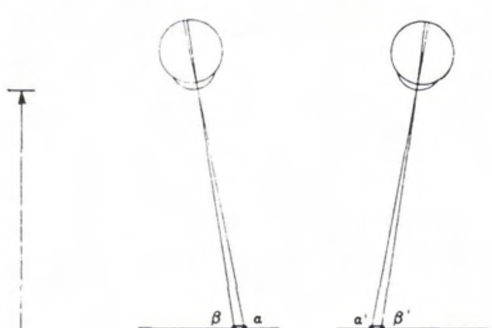

FIG. 1. *Illustrating the simple projection theory.*

FIG. 2. One way to expose the fallacy of the simple projection theory.

The important lesson to be learned from these figures is that a perceptual distance must not be equated to a real distance such as *L* of Figure 1 unless the sign of equality can be defined in some way that gives it a meaning. This is still true even when no aids to vision lie between an observer and a real object. Aniseikonia, whether induced by disease or by artificial means, provides an obvious example of the inequality of perceptual and real distances, and drugs or disease can upset the equation even when the eyes themselves are normal.

Realizing the failure of the simple projection theory, geometers have gone to more elaborate theories, partly in attempts to explain the results of the classical experiments by Ogle and others on the longitudinal horopter. In these experiments, objects lying in a horizontal plane through a subject's eyes were moveable along radial lines. When the subject attempted to arrange them in a single straight line transverse to the line of sight, the line was always curved. It seemed natural to apply the concept of non-Euclidean perceptual geometry, and Luneburg (1947) actually worked out in detail the properties of a Lobachevskian (hyperbolic Riemannian) perceptual space.

The concept of curved space seemed essential to organize the results of the geometrical experiments, and still has some meaning in such cases as a newly-produced aniseikonia, where the subject sees space as obviously curved. However, some simple visual experiments will show that a metrical space, however elaborately defined, can not serve as a complete model for perceptual space. As one example, velocity and displacement are linked analytically and inseparably in any metrical space. But in human vision, a velocity may be perceived in the absence of any displacement, as one may find when stopping at a station after a train-ride. Velocity and position are only two of many aspects of the visual field which are sensed through many different pathways in the brain, and which are linked to other stimuli and to memory in ways that are completely unknown.

PERCEPTUAL SPACE AS A TOPOLOGY

The failure of non-Euclidean metrical geometry was followed by attempts to represent perceptual space as a topological homeomorph of real space. These attempts failed for two reasons. Topology does nothing to explain or manage the characteristics of perceptual space that are in fact metrical. Secondly, the idea of a topological homeomorph implies a one-to-one correspondence between elements of the two spaces; and it is now known that such a correspondence does not exist, in general, even for the retinal events and the neural impulses in the brain.

The trouble with all these theories that attempt to map real space into a perceptual field is that the brain is too good for them. It can provide an accurate model of real space from badly distorted optical input. It does not operate by solving mathematical equations. However, the hopelessness of providing a single geometry for perceptual space does not need to hinder the study of perception. Visual perception in normal observers has some simple rules, and these rules are important in spite of exceptions that occur in special cases.

The Perception of Differential Angular Position

Having learned that perceived geometry is not a one-to-one mapping of real space, we will be careful never to write $L' = L$, where L' is a distance in the perceptual field and L is a distance in real space, unless the sign of equality is defined in some special and limited way for certain conditions of observation. As one example, if L is the measured distance from an observer to a directly-viewed object, one might write $L' = L$, but only in the sense that "when presented with this object at distance L, that distance can be estimated with some accuracy". As the object becomes more abstract and as context is removed, the equation becomes meaningless for monocular vision. Even with stereoscopic vision, the equation will be rendered untrue under sufficiently abstract conditions of viewing. It is simply not true that binocular vision provides an unequivocal perception of real distance from the observer.

There is one quality of real space that is observed very well, however. It is the angle subtended at the eye by the rays from two object points. If the angle is α, we may write

$$\alpha' \equiv \alpha \ (\alpha' \text{ is equivalent to } \alpha) \qquad (1)$$

where α' is the perceived angle, but only with the following special meanings:

- Any normal observer can compare quite accurately two visual angles subtended by two pairs of abstract objects (an example is the comparison of the angles between pairs of stars in the sky) and
- Any normal observer can learn to judge the absolute value of visual angles from a few minutes up to 90 degrees or more.

