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Generic and customised digital image enhancement filters for the visually impaired

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Abstract

This study compares the effectiveness of various image enhancement filters for improving the perceived visibility of coloured digital natural images for people with visual impairment. Generic filters were compared with Peli's adaptive enhancement and adaptive thresholding and custom-devised filters based on each subject's contrast sensitivity loss. Subjects with low vision made within filter rankings followed by between filter ratings. In general, subjects preferred filters with lower gains. Unsharp masking resulted in a significant increase in perceived visibility for some image types ($p \leqslant 0.05$) while Peli's adaptive enhancement, edge enhancement and histogram equalization resulted in borderline improvements. Adaptive thresholding and the custom devised filter did not result in overall improvements in perceived visibility.

Keywords: Low vision; Visual impairment; Digital image processing; Image enhancement; Contrast sensitivity

1. Introduction

The use of image processing to improve the quality of images or to enhance certain desired features for viewing by people with normal vision has been widely used for some years and in many different areas (Lewis, 1990). The potential of digital image enhancement to increase the visibility of images for people with visual impairment is an area which has only been explored by a few researchers to date. There have been two main avenues of published scientific study: the effect of enhancement on text and on picture images.

Lawton (Lawton, 1988, 1992; Lawton, Sebag, Sadun, & Castleman, 1998) applied image processing filters to digitally presented words for three subjects with age-related macular degeneration (ARMD). Her filters were based on the spatial frequency dependent contrast sensitivity loss of each individual and were applied in such a way that the relative contrast was increased in proportion to the contrast sensitivity loss. She demonstrated a 2–4 times increase in reading rates and also found that the magnification of the print could be decreased. However, she used a re-scaling method to address the problem of saturation of the dynamic range, so that there was not an absolute increase in contrast, and indeed there would be a decrease of amplitude of some spatial components. Her dramatic improvements in reading speeds could not be repeated by Fine and Peli (1995) although they used a somewhat different method for enhancing the images. Their technique was not based on the individual observer's contrast loss, and the algorithm was applied in the spatial rather than the frequency domain. They did demonstrate some improvements among 67 subjects with low vision, but only by an average of 13% with a range of 100% decrement to 125% improvement. In a second study (Peli, Fine, & Pisano, 1994a), using filters which

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were subjectively selected by the subjects, they found only average increased reading speed of 10% which was not statistically significant. Additionally there seems to be some paradox about the need to increase the contrast of higher spatial frequencies for text (it is usually the higher frequencies which are most attenuated by the visual system with low vision). Legge, Pelli, Rubin, and Schleske (1985) found that higher and medium spatial frequencies could be removed from text without much decrease of reading speed. Normal observers could still read text which had frequencies above 2 cycles per character removed while Solomon and Pelli (1994) found that 3 cycles per letter noise was more efficient at reducing letter visibility than at other frequencies i.e., it appears that information at 3 cycles per letter is most critical to letter recognition. Leat and Munger (1994) found that text could still be read fluently when band-pass filters of 0.67 octave width centred at 2 and 4 cycles per character were applied and at higher frequencies these band pass filters could be reduced to 0.35 octaves before reading speed was significantly compromised. Thus, it is unclear why people with visual impairment require spatial information to be added back in, while observers with normal vision can still read effectively with this information missing. In addition text is usually available at high contrast or can be made high contrast by existing technology (closed circuit TVs or computer monitors) i.e., the important (low) spatial frequencies for recognition of text characters are already at high contrast.

Alternatively, salient information is present in picture images at a variety of contrast levels. In addition, the important frequencies for recognition may be intermediate and high frequencies, rather than the low frequencies which are sufficient for magnified text recognition (Fiorentini, Maffei, & Sandini, 1983; Hayes, Morrone, & Burr, 1986; Norman & Ehrlich, 1987). It is contrast sensitivity at these intermediate and high frequencies which is often the most compromised in low vision (Leguire, 1991). Thus, a possible approach is to enhance the medium and higher frequencies of picture images (although not those frequencies which are above the low vision resolution limit).

Peli developed two filters which he applied to picture images viewed by the visually impaired (Peli & Lim, 1982; Peli & Peli, 1984; Peli, Goldstein, Young, Trempe, & Buzney, 1991). Adaptive thresholding uses a thresholding technique (pixels in the filtered image are set to either black or white depending on whether they are above or below a particular threshold in the original image). The threshold is dependent on the average luminance of the pixels around the pixel being modified. Thus, this technique means that the threshold varies across the image. The variable with this technique is the size of the area which is averaged to determine the threshold. Adaptive enhancement uses a local averaging technique to split the image into low and high spatial frequency components (Gonzales & Woods, 2002). The high frequency image is increased in contrast. The low frequency image is decreased in contrast to allow extra dynamic range for the increase in contrast of the high and medium frequencies. The resultant high and low frequency images are recombined. Peli et al. applied adaptive thresholding and adaptive enhancement to images of faces (Peli et al., 1991; Peli & Peli, 1984) and video scenes (Peli et al., 1994a) showing significant improvements in visibility with both techniques for subjects with central visual loss, the most common cause being age-related maculopathy (ARM) (Peli et al., 1991). The improvements were significant for about 40% of subjects. They found improvements in a greater percentage of cases with adaptive enhancement than with adaptive thresholding (9 out of 21 = 43% of patients with age-related maculopathy tested with the adaptive enhancement and 6 out of 17 = 35% of patients tested with adaptive thresholding), but this difference may not be significant.

In all these studies, high frequencies which are above the observer's resolution limit were first eliminated, since enhancement of these frequencies will give no benefit, and may decrease the dynamic range available for the increased amplitude of frequencies which are within the resolution limit.

Thus, all the studies to date have applied only one (Fine & Peli, 1995; Lawton, 1988, 1992) or at most two (Peli et al., 1991) types of filter to images and tested their effect on visibility for people with visual impairments. There are no studies published to date which have made comparisons between many different types of filters. Yet there are numerous generic filters which have the effect of increasing the medium to high spatial frequencies which may be effective for people with low vision. Indeed such filters are already being incorporated into video magnifying devices for the visually-impaired (Artic Technologies, 2004; Enhanced Vision, 2004; Harper, Culham, & Dickinson, 1999; Keeler, 2004).

The objective of this study was to compare the improvements in perceived visibility obtained among a range of generic filters which might be expected to improve visibility for people with low vision, and to compare any such improvements with the Peli filters and custom-devised filters based on each individual subject's CS loss. In this study, digital images of generic natural scenes were used, rather than text, since the value for text enhancement is questionable. Coloured images were chosen since most video images of interest to people with low vision will be in colour.

