

Digital enhancement of television signals for people with visual impairments: Evaluation of a consumer product

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Abstract — Technology to improve the clarity of video for home-theater viewers is available utilizing a low-cost enhancement chip (DigiVision DV1000). The impact of such a device on the preference for enhanced video was tested for people with impaired vision and normally sighted viewers. Viewers with impaired vision preferred the enhancement effects more than normally sighted viewers. Preference for enhancement was correlated with loss in contrast sensitivity and visual acuity. Preference increased with increased enhancement settings (designed for those with normal vision) in the group with vision impairments. This suggests that higher enhancement levels may be of even greater benefit, and a similar product could be designed to meet the needs of the large, growing population of elderly television viewers with impaired vision.

Keywords — Low vision, macular degeneration, image enhancement.

1 Introduction

There are over 3 million people with impaired vision in the U.S., and their numbers are increasing steadily with the aging of the population.¹ Central field loss, caused by diseases that damage the central retina, such as macular degeneration and diabetic retinopathy, has a particularly disabling effect on visual function. As the natural retinal locus of high-resolution vision (the fovea) is damaged, patients learn to use a peripheral part of their retina for detail vision, the preferred retinal locus (PRL).² However, contrast sensitivity and acuity decline with retinal eccentricity (the distance of the PRL from the fovea).

A simulation of vision with central field loss may be seen at <http://www.eri.harvard.edu/faculty/peli/>, under the "Videos/ Simulation" page.

The human visual system is responsive over a range of spatial frequencies. A normally sighted person can see gratings of spatial frequencies up to about 25 or 30 cycles/deg. Higher levels of contrast are required for the gratings to be seen as the spatial frequencies increase.^{3,4} The inverse of the contrast detection threshold is defined as the contrast sensitivity. Individuals with visual impairment require higher levels of contrast than normally sighted persons to see most stimuli, and the differences are greater as spatial frequencies increase. This loss in contrast sensitivity can be thought of as having a low-pass filtering effect, although it is actually a nonlinear threshold effect. At some critical frequency, no level of presented contrast is sufficient for the stimuli to be seen. This critical frequency, and the overall contrast sensitivity, vary with the severity of impairment. Figure 1 shows the contrast sensitivity of a normally sighted subject compared with that of subjects with impaired vision

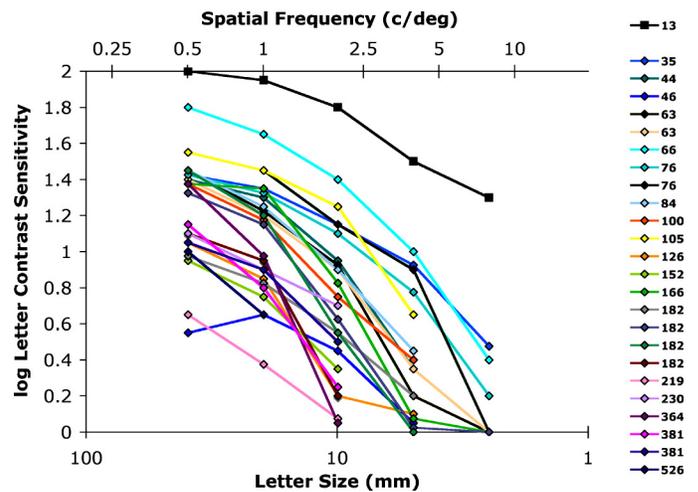


FIGURE 1 — Contrast-sensitivity function measured for letters of varying sizes. As the fundamental spatial frequency (in cycles per degree) of the letters (based on 2.5 cycles per letter) increases, the contrast sensitivity decreases. The sensitivity of all the people with visual impairments is substantially lower than the sensitivity of a normally sighted subject (13, author MF) and decreases more rapidly with frequency, illustrating the low-pass nature of the impairments. The legend shows the denominator of Snellen acuity at 20 ft. (20/X). Contrast sensitivity is defined as the inverse of the contrast threshold needed to recognize the letter.

who participated in this study, illustrating the nature and range of the loss in sensitivity. Most subjects with impaired vision could not recognize low-contrast letter stimuli of fundamental spatial frequencies above 4 cycles/deg at any contrast.

People with vision impairment watch television regularly and to a similar extent as normally sighted viewers.⁵ When asked what they miss in the TV picture, low-vision patients (including our participants) report that they cannot

Extended revised version of a Distinguished Paper presented at the 2007 SID Symposium, Seminar & Exhibition (SID '07) held in Long Beach, California, May 20–25, 2007.

