Visibility of Gradients and Low Spatial Frequency Sinusoids: Evidence for a Distance Constancy Mechanism

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A substantial number of variables affect the visibility of sinusoidal displays. The luminance, spatial frequency (cycles per degree), the number of cycles of sinusoid, and the extent of average-luminance areas adjacent to the sinusoid all affect the observer's sensitivity to a particular experimental target. The experiments that quantify these multivariable relationships also show that changes in display size on the retina have a remarkably small effect on the visibility of a display. These experiments demonstrate a constancy for the visibility of objects despite changes in viewing distance that is reminiscent of other constancies studied by Gestalt psychologists.

Numerous experiments by many authors have made the use of linear systems analysis as applied to the human visual system a familiar topic. The advantages of this type of analysis can be documented by its wide use in optics, theoretical image processing, image evaluation, and a variety of psychophysical experiments studying the human visual system. The use of this analysis is quite satisfactory for optical applications, but attempts to model the entire human visual system require complex models to account for a variety of experimental results. The simplest linear system model is one in which the visibility of any target is predicted by multiplying the Fourier spectrum of the target with the "Modulation Transfer Function" (MTF) of the visual system. This model has been an extremely stimulating heuristic but is generally described by friend and foe alike as incomplete.

One problem is that many "MTF" curves characterize the visual system. Van Ness and Bouman,[1] Campbell and Robson,[2] and Savoy[3] measured visual contrast sensitivity functions at different luminance levels. The results show that one must use a distinct contrast sensitivity function for each particular luminance.

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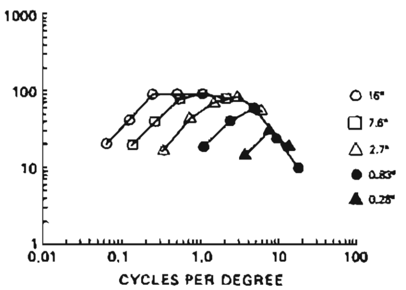

Figure 1. Contrast sensitivity vs. spatial frequency (cycles per degree). The data indicated by ○ were obtained when the square, sinusoid portion of the target subended 16°; □ subtended 7.6°; △ subtended 2.7°; ● subtended 0.83°; and ▲ subtended 0.28°. For each of the five retinal sizes of the display there is a different "MTF" curve. The curves coincide at high values of cycles per degree, but are distinctly different at low values.

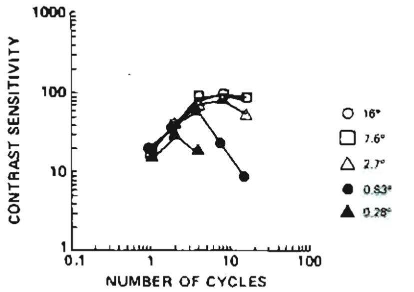

Figure 2. Contrast sensitivity vs. number of cycles. These data are the same as shown in Fig. 1. In this figure the horizontal axis is the number of cycles in the target instead of the spatial frequency. The fact that all the low number-of-cycles data fall on a single line shows that the number of cycles can be used to predict contrast sensitivity to low-spatial-frequency sinusoids.

A wide variety of experiments[4–9] has shown that a different contrast sensitivity function must be used if the display size on the retina is varied. Figure 1 shows five different contrast sensitivity functions measured with five different retinal sizes.[8] In this experiment the CRT display was 8 cm square; the central 5.2 cm square varied sinusoidally in luminance. The rest of the display was a uniform luminance equal to the average luminance of the sinusoidal display. The experimenter chose the spatial frequency of the sinusoidal portion, and the observer adjusted the sinusoid contrast to be at threshold. The data described by open circles were measured when the observer sat 18 cm from the display so that the sinusoid subtended 16°. The second set of data, identified by open squares, was measured with the identical display but with the observer seated at 38 cm so that the sinusoid subtended 7.6°. The remaining three curves were measured with the observer at 107, 351, and 1039 cm so that the sinusoids subtended 2.7°, 0.83°, and 0.28°. Clearly, each size display generated a different "MTF" curve. The curves coincide at high spatial frequencies, and all five curves are distinctly different at low spatial frequencies.

