The Resistance of Selected Hyperacuity Configurations to Retinal Image Degradation

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Traditional visual acuity is based on resolution of stimulus features, whereas hyperacuity (i.e., vernier acuity) is based on relative localization of stimulus features. Since resolution acuity is influenced severely by optical degradation, it is often not a suitable measure of the status of the retinal/neural visual system in conditions of optical degradation. In the present study, the authors investigate the effect of optical degradation on various relative localization tasks. Thresholds for three types of hyperacuity stimuli (line vernier, two-dot vernier, and line tilt) were measured under various degrees of image degradation, produced by viewing the targets through ground glass. The results indicate that when a hyperacuity stimulus is optically degraded, relative localization threshold increases only slightly for certain separations of the comparison features. In comparison with resolution acuity, hyperacuity threshold at the optimum feature separation is quite resistant to image degradation. This finding demonstrates a potential for the clinical application of hyperacuity as a test of visual function in the presence of cataracts and other media opacities. Invest Ophthalmol Vis Sci 25:389–399, 1984

Hyperacuity is a term that describes a special class of visual responses including vernier acuity, detection of line tilt, stereoacuity, and other related tasks. Common to these various responses is an extremely low performance threshold that is on the order of 3–5 sec of arc under optimal conditions, a value considerably below that of traditional visual acuity thresholds. In itself, the fact that a vernier acuity threshold of 3 sec of arc is nearly an order of magnitude smaller than the intercone spacing in the human fovea (25 to 30 sec of arc) implies that some additional information processing, beyond that available at the retinal level, is required for such fine relative localization of features in the visual field. Other properties of the hyperacuity response, e.g., the interocular transfer of the effects of interfering neighboring lines, also suggest a central locus within the visual system for the neural processing subserving this visual ability.

Our goal in the present study is to evaluate the influence of optical degradation of the retinal image on thresholds in selected hyperacuity tasks. In at least one respect, hyperacuity is not limited by the quality of the eye's optics. That is, under optimum conditions the half-width of the point spread function of the human eye is about 1 min of arc, a visual angle very close to the diffraction limit of an equivalent optical system and at least 10 times larger than the threshold in, for example, a vernier alignment task. One might expect that hyperacuity performance is similarly resistant to other optical influences, such as the type of image degradation that might be caused by a cataract or other ocular media opacity.

A test of visual function that is not affected greatly by a poor quality retinal image might be extremely valuable to the clinician faced with the problem of evaluating the functional integrity of vision behind an ocular media anomaly (corneal opacity, grossly irregular cornea, cataract, vitreous opacity, etc). In such cases, ophthalmoscopic imaging of the patient's retina in conjunction with standard (Snellen) acuity testing usually provides insufficient information to determine whether poor acuity is due to reduced image quality and/or a loss of visual function of retinal-neural origin. The data presented here show that certain aspects of the responses to selected hyperacuity stimulus configurations are resistant to rather severe image degradation, suggesting the potential for such clinical application. Furthermore, optimum hyperacuity responses are obtained with localized, foveal viewing of stimuli whose features are confined to 5- to 10-min arc visual angles. Hyperacuity may, therefore, be a good candidate for a test of foveal visual function in the presence of ocular opacities.

In this study, we investigate the stimulus parameters that affect the relationship between retinal image qual-
ity and hyperacuity performance and compare this to resolution performance under similar conditions of stimulus image quality. We chose ground glass blur as the method of producing stimuli with varying degrees of optical degradation. This method mainly attenuates the high spatial frequency components of the stimuli and, therefore, mimics the effects of a uniform type of opacity.\(^2\) The results show that alignment of degraded hyperacuity stimuli can be quite accurate, as long as the “center of gravity” of the blurred light distributions of the two stimulus components can be distinguished.

The following paragraphs provide a brief background of existing tests of visual function behind opacities, and how the hyperacuity test differs from the previously established methods.