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see the details and expressions on people's faces, sometimes to the point of failing to identify who is who in the scene. Neither can they read text on the screen. Some report difficulty following a storyline when they fail to identify a character.

Patients with poor central vision frequently use magnification to increase the size of the image on the retina, which shifts the higher-frequency details into lower frequencies and, therefore, greater contrast sensitivity. Magnification of a TV picture can be achieved with optical devices, such as spectacles and head-borne telescopes. Magnification may also be achieved by sitting closer to the TV, increasing the size of the TV screen, or via electronic zooming of the displayed images.⁶

Increasing image contrast using image processing has been proposed as an alternative or supplement to magnification to make video images more visible to patients with visual impairment.^{7,8} Early applications were inspired by the Adaptive Enhancement algorithm,^{7,9} a high-frequency enhancement that adapts the level of enhancement to local image characteristics. However, those early implementations did not include the adaptive aspects. Yet, the effect of enhancing the higher frequencies' contrast has been shown to be beneficial to these patients, improving their ability to recognize faces from static black-and-white images.^{10,11} DigiVision (San Diego, California) has manufactured a series of devices that perform the same (non-adaptive) enhancement in real time.¹² Several studies using these devices in our lab have shown that patients prefer the enhanced video to the original¹³⁻¹⁵ and had a small improvement in reading rate of enhanced text.¹⁶ These devices, however, have not yet been marketed to the vision-impaired public, mainly because of their high cost.

A recently developed CMOS chip (DV1000, DigiVision) performs similar real-time processing as the earlier, far larger and expensive systems, with additional functionality. In particular, it enables a variety of local adaptations. The DV1000 processes digital video (up to 1080p HDTV resolution) and is designed to be integrated within display devices. The end-product manufacturer may restrict or organize these features in various ways to tune the device for a specific application. One such product, RazorVision (Belkin International, Compton, California, <http://www.pureav.com/razorvision/>), was designed to be used as a simple in-line cable-TV enhancer. It features three preset enhancement levels – Low, Medium, and High. It is supplied only with HDMI/DVI connectors, because it is aimed at the high-definition (HD) viewer market and has not been marketed to those with visual impairments. The RazorVision device retails for about \$250, making the cost of image enhancement realistic for the low-vision market for the first time. DigiVision provided us with a computer-controlled implementation of the system, with the default settings being those used in the RazorVision model.

The purpose of this study was to investigate whether people with vision impairments would perceive any benefit from using this consumer product and whether they could

differentiate between the three preset enhancement levels provided.

2 Methods

2.1 Experimental setup

We presented a sequence of six short video clips, selected to represent various types of programs seen on TV.¹⁷ The videos were taken from DVDs and played using the VLC media player (www.videolan.org). Subjects were seated 3 ft. away from and centered between two 27-in. adjacent standard-definition TVs (approximately 42 in. diagonally from the center of either TV, each spanning about 27° horizontally from that distance). The source video was split so that an unprocessed version was available along with the DV1000-processed version. The two versions were presented on the two TVs, in a counterbalanced sequence described below, and the subjects were asked which TV picture they preferred (forced choice). Subjects with visual impairment were asked which picture appeared clearer to them, whereas normally sighted subjects (to whom the effect of the image processing was often evident) were asked simply for their preference. Subjects were encouraged to move their head appropriately to examine the two TV pictures.

The TVs were identical in so far as they were both of the same model, bought at the same time, and from the same store. They did not come from the same batch number, so we could not be sure of equal manufacturing specifications. In the default factory setting, the picture did not appear to have equal brightness and contrast on both screens, so one TV was adjusted slightly until the picture display appeared subjectively equivalent, using both moving video and static test-pattern generator signals. Only the brightness and contrast controls were adjusted, on the left-hand television. The experiment was designed to be tolerant to differences in image display on each television (see below).

Unlike the RazorVision commercial model, the device we used provided analog S-Video input and output, using analog-to-digital and digital-to-analog circuitry surrounding the DV1000. The device controls allowed selection between an Off mode and the three preset levels (Low, Medium, and High). The Off mode transmitted the video with no enhancement processing (though A/D and D/A processing was still performed). Examples of the effect of these preset enhancement settings are shown in Fig. 2. The DV1000 control software allowed selection of the active mode. While the software enables changing many of the internal parameters of the system, the default settings matched those of the RazorVision model and were not modified in the current study.