Figure 2 shows what happens when we replot the data in the first figure as contrast sensitivity vs. number of cycles. Here all the low-spatial-frequency data form a single curve, implying that the only information necessary to predict the contrast sensitivity of a particular target is the number of cycles. Regardless of the size of the targets and hence regardless of nominal spatial frequency, observers have the same contrast sensitivity to a one-cycle target within the range of 0.28° to 16°. The juxtaposition of the conclusions drawn from Figs. 1 and 2 gives us a simple description of the experimental results. For each size of display the observer's contrast sensitivity function has a different shape. Sensitivity falls off a both high and low spatial frequencies. The high spatial-frequency data coincide on the spatial frequency (cycles per degree) graph while the low number of cycles data coincide on the number of cycles graph. In order to predict the contrast sensitivity for any particular size one needs to determine if the spatial frequency is above the peak of the contrast sensitivity curve. If it is greater than the peak, then contrast sensitivity depends on the spatial frequency. If it is below the peak of the curve, then contrast sensitivity depends on the number of cycles.

Recently we discovered a substantial dependence of sinusoidal threshold on nonsinusoidal parameters of the display.[8] Figure 3 shows a series of targets in which the sinusoid dimensions are constant and the amount of average-luminance flank on either side of the sinusoid is varied. Below each target diagram are the average contrast sensitivities for two observers. The observers have contrast sensitivities of 13 and 14 for the sinusoid in a black surround, whereas they have sensitivities of 70 and 51 to the same sinusoid with a 9.4° average-luminance flank added to each side. In this experiment the area of the retina covered by the 12° × 20° target is 16 times that of the 12° × 1.25° target. To be certain that our experimental results were not affected by fluctations in the size of the natural pupil we repeated the experiment using a 2.5-mm artificial pupil. We did not find a significant change in contrast sensitivity due to the substitution of the artificial pupil for the natural one.

All of the experiments cited above show that we must specify spatial frequency, luminance, number of cycles, and the nonsinusoidal parameter of flank width in order to predict observer contrast sensitivity. These same experiments that have demonstrated complex, multi-variable relationships have also provided some fascinating systematic results. They suggest a new generic hypotheis: namely, the human visual system is designed to give a constant response for all viewing distances. Of course, objects can subtend such small visual angles that the system cannot resolve them. This diminished visibility is equivalent to attenuation of sensitivity to frequencies higher than the peak of the "MTF" curves. The

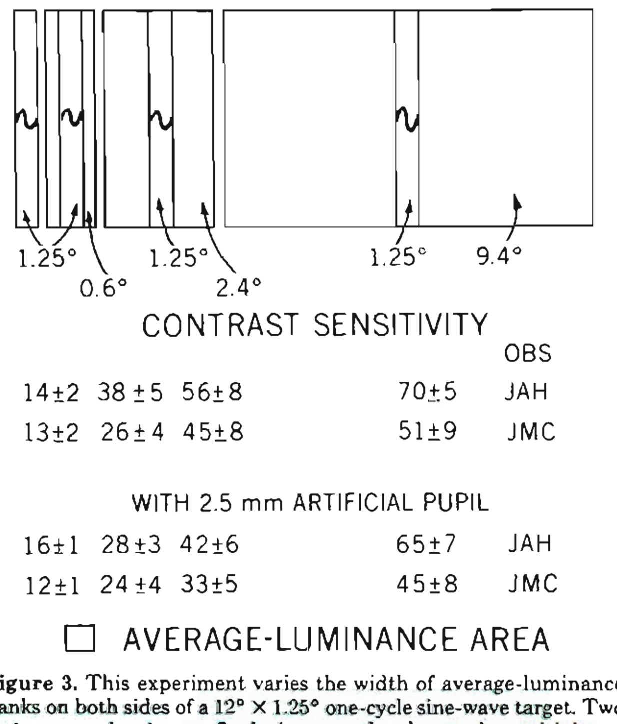

Figure 3. This experiment varies the width of average-luminance flanks on both sides of a 12° × 1.25° one-cycle sine-wave target. Two 9.4° average-luminance flanks increase the observer's sensitivity to the sine wave by roughly a factor of four. Nearly identical results were obtained with and without a 2.5-mm artificial pupil.