Several optical and physiologic requirements must be satisfied for adequate performance on a visual acuity task, including good retinal image quality and intact information processing within the retina, optic pathway, and visual cortex. However, a defect in the optics of the eye, while resulting in poor resolution acuity (and in many cases precluding a direct view of the retina), need not make it impossible to evaluate the integrity of the rest of the visual pathway. Several tests are presently in use in the clinical environment, but unfortunately these generally fail when needed the most.

One of the more promising methods of assessing visual function in cataract patients is the technique of interferometric acuity. Two laser beams (emanating from a common source) can be passed through “windows” in a cataract to produce an interfering luminance grating on the retina.\(^8,12\) This method, if properly used, is likely to reflect the integrity of foveal function. However, if the grating pattern subtends a large area (such as the 5° fields typical of certain of these instruments), and if the stimulus is very bright, visual performance in parfoveal retinal areas is enhanced.\(^12\) These conditions can lead to relatively good acuity readings (eg, 20/30 to 20/50), even when the media are clear, and the central fovea is nonfunctional. Therefore, with clouded media, conclusions pertaining to foveal function based on interference acuity must be viewed with caution. Furthermore, in cases where effective and necessary windows in the opacity do not exist, interference may be compromised to the extent that readings cannot be obtained.

Other tests of visual function with the capability of “penetrating” ocular opacities have somewhat similar drawbacks. Flash and flicker VER (visual evoked response) and ERG (electroretinogram) techniques require bright stimuli in order to penetrate the cataract and elicit measurable responses. Even a small-field stimulus would be scattered by the opacity and stimulate relatively large retinal areas. Under such conditions, the peripheral retina might dominate a flicker sensitivity test, and foveal function could not be discriminated from peripheral retinal response.\(^13\) In another type of test (developed by D. L. Guyton and J. S. Minkowski), a Snellen acuity chart is presented in Maxwellian view through an opening in the opacity. However, in addition to requiring a clear window, this method works best for mild opacities.

Hyperacuity tests overcome the disadvantages of the interference acuity, VER, ERG, and other known tests. First, an opening or window in the cataract is not a prerequisite for obtaining a meaningful hyperacuity response. Second, hyperacuity falls off rapidly with retinal eccentricity,\(^6\) such that a normal fovea will produce much lower thresholds than any peripheral retinal area. Third, increasing intensity and contrast above critical values does not improve hyperacuity in the presence of blur as it does resolution acuity (ie, if the target can be detected, it can also be aligned) in a normal observer.\(^17\) Also, stimuli confined to small retinal areas (less than 30-min arc) produce the lowest thresholds.\(^18\) Thus, well-defined visual field points can be evaluated.

As we will show in the following report of results, selected properties of the hyperacuity response are relatively resistant to blur. This property can be understood once it is realized that hyperacuity is not a resolution task. The ability to resolve two small points of light is a function of the aperture and quality of the optical system. On the other hand, the ability to localize the position of a point of light relative to its surroundings is possible with blurred, low-contrast imagery. The “center of gravity” of the light distribution can be found with arbitrary precision when the signal/noise ratio is adequate, and when sufficient neural information processing functions are intact. The hyperacuities show remarkably low spatial thresholds because they reflect the relative localization capabilities of the human visual system.

The differences between resolution and localization can be considered constructively in the spatial frequency domain. In the extreme, visual acuity tests (Snellen letters, Landolt C’s, grating or checkerboard targets) are based upon differences in the high spatial frequency content of their Fourier spectra. Defects in the ocular media primarily reduce or distort the information in precisely this high frequency region. On the other hand, previous evidence suggests that relative localization of two features is dependent upon the integrity of the entire spatial frequency spectrum of the stimulus, not just the high frequencies.\(^17,19\)

The question posed in this report is: which type of hyperacuity configuration has the property of being most resistant to attenuation of high spatial frequencies? The results that follow quantify the effects of blur on three types of hyperacuity and establish norms for
the development of a clinical test of vision in cases of ocular opacity. Such clinical applications will be the subject of later reports.

