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Computation of texture and stereoscopic depth in humans

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Abstract

The computation of texture and of stereoscopic depth is limited by the eyes and by the subsequent stages of the visual system in humans, and by the quality of the optical 'front end` as well as by the computational hard- and software in machines. The quality of the optics and the resolution of the opto-electronic transducer (e.g. the retina) limit spatial resolution, and, consequently, the discrimination of textures. In stereoscopic depth, thresholds far below the grain of the input-device (in humans: the photoreceptor diameter) can be attained. This extreme accuracy in locating a stimulus, called hyperacuity, is due to interpolation between the positions of the input elements, such as the photoreceptors in humans. Interpolation is most likely a feat achieved by the visual cortex, depending on a good signal-to-noise ratio of the stimulus representation. Again, resolution and contrast modulation are critical factors. The algorithms used by the human brain to discriminate between textures and to compute stereoscopic depth are very fast and efficient. Their study might be beneficial for the development of better algorithms in machine vision.

Resolution limits of the optics and "opto-electronic interface" in humans.

All visual information available to the brain is acquired through the eyes. It is therefore evident that properties of the optical media and of the retina impose limits upon visual perception — even in tasks that are thought to be primarily mediated by the visual cortex, such as vernier acuity and stereoscopic depth perception. We will review factors limiting the computation of texture and stereoscopic depth in humans. Firstly, the role of the optics and of the photoreceptors of the retina will be discussed. Next, we give a brief outline of the still controversial issue of texture perception and of the underlying computational mechanisms, followed by a description of the basic concepts of stereoscopic vision and hyperacuity. A number of factors that limit both the perception of texture and of stereoscopic depth are reviewed: the quality of the retinal image, blur, luminance, contrast, temporal factors, motion, stimulus area and retinal position.

The optic media of the human eye limit resolution of the retinal image to around 100 to 120 points (50-60 cycles) per degree of visual angle (Westheimer, 1960; Röhler, 1962; Campbell & Green, 1965; Campbell & Gubisch, 1966; Campbell & Robson, 1968). Hence, two points of the visual world are fused on the retina if their spatial separation is below 0.5 arcmin. This limit for two-point resolution is achieved only under the most favorable conditions, such as perfect optic media, an optimal pupil size, and ray-paths near the axis of the optical system (cf. e.g. Green, 1967; Campbell, 1974). Incidentally, the optics of the human eye approaches a perfect optical system for pupil sizes up to 3-4 mm, with the highest resolution between 2.5 and 4 mm (Röhler, 1962; Campbell & Gubisch, 1966).

The resolution attainable by the human retina closely matches the maximal resolution of the optic. In the foveolae where the photoreceptors are smallest and most densely packed, their spacing is around 2-3μm (Curcio et al.,1987), again allowing a maximal resolution of around 100-120 pixels per degree, corresponding to around 50 to 60 cycles per degree of a periodic pattern such as a sinusoidal grating. Most observers do not achieve such high resolutions — and this is why a resolution limit of 1 arcmin (20/20 or 1.0) is conventionally accepted as full vision by ophthalmologists.

Given these limitations of the attainable spatial resolution imposed by the optics and by the retina, visual thresholds of around 3 arcsec or below are astonishing. Such thresholds are regularly obtained in a number of the so-called hyperacuity tasks such as vernier acuity and stereoscopic depth perception (Wülfing, 1892; Andrews, Butcher & Buckley, 1973; Westheimer, 1976; cf. already Vernier, 1631). Positional information far below the photo-receptor spacing can be correctly evaluated in the visual system, while the detection of other image attributes is limited to a precision corresponding to the spacing of photoreceptors, and finer patterns appear as homogeneous gray. Since this paper is concerned with limits of visual perception, we shall consider

what the limits of texture discrimination might be and then proceed to stereoscopic vision.

The computation of texture

A texture is said to exist when part of a visual scene contains regular detail which is finer than the size of the surface which contains the detail. For example, a wooden board has a fine-grained, reasonably regular surface texture which is a property of the surface of the material rather than whatever shape is described by the outer edge of the board. Thus, texture tells us about surfaces, rather than shapes.

Under most normal viewing conditions, the edge of a textured object will give rise to a strong luminance and/or color discontinuity. Thus, a visual system which ignores texture altogether may successfully detect the object contour. However, there are situations in which an object is camouflaged, having the same mean luminance and color as its background. But even if the color and luminance are well matched, it may be that the texture of the target is different from that of its immediate background. Both motion and stereoscopic depth can be computed from arrays of points which are correlated either between the eyes or between different points in time — without the requirement of prior analysis of complex shape. Texture is an important cue also to object recognition through scene segmentation by means of motion or depth gradients. Since camouflage is much favored by evolution, it is not surprising that visual systems have evolved which include texture discrimination (and detection of stereo depth from texture elements, as in random-dot stereograms) as part of their array of segmentation modules.

We will address the basic question of how the visual system encodes texture and maps discontinuities in it.