These propositions are stated without any substantiation from the literature of visual psychology, but the reader can test them for himself. Even the well-known optical illusions do not seem to contradict them to any important degree.

Thus the perceived visual angles have a close correspondence with actual visual angles. These are only angles, however, and the correspondence does not provide a metric for perceptual space. If, for example, a visual angle is created by an object of width, w, at a distance, L, we can only write

$$\frac{w'}{L'} \equiv \frac{w}{L} \qquad (2)$$

with the specific meaning above; but observations of abstract objects will not allow us to write $w' \equiv w$ or $L' \equiv L$ separately.

Differential Depth Perception

The specific, powerful, and precise perception of depth *differences* must now be treated independently of any judgement of absolute distance from the observer's eyes. Accurate judgement of distance is often possible, but this invariably depends upon context such as perspective (or vergence). It should be clear that the mind can easily deal with such quantities as depth difference and depth itself simultaneously, even if the bases of judgement are quite different, perhaps using different parts of the brain in the process.

It seems reasonable to look for an expression analagous to visual angle that will apply in three-dimensional perception. Like visual angle in the two-dimensional field, it must be a differential expression involving only the angles between rays of light entering the eyes. It may then be possible to write an equation linking quantities in stereoscopic perception with quantities in real space, with the same sort of limitations that were placed on the equation of angular perception above.

Such an expression can be obtained by invoking some simple facts connected with the perception of simple objects under conditions that do not include any clues to depth except stereopsis itself. These facts are as follows:

- The depth dimension of a solid of any shape is seen correctly relative to its transverse dimensions, independently of its size or distance;
- The three-dimensional shape of an object is perceived as the same by all normal observers whatever their eye bases; and
- Angular subtense is perceived correctly in the sense described, so that Equations 1 and 2 may be used.

In the following discussion, abstract objects of small size situated at moderate distances from the observer will be considered. The results are not limited to such conditions, however, because the brain can easily handle the changes in geometry of the rays that occur when the object becomes larger or comes closer to the eyes. Some photogrammetrists have attempted to describe the visual space model for close objects, using elaborate geometrical constructions. Such exercises are useless because the brain does not operate by solving mathematical equations. Again, extremely small objects or objects at great distance do not need to be considered because they are beyond the range where stereopsis operates.

Consider an object of any specified shape, of depth d, and a lateral dimension w, presented to an observer with eyebase b at a distance L (Figure 3). The angular subtense presented by the lateral dimension is

$$\alpha = w/L \tag{3}$$

The angular parallax ϕ subtended by the eyebase at the object (the vergence angle) is approximately b/L radians and the differential angular parallax between the front and rear of the object is

$$\rho = \frac{d.b}{L^2} \tag{4}$$

This differential angular parallax is the property of the rays that produces relative retinal displacement and provides the stereoscopic clue to perceived relative depth. By itself, ρ does not provide a clue for a judgement of absolute depth, any more than α provides a clue for the actual width of an object.

If vergence and accommodation are fixed and if the object is isolated from perspective context, the

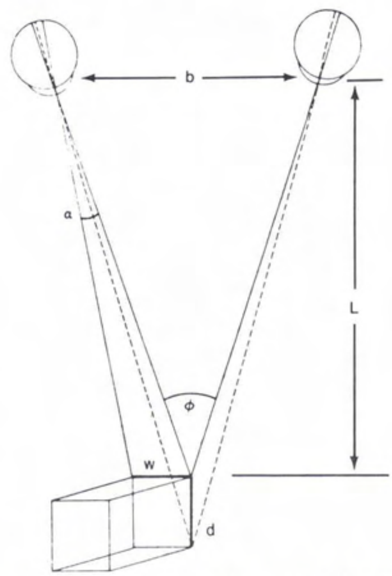

FIG. 3. Stereo vision without optical aids.

only clues that can provide perception of the depth-to-width relationship are the differential angular quantities α and ρ, the quantities that affect the sizes and the disparities of the retinal images. Since the shape of an object is perceived as the same by all observers at all distances, there must be an expression combining α, ρ, L, and b that is independent of L and b and that evaluates an accurately perceived property of the shape. Such an expression is

$$P = \frac{\rho}{\alpha^2.b} \tag{5}$$

Any one of an infinite number of algebraic functions of P would be equally valid (its inverse, for example) because the brain does not use algebra.