Materials and Methods

A cathode ray tube (CRT) vector display system (HP 1350S) driven by a PDP 11/23 computer was used to display all stimulus patterns. The white (P4) phosphor was set at an intensity level such that a 1.5 mm by 1.5 mm uniformly lit screen area had a luminance of about 550 cd/m² (measured with a Pritchard photometer). The dark areas of the screen had a background luminance of less than 0.1 cd/m² under the room illumination conditions used during these experiments. All targets were composed of white lines on a 1022 by 1022 raster, spaced .17 mm apart. At the viewing distance of 5.7 m, this line spacing corresponded to a minimum target displacement of 6 sec of arc.

A typical hyperacuity experimental run consisted of 120 trials. On each trial a fixation pattern (four corners of a square, 30-min arc on a side) appeared for a fixed duration, usually .5 sec. The hyperacuity stimulus then appeared for .5 sec in 1 of 11 configurations. Thus, for a vernier target, the upper line could be horizontally offset one, two, three, four, or five units (multiples of the 6-sec arc raster unit) to the left or to the right of the lower line, or it could be aligned exactly horizontally with the lower line. Within a 2-sec inter-trial-interval, the subject pressed either a left or right response key corresponding to his or her judgment of the location of the upper line with respect to the lower line. If the response was incorrect, a large “X” was briefly flashed on the CRT screen. The direction of the offset was varied randomly from trial-to-trial and its magnitude on any single trial was determined according to the scheme described below.

Throughout the run, responses were recorded and periodically analyzed (every ten trials) by the computer. Using an adaptive probit estimation (APE) algorithm developed by Watt and Andrews, subsequent stimulus presentation parameters were adjusted dependent upon the subject’s current and past performance. At the end of a run, the proportion of “upper line to the right” responses was calculated for each target offset presented during the run, in order to generate a psychometric function ranging from 0% to 100% correct. Probit analysis was used to estimate the median and slope (and their standard errors) of the function relating probit value to stimulus displacement. The median (ie, 50% correct point) provides an estimate of the observer’s perception of alignment relative to true gravitational vertical alignment, while the slope is used to calculate the just detectable deviation (ie, 75% correct point) from perceived alignment that we defined as hyperacuity threshold. Each threshold plotted in the figures below was determined from a total of 240 or more trials obtained in two counterbalanced runs. Daily sessions lasted about ½ hr during which several different parameters were tested. Two such sessions were required to obtain the data for each blur condition.

Subjects were one of the authors and two students recruited from the School of Optometry at the University of California, Berkeley. All subjects wore appropriate, refractive corrections and viewed the stimuli binocularly throughout these experiments. The results presented here were collected after each subject’s hyperacuity performance had stabilized over a number of practice sessions (a total of 7,000 to 8,000 practice trials).

In order to systematically vary the amount of retinal image degradation, we placed a ground-glass plate between the CRT screen and the observer. When the ground glass is placed very close to the CRT screen, only the higher spatial frequencies are affected. As the CRT-to-glass distance is increased, the stimulus becomes more blurred and the attenuation of high spatial frequency information extends down to lower frequencies. These stimulus manipulations are shown graphically across the bottom of Figure 1, and the stimulus appearance is illustrated across the top of Figure 1. Close-up photographs of the stimuli (two-dot vernier) are shown with no ground-glass screen interposed (far right) and with the ground glass placed 10 cm, 20 cm, and 40 cm from the CRT screen. The curves shown below the photos plot the corresponding one-dimensional Fourier transform of the luminance profile of one of the stimulus dots, obtained by sampling the luminance of a small area of the screen as the stimulus was stepped horizontally across the CRT. Note that this is not the Fourier spectrum of the entire stimulus display as seen by the subject, but only of a one-dimensional cut through one of the stimulus lines. These Fourier spectra show that the unblurred stimulus consists of spatial frequency components up to 60 cycles/degree, and that the ground-glass blur produces an orderly and severe attenuation of high frequencies above approximately 10 cycles/degree (10-cm glass-to-screen distance), 5 cycles/degree (20-cm glass-to-screen distance), and 2.5 cycles/degree (40-cm glass-to-screen distance). As we show below, these severely degraded stimuli provide sufficient information for the relative localization process to function quite well.