Several models of texture discrimination have been suggested. Both Marr (1976) and Julesz and Bergen (1983) proposed that the visual system evaluates the density of "textons" in a region of visual space. A texton is a feature extracted from the image, such as a line segment (at a given orientation), an elongated blob, a termination, or an intersection. The texton theory holds that the only important measure is texton density, and not the exact spatial organization of the group of textons. This "local phase insensitivity" was investigated for grey-level stimuli by Rentschler, Hübner, and Caelli (1988) and found to hold for these, as well as for the more traditional line-drawn stimuli. Thus, classical texture vision does not evaluate the spatial relationship between elements, it only responds to their number.

Marr (1976,1982) considered an over all scheme of a primal sketch based on edge tokens, computing textons and performing simple statistics on them. This approach was extended by Voorhees and Poggio (1988) who proposed how to compute statistics on the textons.

(a)   (b)   (c)
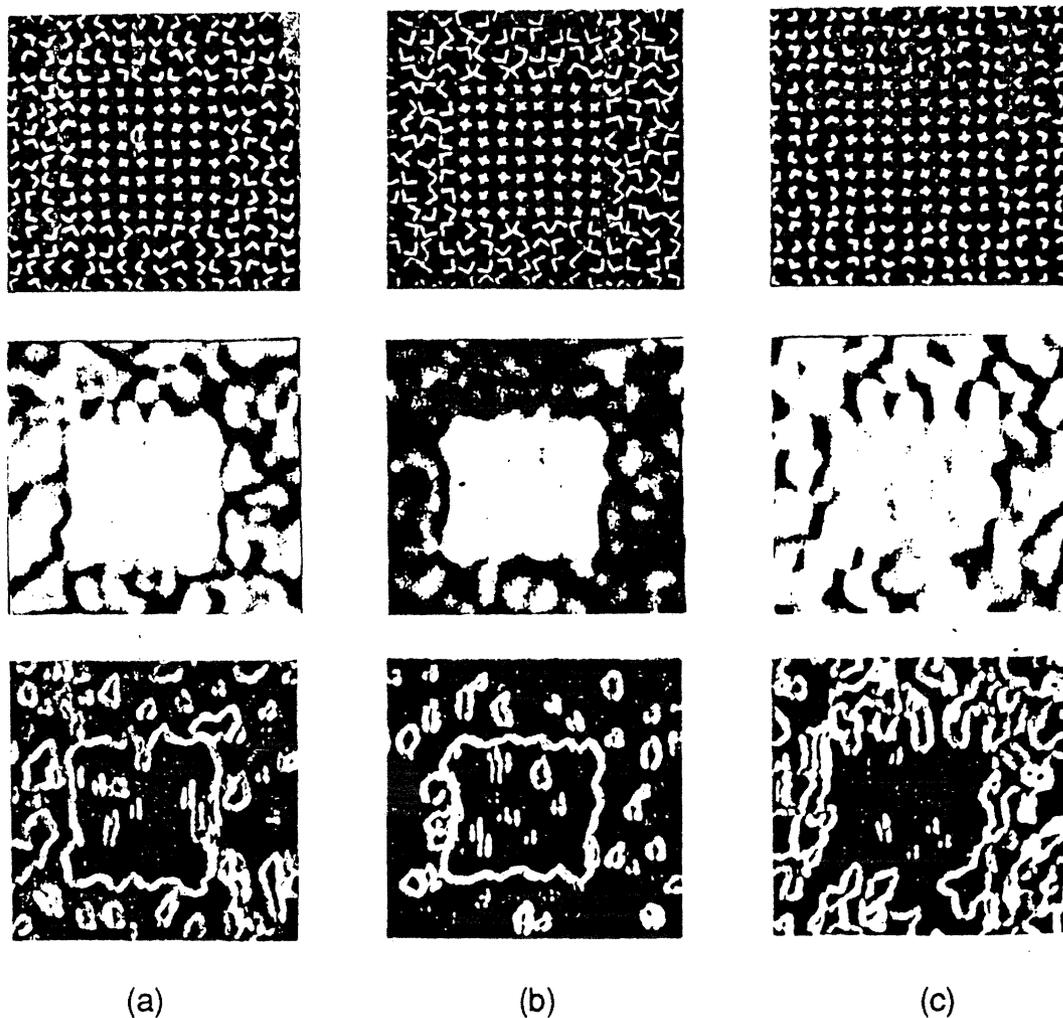
Fig. 1 The top row shows three texture-discrimination stimuli recreated from Bergen and Adelson (1988). Image (b) is the easiest to discriminate, image (c) the hardest, and image (a) is intermediate. The middle row shows the rectified Gabor-filter outputs from Griffith's et al. (1988) computational model. It is apparent that image (b) gives the strongest figure-ground separation. The bottom row shows the texture-segmentation loci extracted from the three images. Image (b) gives the cleanest segmentation line, whereas in image (c) there are many spurious distractors.