Substituting the expressions of Equations 3 and 4 into Equation 5, it is seen that the correctly perceived property of the object is

$$P = d/w^2 \tag{6}$$

If this simple logic is correct, stereoscopic depth exaggeration must involve the first power of the depth in comparison with the second power of the lateral dimension. This should not be surprising, because most of the objects that we see in nature are three-dimensional, with a frontal area rather than a single transverse dimension. We are accustomed to think of a depth-to-width ratio, but perhaps 'depth-to-area' is a more realistic version of what we really perceive.

The following relationships between perceived and real quantities can now be written:

$$\left(\frac{\rho}{\alpha^2\, b}\right)' \equiv \frac{\rho}{\alpha^2\, b} \tag{7}$$

and

$$\left(\frac{d}{w^2}\right)' \equiv \frac{d}{w^2} \qquad (8)$$

Since these are relationships between unlike quantities, the sign joining the two sides must be carefully defined as follows: "the geometrical factor on the right-hand side of the equation is correctly perceived by the normal observer under ordinary conditions of viewing."

Since α is itself correctly perceived separate from other context, it should be possible to modify Equation 7, using Equation 1, to produce another theorem in stereoscopy:

$$\left(\frac{\rho}{b}\right)' \equiv \frac{\rho}{b} \qquad (9)$$

then using Equation (4),

$$\left(\frac{d}{L^2}\right)' \equiv \frac{d}{L^2} \qquad (10)$$

That is, the normal observer can make a correct assessment of the ratio of the depth of an object to the square of its distance. Presumably one could learn to give numerical values for this ratio for different objects at different distances, just as one can give estimates of visual angle without making an accurate estimate of either the distance or depth separately.

Stereopsis in Photogrammetry and Photointerpretation

Consider a normal stereoscopic pair of photos of an object of width W and depth D, taken at a distance H with camera base B, and at a scale S such that $W \cdot S = \omega$ and $D \cdot S = d$. The image width on each photo will be w, and the differential linear parallax will be

$$\Delta p_x = d \cdot \frac{B}{H} \qquad (11)$$

The stereopair is now viewed at an effective distance L. This may be the actual distance of the photos from the eyes (as it is in unaided vision or, very nearly, with a pocket stereoscope) or a reduced distance calculable from the magnification of the stereoscope. In any case the distance L is defined by

$$\alpha = w/L \qquad (12)$$

where w is the image width and α is the actual angle subtended at the eye by the image. Whatever the optical system, the width and the differential linear parallax are magnified in the same ratio, and the differential angular parallax will be

$$\rho = d \cdot \frac{B}{H} \cdot \frac{1}{L} \qquad (13)$$

Under these circumstances, for an observer with eyebase b, the quantity P from Equation (5) becomes

$$P = \frac{\rho}{\alpha^2 b} = \frac{d}{w^2} \cdot \frac{B}{H} \cdot \frac{L}{b} \qquad (14)$$

Then, using Equations (7) and (8), we get

$$\left(\frac{d}{w^2}\right)' \equiv \frac{d}{w^2} \cdot \frac{B}{H} \cdot \frac{L}{b} \qquad (15)$$

It might be possible to verify or disprove this equation experimentally, but even if we perceive d/w^2 or its modified value in Equation 15 correctly, we want to measure $(d/w)'$ to find the exaggeration of depth as it is usually defined. Combining Equation 10 with Equation 15,

$$\left(\frac{d}{w^2}\right)'\left(\frac{d}{L^2}\right)' \equiv \left(\frac{d}{w}\right)^2 \cdot \frac{1}{L.b} \cdot \frac{B}{H} \qquad (16)$$

The next step is basically different from the ones above. In every case so far, perceived quantities and real quantities have been separated and the sign of equivalence has the meaning given below Equation 8. We now transfer a perceived quantity from the left to the right and write an equation in perceptual space

$$\left(\frac{d}{w}\right)^2 = \left(\frac{d}{w}\right)^2 \cdot \frac{1}{L.b} \cdot \frac{B}{H} L'^2 \qquad (17)$$

Extracting the square root of perceptual quantities is justified, because the brain perceives without regard to the function of an expression presented to it, and

$$\left(\frac{d}{w}\right)' = \left(\frac{d}{w}\right) \frac{1}{(L.b)^{1/2}} \left(\frac{B}{H}\right)^{1/2} \cdot L' \qquad (18)$$

Defining stereoscopic depth exaggeration as

$$E = \left(\frac{d}{w}\right)' \Big/ \left(\frac{d}{w}\right) \qquad (19)$$

Then

$$E = \frac{1}{L.b^{1/2}} \left(\frac{B}{H}\right)^{1/2} \cdot L' \qquad (20)$$

This important equation relates the perceived stereoscopic exaggeration of depth to the perceived image distance L'. It asserts that the exaggeration is proportional to the square root of the base-to-height ratio, and it provides a means of actually measuring image distance in perceptual space by making measurements of depth exaggeration. The experiments described below will test this theory and will show that the normal observer mentally places the visual stereomodel at a normal reading distance whenever a stereoscope or stereoplotter is used.

