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Clinical evaluation of stereopsis

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ABSTRACT

Principles of the design and administration of clinical stereopsis tests are outlined. Once the presence of the distinct sense of the third dimension by binocular vision alone and without help from monocular cues has been established in a patient, the examination can proceed to the measurement of stereoscopic acuity. Best results are obtained with high-contrast, sharp, well-articulated and uncrowded elements from easily-recognized target sets, displayed with no time constraints. Polarization is the preferred method of right/left eye separation; time-sharing at a minimum of 60 Hz on computer displays with counterphase occluding goggles is a feasible procedure. Random-dot stereograms are problematic because not all observers can disentangle the coherent global disparity on a first view.

1. Introduction

Forward placing of the two eyes during vertebrate evolution resulted in overlapping visual fields of the two eyes. The consequent dual imaging of the same objects on the right and left retinas led to the development of special circuitry that ensures a unified representation of the world while at the same time allowing information about the third spatial dimension to be extracted by comparison of the somewhat differing aspects of targets that arise when imaged from two separate vantage points.

This is the faculty of stereopsis, a facility to gauge spatial relationships in the third visual dimension. It is subserved by dedicated neural circuits grafted on the more elemental ones for processing the object space projected by the eye's optics on the two dimensional retinas and from there by retinotopic relays into the visual brain.

The geometry of the situation can be simplified to the case of a point target in the mid-sagittal plane at a distance z from an observer with inter-ocular separation a. To a satisfactory first approximation when z is large compared to a, the z co-ordinate of the point can be defined by γ, its *binocular parallax*, where $\gamma = a/z$ in radians. A patient's ability to estimate γ depends on a variety of factors, but this is not the subject of the current contribution, which is rather the judgment of *differences* in the antero-posterior distances of objects. This is achieved by gauging differences in binocular parallax, called *disparity*. When Δz is small (Fig. 1), it is related to $\Delta\gamma$ by the equation

$$\Delta\gamma = (a/z^2)\Delta z \tag{1}$$

Disparity is defined in an observer's object space and, as is evident from the equation, depends in each instance on a, the observer's interocular distance (~65 mm), on z, the target distance, and on Δz, the distance difference. It is an angle, and when a, z and Δz are in the same units, say cm, it is in radians. For conversion, it is handy to remember that each radian contains 57.3°, 3438 min or 206,265 arcsec.

1.1. Subjective "depth" versus objective "disparity"

It is conceptually important to distinguish between observers' sensory experiences as reported by them and the geometrical arrangement of the physical stimuli which can be objectively measured. It is helpful to maintain this separation also semantically, and to refer to the former as "depth" and the latter as "disparity," much as one differentiates "brightness," the subjective attribute, from the stimulus "luminance," specified by physical measurement.

1.2. Stereopsis versus monocular depth clues

At the outset the categorical distinction needs to me made between stereopsis and the ability to judge the three-dimensional disposition of objects in the visual field from other cues. With a refined perceptual apparatus and experience, it is possible to navigate exceedingly well in the visual world by what are called *monocular depth cues* because they are available to a patient when using only one eye. Here are some examples of monocular depth cues: A known object subtends a smaller visual angle the more distant it is, contours known to be parallel, such as streets or railroad tracks, converge according to laws of perspective, nearer targets

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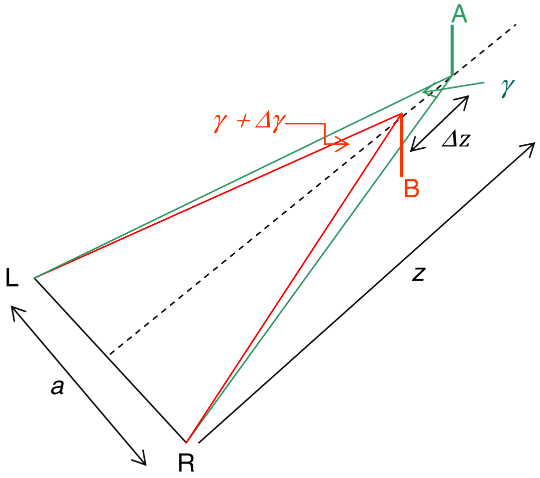

Fig. 1. Schematic geometry of the Howard–Dohlman stereoacuity test. Peg A is fixed at a distance z from the observer, whose left (L) and right (R) eyes are a distance a apart. The observer's task is to set peg B so that it is just discriminably nearer than A. The binocular parallax of A, in radians, is a/z. With respect to A, B has disparity $\Delta\gamma = a/z^2)\Delta z$.

interpose themselves and therefore partially obscure more distant ones, shadows are assumed to arise from a sun shining from above. The fact that good three-dimensional information can be gleaned from purely monocular viewing, as has been the practice in visual arts and displays for nearly a millennium and is embodied in the entertainment industry so much that 3D showing is regarded as an extra-ordinary event, does not mitigate the distinct, non-substitutable role of stereopsis in the every day visual experience of a patient and the impoverishment that results when absent. Nor does the occasional report of competent one-eyed pilots.