The main research questions were:

1. Are there any generic filters which improve perceived visibility equally to, or better than, a custom devised filter? If this was found to be true, it would simplify the implementation of such filters, as then filters need not be individually tailored.

2. Is the optimum filter(s) dependent on the type of image?

2. Method and materials

2.1. ImageLab

The filters were implemented with ImageLab software (Kennedy, Leat, & Jernigan, 1998) which runs on the NeXStep platform of a desktop computer. This allows a large number of filters to be applied in either the spatial or frequency domain. Most of the filters can be applied with either RGB or HSB separation. In the former case, each colour signal is processed individually and then added together to create the final processed image. In the latter case, the luminance signal only is processed, after which it is recombined with the hue and saturation signals. In either case, clipping was used instead of rescaling. In clipping any pixel values which were outside the dynamic range of the display (above 255 or below 0) after processing, were reset to 255 or 0, respectively. Clipping allows the increases in contrast in the mid ranges of pixel values to be maintained. The alternative technique for dealing with the problem of exceeding the dynamic range is rescaling. In this method, the maximum pixel value after processing is set to 255 and the minimum is set to 0 and the intermediate values are rescaled proportionally to fit in between.

ImageLab allowed the application of generic filters such edge detectors, low and high pass filtering, unsharp mask filters, and histogram equalization, which may be found described in any general textbook on image processing, e.g., Gonzales and Woods (2002). Low and high pass filtering was done with difference of Gaussian (DoG) filters, which technically are band-pass filters, but the parameters can be chosen so that they are relatively a high or low pass filter with respect to the human visual system. The unsharp mask filter functions by undertaking a local average over the area of the mask i.e., the average of the pixel elements in a square mask is assigned to the central pixel. The mask may be varied in size, e.g., 3×3, 5×5, 7×6 etc. The low frequency image thus obtained is subtracted from the original image to isolate the high frequency components. The high frequency components are added back to the original image resulting in a high frequency emphasis or sharpening filter.

Some algorithms specific to ImageLaB included the overlay feature, which gave the ability to combine of two versions of a filtered image in differing proportions e.g., 60% of image A with 40% of image B. The overlay was used to combine a percentage of a filtered image with a percentage of the original, unfiltered image. It was used with the Sobel edge detector (Gonzales & Woods, 2002). The Sobel filtered image was added in varying proportions to the original image to give the result of edge enhancement. ImageLab also included a contrast stretch which increased the slope of the input/output graph. This was included to "mimic" the effect of simply increasing the contrast of a TV or video screen. The parameters which could be adjusted for the contrast stretch were the slope and the X intercept of the line (Fig. 1). For this study, the slopes and intercepts were chosen so that there the change in mean luminance was minimized i.e., the centre of the slope portion of the input/output graph was maintained at the centre of the output range.

ImageLab also allowed filtering using fast Fourier transforms (FFTs). This was used to apply a DoG filter in the frequency domain and to undertake band-pass filtering of an image. The band-pass filters were Gaussian filters which were one octave wide at half height. The amplitude of each spatial frequency band could be amplified or attenuated by a chosen gain factor and was then recombined to form the final image. ImageLab defines spatial frequency in terms of cycles per picture width and height, and this was recalibrated into cycles/deg.

Lastly ImageLab was able to apply both Peli filters (adaptive thresholding and adaptive enhancement—Peli & Lim, 1982; Peli & Peli, 1984). In adaptive thresholding the only parameter that is varied is the mask size. In adaptive enhancement, the low frequency component is determined by averaging and the mask size for this averaging is one variable. The slope determines the degree of attenuation of the low frequency components. It is the slope of the low frequency input/output graph

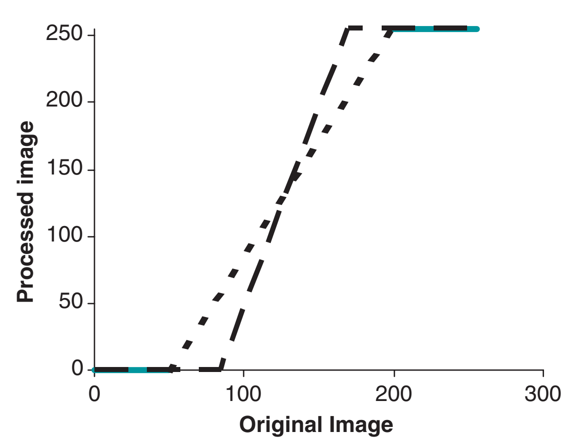

Fig. 1. Input and output pixel graph for the contrast stretch filter. Two examples are shown by the dotted and the dashed line. The variable parameters were the slope and the intercept. In this study these parameters were chosen so that the response line always crossed the centre of the input and output pixel range, so that there was no mean change in luminance.

(which would be set at less than one, in order to attenuate the low frequencies). The value is the Y intercept of the low frequency input/output graph. In the present study the value was chosen so that there was no overall change in average brightness. It was found that the final result of the Peli filter was not strongly affected by changes in the slope and value and therefore these parameters were kept constant. The high frequency component is obtained by subtracting the low frequency components from the original image. Although ImageLab had the facility to apply a function for the high frequency gain—$k(fL)$ in Peli and Lim (1982), we used a constant high frequency gain across all pixel values. This was because there would not be prior knowledge of the distribution of pixel values in any given image and the desire was to determine a general purpose algorithm which could be applied to a range of images. We also included versions of the Peli adaptive enhancement filter based on the parameters used in Peli et al. (1991) and only varied the mask size, which was not specified in that publication.

2.2. Images

The 1134 × 832 pixel 24 bit colour images were displayed on a high resolution 21 in. Sony Trinitron monitor at a viewing distance of 50 cm. The average luminance of the screen was 60 cd/m^2 measured with a Minolta Chroma Meter CS-100. The display had a linear relationship between pixel value and luminance. This was measured by creating a grey square image of equal pixel value (for red, green and blue). The pixel values were all varied between 0 and 255 and the luminance was measured with the same luminance meter. Fourteen images were selected in each of four classes; single full face, multiple faces (head and shoulders), outdoor scenes (street scenes with activity) and sports events. These were chosen to be representative of scenes in films and TV programmes. The images were first filtered with a Gaussian low-pass filter with a half height cut-off at 10 cycles/deg (Peli, 1992). This was to avoid unnecessarily enhancing high frequencies beyond the subject's acuity limit which would further compromise the dynamic range of the enhanced image and to decrease noise. Most of the subjects did not have visual acuity better than 6/18.