Sixteen times during the video presentation, the enhancement level in use by the device and the television (right or left) to show the processed video were selected by the experimental control software. Two sets of the four orders of enhancement level (Off, Low, Medium, and High) were randomized, one for each television. Of the 70 possible

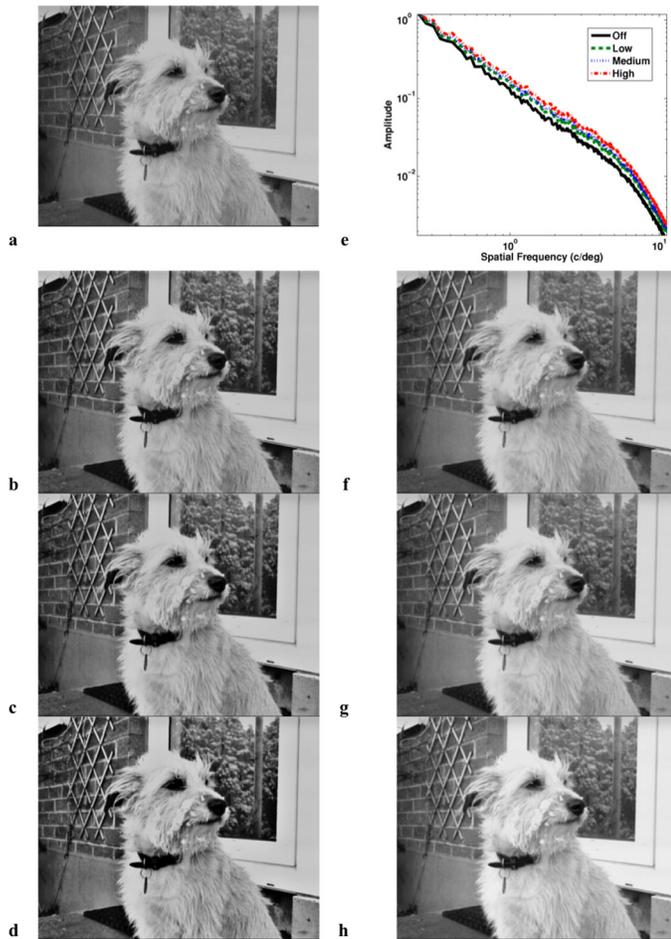


FIGURE 2 — Illustration of the video processing of the DV1000 device used in the study. (a) No enhancement (off), (b) low, (c) medium, (d) high enhancement. The enhancement effect varies according to the local spatial-frequency content of the image and the local luminance; note, for example, the enhancement of details in the tree reflection in the window and the enhancement of contrast of the dog's facial features, but the reduction of visibility of smaller details in and around the eyes. Similarly, the high contrast of the collar against the light fur results in masking of finer details on the collar itself. The device settings (Fig. 3) can be tuned to achieve optimal results for an intended application/image. (e) Spatial frequency amplitude spectra of the image results of all four settings, given in cycles/degree assuming the seating setup used in the study (showing radial-averaged FFT amplitude). Frequencies between 0.3 and 8 cycles/deg are shown, as this is where the patients' losses are greatest (see Fig. 1) (f–h). For comparison, the gray levels of the image shown in (a) were shifted and expanded such that its minimum, maximum, and midpoint $[(L_{\max} + L_{\min}) \times 0.5]$ luminance were equal to the DV1000-processed images. No local enhancement of features is apparent, and smaller details are not affected by increased local contrast elsewhere. DV1000 images were recorded using the luminance component only of the S-Video output into a Canon ZR85 camera and captured using Adobe Premiere 6.5 (Adobe Systems, Inc., San Jose, California). The color component is omitted for clarity; the bulk of the effective enhancement is done in the luminance channel only.

orders of four in eight television selections, 24 were selected at random. The sequence was repeated for a total of 16 presentations. This randomization ensured that four presentations of each enhancement level were made per subject, with each presented on both televisions twice. Equal presentations of conditions on both screens ensured no false bias of preference for any enhancement level due to display dif-

ferences or subject bias, though such effects could mask a real preference (see Sec. 2.4). The 12 normally sighted control subjects (see Sec. 2.3) viewed 12 of these same 24 presentation sequences, selected at random.

The switching of the processed and unprocessed video presentations between the two TVs was achieved using an Extron MMX 42 SVA RCA video-switching unit (Extron Electronics, Anaheim, California). This device accepts up to four S-Video and audio inputs and can switch any of these to one or both of two S-Video and audio outputs. The device can be controlled via an RS-232 serial cable. The custom-software program started video playback at the correct video, set the video switch to output the processed and unprocessed videos to the appropriate TVs, controlled the DV1000 software to select the correct enhancement level,^a and recorded the subject's choice of preferred image.