Results

Results for two subjects using three different hyperacuity stimulus configurations are shown in Figures 2, 3, and 4. In Figure 2, the stimulus consisted of two dots (1 min arc by 1 min arc) vertically separated by
Fig. 1. Top, Photographs of the two-dot stimulus for the four blur conditions, ranging from maximum image blur (40-cm glass-to-screen distance) on the far left, to minimum (no ground glass) on the right. The widths at half-height of these luminance distributions are 21-min arc, 11-min arc, 6-min arc, and 1-min arc; from left to right. Note that even when the stimuli are most blurred (left), the "center of gravity" of both the top and bottom comparison features is apparent and localization is possible. Bottom, Fourier amplitude spectra for the four corresponding stimuli are plotted (see text for details). In both panels, conditions from maximum blur to focus change from left to right.
Fig. 2. Hyperacuity thresholds for the two-dot vernier stimulus (each dot subtends 1-min arc × 1-min arc) are plotted as a function of the vertical gap separating the two dots for various amounts of stimulus blur: (O) no blur, (⊙) 10-cm blur condition, (□) 20-cm blur condition, (Δ) 40-cm blur condition. A, Subject RW; B, Subject GP.
quires judging the tilt of a single line relative to a vertical one. The metric, in this case, is the uppermost curve shows that with spatial frequencies above 3 cycles/degree almost totally eliminated, hyperacuity is remarkably good, as a threshold of only 22-sec arc is attained with a 16-min arc gap. The results plotted in Figure 2B for subject GP are similar, as both subjects show an orderly increase in both optimum gap and threshold as blur is increased. The results from these two subjects suggest that the spatial limits (ie, gap) for optimum hyperacuity performance generally increase in proportion to the amount of blur.

Results for a vernier alignment task with lines 10-min arc long and a variable-sized vertical gap are shown in Figure 3. Curves for focused, moderate blur, and severe blur are included for two subjects. Similar to the two-dot vernier task, blur has a more severe effect on alignment threshold at the small gap sizes. However, for this stimulus configuration, the threshold versus gap curves are not as clearly differentiable as they are for the two-dot stimulus. With increasing blur, the effect of changing the gap diminishes, and the function relating threshold and gap loses its distinctive shape.

Another type of relative localization stimulus requires judging the tilt of a single line relative to a vertical one. (No separate comparison stimulus, as such, is presented.) The metric, in this case, is the relative linear displacement of the upper end of the line with respect to the lower end in seconds of arc of visual angle. The results plotted in Figure 4A, B indicate that with well-focused stimuli, a line 8- to 16-min arc in length is optimum for this task for the two subjects. Longer and shorter lines produce higher thresholds for detection of tilt.

The effect of blur on the thresholds for this task is similar to the results for the vernier tasks in that the detection of line tilt for short lines is affected more severely by blur than for longer lines, and the optimum line length (for minimum threshold) increases with blur. However, several differences between the vernier and line tilt hyperacuity judgments are apparent. Most important is a comparison of the effects of blur on the two-dot vernier task with 16-min arc gap and on the line tilt task with a 16-min arc line (eg, subject RW, Figs. 2A, 4A). When the stimuli are degraded severely (40 cm glass-to-CRT condition), displacements less than 30-sec arc can be detected in the two-dot stimulus, whereas the upper end of a single line must be displaced by almost 100-sec arc before the line can be seen as tilted from the vertical. Thus, in the comparison of these two stimuli, although blur tends to affect the shapes of the threshold curves similarly, it affects their magnitude very differently. As in the previous task comparison, two apparently similar hyperacuity responses are affected very differently by image degradation. Due to these considerations, the two-dot hyperacuity target provides the better stimulus for distinctly assessing and minimizing the effect of blur.