2.3. Preliminary study

In addition to the custom-designed multiplicative filter, the types of filters included in the study are shown in Table 2. The Sobel edge detector is a standard edge detector, although more recent are the Marr–Hildreth (Marr & Hildreth, 1980) and the Canny (Canny, 1986) edge detectors. Both of these are more successful than the Sobel at identifying the edges in noisy images. However, the purpose of this study was to improve the visibility of reasonably good quality images for people with a poor visual system (rather than increasing the visibility of poor, low contrast or noisy images for people with a normal visual system). With pre-filtered images that are not noisy or low in contrast the performance of the Sobel, Marr–Hildreth and Canny edge detectors are similar, and so the Sobel was chosen, as it requires less computational time, and was applied as an edge enhancer i.e., the result of the edge detector was added back to the original image.

It will be noted that the outcome variable for the whole of this study is subjective preference by the subject based on perceived visibility. This is used either with ranking of images or with assigning a visibility rating. This method was chosen because the aim of the study was to compare a large number of filters and based on the experience of Peli, who found that subjects were able to reliably choose a level of enhancement and robustly indicate their preference for filtered images on a scale of perceived image quality (Peli, 1999). As well as being very time consuming with many filters to compare, designing questions that will measure an objective difference in visibility is not always successful (Fine, Peli, & Brady, 1998; Peli, 1999; Peli & Fine, 1996). In their studies, subjects with low vision were surprisingly accurate at answering such questions, even before the use of image enhancement, rendering many questions useless. This creates a ceiling effect, making changes in accuracy difficult to measure. In their 1994 study (Peli, Lee, Trempe, & Buzney, 1994b) 6 out of 11 subjects did not show any improved recognition of faces with their preferred filters, because they already had good recognition with the original images, and only 3 of the remaining 5 showed a demonstrable improvement in recognition. In their more recent study (Fine et al., 1998) they conclude that "performance evaluation…remains elusive" and that in future investigations they will assess preference. Additionally, in Peli's studies, not more than two filters were compared in a single study (different sets of faces or other images being required for each filter). Comparing more filters by means of a recognition performance would become very time consuming and exhausting for subjects. Therefore, since we wanted to compare a wide range of filters, subjective perceived visibility was chosen as the more efficient means and because measuring changes in actual performance is likely to run up against ceiling effects.

Since there are an almost infinite number of potential versions of filters, six subjects with low vision were invited to view a wide range of versions of the filters and to rank them for perceived visibility. These were subjects marked with an asterisk in Table 1. The filters and their parameters considered at this stage are shown in Table 2. For speed of processing and viewing, these were applied to small cropped portions of two images (a face

Table 1
Subjects taking part

Subject number	Age	VA (logMAR)	Diagnosis
1	42	0.9	RP
2	47	1.8	Hereditary retinal dystrophy
3	50	0.4	RP
4	52	0.9	Atypical Stargardt's macular dystrophy
5*	55	0.2	Multiple cerebral infarct
6*	59	0.7	Best's vitelliform macular dystrophy
7	59	1	ARMD
8	62	0.3	DR
9*	65	0.4	ARMD
10	65	1.7	ARMD
11	72	0.4	DR/ARMD
12*	72	1.2	ARMD
13	73	1.3	ARMD
14	73	1.2	ARMD
15	74	0.8	DR
16	74	0.9	ARMD
17	75	1.2	ARMD
18	75	1.6	Glaucoma/DR
19	77	1.1	ARMD
20	77	0.8	ARMD
21	78	0.5	ARMD
22	79	1.0	Glaucoma/DR
23	79	0.9	ARMD
24	79	1.3	ARMD
25*	80	0.9	DR/ARMD
26*	80	1.3	ARMD
27	80	1.1	Glaucoma
28	80	0.9	ARMD

* = subjects who took part in the preliminary study.
ARMD = age-related macular degeneration, DR = diabetic retinopathy, RP = retinitis pigmentosa.

and a street scene). The images were not reduced in size compared to the images used in the final study, but were cropped i.e., the image processing remained the same relative to spatial frequency components of the face or other details in the image. Cropping allowed several images to be displayed concurrently on the screen for speed of comparison. Subjects viewed the images with the best or preferred eye and with best refractive correction in place. Comparisons were only made within type of filter i.e., the subject was asked to compare different parameters of each filter type, and not to compare different filters. For each filter type, four versions of the image were displayed simultaneously and the subject was asked to rank the images in terms of perceived visibility. The order of the filters was randomised. The least preferred filter was eliminated and other versions added until all versions had been shown. The remaining four filters were ranked in order of preference for visibility, the least to the most visible.

It was noted that there was some variation of which was the most preferred filter among subjects. However, there was agreement between observers in that some filter versions were consistently not preferred by any subject for either image. These filters were eliminated from further study. The results of this preliminary study are shown in Table 2.

2.4. Subjects

Twenty-eight subjects aged 40–80 years with low vision due to a variety of disorders took part (Table 1) plus 10 subjects with normal vision. All subjects gave written consent for taking part in the study and the study followed the tenets of the Declaration of Helsinki and was approved by the Office of Research Ethics at the University of Waterloo. All subjects were refracted and wore their full correction, plus near addition for the viewing distance of the screen. Visual acuity was measured with the Bailey–Lovie logMAR chart with single letter scoring.

Contrast sensitivity between 0.25 cycles/deg and the highest spatial frequency that was detectable by the subject was determined with Morphonome software on a MacIntosh computer (Tyler & McBride, 1997). Contrast thresholds higher than 8 cycles/deg were not measurable for any subject. The order of spatial frequency was randomized. Luminance was 60 cd/m^2 and the stimulus was a vertical sinusoidal grating with a two-dimensional Gaussian envelope (Gabor function) which resulted in a width of 4 cycles when above threshold. A temporally separated 2ATFC staircase method was used with abrupt onset and offset of the gratings. The stimulus duration was 1 s and the inter-stimulus interval was 583 ms. Each potential stimulus presentation time was indicated with a beep. The abrupt (square wave) on and off presentation was used in order to mimic the visual experience of observing a visual scene with abrupt changes of stimulation due to saccades. Peli et al. (1991) suggest that threshold measurement with this type of presentation yields a more accurate representation of CS relevant to the visual perception of complex scenes. The viewing distance was 50 cm.