A rivaling class of theory which has been proposed for texture discrimination is Fourier analysis of the scene. While this had the advantage of being more tractable computationally than the feature-extraction models (since it is often difficult to extract classic textons from a cluttered natural scene), evidence seemed to be pointing against this approach as being the one adopted by the human visual system. Mayhew and Frisby (1978) as well as Julesz and Caelli (1979) all argue that a Fourier model does not account for observed performance. Griffiths, Troscianko and Knapman (1988) found that a Gabor-

filter model (i.e., local Fourier analysis) followed by rectification and gradient-based segmentation provides a good fit to the data of Mayhew and Frisby (1978). Secondly, there has been progress recently in developing computational models which achieve texture segmentation by computing parameters of elongated blobs (contrast, elongation, orientation) and to do statistics to find texture boundaries (Voorhees, 1987; Voorhees and Poggio, 1988), and those using Gabor filters (Daugman, 1987; Griffiths et al., 1988; Lively and Walters, 1988). Others have used a size-tuning approach (Bergen and Adelson, 1988). As the computational models are being developed, so it seems that differences between them are eroding. For example, the elongated-blob model is not very different from one which used elongated blobs with sidelobes (Gabor filters). Both the models of Voorhees and Poggio (1988) and of Griffiths et al. (1988 see Fig. 1) can account for the rank order of discriminability of textures shown in the paper by Bergen and Adelson (1988).

Caelli (1988) also argues that there is similarity between his adaptive model and the original dipole-statistics model of Julesz. So, in spite of what seem to be very different approaches, the differences in implementation are small. On pragmatic grounds, Julesz and Kröse (1988) argue that simple filter theories should be looked at before going to complex filters.

The computation of stereoscopic depth and hyperacuity

While the computation of texture is limited to textures with a grain not finer than the grain of the input device, perceptual thresholds in the so-called hyperacuity tasks like vernier acuity and stereoscopic depth perception can be an order of magnitude lower, i.e., 3 arcsec or below. One possible explanation for such low thresholds was proposed by Hering (1899). He assumed positional averaging would take place along the edges of the stimuli. But experiments with dot stimuli instead of lines (Ludvigh, 1953) proved that spatial averaging along lines is not a necessary prerequisite. Still, the low thresholds can be explained both intuitively and formally.

If the modulation transfer function of the eye's optics were much better than it actually is — having a higher aperture and transmitting higher spatial frequencies — a point in the visual world could be imaged upon the retina as a point with a diameter clearly below the photoreceptor diameter. In that case, it would be impossible to determine the position of the point with an accuracy below the diameter of a photoreceptor. Projections to all parts of a photoreceptor would stimulate the receptor equally well. (A possible way to achieve transphotoreceptor accuracy in this case would be to move the point relative to the retina in a defined way.) Fortunately, the eye's optical system does not achieve such a high resolution, but smears even the image of an infinitely small point over several photoreceptors according to a gaussian-shaped point spread function. The point spread function, i.e., the luminance distribution produced on the retina by a point in the outer world, has a half width of around 0.5 arcmin for near-axis imagery.

A point, projected upon the exact middle of a photoreceptor stimulates all the neighboring receptors by an exactly identical degree (Fig. 2a). A lateral displacement, even by a fraction of the photoreceptor diameter, will stimulate the neighboring photoreceptor on this side stronger than the one on the opposite side (Fig. 2b). The position of the intensity maximum (i.e., the position of the point) can thus be calculated with a precision far below the photoreceptor diameter by comparing the relative excitations from a number of neighboring photoreceptors. The precision of this spatial localization is only limited by the signal-to-noise ratio in the system, since fluctuations in the receptor excitation will limit the precision and reliability of the calculation of position.
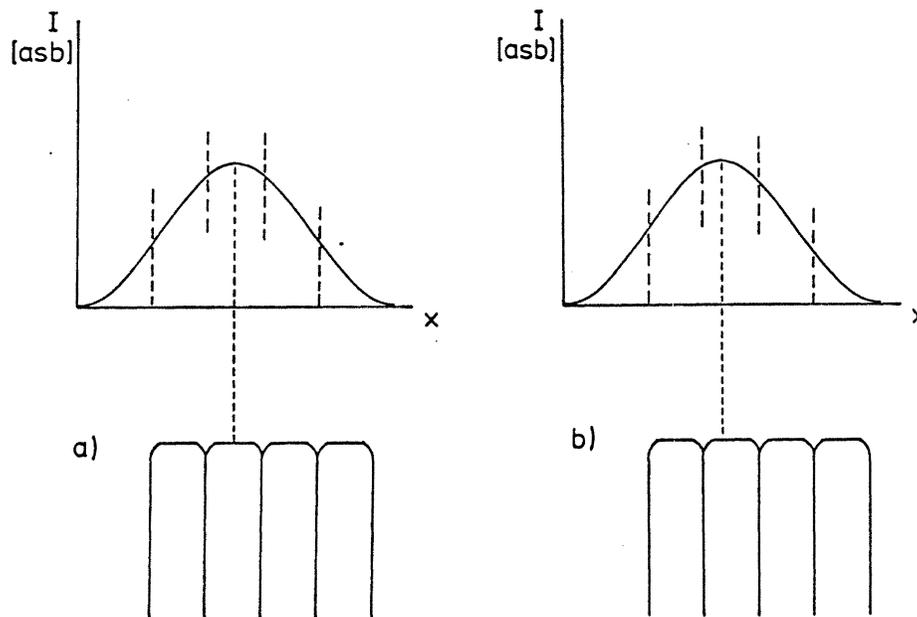
Fig.2 The optics of the eye transforms even the smallest point into a luminance distribution on the retina with a half-width of at least 20 arcsec, as indicated in the upper part. Thus, every retinal image will extend over several photoreceptors (receptors are schematized in the lower part). In (a), a bright point is located exactly on the middle of the photoreceptor and all surrounding photoreceptors are equally stimulated. If the point is moved even by a fraction of a receptor diameter, the neighbor on this side will be more strongly stimulated than the one on the opposite side (b). The ensemble of neighboring receptors can provide positional information beyond the receptor diameter.