Measurement of Stereoscopic Depth Exaggeration

To test the theory presented in Equation 20 above, two methods were created to measure stereoscopic depth exaggeration. The first one requires only a stereoscope, a parallax bar, and an airphoto stereopair.

The Parallax Bar Method

In this simple method, a stereopair of airphotos of known scale is selected which contains the images of a small flat-roofed building. The absolute parallax, p_x, and the differential parallax, Δp_x, for the height of the building are measured in the usual way, and the height, h, of the building is calculated. The width of the image of the building is measured with a measuring magnifier or microscope and the corresponding building dimension, w, is calculated. Now the floating mark is set so that it appears to be at a distance above ground equal to the width of the building and the differential parallax, $\Delta p_x'$, from the ground is measured. The stereoscopic depth exaggeration is then calculated as

$$E = \frac{\Delta p_x}{(\Delta p_x)'} \cdot \frac{w}{h} \qquad (21)$$

This test may be made quickly, but may be affected by the observer's conscious or unconscious estimate of the real ratio of the height to the width of the building. Special photography would have to be flown to provide a wide range of base-to-height ratios.

The Abstract Object Method

In this method, a serious attempt was made to measure stereoscopic depth exaggeration rather than to estimate it. Sets of regular objects with different depth-to-width ratios, in different shapes and sizes, were made up and photographed with a wide range of base-to-height ratios. The photos were examined under a common mirror stereoscope with magnifying binoculars, and the observer was asked to determine which object appears to have a depth equal to its width. This is essentially a null method which should avoid some of the subjectivity of estimations of exaggeration.

Perspective effects were avoided by using small objects (8 to 20 mm in width) photographed at a distance of one metre. Shadow effects were avoided by placing the objects on a luminous background and by giving them a balanced front illumination. The photos were reproduced as slides at small scale so that the images would be representative of the images of objects that are commonly seen in airphotos. The camera used was a 35-mm Leica with a 21-mm lens, which provided a maximum base-to-height ratio of 1.4 : 1. The scale of the photos was 1:47.6, so the image sizes ranged from about 0.17 to 0.42 mm.

The test objects were made in the form of cones, cylinders, and rectangular parallelipipeds. An example of a set in the cylindrical form is shown in the stereopair of Figure 4, which was photographed at a base-to-height ratio of 0.6. Under the stereoscope (a Wild ST4 with 3× binoculars) the stereopairs made at different base-to-height ratios were placed so that only the images of the objects themselves were visible through holes in an opaque mask over a light-table. These holes were at such a separation that, when each observer adjusted the distance between the binoculars of the stereoscope to match his eyebase, his eye axes were parallel. The experiments were randomized to hide the base-to-height ratio of each pair from the observer.

Results

Figure 5 shows a plot of the means of the results for three skilled observers. The ordinate is $\ln(w/h)$, where w/h is the width-to-height ratio of the object that seems to be equal in height and width, and is thus a measure of the exaggeration. The abscissa is $\ln(B/H)$, where B/H is the base-to-height ratio of the stereo-pair. In these tests, the geometric distance to the photos, including the effect of the

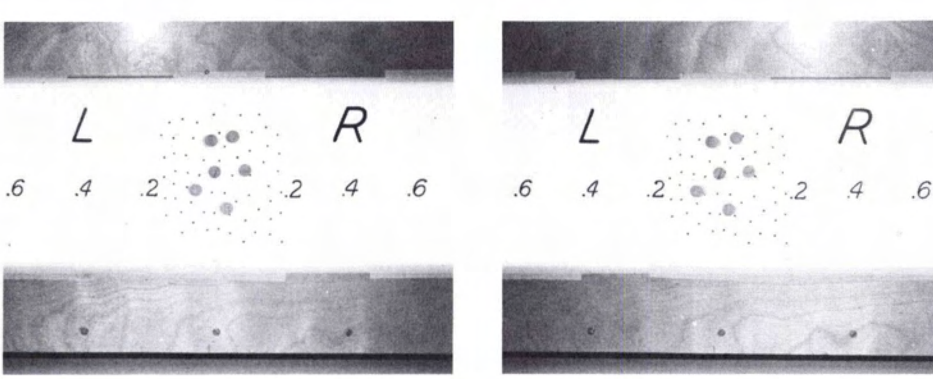

Fig. 4. A stereopair of a test object photographed at a base-to-height ratio of 0.6.

