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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 counter-phase 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

$$\Delta\gamma = (a/z^2)\Delta z \quad (1)$$

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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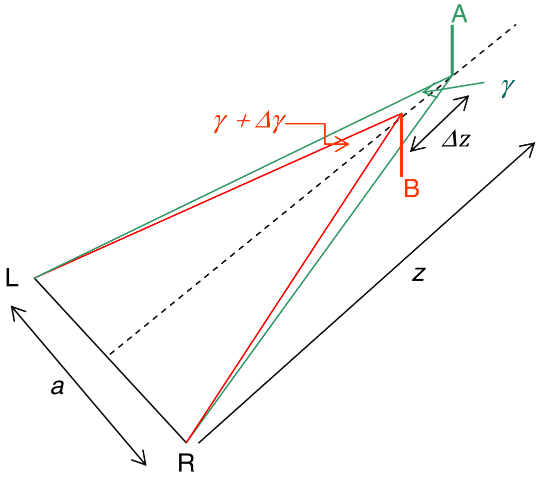

Fig. 1. Schematic geometry of the Howard–Dohlman stereoacuity test. Peg A is fixed at a distance z from the observer, whose left (L) and right (R) eyes are a distance a apart. The observer's task is to set peg B so that it is just discriminably nearer than A. The binocular parallax of A, in radians, 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 displays will remain a hurdle. Computer monitor pixel size does not yet reach down to good observers' stereo threshold at arm's length. Hence sub-pixel resolution procedures, known to be employed by the human visual system, will have to be employed.

3. Clinical questions

Of interest in the clinic are the two extremes of stereopsis performance, at one end its very presence in a qualitative way and, at the other, stereoacuity thresholds. To reach the latter, all interacting variables need to be set at their optimum. But when integration of the two uniocular pathways may have been compromised by developmental or pathological interference, a clinician wants first of all to settle the question of the presence, in its most rudimentary form, of a subjective experience of three dimensionality that perforce can be attributed to the purely binocular nature of a stimulus and not to any of the many secondary clues that could be employed by the one-eyed.

Is stereopsis present? A target pair shown to the right and left foveas might be seen single, and even when both eyes are participating and a check test rules out suppression, the patient may still be stereoblind.

The simplest procedure is to have a patient hold a pair of knitting needles one in each hand and try to have the two points touch. In the presence of functioning stereopsis, this can be done with an error of less than a millimeter in the antero-posterior dimension, whereas with only monocular clues the error is in terms of centimeters. Simpler still is for the examiner to extend a finger from each hand and determine how good the patient is in estimating front–back juxtaposition.

Coarse and fine stereopsis. In what follows most of the emphasis is on the measurement of stereoacuity and the conditions that optimize performance. Nevertheless some kind of qualitative stereoscopic sense of depth can be conveyed in many other visual situations. As is the case with all spatial tasks, stereoacuity diminishes with retinal eccentricity. More surprising is the fact that binocular single vision is not a pre-requisite to stereoscopic depth which can also be experienced with certain kinds of diplopic targets. Conversely, as mentioned above, a reported superimposition of the right and left-eyed images, even when giving the appearance of fusion, can in some conditions occur without engaging the faculty of stereoscopy. The clinical disambiguation of these situations is beyond the scope of this presentation.

There can be no stereopsis testing, clinical or otherwise, without the instrumentation that permits presentation of either real-space targets minutely differentiated in the third dimension or of defined images separately to the two eyes, but the primary focus for the actual tests has to be on the visual patterns and testing conditions. The variable is, of course, disparity and the task is to relate it to the patient's response. Researchers often concentrate on the proper psychophysical technique for reaching reliable quantitative data, but in a clinical setting this is more or less taken for granted. Correction of refractive errors, a staple of optometric practice, uses for an end point a visual acuity determination about which a seasoned clinician asks no lessons in psychophysical methodology. The same applies to stereopsis, where the decision between the advantages of frequency-of-seeing or staircase methods are best left to the laboratory scientist.