These considerations can be proven formally. Shannon (1948) showed in the so-called sampling theorem that any function can be reconstructed completely if it is sampled at a sufficiently high frequency. The sampling frequency must be at least slightly more than twice the highest frequency present in the signal. As Barlow (1979) and Crick, Marr and Poggio (1981) have pointed out, the conditions of the sampling theorem are met in the human eye. The signal (the

luminance distribution coming from objects of the outer world) is bandlimited by the optics of the eye to spatial frequencies below approximately 50 to 60 cycles per degree (as mentioned above), and moreover, the modulation of the frequencies at the upper end of the transmitted range is rather small. The foveal photoreceptor density, corresponding to slightly more than 120 receptors per degree, samples this luminance distribution slightly more than twice for the highest spatial frequencies. Hence, appropriate filtering can reconstruct the original luminance distribution from the information of the single photoreceptors, in principle, with unlimited accuracy. In practice, of course, the precision in the filtering or interpolation process is limited by noise at different stages of the system and by several characteristics of the filters (cf., e.g., Wilson, 1986).

As Julesz (1971) has shown, stereoscopic depth is also experienced with visual noise, given binocular disparities between the otherwise identical images to both eyes. Circumscribed regions of noise sharing a common disparity are perceived at the same depth plane and their outline forms a shape. Stereoscopic vision thus allows us to perceive shapes defined by common depth and is another feat to break camouflage. Marr and Poggio (1976,1979) and Marr, Palm, and Poggio (1978) solved the underlying computational problems.

Optical image quality, blur, luminance, and contrast.

The cortical representation of the visual world in humans has a two-point resolution that is directly limited by the properties of the eye's optical apparatus and by the density of retinal photoreceptors. It is also limited by the convergence of photoreceptors upon ganglion cells, whose axons transmit the information about the visual world to the geniculate body from where it is relayed to the visual cortex. On the other hand, positional information can be obtained that is far more accurate than two point resolution. The attainment of such high positional accuracy or hyperacuity is made possible by the failure of the eye's optics to transmit spatial frequencies that are high enough to cause false resolutions ("aliasing") in the interpolation process.

Optimal computation of stereoscopic depth requires a sharp image, i.e., high spatial frequencies. The exact localization of the intensity maximum could in principle be calculated also from a very blurred image that contains only low spatial frequencies. But localization is much more difficult to achieve with shallow luminance gradients, as on the right of Fig. 3, than with steeper ones, as on the left of that figure, since in the second case the same amount of intensity noise corresponds to a much higher positional uncertainty or error than in the first. Therefore, it is to be expected that thresholds for stereoscopic depth perception depend on the luminance and especially on the contrast and sharpness or spatial-frequency content of the stimuli. Hyperacuity- localization indeed deteriorates with decreasing contrast in vernier acuity (Foley-Fisher, 1977; Bradley & Skottun, 1987; Krauskopf, pers. comm.; Westheimer, pers. comm.), the detection of spatial discontinuities (Morgan, 1986), as well as in stereoscopic depth perception (Lit, Finn & Vicars, 1972; Halpern & Blake, 1988; cf. also Frisby & Mayhew, 1978, for the stereoscopic contrast sensitivity function).
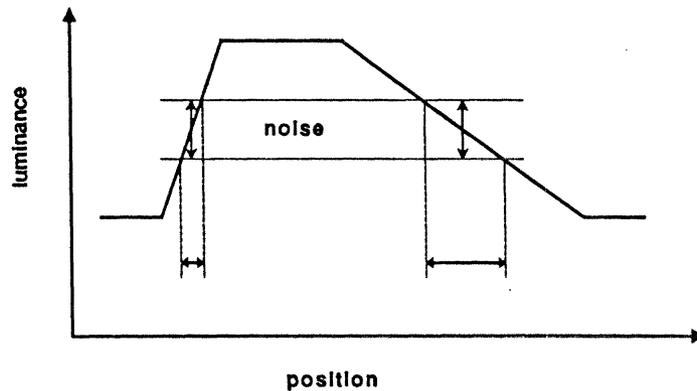
Fig. 3 Noise in the system with identical amplitude (e.g. receptor-noise; vertical arrows) leads to a larger positional error (horizontal arrows) in the determination of horizontal position of shallow luminance gradients (right side) than of steeper ones (left side).