Monocular contrast sensitivity (with the eye with best VA) for 10 normally sighted subjects was measured as above. The mean normal contrast sensitivity was determined for five 40–60 year olds and five 60–80 year olds. The exclusion criteria for the subjects with normal vision were:

- refractive error greater than ±6DS or ±2.5DC,
- any history of amblyopia, strabismus or eye disease,
- lenticular opacities in the undilated pupil area as determined by direct ophthalmoscopy,
- ocular abnormalities (greater than 4 drusen) in an area of 1 disc diameter around the fovea or pigmentary changes,
- systemic disease (hypertension, diabetes, or vascular disease) or medication with known ocular involvement,

Table 2
Filter types and the parameters for the within filter rankings

Parameters			Result of preliminary study (6 subjects)	Result of within filter comparisons for the face image (all subjects)	Result of within filter comparisons for the outdoor image (all subjects)
Peli's adaptive enhancement (modified)					
	Mask	High frequency gain			
Slope = 0.5	5	16	Most preferred	8	5
		32	Sometimes preferred	2	5
		64	Eliminated	0	0
Value = 60	9	16	Sometimes preferred	11	8
		64	Sometimes preferred	7	10
Peli's adaptive enhancement (as per Peli et al., 1991)					
Slope = 0.9		Mask = 9	Most preferred	11	12
High frequency gain = 5		Mask = 15	Eliminated	0	0
Value = 13		Mask = 21	Sometimes preferred	17	16
Peli's adaptive threshold					
Mask = 5			Most preferred	10	3
Mask = 9			Sometimes preferred	8	12
Mask = 15			Sometimes preferred	10	13
Difference of Gaussian					
Centre		Gain = 5	Most preferred	11	8
frequency = 2 cycles/		Gain = 10	Eliminated	0	0
deg ≈ 6/90		Gain = 20	Eliminated	0	0
		Gain = 40	Eliminated	0	0
Centre		Gain = 10	Sometimes preferred	4	0
frequency = 4 cycles/		Gain = 20	Sometimes preferred	6	2
deg ≈ 6/45		Gain = 40	Eliminated	0	0
		Gain = 80	Eliminated	0	0
		Gain = 160	Eliminated	0	0
Centre		Gain = 40	Sometimes preferred	1	4
frequency = 8 cycles/		Gain = 80	Sometimes preferred	2	4
deg ≈ 6/22.5		Gain = 160	Sometimes preferred	4	4
Unsharp masking					
RGB		3 × 3 mask	Most preferred	15	12
		5 × 5 mask	Eliminated	0	0
		7 × 7 mask	Eliminated	0	0
HSB		3 × 3 mask	Most preferred	13	16
		5 × 5 mask	Eliminated	0	0
		7 × 7 mask	Eliminated	0	0
Contrast stretch					
Slope 1.5, X intercept = 43			Sometimes preferred	5	10
Slope 2, X intercept = 64			Sometimes preferred	7	9
Slope 3, X intercept = 85			Sometimes preferred	16	9
Histogram equalization					
RGB			Sometimes preferred	7	6
HSB			Sometimes preferred	21	22
Sobel edge enhancer, HSB					
Parameters changed (percent of each image)					
Sobel = 20%, original = 80%			Most preferred	20	12
Sobel = 36%, original = 64%			Sometimes preferred	6	6
Sobel = 50%, original = 50%			Sometimes preferred	2	9
Sobel = 66%, original = 34%			Eliminated	0	1
Sobel = 80%, original = 20%			Eliminated	0	0
Sobel edge enhancer, RGB					
Parameters changed = percent of each image					
Sobel = 20%, original = 80%			Most preferred	24	18
Sobel = 36%, original = 64%			Sometimes preferred	4	8
Sobel = 50%, original = 50%			Sometimes preferred	0	1

Table 2 (*continued*)

Parameters	Result of preliminary study (6 subjects)	Result of within filter comparisons for the face image (all subjects)	Result of within filter comparisons for the outdoor image (all subjects)
Sobel = 66%, original = 34%	Eliminated	0	1
Sobel = 80%, original = 20%	Eliminated	0	0

Subjects were asked to rank the filters variations in order of perceived visibility. Comparisons were only made within groups of similar filters as shown in each sub-section of the table. The column showing the preliminary study results (for 6 subjects) shows which filters were eliminated from the study and which filters were sometimes or often preferred. Filters that were not ranked first by any of the six subjects in the preliminary study were eliminated from further study. The final two columns show the results from all 26 subjects, as the number of times each filter version was ranked as the most preferred filter.

- best corrected visual acuity less than 6/7.5,
- intra-ocular pressure greater than 21 mmHg.

2.5. Experimental design

Since there was some variation of preferred filter found in the preliminary trials with the six low vision subjects, it was decided that each subject should view the remaining versions of the filters and that the subject's own preferred version of the filter would be used in the final study. This was done in order to make a valid comparison between filters, since it would not be a "fair" evaluation to compare a less than ideal version of one filter for one subject with an ideal version for another subject. The purpose of the study was to determine the optimum type of filter that would suit the maximum number of persons with low vision and to determine if any generic filters would result in equal improvements to a custom devised filter.

The same procedure was used as in the preliminary study, with the exception that the filter versions indicated in Table 2 were eliminated. Thus, the subjects were asked to rank versions of each filter for two cropped pictures, and the subject's own preferred version of each filter was used in the final study.

The enhancing filters used in the final study are shown in Table 3 and examples are shown in Fig. 2. The custom multiplicative filter was based on each low vision subject's contrast sensitivity loss. The ratio of the subject's contrast threshold and average normal CS (for the similar age group) was used to determine the calculated gain at each spatial frequency. This was similar to the procedure used by Lawton (1988, 1992) although the method of implementation was different, and is based on studies of supra-threshold contrast perception which show that discrimination is proportional to C_{th}/C where C is the test contrast and C_{th} is the contrast threshold (Georgeson & Shackelton, 1994; Legge & Kersten, 1987). These gains turned out to be quite high (often of the order of 14 or greater) owing to the subjects' severe CS loss, and resulted in gross distortion and loss of information in the image due to exceeding the dynamic range. Therefore the calculated gain up to the maximum limit in Table 4 was applied. These limits were determined empirically, as being the maximum

Table 3
Filter used for between filter ratings

Filter	Parameter
Modified Peli's adaptive	Mask size, slope, low and high frequency gain
Peli's adaptive (Peli et al., 1991)	Mask size, slope, low and high frequency gain
Peli's threshold	Mask size
DoG	Central frequency, gain
Unsharp masking	Mask size, signal mode (HSB/RGB)
Contrast stretch	Slope, intercept point
Histogram	Signal mode (HSB/RGB)
Sobel edge enhancer (HSB)	Percentage of Sobel edge detector used
Sobel edge enhancer (RGB)	Percentage of Sobel edge detector used
Custom multiplicative (Bandpass)	Gain value at each frequency
Unenhancing filters	
Band pass	Gain < 1
Low pass	Cut-off frequency = 6/90
DoG	Central frequency = 6/90, gain < 1

The parameters shown indicate the parameters that varied between subjects. For each subject only one version of the filter was used, individually tuned for that subject.