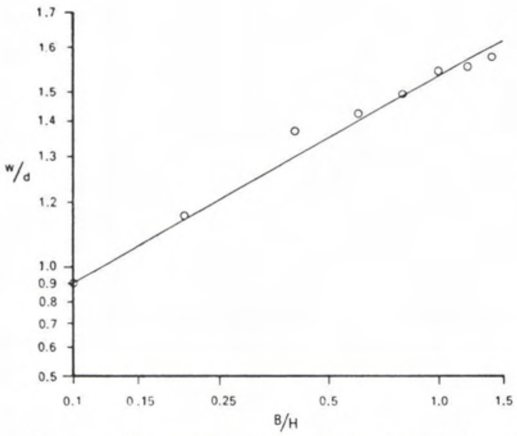

FIG. 5. Depth exaggeration versus base-to-height ratio.

magnification of the binoculars, was $L = 80$ mm. The mean eyebase of the observers was 65 mm. The equation of the straight line, fitted by least squares, is

$$\frac{w}{h} = 3.36\left(\frac{B}{H}\right)^{0.55} \tag{22}$$

The exponent is so close to 0.5 that the form of Equation 20 is given strong support.

Converting Equation 20 into

$$L' = E \cdot (L.b)^{1/2}\left(\frac{B}{H}\right)^{-1/2} \tag{23}$$

and comparing it with Equation 22, the value of L is found to be, approximately,

$$L' = 3.36\ (L.b)^{1/2} = 242 \text{ mm}$$

This remarkable result shows that the observer tends to place the mental stereoscopic model at a comfortable reading distance, even though the stereoscope is focussed for infinity and the eye axes are accurately parallel.

The graph of Figure 5 was chosen from a large number of results that contained considerable variability. It is presented without any claim that it proves the theory, because more experimental work is needed to take account of factors that were neglected. However, among all of the results to date, the perceptual distance L' remained within a range of $+150$ mm to $+270$ mm when calculated by the method given above. This work is continuing, with inclusion of a study of the effects of vergence and accommodation upon the perceived image distance.

SUMMARY

The following assumptions are made about normal stereovision without optical aids:

- Visual angle subtended at the eye is correctly perceived; and
- Three-dimensional shape is correctly perceived, independently of distance to the object and of the observer's eyebase.

From these facts the following theorems are derived:

- From the geometry of an object or a stereopair, in combination with the eyebase and the physical viewing distance, the observer perceives the shape according to the value of the expression

$$\frac{\rho}{a^2 b}$$

which reduces to the value of the ratio d/w^2 for direct viewing;
- The observer also can perceive correctly the value of d/L^2 in real space or in the visual stereomodel;
- With the assistance of measurements of stereoscopic depth exaggeration, it is possible to find the perceived distance to a visual stereomodel; this distance is a normal reading distance, in the customary use of a stereoscope; and
- The exaggeration of depth in stereopairs varies approximately with the one-half power of the base-to-height ratio of the photographs (this finding cannot be considered proven and is being investigated further).

CONCLUSIONS

The theory and experiments described show that it is possible to give actual dimensions to the perceptual model that is seen under the commonest conditions of photogrammetry and photointerpretation. The distance to the model from the observer can be determined by measuring stereoscopic depth exaggeration, and turns out to be close to the observer's usual reading distance. The effects of convergence and accommodation can now be investigated in terms of their influence on this perceptual distance. It now becomes possible, for the first time, to talk of actual dimensions in the visual stereomodel; because once the visual distance is determined, the observer's natural ability to judge visual angles allows the judgement of lateral dimensions. Furthermore, it has been shown that the observer can make a good estimate of the depth of a stereoscopic image compared to the square of its lateral dimensions or the square of its distance; so that the third dimension can also be sensibly referred to as an actual distance in millimetres within the visual field.

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Dedication

This paper is dedicated to the memory of the late Dr. Kenneth B. Jackson ("K.B.", to all his students at the University of Toronto), who introduced the author and thousands of others to the wonders of stereovision.

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