Spatial resolution decreases, of course, with blurring caused by imperfect focussing, e.g., errors in refraction of the eye. As a rule of thumb, acuity — and the resolution of textures — decreases by a factor of 3-4 per diopter of refractive error (Diepes, 1975; cf. also Green & Campbell, 1965). Spatial resolution also depends critically upon the luminance and contrast of the test targets. Fig. 4, taken from Aulhorn (1964), illustrates the relation between resolution and luminance (cf. Ludvigh, 1941, for the effect of contrast).
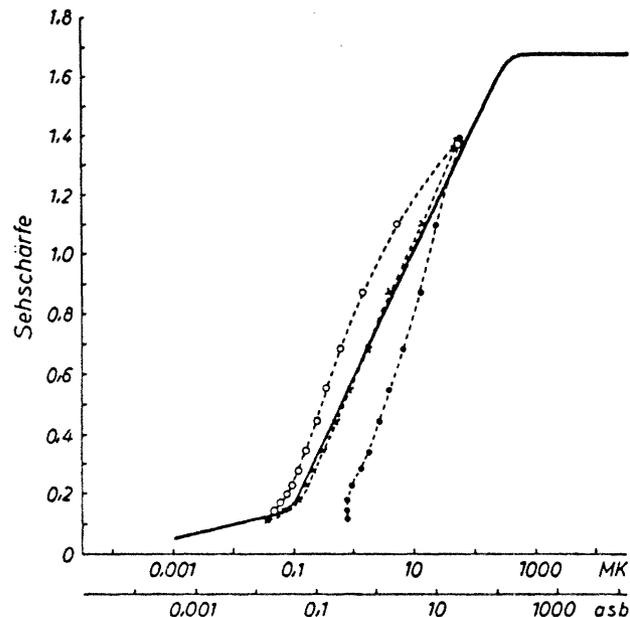
Fig. 4 Visual resolution as a function of the luminance of the test-stimuli increases almost linearly over a wide range to approach asymptotically the optimal level of performance. o-o: surround completely dark; solid line: data from König (1897); x-x: data of Aulhorn under conditions identical to Königs' ; ●-●: surround 10 asb (from Aulhorn, 1964).

As expected, thresholds for vernier discrimination (Krauskopf, pers. comm.) and for stereoscopic depth perception increase with blurring of the underlying retinal images. Stigmar (1971) measured the influence of optical image degradation, induced by spectacle blur, on stereoscopic depth perception and vernier acuity. Performance in a vernier detection and in a stereoscopic depth discrimination task deteriorated with blurring of the test targets — but less than spatial resolution did (cf. Fig. 5; and Foley-Fisher, 1977, for vernier acuity).
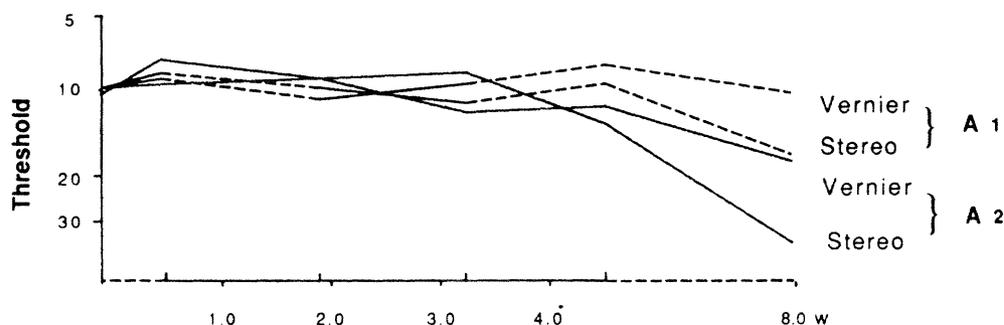
Fig. 5 The influence of stimulus blur on thresholds for vernier acuity and stereoscopic depth perception. Thresholds are shown on the ordinate (arcsec^{-1}), blur in diopters of spherical lenses on the abscissa, corresponding to half-widths of the stimuli between 0.5' and 7.6'. A_1 shows the results for abutting stimuli, A_2 shows results for stimuli with a gap (from Stigmar, 1971).

Julesz (1971) determined the dependence of stereo thresholds upon blurring in one eye. Performance was relatively good, even with one image considerably blurred. Julesz offered the explanation that the low spatial frequencies in both retinal images suffice to elicit the impression of depth.

Temporal factors

The number of quanta reaching each photoreceptor increases with stimulus luminance and presentation time. A given amount of noise inherent in the visual system's neuronal machinery will introduce a larger positional uncertainty for weak signals (elicited by fewer quanta) than for strong signals, and thresholds increase for shorter presentation times both for resolution (cf. Barlow, 1958; Olzak & Thomas, 1986) and stereovision (Fig. 6; Ogle & Weil, 1958). The contrast sensitivity function, i.e., thresholds for different spatial frequencies, also depends strongly on temporal frequency (Kelly, 1972).