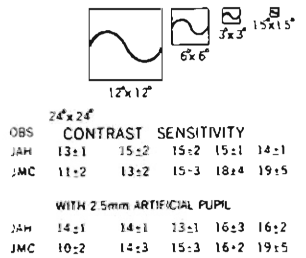

Figure 4. Target visibility as a function of viewing distance is measured by threshold contrast sensitivity. This experiment varies both the height and the width of one-cycle sine-wave targets by increasing the distance between the constant-size display and the observer. Contrast sensitivity remained essentially constant despite a 16 to 1 change in linear dimensions and a 256 to 1 change in area. Nearly identical results were obtained both with and without a 2.5-mm artificial pupil.

new hypothesis is that the composite visual system gives a distant-invariant response for any display *at low spatial frequencies.* This hypothesis is reminiscent of Gestalt observations of size, brightness, and color constancies. In "distance constancy" visual sensitivity to low-spatial-frequency components remains constant independent of the distance between the observer and the object. In other words, despite the fact that the image changes in size on the retina, the object has a constant appearance provided the components of that object are of lower frequency than the peak of the MTF curve. The experiments that have shown a dependence on number of cycles provide substantial support for the existence of a distance constancy mechanism.

We begin with the data from contrast threshold measurements. The observer is asked to adjust the amplitude of a sinusoidal modulation about a mean display luminance until the modulation is just visible. The data for two observers using a sinusoid target with a black surround[9] are shown in Fig. 4. The targets varied from 24° × 24° to 1.5° × 1.5°, a factor of 16 in linear dimension and a factor of 256 in area. Since each target had only one cycle of sinusoid, the nominal spatial frequency varied from 0.04 to 0.7 cycles/degree. One observer reported no change in contrast sensitivity while the other reported a change from 11 ± 2 to 19 ± 5, that is, a change by a factor of 1.8. The introduction of a 2.5-mm artificial pupil did not produce a significant systematic change in contrast sensitivity for any target. All of the targets have one cycle of sinusoid and all have essentially the same visibility. Despite changes in spatial frequency of the sinusoid by a factor of 16, the observer reports an essentially constant threshold as a function of viewing distance.

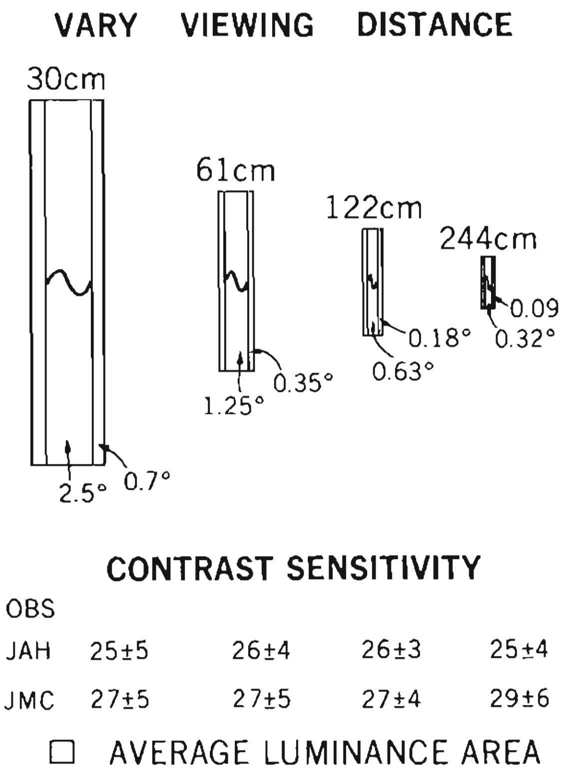

Figure 5. Target visibility as a function of viewing distance is measured by contrast sensitivity. Tall, thin targets give results very similar to those for square targets. Despite large changes in sine-width, spatial frequency of the display, and average-luminance flank width, the two observers report essentially constant target visibility at different viewing distances.

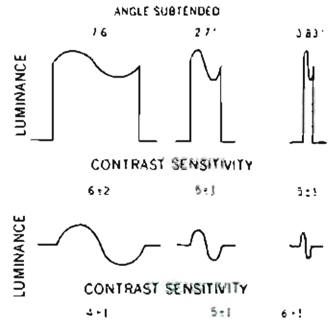

Figure 6. Target visibility as a function of viewing distance is measured using a contrast matching experiment. Here the observer adjusts the contrast of the sinusoidally varying target until it appears to have the same contrast as a one and one-half cycle standard with a contrast of 0.1. The observer chooses the same suprathreshold contrast despite changes in viewing distance. The figure shows diagrams drawn to scale of target contrasts chosen to match the standards along with numerical values of the matches expressed as contrast sensitivity. The upper part of the figure shows matches to a sinusoid with a black surround while the bottom half of the figure shows matches to a sinusoid with an average-luminance surround. Despite changes in viewing distance the observer makes essentially the same match.