The way in which various amounts of blur alter threshold on a resolution acuity task and on the two-dot hyperacuity task are compared in Figure 5. A stimulus consisting of a square with a central bar that could be oriented either vertically or horizontally was used as the resolution target. The target was generated in a fashion analogous to a Snellen optotype, such that the widths of the elements making up the stimulus were proportional to the size of the whole figure. Thus, a line element size of 1-min arc would be used to generate a square block figure that is 5-min arc on a side. (This stimulus was used in order to minimize the contribution of relative luminance cues. For example, when a Snellen “E” is viewed through image-degrading ground glass, one side of the blurred image is brighter than the other, providing the observer with a cue to the orientation of the symbol.) Resolution thresholds were determined by a method analogous to the hyperacuity experiment using the adaptive probit algorithm. A range of target sizes was chosen to obtain a psychometric function that varied from 0% to 100% correct. The observer’s task was to indicate whether the central bar was horizontal or vertical by pressing one of two buttons. Threshold was defined as the line element size which would produce a 75% correct response, estimated by probit analysis.

The top curve in Figure 5 shows the increase in resolution acuity thresholds (determined with the stimulus described above) with increasing blur. Hyperacuity performance for very small gaps (eg, 1-min arc gap; diamond symbols) is affected by blur in much the same way as resolution performance, indicating that at these gaps, hyperacuity threshold is nearly a constant fraction of resolution threshold irrespective of amount of blur. At larger gaps (eg, 32-min arc gap, circle symbols) hyperacuity threshold remains fairly flat across levels of blur, indicating that hyperacuity is affected at a much slower rate than is resolution acuity as blur is increased. The effect of blur on optimum hyperacuity performance can be seen by plotting the lowest hyperacuity thresholds obtained for each blur condition, as a function of blurred line width (bottom curve). This curve shows that with increasing...
Fig. 3. Hyperacuity thresholds for a vernier stimulus consisting of two vertical lines, 10-min arc long, are plotted as a function of the vertical gap separating the inner end points of the lines, for different blur conditions. Symbols are as in Figure 2. A, Subject RW; B, Subject BM.
Fig. 4. Hyperacuity thresholds for a tilting line stimulus (line width = 0.2 min arc) are plotted as a function of the length of the line, for the different blur conditions. Symbols are as in Figure 2. A, Subject RW. B, Subject GP.
blur, optimal hyperacuity performance deteriorates only slightly, in marked distinction to the large affects of blur on resolution acuity.

Discussion

Our main goals in this study were to quantify the effect of degradation of the stimulus retinal image on selected hyperacuity responses, and, thereby, define a type of hyperacuity configuration that could be useful for clinical assessment of visual function in the presence of ocular opacities.

Our results show that relative localization of stimulus features is possible to very precise levels when the retinal image is degraded severely. Since we have used a type of image degradation that acts essentially as a low-pass spatial filter (Fig. 1), we can conclude that the visual process that generates the hyperacuity response is not dependent on high spatial frequencies only. The integrity of spatial frequency components below 2 to 10 cycles/degree is sufficient to generate a precise, relative, feature localization in certain conditions. Conversely, the results also suggest that under certain circumstances, high spatial frequency components are very important for the hyperacuity mechanism. For example, when the two stimulus features are placed close together (less than 4- to 8-min arc apart), even moderate blur has a large effect on the alignment threshold, and this effect seems to parallel the effect on resolution acuity.