Time is critical for fine stereoscopic depth discrimination in another respect. Stereoscopic depth perception is based on the computation of binocular disparities between simultaneously presented images of both eyes

(Wheatstone, 1838; Julesz, 1971). Thresholds increase with increasing asynchrony between the presentations of the targets to both eyes. But even when the presentations do not overlap in time, they may still elicit an impression of depth, probably mediated by some kind of visual spatial memory. This memory stores information for at least 200 msec, since presenting the images of both eyes alternately at a minimal frequency of about 5 Hz is sufficient to elicit a ·clear impression of stereoscopic depth (Guilloz, 1904; Ogle, 1963; Herzau, 1976). Interestingly, the subjective impression of depth is less when the stimuli are presented alternatingly to both eyes than when they are shown simultaneously. The larger the asynchrony in stimulus presentation to both eyes, the smaller the impression of depth elicited by these stimuli.
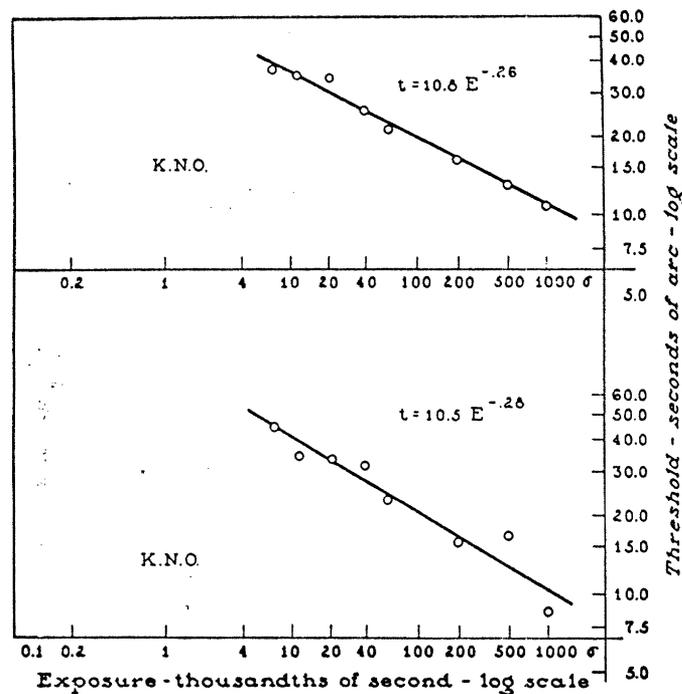
Fig. 6 Thresholds for stereoscopic acuity as a function of presentation time for stimuli slightly in front of (upper part) or on the fronto-parallel plane (lower part; from Ogle & Weil, 1958).

Retinal image motion.

Moving an object in the outer world while the eye is stationary, or moving the eye while the objects in the visual world are stationary, both cause a movement of the stimulus across the retina. A moving target stimulates each single photoreceptor for only a short time. The exact duration of stimulation depends on the relative velocity between the motions of the eye and of the object, as well as on the size of the retinal photoreceptors. The photoreceptor diameter in turn is a function of retinal eccentricity, i.e., distance and direction from the fovea centralis in man.

Resolution of moving gratings or Landolt C's decreases at velocities above 4 deg/sec (Westheimer & McKee, 1975; Burr,1979). Poggio and Reichardt (1973) for flies, and Diener et al. (1975), as well as Watson (1986) for humans have argued that detection of moving patterns depends on the product of spatial and temporal frequencies of the stimulus (see, however, de Graaf, Wertheim, Bles & Kremers, 1990). As a consequence, lower spatial frequencies should tolerate higher velocities than do high spatial frequencies. Performance at high temporal frequencies indeed deteriorates more for high spatial frequencies than for low ones (Kulikowski & Tolhurst, 1973). Therefore, resolvability of moving textures will generally decrease with increasing speed and increasing spatial frequency (corresponding, broadly speaking, to smaller texture elements), the amount of threshold elevation depending on the given texture and its speed.

Westheimer and McKee (1975) found that detection thresholds for vernier targets moving at velocities up to 4°/sec were basically unaffected (cf. also Morgan & Benton, 1989). This speed corresponds to a movement of the stimulus over approximately 500 foveal photoreceptors, leaving 2 msec of stimulation time for each photoreceptor. A stationary target presented for only 11, let alone 2 msec, had a significantly higher threshold, whereas the threshold for a 200 msec presentation of a vernier moving at up to 4°/sec corresponds roughly to that of a stationary vernier (Fig. 7; Westheimer & McKee, 1975). Thus, stereo thresholds are better if many photoreceptors are sequentially stimulated for a short time (as in moving targets) than if a single photoreceptor is shortly stimulated (as in a shortly presented stationary stimulus). The better results obtained with moving targets are another indication that the visual system is able to pool the information emanating from different photoreceptors.
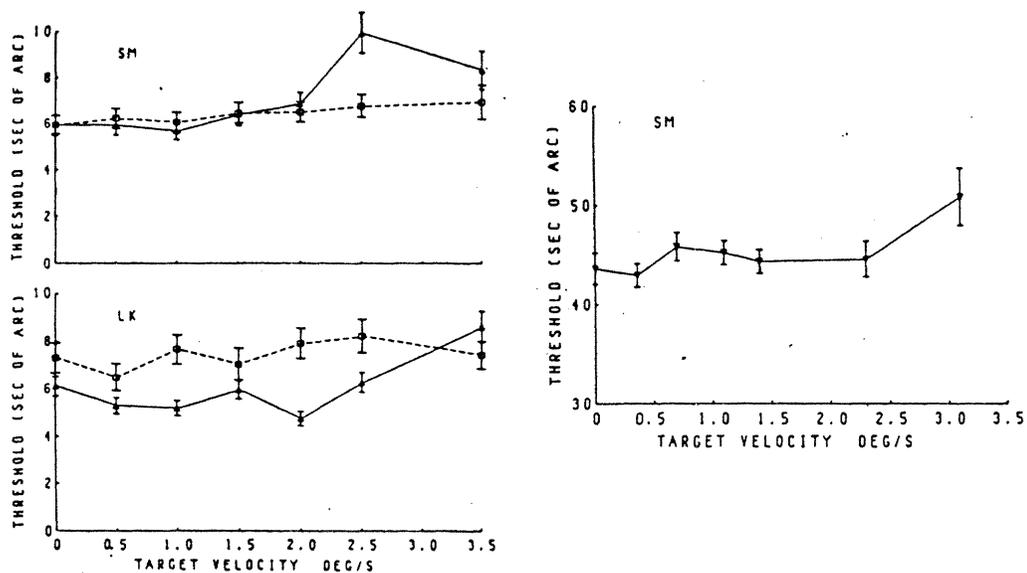
Fig. 7 Thresholds for vernier acuity (left part) and Landolt C resolution (right part) as functions of target velocity (from Westheimer & McKee, 1975).