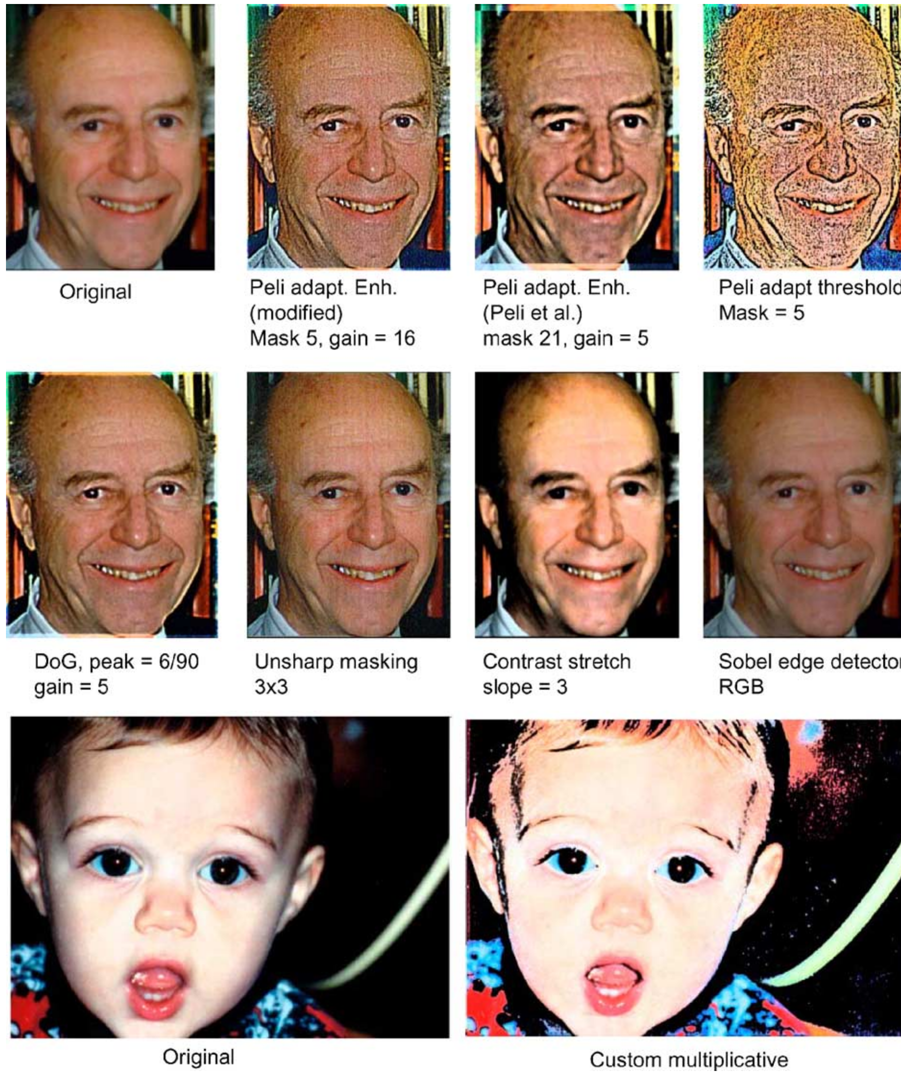

Fig. 2. Examples of filters.

Table 4
Maximum gain factors according to centre spatial frequency for the custom-devised multiplicative filter

Spatial frequency (cycles/deg)	Maximum gain factor
0.25–0.50	<2
1–2	<4
4	<6
8	<8

gain that could be applied without gross distortion and loss of spatial information. It should be noted that Lawton (Lawton, 1988, 1992; Lawton et al., 1998) also reduces the gain by the use of a max gain factor and that this factor was empirically determined. Thus, in most cases it was not possible to fully compensate for the CS loss experienced by low vision observers.

Three filters that deliberately degraded the image were also included. This was to prevent the subjects from having an expectation set that all filters should improve the image. These were (a) a low-pass Gaussian filter with a high frequency cut-off (at half-height) of 2 cycles/deg, equivalent to 6/90 (low pass filter), (b) a band-pass filter with gains of <1. (c) a DoG filter with a centre frequency gain of 0.8 at 6/90. Lastly, an image with no filtering was included i.e., identical to the original image, was included. This resulted in 14 filters for each image type. Thus, there were 14 different images in each of four image classes and 14 types of filters (10 enhancing filters, three unenhancing filters and one unfiltered image i.e., identical to the original). Subjects, image and filter were counter-balanced in a Latin square. Table 5 shows an example of how this would work for five filters and five images in one image category. In this study there were 14 images in each category, since there were 14 filters. Thus, subjects rated a total of 56 images (14 filters × 4 image categories) and

Table 5
Example of Latin square used to counter-balance subjects, filters and images for one image category (face)

	I_1	I_2	I_3	I_4	I_5
Face images					
F_1	S_1	S_2	S_3	S_4	S_5
F_2	S_5	S_1	S_2	S_3	S_4
F_3	S_4	S_5	S_1	S_2	S_3
F_4	S_3	S_4	S_5	S_1	S_2
F_5	S_2	S_3	S_4	S_5	S_1

The example is for five filters, and therefore five images would be used. Subject 1 would view image 1 filtered with filter 1. In the study 14 filters, and therefore 14 images were used in each image category.

each subject viewed a different image for each filter, thus off-setting any tendency for a particular image to benefit from a particular filter. The images were presented randomly in each image category. Subjects were informed that some filters might improve the image while others might make it less visible. Subjects were shown the original image followed by the enhanced image and were asked to give a rating of its perceived visibility between -100 (where a negative score represented a poorer image) and +100 (a positive score better visibility than the original) with 0 = no better or worse.

3. Results

3.1. Within filter rankings

The results of the within filter comparisons showed that filters with high gains and more exaggerated enhancements were not preferred by any of the six subjects who took part in the preliminary study (see Table 2). For example, for the DoG filter, the higher gains with the centre frequency at 6/45 and 6/90 were least preferred by all six subjects. It must be noted that a given gain at low frequencies results in a more distorted image (more clipping) than the same gain applied at a higher frequency. Thus, the higher gains at 6/22.5 were not eliminated. There was a trend that the unsharp masking filters with larger masks were not preferred. A larger mask used for averaging means that a wider band of lower frequencies, possibly including some medium frequencies, may be attenuated and there is emphasis of only quite high frequencies. The 3×3 unsharp mask that was preferred has less effect on the low and medium frequencies while approximately doubling the amplitude of the high frequencies.