The sequence of videos was started at a video determined by subject number; *e.g.*, the sequences for subjects 1 and 7 began at video number 1. Not all subjects saw all of the available videos, as the sequence length varied depending on individual response time, often not exceeding the length of the first video presented. Audio was provided to the subjects at a low level.

2.2 Image enhancement

The adaptive enhancement algorithm, as applied in the DV1000, is illustrated in Fig. 3. The system first applies a low-pass filter (averaging over a Gaussian kernel window) to the image, x , to produce a mean local luminance image, \bar{x} . Subtracting \bar{x} from the original image provides an unsharp (high-pass filtered) version.^{8,19} For NTSC-resolution video (used here), the size of the averaging kernel used in this operation (which determines the spatial frequencies being enhanced) can be varied from 3.4% to 19.6% of horizontal screen size. The Gaussian kernel size of 9.8% of screen width (full width at half maximum) used in the RazorVision product was applied here. The high-pass filtered version is then amplified by an enhancement gain control, c . The value of c applied at every pixel is the product of a number of multiplicative gain functions, including those based on \bar{x} and x at the corresponding pixel. Typically higher gain is applied at moderate values of both x and \bar{x} than near the extremes of the luminance range. This is done to avoid image distortions due to saturation and cut-off at the bright and dark ends of the luminance range, respectively,²⁰ and represents the first adaptation aspect of the algorithm. Other gain functions are available in the DV1000 (Fig. 3), but were not used here. The enhanced high-pass version of the image is then added to a modified version of the local luminance mean, \bar{x} . The modified \bar{x} , called the background, can also be adjusted adaptively (as a function of \bar{x}), although

^aThe data presented here were obtained using a modified version of the system/software that prevented errors we believe added noise to data previously reported.¹⁸

all cases where $p \leq 0.038$). The data from these subjects were removed from subsequent analyses. The vision-impaired subjects' blind spot and better eye status agreed with the TV bias side (two to the left and two to the right). Of the remaining 20 subjects with vision impairment, seven had no left/right bias, five had an insignificant left bias, and eight had an insignificant right bias. A number of the normally sighted subjects noted slightly higher levels of red in the right-hand television, and the one discarded normally sighted subject data had a bias to the right. Of the remaining 11 subjects without vision impairment, two had no left/right bias, six had an insignificant left bias and three had an insignificant right bias. We confirmed this (small) color difference was present using a photometer characterization of the displays used (this showed a slightly higher red luminance in the right television (by 0.73 cd/m^2 on average), and a slightly higher green (by 0.22 cd/m^2 on average) and blue (by 0.22 cd/m^2 on average) luminance in the left-hand television). Data without significant side bias was pooled across the presentation side for each subject so that their preference for each level of enhancement (proportion of four responses) was known. In this preliminary and in all subsequent analyses an alpha level of 0.05 was used. Non-directional (two-tailed) p values are given for the remaining tests.

Due to the discrete nature and non-normal distribution of the data, non-parametric tests were used for the subsequent analyses, and exact rather than asymptotic significance values were calculated. Kendall's Tau-b (τ) was used as a measure of correlation between visual impairment and number of presentations preferred at each enhancement level. The low number of responses per enhancement level in our data led to many "ties," where rank order increases in one variable but is tied (static) in the other. The Kendall's Tau-b (τ) test corrects for such ties in the data. The Friedman test (χ^2) gives a measure of how much the use of different treatments (enhancement levels in our case) affects an outcome (number of preference responses) from the same subjects. Because a large change in response was expected between the Off and other (real) levels of enhancement, the test was also applied across the three levels of enhancement only. When this test shows significance, it is typically followed by a test that compares pairs of treatments; here the Wilcoxon Signed Rank test (T) was used. This allowed each level to be compared against the preference for the Off mode, thus examining the preference for the effect of the algorithm rather than any potential side effect of the A/D and D/A processing. It also allowed differences in preference within the three levels to be tested for significance. In addition, the total proportion of Off responses was compared against a uniform distribution of no preference (2 out of 4), also using the Wilcoxon Signed Rank test. To compare the differences in preference between the vision impaired and normally sighted groups, the two-sample Kolmogorov-Smirnov test (D) was performed. This gives a measure of how different the population distributions are. For the two measures where a significant difference between

populations was found, a permutation test was performed to ascertain if there was a significant change in the mean value (rather than simply a change in the distribution). The test establishes the proportion of permutations of the data that have a group mean greater than or equal to the overall mean observed.²⁴ All tests were carried out using SPSS version 14 (SPSS Inc., Chicago, IL) except for the permutation test,²⁵ which was implemented using Matlab (The Mathworks, Natick, MA). Power calculations were performed using StudySize version 2.0 (CreoStat HB, V. Frolunda, Sweden). Data from this study is available on our Web site (<http://www.eri.harvard.edu/faculty/peli/>).