Burr (1979) has measured thresholds for the correct identification of vernier offsets in continuously and discontinuously moving targets. His results are in close agreement with those by Westheimer and McKee (1975) in that motion with speeds up to 4 degrees per second does not increase thresholds in continuously moving targets. His results were confirmed in a study by Fahle and Poggio (1981) who additionally proposed a model for the pooling of information coming from different photoreceptors.

Stimulus area and retinal position

The size and information of the elements limits performance in texture discrimination, and the size of the textured area can be a factor of importance, as well (since the smaller the area, the less the degree of polarization in Gabor-filter channels). In hyperacuity tasks such as vernier acuity, the size and exact configuration of the stimuli are critical. Extensive experiments performed in different laboratories suggest the existence of a spatial integration zone. This integration zone is around 10 arcmin wide and 20 to 30 arcmin long in both vernier acuity and stereoscopic vision (Westheimer & Hauske, 1975; Westheimer & McKee, 1977; Butler & Westheimer, 1978; Watt, Morgan & Ward, 1983; Fahle & Kloos, unpublished).
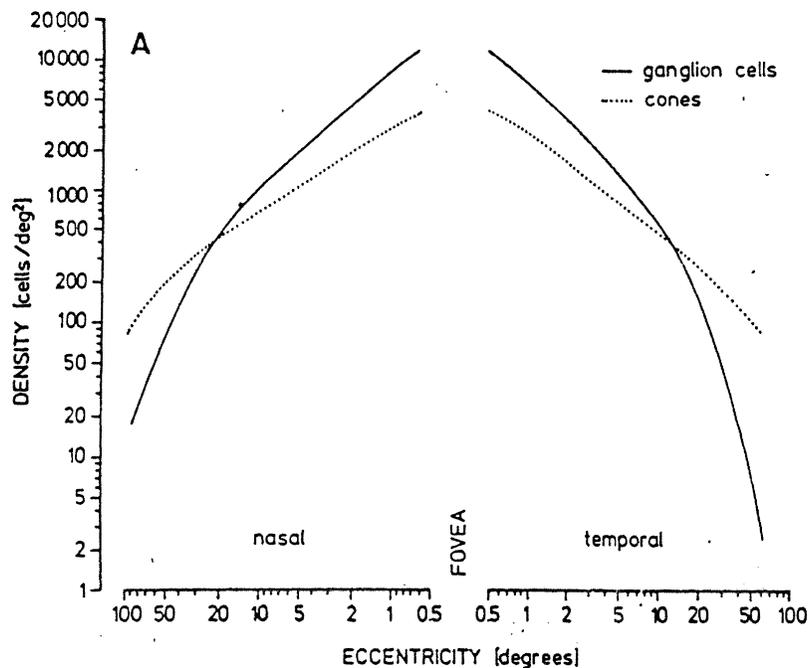
Fig. 8 Cone and ganglion cell density at different retinal positions (modified from Wässle et al., 1990).

Thresholds for most visual tasks depend critically upon the position of the stimulus in the visual field, i.e., on which part of the retina is stimulated. In humans, the photoreceptor density is by far highest in the fovea, mean distance