These monocular depth cues, as well as the relative motion of images with head movement, highlight a problems associated with clinical stereopsis tests. Because the aim is to ascertain, qualitatively and quantitatively, the functioning of a patient's apparatus for binocular disparity processing, special precautions need always be taken to ensure that a patient's response is based on detection of disparity and is not secondary to judgments about target location in 3-space that could have been made with just one eye. Many clinical stereo tests, therefore, include a simple check that both eyes are in fact participating.

2. The paradigmatic stereo test

Consideration of one of the first and still one of the best clinical procedures, the Howard–Dohlman two-rod tests (Howard, 1919), is instructive.

It is typically implemented (Fig. 1) by showing the observer two thin rods at a distance of 6 m, seen in an otherwise empty field against a uniformly-lit background. One rod is fixed and the other can be moved back and forth by the observer, who is instructed to set it to appear just detectably nearer than the fixed rod. When that has been accomplished, we have the values for the three variables to be inserted on the right-hand side of the equation. For example, if the inter-ocular distance is 6.5 cm, the fixed rod distance 600 cm and the just-discriminable difference 3 cm, these values yields a disparity threshold of $3 \times 6.5/600^2$ radians or 11 arcsec.

In this testing procedure the observation time is not limited, targets are simple, single, do not have to compete with or be disambiguated from other features in the visual field, and their visual attributes other than disparity remain invariant throughout the process of measurement. [The visual angle subtended by the rod's width does change with z position, but the 0.5% difference remains below the detection threshold for that variable.] As will be seen below, the conditions all serve to optimize performance.

The disparity threshold, small in terms of angle subtended at the eye, constitutes a challenge in implementing stereo tests. It is here accommodated by the very long observation distance. In the equation, Δz and z have an inverse square relationship so that a tenfold reduction in the target distance, say from 600 to 60 cm, brings about a hundredfold decrease in the just discriminable distance interval to 0.3 mm or about 1/100 of an inch. And indeed a good observer has no difficulty detecting, by stereoscopy, the indentations within the profiled head on a coin at arm's length.

While it is good practice to use objects with real three-dimensional features, the small distances in physical space when the tests are carried out in confined spaces create difficulties that, as a consequence, lead to the adoption of an altogether different strategy for stereo testing: stereograms. Instead of physically arranging test targets in the patient's three-dimensional space of objects, a pair of two-dimensional reproductions is generated of the view of that space from the vantage point of the patient's right and left eyes. These are then presented separately and each directed to its intended eye. In this way, small *front-to-back* position differences in three-dimensional object space are represented as small *right–left* positional differences in the stereogram pair. The geometry of this conversion has been treated elsewhere under the term *stereoscopic depth rendition*, but as a guide, a 20 arcsec disparity, shown at 40 cm to an observer with 6.5 cm interocular distance, would be represented by a lateral position displacement between the right and left stereograms of less than a tenth of a millimeter.

Because real-space simulation of three-dimensional configurations by controlled generation of appropriate electro-magnetic disturbances for direct unmediated view by the observers' eyes (hologram) is still in the future, clinical testing of stereopsis nowadays centers largely on utilizing devices that allow uncomplicated view of suitable stereograms.

The practical questions, apart from creating patterns with such minute texture, is their display. In the early days of stereoscopy, this was achieved by mirrors or prisms which inevitably require care in head and eye placement. This is still the case with procedures in which right and left stereograms are physically interleaved in narrow vertical strips and optical means are used to diverge the paths by the several centimeters needed to project them into the two eyes.

For these reasons, the most popular way of displaying stereograms is to show the right and left eyes' views not side by side but superimposed. The best known example is to print, superimposed on a single panel, one eye's target in red ink and the other's in blue–green, with non-overlapping wavelength bands, to be viewed through colored filters that ensure that each retina receives only the image intended for it. They are called *anaglyphs*. Technically more complicated but visually less intrusive is the process of separation by transilluminated polarized panels, with orthogonal viewers for the two eyes. In either case, viewing is through goggles. Because the printed colors depend on the kind of illumination and may not always be matched to the transmission of the goggles and hence may introduce significant interocular differences in light level, polaroids are preferred.

For the future, the most promising of the techniques, and one on the verge of widespread realization, is right/left time-sharing, made possible by computer display refresh rates so fast that the inter-ocular delay is negligible in practice. The right and left eyes' views are written sequentially on alternate pages and their display synchronized with a viewing device with right/left eye occlusion in counterphase, or by transmission through panels with rotating circular polarization; here the analyzers in front of the two eyes can be passive. Rapid progress in optical technology bids fair to advance these procedures further. The fine grain needed in stereo