The consequences of blurring the two-dot hyperacuity stimuli are illustrated in Figure 6. In each blur condition, the curves shown in Figure 2 exhibit an optimum feature separation (gap) where threshold is lowest. Optimum gaps of approximately 4-, 8-, 16-, and 24-min arc are indicated for subjects RW and GP for no blur, 10 cm, 20 cm, and 40 cm blur conditions, respectively. In Figure 6A, we have plotted the three-dimensional representation of the spatial luminance profile of the two-dot stimulus with no blur and the optimal gap of 4-min arc. In this case, the luminance profiles of the two dots do not overlap at all, and contrast is very high. The corresponding stimulus profile in the 10-cm blur condition with the optimal 8-min arc gap (Fig. 6B) shows that contrast is reduced by about a factor of four, but distinct, separate peaks of the two luminance profiles are still present. In the 20-cm and 40-cm blur conditions (Figs. 6C, D), the peaks of the luminance profiles are separated by the optimal gaps of 16- and 24-min arc, respectively. Contrast is severely reduced, and the luminance distributions overlap substantially to fill in the gap between the peaks. In fact, a comparison of Figure 2 and the plot in Figure 6D indicates that even when the two
Fig. 6. Luminance profiles of the two-dot vernier stimulus are shown for the four blur conditions: A, focused; B, 10-cm screen-to-glass distance, C, 20-cm screen-to-glass distance; D, 40-cm screen-to-glass distance. The spatial separation between the peaks of the distributions selected are 4-min arc in A; 8-min arc in B; 16-min arc in C; and 24-min arc in D. Note the increase in horizontal scale from A through D.

dots are blurred to the extent that they can just be resolved, the alignment threshold is still less than 30-sec arc.

As stated above, a second goal of this study was to design a hyperacuity test to assess visual function in the presence of ocular opacity. Hyperacuity taps a unique visual response that is sensitive to both feature separation and blur. Clinically, a desirable test is one for which large changes in response are observed with changes in stimulus parameters, but which also is resistant to changes in nonstimulus variables, eg, optical blur. The two-dot vernier configuration, of the three we tested, seems to be most sensitive to feature separation (gap between the dots) and least affected by blur. The threshold versus gap function maintains a U-shape even when the stimuli are blurred, and the minima of the U-shape curves yield a threshold measure less affected by blur than standard resolution acuity. For gaps larger than 16-min arc, blurring the stimulus has a very small effect on the hyperacuity response. On the other hand, the line orientation task is more severely affected by blur, and the vernier task with 10-min arc lines does not exhibit a unique shape for the threshold versus gap function with varying blur conditions. Thus, the two-dot configuration appears to be the best candidate for a useful clinical test.

In summary, low-pass spatial filtering of selected hyperacuity stimulus configurations increases both the spatial limits for the optimum hyperacuity response (optimal gap) and hyperacuity threshold levels. However, features can be aligned precisely even when the combined two-point blur distribution may or may not
be resolved. A vernier acuity test configuration consisting of two small points of light separated by a gap ranging from approximately 2 min to 2 deg seems well-suited to clinical application in cases of media opacities, since thresholds at the optimum spatial separation (gap) are less affected by image degradation than is resolution acuity.

The potential utility of the hyperacuity test in the evaluation of vision behind media opacities is dependent upon the results of several additional steps in its development as a clinical tool. First, a more rapid means of assessment must be devised for routine application. Second, the relationship between the various parameters of hyperacuity performance (eg, gap, eccentricity) and resolution acuity must be established within a clinical population. Third, the extent to which losses in these two measures parallel one another under conditions of optical and/or retinal-neural anomaly must be investigated. These three points have been addressed successfully in separate studies in this laboratory.22 Hyperacuity measurements were obtained in a number of cataract patients with otherwise normal visual systems and in patients with retinal lesions for whom we degraded artificially the stimuli to simulate the effects of cataracts. The relationship between hyperacuity threshold and gap is a very sensitive indicator of the optical-degrading effects of the cataract. On the other hand, the variation of threshold across eccentricity is rather independent of image degradation but very sensitive to relative retinal function. Results from our initial clinical trials of these techniques indicate that optically-based visual loss can be distinguished from loss due to a combination of media opacity and retinal lesion. Thus, the present report defines the most useful parameters of the hyperacuity stimulus, while our subsequent studies will describe the successful application of hyperacuity as a clinical tool.

Key words: hyperacuity, vernier acuity, relative localization, resolution, visual acuity, image degradation, ocular opacity simulation

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