It is not surprising that the Sobel edge enhancers with lower percentages of the original image were eliminated, as these resulted in a darker image. For the Peli adaptive enhancement filters, the results were less consistent.

The results of all 28 subject's within filter rankings are also shown in Table 2. It can be seen that there is considerable variability between subjects. However, some trends can be noted. When the contrast stretch was applied to faces, there was a more frequent preference for greater increases in contrast, but when applied to the outdoor scene, there was a wide spread of preference. The HSB histogram equalization was more frequently preferred to the RGB mode for both images. For the DoG, there was a trend to prefer lower gains, except for when the gain was applied to higher frequencies. The Sobel filter with the least percentage of edge detection added was preferred (which has the least effect on overall luminance of the picture). There was considerable variation in preferences for the Peli filters.

3.2. Between filter ratings

The mean perceived visibility rating for each filter in each image class was analysed using a repeated measure ANOVA. There was a significant effect of filter ($F = 30.31, p < 0.0001$), but no effect of image class ($F = 0.33, p = 0.803$). There was a significant interaction between image class and filter type ($p < 0.0001, F$ value = 3.33). Mean subjective rating response for each filter type and each image class for all subjects is plotted in Fig. 3.

Considering Fig. 3, it can be seen that there is some variation between subjects. However, it should be noted that there was least variability in subject's ratings for the original image. In this case the subjects were quite consistent in rating the original image as close to the comparison original image. The means were slightly positive.

Table 6 shows the filters according to image type which resulted in ratings that were significantly different from zero or approaching significance (*t*-test). Since a number of comparisons were made, an adjusted Bonferroni procedure was used (Jaccard & Wan, 1996). It can be seen that there were a number of filters which resulted in a significant decrement in perceived visibility. This included those that were designed to make the image poorer (the low pass and band pass with gain <1), although the DoG filter with gain <1 did not make a significant difference. The other filters which resulted in a significant decrement in perceived visibility were the custom multiplicative and the Peli adaptive threshold which both resulted in poorer perceived visibility for all image types and the modified Peli adaptive enhancement for certain image types. Enhancing filters which resulted in a significant improvement in perceived visibility were the unsharp mask and the Peli adaptive enhancement according to Peli et al. (1991). There were two filters which nearly resulted in significant improvements; the RGB Sobel edge enhancer and the contrast stretch. Filters which resulted in no significant change in the perceived visibility for any image type were histogram equalization, the DoG filter and the HSB Sobel edge enhancer. It must be noted that the original image was

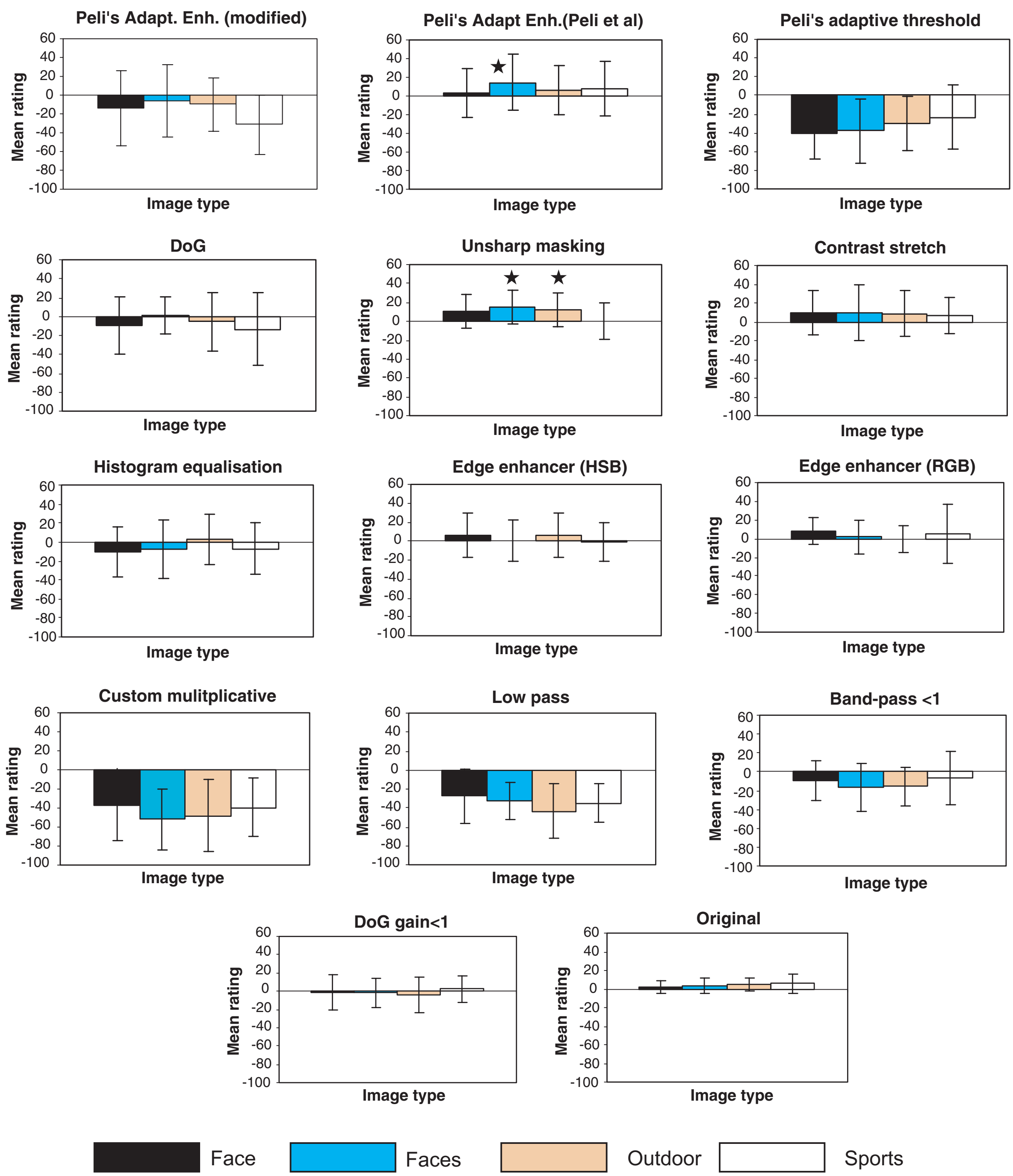

Fig. 3. Mean perceived visibility rating and standard deviations, against image class for each filter type. Values below 0 indicate that the perceived visibility was poorer with the filter, 0 indicates equal perceived visibility to the original, and values greater than 0 indicate improved perceived visibility. The filters marked with ∗ are those that reached significance using the adjusted Bonferroni method.

judged as significantly better for the outdoors and the faces images.