3 Results

Figure 4 shows that the subjects with impaired vision had a clear preference for the enhanced video at all levels of enhancement. The Friedman test shows a significant effect on preference of the change in enhancement level only when the Off mode was included in the analysis ($\chi^2_{3,20} = 22.3$, $p < 0.0001$) but not among the 3 levels of enhancement ($\chi^2_{2,20} = 2.84$, $p = 0.272$). This finding was confirmed by the Wilcoxon Signed Ranks test where only the differences between each level of enhancement preference and the Off mode were significant ($T_{19} \geq 97.0$, $p \geq 0.004$). There was a small preference for the Off level over the unprocessed image (0.53), which was shown on the other screen without passing through the system (see Sec. 2.1). This preference was not found to be significant ($T_{19} = 40.5$, $p = 0.833$).

Figure 4 also shows the results for the normally sighted subjects. The preferences for enhancement clearly differed between the two groups. Here the effect of a change in enhancement level was also significant ($\chi^2_{3,11} = 8.59$, $p = 0.030$). While the normally sighted controls showed a preference for the lowest level of enhancement, they

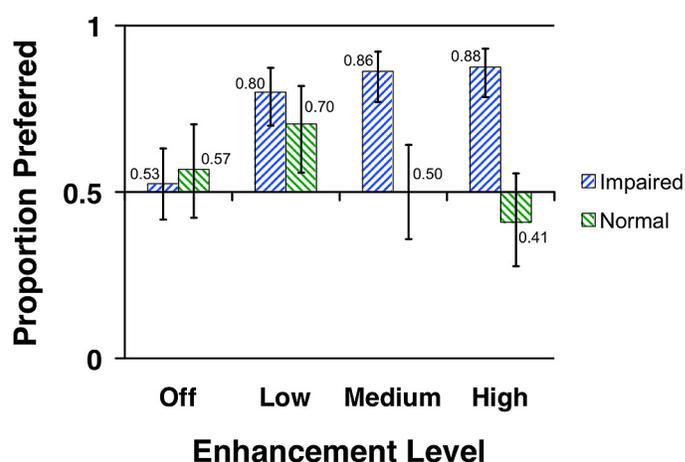


FIGURE 4 — Proportions of video presentations preferred at the various enhancement settings in comparing the enhanced to the unprocessed video for the impaired and normal-vision groups. 0.5 represents an overall level of no group preference either way. Levels above this represent a preference for the enhancement; levels below represent an overall rejection of the enhancement relative to the original. The error bars represent the 95% confidence intervals.

rejected the device more frequently as enhancement increased, showing a significant change within the three levels of enhancement ($\chi^2_{2,11} = 9.83, p = 0.005$), unlike the vision-impaired group and a significant paired difference between the Low and High levels ($T_{10} = 0.0, p = 0.004$). Here, too, there was a preference for the off level over the unprocessed image (0.57). This preference was also not found to be significant ($T_{10} = 6.00, p = 0.531$). A test of the difference in the distribution of enhancement preferences between the two groups shows significance at the Medium and High enhancement levels ($D_{20,11} \geq 0.445, p \leq 0.018$). Permutation tests reveal a significant change in the mean at the Medium ($M_{20} = 3.45, M_{11} = 2.00, 1 \times 10^6 - 1$ permutations, $p = 0.002$) and High ($M_{20} = 3.50, M_{11} = 1.64, 1 \times 10^6 - 1$ permutations, $p = 0.001$) enhancement levels.

For the vision-impaired subjects, the preference for the Low enhancement level was significantly negatively correlated with contrast sensitivity at 2 and 8 cycles/deg ($\tau_{19} \leq -0.405, p = 0.027$) and approached significance at 1 cycle/deg ($\tau_{19} = -0.355, p = 0.053$). Acuity (in logMAR, where higher values indicate poorer vision) was positively correlated with the preference for the Low enhancement level ($\tau_{19} = -0.440, p = 0.017$).