Similar experiments with a sinusoidal portion surrounded by an average-luminance portion gave very similar results. Here the sinusoidal portions subtended 16°, 7.6°, 2.7°, 0.83°, and 0.28°. The proportions of average-luminance dimensions to sinusodial dimensions were fixed. The surround was 4° on all four sides of the 16° sinusoid, and so forth. The averages of two observers' contrast sensitivities were 21, 20, 19, 17, and 15. Again the observers gave essentially the same threshold at all viewing distances. Using similar displays with two cycles of sinusoid gave contrast sensitivities[9] of 37, 41, and 44 for 16°, 7.6°, and 2.7° sinusoids. The remaining targets with two cycles had spatial frequencies at or above the peak of the contrast sensitivity curve. When the same size targets had 4 cycles, the averages of two observers' sensitivities[9] were 81, 67, and 70. At greater viewing distances the spatial frequencies again become greater than the MTF peak.

Very similar results were found using tall, thin sinusoidal patterns instead of square ones. The data in Fig. 5 show very little change in contrast sensitivity as a function of viewing distance.[9] These experiments using average-luminance surrounds are of particular interest when one recalls the experimental results shown in Fig. 3. Changes in width of average-luminance flank adjacent to the sinusoid have a sizable effect on the visibility of the sinusoid. In the present experiment, we vary the width of the flank at the same time we vary the width of the sine wave. Since the observer reports that the visibility is essentially constant, we might conclude that the effect of flank width depends on sine width and that proportional changes in both leave contrast sensitivity unchanged.

An object's visibility can be characterized by other proce-

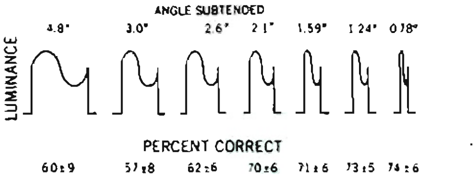

Figure 7. Target visibility as a function of viewing distance is measured by the percent correct identification of the orientation of the octogonal one-cycle sinusoidal display. These values are the averages of the values for eight observers each of whom made 16 observations. The results are expressed as the mean plus and minus one standard error in order to represent the variability among many observers. Despite changes in viewing distance the observer identifies the orientation of the display with constant accuracy.

dures, such as matching the apparent contrast of a target to a standard target. In experiments of Savoy and McCann[6] the observer was given a 0.1 contrast, 1.5 cycle target as a standard and asked to adjust the contrast of other targets with different numbers of cycles until they appeared to have the same contrast. This experiment was performed at three different viewing distances. Figure 6 shows the results of these contrast matches, by displaying luminance profiles of two sets of three targets that were chosen to match the standard. One set used an average-luminance surround around both the test sinusoid and the standard; the other set used a black surround around both. We also represent the results using the variable "contrast sensitivity." Since the experiment used contrast matching instead of contrast threshold, the values are proportionally smaller. The results show that suprathreshold visibility is constant despite changes in display size on the retina due to different observer distances.

Another technique of measuring threshold visibility is to ask the observer to detect the direction of a gradient or a grating. McCann et al.[5] performed experiments in which the observer had to choose one of four possible orientations. For this experiment they prepared seven octagonal targets, 4 cm on a side. They chose the octagonal shape so that they could use a four-alternative forced-choice procedure; the subjects were asked to identify the orientation of the gratings from four possible orientations. Reflectance was constant in one direction, but in the perpendicular direction the reflectance varied sinusoidally. When the display was not visible, the observer could do no better than chance or 25% correct. When the display was clearly visible, the observer could identify the orientation 100% of the time. We defined 63%, the mid-point between 25 and 100%, as threshold of visibility. With one-cycle sinusoidal targets a particular target was correctly identified 60% of the time when it subtended 4.8°. Figure 7 shows the results for seven observer distances that cover retinal sizes from 4.8° to 0.78°. The results in terms of percent correct are 60, 57, 62, 70, 71, 73, and 74. Again visibility is essentially constant despite changes in viewing distance.