3.3. Analysis with respect to ocular disorder and central versus peripheral visual field loss

Eighteen of the subjects had a diagnosis of maculopathy. The preference of these subjects for filters was analysed separately. The other subjects were analysed as one group, as there were not sufficient numbers to undertake meaningful statistical analysis in further sub-groups. For example, there were only three subjects with glaucoma. The results for the filters which showed significant or borderline improvements in perceived visibility for all subjects, are plotted in Fig. 4 with the subjects split into those with maculopathy and those with

Table 6
Filters applied to image types that reached or approached significance

Image type	Filter	Mean rating	*p*-Level	Divisor	Modified *p* level for significance
Face	Low pass	−27.61	<0.0001*	22	0.0022
Face	Custom multiplicative	−36.75	<0.0001*	21	0.0024
Faces	Custom multiplicative	−51.96	<0.0001*	20	0.0025
Face	Peli adaptive threshold	−39.93	<0.0001*	19	0.0055
Faces	Peli adaptive threshold	−39.93	<0.0001*	18	0.0028
Faces	Low pass	−32.29	<0.0001*	17	0.0029
Outdoors	Custom Multiplicative	−47.86	<0.0001*	16	0.0031
Outdoors	Peli adaptive threshold	−29.64	<0.0001*	15	0.003
Outdoors	Low pass	−43.36	<0.0001*	14	0.0036
Sports	Custom multiplicative	−39.29	<0.0001*	13	0.0038
Sports	Modified Peli	−31.50	<0.0001*	12	0.004
Sports	Low pass	−35.32	<0.0001*	11	0.0045
Faces	***Unsharp masking***	14.57	0.0002*	10	0.005
Faces	Band pass < 1	−15.29	0.0005*	9	0.0055
Faces	Band pass < 1	−16.43	0.0021*	8	0.0063
Sports	Peli adaptive threshold	−23.18	0.0015*	7	0.007
Outdoors	Original	4.60	0.0017*	6	0.008
Faces	***Peli et al.***	14.54	0.0176*	5	0.01
Outdoors	***Unsharp masking***	11.71	0.0018*	4	0.0125
Sports	Original	5.71	0.0074*	3	0.0167
Face	*Unsharp masking*	10.11	0.0367	2	0.025
Faces	Original	3.50	0.039	1	0.05
Face	*Edge enhancer (RGB)*	8.53	0.064		
Outdoors	*Contrast stretch*	8.79	0.0655		
Face	Peli modified	−14.21	0.067		

The adjusted Bonferroni method is used to control for type 2 errors (false positive) (Jaccard and Wan, 1996). The final column gives the modified *p* value for each *t* test to reach significance. Those that reach significance are indicated with *. Enhancing filters which gave a significant improvement are shown in bold italics and those that gave a borderline improvement are shown in italics.

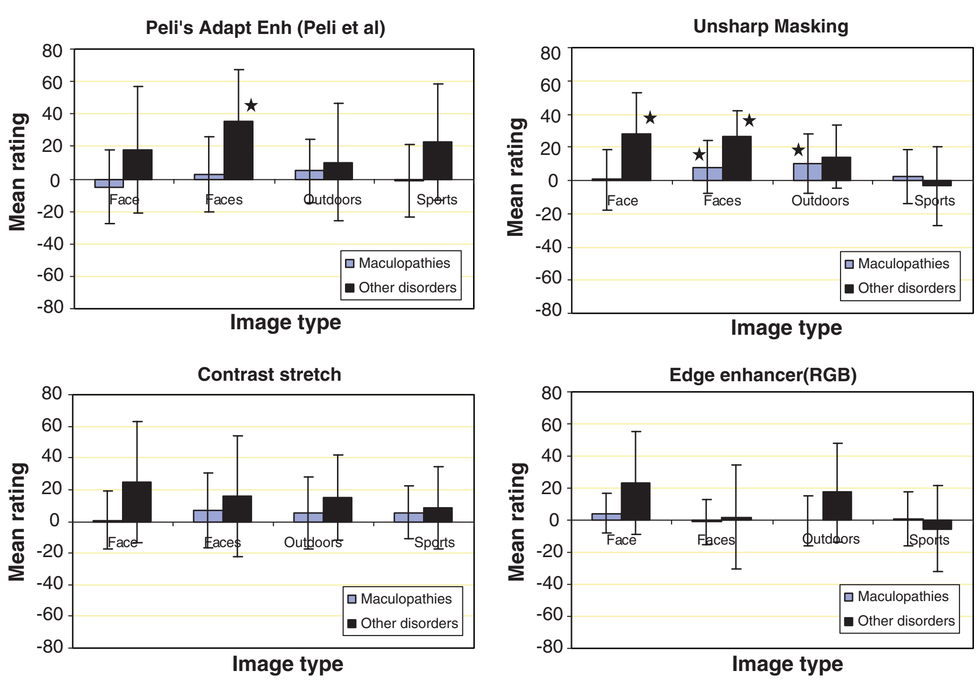

Fig. 4. Mean perceived visibility rating and standard deviations, against image class for four filter types. Subjects are divided into those with maculopathies and other disorders. Values below 0 indicate that the perceived visibility was poorer with the filter, 0 indicates equal perceived visibility to the original, and values greater than 0 indicate improved perceived visibility. The filters marked with * are those that reached significance using the adjusted Bonferroni method.

Table 7
Filters applied to image types that reached or approached significance for subjects with maculopathy vs other disorders

Image type	Filter	Mean rating	*p*-Level	Divisor	Modified *p* level for significance
Maculopathies					
Outdoors	***Unsharp mask***	10.3	0.025*	2	0.025
Faces	***Unsharp mask***	7.9	0.49*	1	0.05
Other disorders					
Faces	***Unsharp mask***	26.5	0.000*	5	0.01
Faces	***Peli et al.***	35.5	0.006*	4	0.013
Face	***Unsharp mask***	27.6	0.007*	3	0.017
Outdoors	*Unsharp mask*	14.2	0.041	2	0.025
Face	*Edge enhancer(RGB)*	23.2	0.047	1	0.05

The adjusted Bonferroni method is used to control for type 2 errors (false positive) (Jaccard & Wan, 1996). The final column gives the modified *p* value for each *t* test to reach significance. Those that reach significance are indicated with *. Enhancing filters which gave a significant improvement are shown in bold italics and those that gave a borderline improvement are shown in italics.