4. Optimal conditions for best stereo performance

Just as visual acuity is a determination of the limit of (two-dimensional) spatial discrimination, stereoacuity is a measurement of depth threshold and, as all such tests, should be carried out under the conditions that bring forth the best performance.

Here is a list of stimulus variables that should be optimized in a determination of stereo-acuity:

1. *Brightness.* The targets, or the background against which they are viewed, should be well in the range of photopic luminances, preferably at least 30 cd/m^2 (Mueller & Lloyd, 1948; Westheimer & Pettet, 1990). The phenomenon first described by Wilcox (1932) of a decrement of performance at very high luminances (>1000 cd/m^2) may also apply to strereoacuity.
2. *Contrast.* Stereoacuity suffers from reduced contrast more than other hyperacuities. A Michelson contrast of a minimum of 0.1, but preferably 0.3 should be provided (Westheimer & Pettet, 1990).
3. *Image sharpness.* The tendency towards esoteric patterns such as Gabor patches should be resisted. Any defocusing, image degradation or spatial filtering is detrimental to stereoacuity (Westheimer & McKee, 1980b) which is best with crisp targets. Binocular image differences, as in uncorrected or induced anisometropia or aniseikonia, are invariably disadvantageous.
4. *Exposure duration.* Ogle and Weil (1958) found stereoacuity to improve by a factor of 4 as exposure duration was lengthened from 10 to 1000 ms. The data of Westheimer and Pettet (1990) suggest that stereoacuity stimuli should last a minimum of 200–400 ms.
5. *Binocular synchrony.* The comparison process that is involved in disparity detection can operate only within a binocular synchrony window of a very few tens of milliseconds (Westheimer, 1979); right/left target alternation should be at a rate no less than 30 Hz (Wist & Gogel, 1966).
6. *Feature isolation.* There is ample evidence that in order to discriminate disparity, features should be articulated well, separated by a minimum of 10 arcmin in the fovea (Westheimer & McKee, 1980a), and not be part of a planar structure such as a row of dots (Fahle & Westheimer, 1988) or a sheet of small elements (Mitchison & Westheimer, 1984). This phenomenon is now part of the widely-studied topic called crowding.
7. *Target familiarity and perceptual learning.* More than other visual thresholds, stereoacuity improves with target familiarity. Unlike foveal visual acuity, perceptual learning is the rule rather than the exception in measurements for the determination of stereo thresholds (Fendick & Westheimer, 1983) so that the first numerical value is not a reliable guide of a subject's ultimate ability. Moreover, training on one set of targets does not necessarily transfer to others (Coutant, 1993). However, as stereo thresholds improve with perceptual learning, some of the more physiologically-based performance features, such as crowding or threshold rise with retinal eccentricity, remain proportionally invariant (Westheimer & Truong, 1988).

The question of contours is often raised. To begin with, stereopsis, a spatial localizing task even if complicated by the need for interocular detection, depends on some sort of differential stimulation of neighboring retinal locations, whether or not the words

Fig. 2. Three-line stereogram in which the relative placement of the lines in the right and left panels cannot be used by even a knowledgeable observer for a reliable judgment of their depths.

"border" or contour" are applied. The question is how, not whether, the contour is generated. Lines or edges are typical modes of marking location, but this can be achieved also by a sequence of shorter segments, and indeed it has been demonstrated that some cortical orientation-selective elements in the primate visual cortex respond even to "illusory' contours. Hence the emphasis, while primarily on the location of the discontinuity will also be on the image characteristics such as gradient sharpness and magnitude of contrast step.

Though a sophisticated and knowledgeable observer might sometimes be able to infer their expected depth from the relative placement of the symbols in the right and left panels, there are displays in which even this facility will fail (Fig. 2). This is because the spatial operating ranges for two-dimensional locational hyperacuity and for stereoscopic processing differ quite substantially (Westheimer & McKee, 1979).