increasing by approximately a factor of 5 from the fovea to an eccentricity of 10°
(Curcio, 1987), and in monkeys the mean distance between ganglion cells
seems to increase by a similar factor (Wässle et al., 1990). The lower
photoreceptor- and ganglion cell density in the periphery causes a decrease of
visual resolution that seems to be proportional to the decrement of the density of
photoreceptors (Wertheim, 1894; Østerberg, 1935; Low, 1951; Weymouth,
1958; van Buren, 1963; Levi, Klein & Aitsebaomo, 1985; Wässle et al., 1990; cf.
also Rovamo & Virsu, 1979). Fig. 8 shows the decline in photoreceptor and
ganglion cell density in primates. For eccentricities above 5 deg., resolution is
limited by the retina rather than by the optics of the eye (Green, 1970).
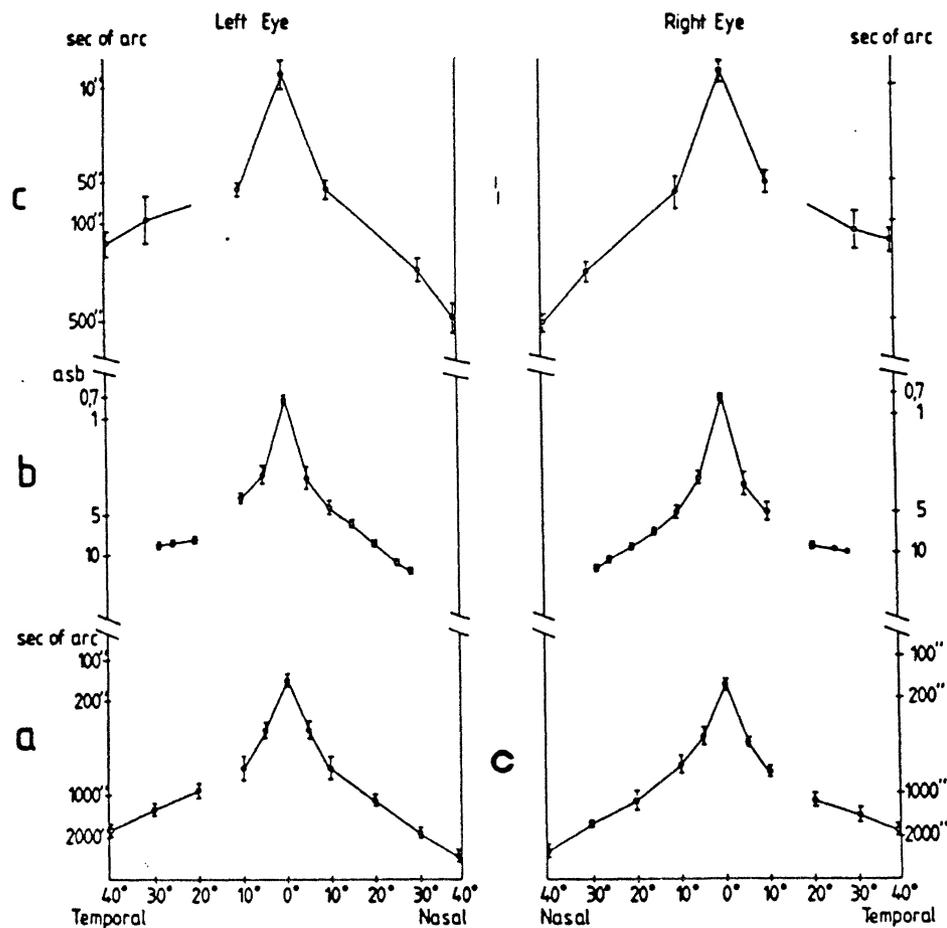
Fig. 9 Thresholds for Landolt C resolution (a), detection of differences in
luminance (perimetry; b), and vernier acuity (c) as functions of
eccentricity. A naso-temporal asymmetry appears in (a) and (b), but is
more pronounced in (c) (from Fahle & Schmid, 1988).

The decrease of stereoscopic depth perception and vernier acuity with eccen-
tricity is steeper than that of two-point resolution, both within the central part of
the visual field (Westheimer, 1982; Fendick and Westheimer, 1983; Levi et al.,

1985), and in the periphery (Fig. 9; Fahle & Schmid, 1988), and might be better approximated by the decrease in ganglion cell than in photoreceptor density (cf. Wässle et al., 1990). Incidentally, resolution at 30° eccentricity is around 30% better in the temporal than in the nasal hemifield. Hyperacuity, as measured by vernier acuity, shows a much stronger naso-temporal asymmetry of 200% at the same eccentricity (cf. Fig. 9; Fahle, 1983; Fahle & Schmid, 1988). The cortical projections of both eyes are similarly asymmetrical in the periphery of monkeys (LeVay et al., 1985), and the ganglion cells seem to be, too (Wässle et al., 1990).

Stereoscopic vision (and hyperacuity in general) is probably a feat of the visual cortex, as extensive interactions between the projections of both eyes occur exclusively there. Further clues for the cortical origin of hyperacuity are that only there, disparity sensitive neurons have been found (Poggio & Poggio, 1984), the existence of a kind of dichoptic vernier acuity (cf. McKee and Levi, 1987; Fahle, 1990), and that the optic nerve does not have a sufficient number of fibers to transmit explicitly-interpolated positional information as required for hyperacuity tasks (Fahle, 1988).

To sum up, both the perception of texture and of stereoscopic depth are limited by a variety of factors determined by the input device, such as the eye, and by the subsequent stages of information processing in the visual system. We have discussed here limitations imposed by the optical apparatus of the eye and by the retina upon spatial resolution and hyperacuity, by stimulus luminance, contrast, motion, temporal factors and retinal position.

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