A related experiment[5] used linear gradients of luminance. We used square targets in which reflectance changed along one axis and remained constant along the perpendicular axis. Again, the observer was asked to identify the direction of the gradient. We studied at five distances a target that was correctly identified 68% of the time when it subtended 4.8°. The percents correct for these five viewing distances were 68, 79, 68, 70, and 74. Luminance profiles of the target, drawn to scale, along with angular sizes and rates of change of luminance on the retina are shown in the top half of Fig. 8. The bottom half of the figure shows five targets with the same five angular sizes as above, but this time all targets produce the same rate of change of luminance on the retina. The visibility varies from 93% correct to 77, 68, 54, and finally to 48% correct for the smallest target. As already shown with sinusodial targets, visibility does not depend on the rate of change of luminance

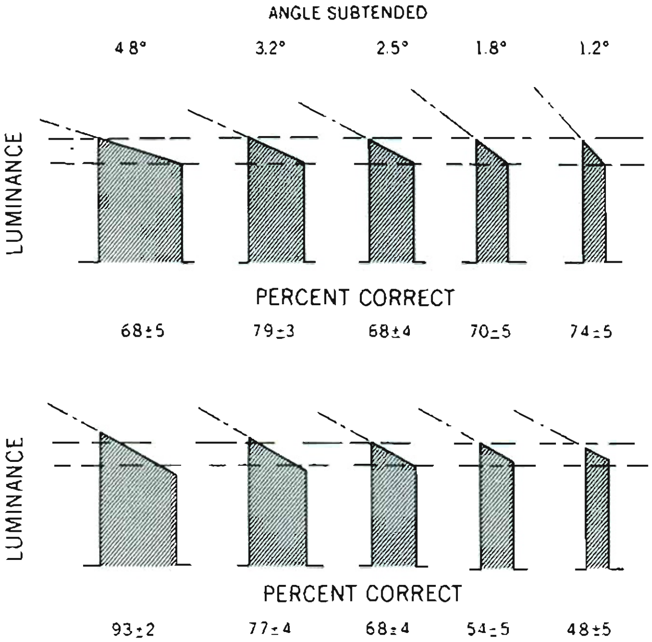

Figure 8. (top). As in the previous figure, visibility as a function of viewing distance is expressed as percent correct identification of orientation. The gradients are linear. The data shown are the mean plus and minus one standard error of the mean for 12 observers with 16 trials per observer. Again visibility is essentially independent of viewing distance.
(bottom). These targets have identical rates of change of luminance on the retina but different target sizes. Visibility varies from 93 to 48% correct, which demonstrates that rate of luminance change on the retina is not the dominant variable for the visibility of linear gradients. These identical rates of luminance change were produced by five targets of different contrast viewed from five distances. All five targets exhibited similar independence of visibility from viewing distance.

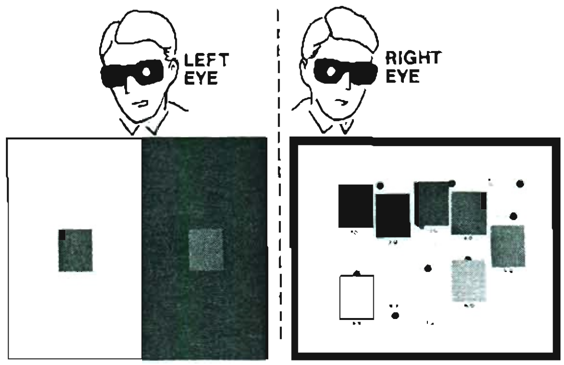

Figure 9. This diagram illustrates the lightness-matching experiments used to quantify the changes in lightness due to a white and an adjacent black surround. The observer was asked to find a match in a standard array of lightnesses (right eye) for each area in the display to be studied (left eye). The standard array provides a constant surround around each chip, a constant illumination falling on each chip and as much as possible a constant state of adaptation because the observer's right eye sees only the standard display. The left eye views a series of different displays in which the size of gray areas and the size of black and white surrounds are varied. The chips in the standard are experimentally chosen by a bisection procedure so the lightness difference between each adjacent chip is the same for each step from 1 to 9. If the observer does not find an exact match in the standard, he is instructed to interpolate to the nearest tenth of a lightness unit.

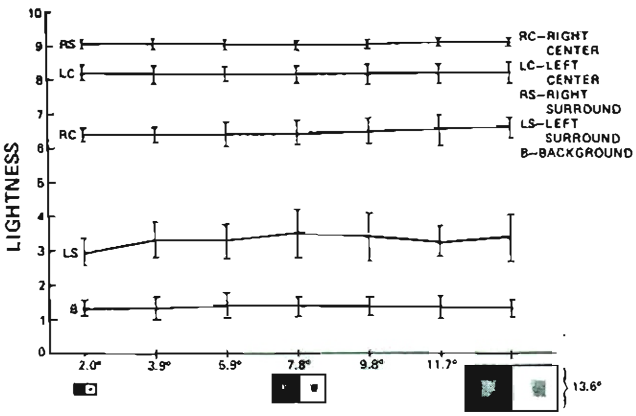

Figure 10. Visual response as a function of display size is measured by the lightness of the matching areas. The vertical axis is lightness chosen by observers and the horizontal axis is the size of the entire display. The data are the mean plus and minus one standard deviation of the mean for five observers. The table on the right identifies each area. Of particular interest are the left center (*LC*) and right center (*RC*) gray areas that have identical luminances. Despite changes in size equivalent to viewing distance changes, the effects of surrounding white and black areas are constant.