4 Discussion

We found that subjects with a wide range of central retinal vision impairment were able to see the effect of the DV1000 device from the distance they typically use for TV viewing (shorter than that used by normal viewers). They showed a clear preference for the enhancement, even at the modest enhancement levels designed for normally sighted people. In contrast, normally sighted subjects preferred the enhanced images only for the Low level, had no preference for the Medium level, and rejected the High level enhancement (this latter effect was significant when compared to the level of preference for the Low level). This rejection (or lack of preference) by the normally sighted subjects may be due to the close viewing distance used in our study. At this distance, which was shorter than that normally used by these subjects, the enhancement was applied at lower spatial frequencies (already visible to the normally sighted). Evaluation of the preference by normally sighted users of the system should be carried out at the normal viewing distance. Higher spatial frequencies present in HDTV pictures (for which the commercial version of the product was designed) were not present here. We also noted a degradation of the picture sharpness and some luminance saturation with the inclusion of the video-splitting equipment used. This may have reduced some of the higher frequencies available for enhancement, making normally sighted subjects more likely to reject the enhancement of a sub-standard picture. Future studies of this enhancement with normally sighted viewers should utilize higher fidelity equipment.

The preference among the vision-impaired subjects for the enhancement increased with increasing levels of

enhancement (Fig. 4), although a significant change was not found within the range of enhancement levels (Low to High). The number of subjects and number of tied differences within subjects (due to the low number of responses per enhancement level collected per subject) limited the power to find a significant effect of the Wilcoxon Signed Ranks test to at best 15%, when examining the small differences between preference for different enhancement levels in the vision impaired population shown in Fig. 4. To examine more rigorously the change in preference at different levels of enhancement would require more responses, giving more possible levels and hence fewer ties.

We would expect that further enhancement would eventually lead to image distortions that will be rejected by the viewers (vision-impaired subjects). The finding of such a rejection effect in the normally sighted group supports this expectation. However, it is likely that even higher levels of the enhancement we used could be beneficial for people with impaired vision, as the peak of the function may not have been reached. A similar device could easily be developed for this population, providing higher levels of enhancement – and possibly enhancing different (lower) spatial frequencies. Distortions caused by this method of enhancement may be reached at a relatively low level due to local image saturations.²⁶ The more fully locally adaptive capabilities of devices such as the DV1000, combined with newer, high-dynamic-range displays,²⁷ may reduce this limitation by providing higher dynamic range for these higher levels of enhancement (within the light and dark areas of the image prone to saturation). We are planning follow-up studies that will explore the value of the wider range of parameters available, with standard displays as well as high-dynamic-range displays and will attempt to identify the useful range of enhancement.

We found significant correlation between the preference for level of enhancement and the vision-impaired subjects' visual acuity. There was also significant correlation with contrast sensitivity. These correlations were only at the Low level of enhancement. The lack of a relationship at the two higher enhancement levels suggests that the lowest level of enhancement did not always benefit those with the lowest levels of impairment, but as the level rose, all patients tended to benefit more. Tracking the preferred parameters along a scale using a new method for evaluating perceived quality of video that we recently introduced²⁸ is more likely to further probe the relationship between preferred enhancement and visual impairment. In that study,²⁸ we also found correlation of level of enhancement with contrast sensitivity at 4 cycles/deg (significant) and at 0.4 cycles/deg (approaching significance). Also in that study (and here) frequencies in the order of 1 to 10 cycles/deg were enhanced. The enhancement in the current study was limited to a high range of frequencies as the settings were designed for normally sighted observers. Studies with lower spatial frequencies enhanced may be easily conducted with the current system and the available software control.

The number of responses collected from each subject for each condition was deliberately limited in this initial study, giving only a 60% chance of detecting a side bias at the $p < 0.05$ level in any one subject, and giving many tied ranks for statistical analyses (see above). A future study using the same paradigm should include many more responses, allowing differences in preference to be more clearly explored.

Acknowledgments

We thank Rick Hier of DigiVision for providing the device and his assistance with the control software; Miguel Angel Garcia-Perez, Alex Bowers, Russell Woods, Henry Apfelbaum, and Matt Bronstad for advice on data analysis; Fuensanta Vera Diaz for assisting with data collection; Long To for assistance in display characterization; and Doris Apfelbaum for recruitment of participants. Neither author has any financial interest in the DigiVision or the Belkin devices. Supported in part by NIH grants EY05957 and EY12890.

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