5. Clinical testing

The consideration in the previous sections imply that, to be most effective in the measurement of stereoacuity, targets should be:

few in number,
well articulated,
sharply delineated and in good focus binocularly,
with high contrast and, at a minimum, medium photopic luminance,
exposed for at least a good fraction of a second with binocular asynchrony of no more than a few tens of milliseconds.

For reliable clinical measurements they should be minimally encumbered by the influence of prediction, memory and as far as possible, devoid of non-stereoscopic clues to depth.

These conditions are well met by panels, originally part of the Keystone stereo sets and also included, at least in rudimentary form, in the TNO series, modeled after the Snellen visual acuity charts. They have several rows of well-separated symbols or letters, of high contrast and minimally 20/40 or 20/60 in size, in which one symbol or letter in each row of several well-separated elements has disparity, appearing either in front or back of the others in its row, with progressively decreasing disparity in sequential rows. To ensure that the very small monocular position differences which code for disparity cannot be used for cues, the elements might be spaced somewhat irregularly in each row (Fig. 3).

A class of target that fails to match at least some of these criteria is the random dot stereogram. Made of many small tokens, arrayed in a way so that a subset forming a geometrical feature such as a circle or square has a disparity, it has the remarkable property of hiding the outline of the feature in the monocular views (Julesz, 1960). Only to someone who has stereo vision and whose visual apparatus can disentangle the many small and irrelevant right/left disparity associations in favor of the coherent global one, will the feature be evident. Solving a random-dot stereogram requires stereopsis, but in addition a set of higher processes, which initially takes time (Harwerth & Rawlings, 1977) but eventually can lead to a quick and often instantaneous percept. This means that the negative outcome of a single quick random-dot stereogram test cannot be accepted as evidence of lack of stereopsis, but a positive one is conclusive. Since the individual elements making up the panel should be articulated separately, their size, which in most instances determines the minimum disparity, precludes demonstrating superior stereo acuity.

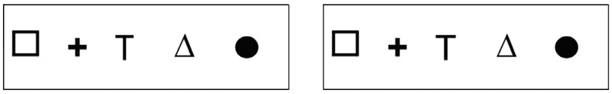

Fig. 3. Sample line of a right/left pair of stereogram panels for a stereoacuity test in which stimulus conditions are optimized. Sharp, clearly separated features are members of ensembles already known to the patient (alphanumeric characters or geometrical shapes). One symbol in each row has disparity and should be recognized as either in front or behind the rest. Locations in row are not quite regular so that lateral position cannot be used as a depth clue. Vertical arraying of such rows with progressively diminishing disparity would generate a chart that can be utilized in the manner of the Snellen chart for visual acuity.

Pending the availability of 3D computer mechanisms adapted for clinical use, the recommended test procedures that minimize interacting factors, once the knitting needle check has been satisfied, are either

(1) A set of translucent plates of a range of thicknesses, with highly-visible emblems on one face except the ones with disparity, which are on the other face (e.g. the Frisby test or a home-made variant), or
(2) A polaroid stereogram with rows of symbols or letters, slightly jittered in position to preclude guessing, one in each row with disparity diminishing from, say, 200–10 arcsec. For near viewing, the interocular position differences would be in the range of 1–0.05 mm.

Under ideal conditions, a trained observer can achieve stereo thresholds as low as 2 arcsec, better even than the best monocular location hyperacuity. This is not, however, the goal of a clinical test, where 10 arcsec would be a very respectable performance and where a normal observer should manifest a reading of better than 1 arcmin on a first test.

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The list below is not intended to fully cover the literature on clinical stereo testing, but merely to serve as documentation for specific points made in the text. Fortunately, workers in the topic have available as an invaluable resource the monumental two-volume compendium by Howard (2002). Two more extensive reviews (Westheimer, 1994, 2011) deal with related areas of stereoscopic vision.

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