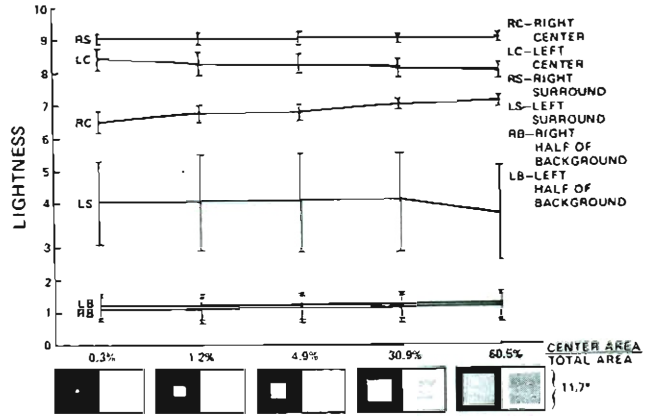

Figure 11. In a set of experiments parallel to those shown in Fig. 10, the sizes of the white and black surrounds were held constant while the sizes of the identical luminance gray areas were changed. Here the matching lightnesses for areas *LC* and *RC* change considerably.

on the retina. Instead, a particular contrast target has a constant visibility.

The final set of experiments uses very different psychophysical techniques as well as a very different kind of target. We study the effect of display size on targets that show changes in lightness due to the surrounding areas. The target shown in the left half of Fig. 9 consists of two gray papers: one on a white surround and one on a black surround. Despite the fact that the two gray areas send the same luminance to the eye, they do not appear the same lightness.*

We used a lightness matching technique[10] in which the observer chose a lightness in a standard display to match each area in the test targets. In one set of experiments the overall size of the target varied from 13° × 26° to 2° × 4°. The proportion of central gray area to surrounding white and black areas remained constant. The observers were asked to match the right center (*RC*), left center (*LC*), right surround (*RS*), and left surround (*LS*) to the standard. The difference between lightnesses matching areas *RC* and *LC* is a measure of effects of the surround as we change display size. As shown in Fig. 10 the values of *RC* and *LC* are constant. The effect of the surround is constant. The changes in these targets are the same as those produced by having the observer view a single target at a variety of distances. Again it appears that there exists a mechanism that gives a constant visual response despite changes in viewing distance.

A second very similar experiment is to leave the size of the surrounding areas constant and to vary the size of the pair of central areas that have identical luminances. Diagrams of targets and experimental data are shown in Fig. 11. Again the areas of interest are *RC* and *LC*. Here the proportion of center area to surround changes, and the observer reports a change in lightness of both *RC* and *LC*. Whatever the mechanism responsible for the different gray sensations, it has a constant effect when the proportions of the target are held constant. We reach the same general conclusion from these lightness-matching experiments that we have with other types of experiments. Changes in display size that mimic changes in viewing distance produce a constant visual response. Changes in the size of individual areas that upset the proportions of the target cause changes in visual response.

One may choose to analyze these results in either the object domain or in the Fourier domain; in simple models one is merely a transformation of the other. With more complex models which include thresholds, other discontinous or nonlinear functions, transformations between the object and Fourier domain are not as easy. Regardless of one's preference of domain, the visual system has a mechanism that generates a constant response when the display changes with viewing distance.

In summary, experiments using many different targets and many different experimental techniques document the constancy of vision as a function of observer distance or target size. This paper has described experiments using targets with linear gradients, low-spatial-frequency sinusoids with both black and average-luminance flanks, and simultaneous contrast targets. These experiments use threshold contrast, contrast matching, forced-choice orientation detection, and lightness matching as measures of visibility. In each case, the visual system reports constant appearance over a wide range of image sizes and spatial-frequency values. Instead of attempting to analyze the visual system in terms of responses to spatial frequency, number of cycles, and flank width, it may be productive to begin by finding a mechanism that can account for constant visual appearance despite change in retinal size.

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*This phenomenon should not be confused with certain adjacency effects in photographic development in which areas having identical exposure develop to different densities because of different rates of developer oxidation in the surrounding areas.