Table 8
Filters applied to image types that reached or approached significance for subjects with central vs peripheral field loss

Image type	Filter	Mean rating	*p* Level	Divisor	Modified *p* level for significance
Central visual field loss					
Faces	***Unsharp mask***	16.42	0.003*	2	0.025
Outdoors	***Unsharp mask***	10.21	0.034*	1	0.05
Peripheral visual field defects					
Faces	***Unsharp mask***	10.67	0.008*	4	0.013
Outdoors	***Unsharp mask***	14.89	0.017*	3	0.017
Face	*Unsharp mask*	6.33	0.03	2	0.025
Outdoors	*Histogram equalization*	14.78	0.041	1	0.05

The adjusted Bonferroni method is used to control for type 2 errors (false positive) (Jaccard & Wan, 1996). The final column gives the modified *p* value for each *t* test to reach significance. Those that reach significance are indicated with *. Enhancing filters which gave a significant improvement are shown in bold italics and those that gave a borderline improvement are shown in italics.

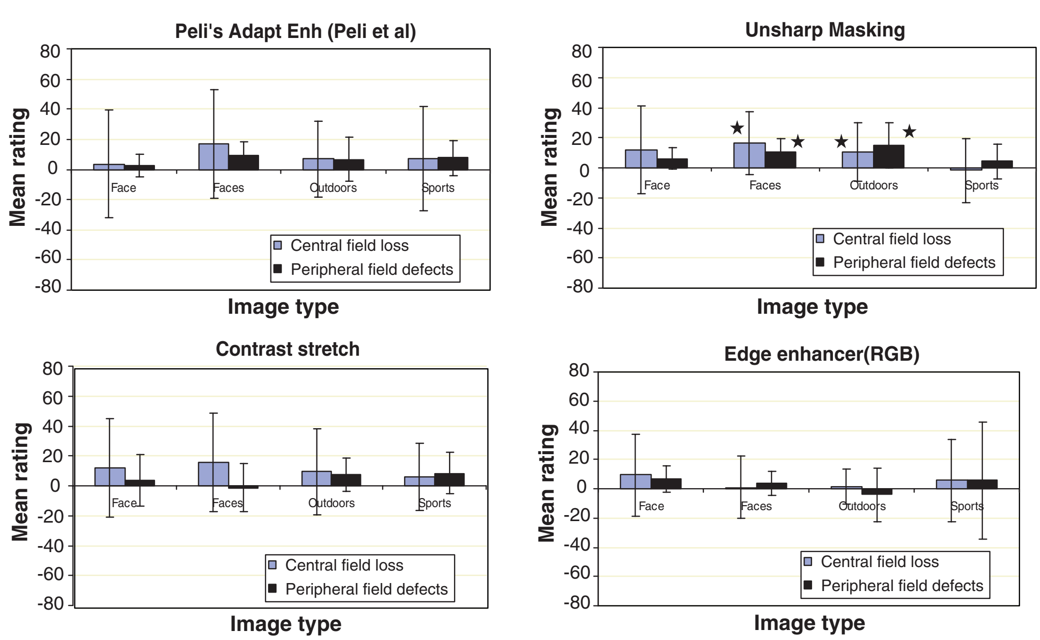

Fig. 5. Mean perceived visibility rating and standard deviations, against image class for four filter types. Subjects are divided into those with central visual field loss and peripheral visual field defects. Values below 0 indicate that the perceived visibility was poorer with the filter, 0 indicates equal perceived visibility to the original, and values greater than 0 indicate improved perceived visibility. The filters marked with $*$ are those that reached significance using the adjusted Bonferroni method.

other disorders. For the subjects with maculopathies the unsharp mask was again the filter which showed significance for some image types (faces, $p = 0.049$ and outdoor images, $p = 0.025$). For the other disorders, the unsharp mask and the Peli et al. filter gave significant improvements for face and faces images. The unsharp mask and RGB edge enhancer gave borderline subjective improvement for the outdoor and face images, respectively (Table 7). It is of interest to note that, on average, the subjects with maculopathy reported less overall improvement in perceived visibility than subjects with other disorders.

A similar analysis was performed for subjects with central ($n = 19$) versus peripheral field loss ($n = 9$). The results are shown in Table 8 and Fig. 5. The results might be expected to be similar to those based on diagnosis, as most subjects with maculopathy would be expected to demonstrate a central field loss. Indeed, in terms of the filters which reached significance for perceived improvements in visibility, the results are similar. The unsharp mask gave significant improvement in perceived visibility for faces and outdoor scenes for subjects with both central field loss and peripheral field defects. However, the Peli et al. filter did not reach significance in this sub-analysis. In this division of subjects, there is no obvious difference in average perceived improvements between those with central field loss and peripheral defects.

4. Discussion

The first main result (from the within filter rankings) is that subjects preferred lower gains and filters which give less exaggerated enhancement. This can be seen from the results of the preliminary study and the filter rankings for all subjects (Table 2). For example, all the DoG filters with high gains at low spatial frequencies were eliminated in the preliminary study. For the Peli modified filter, those filters with the higher gains, were either eliminated in the preliminary study, or not so frequently ranked as the best version of the filter by all subjects. It seems that larger gains can be tolerated at high frequencies. The higher mean rating of the Peli et al. filter over the modified Peli filter also indicates this. The modified Peli filters had higher gains than the Peli et al. filters. Another difference between the Peli et al. filter and the modified Peli was the slope and intercept of the low frequency components. The low frequency components were more attenuated for the modified Peli filter. This may have led to a loss of information at frequencies that subjects do use for recognition. The other difference between these two filter types was the mask size, which was larger for the Peli et al. filter. This would result in a different cut off between the "low" and "high" components. In the Peli et al. filter a smaller range of low frequencies would be attenuated and more "medium" frequencies would be enhanced than in the modified Peli filter. The finding that lower gains are preferred is in general agreement with previous studies. Peli et al. (1994a), using the adaptive enhancement, found that subjects preferred a gain of 2.4 which was towards the higher end of the gains that they applied. However, this is towards the lower range of gains that were applied in the present study. Peli et al. (1994b) applied band pass filtering to images of faces and also found that subjects with low vision preferred relatively low levels of amplification (mean 2.4).

The between-filter ratings results (Fig. 3 and Table 6) with the original "control" filter indicate that the subjects did have, on average, a bias towards expecting that the visibility of the images would be improved. There was a significant, but small, positive effect for the original image, for some image types (Table 6). This was despite the fact that they were informed that there were some filters which might make the visibility poorer. However, the spread of results was small, which indicates that most subjects gave a similar rating to the original image i.e., can see that the two images are similar.

The significant negative result with two of the unenhancing filters (the band-pass <1 and the low pass filters), was as expected and indicates that subjects were able to perceive differences in images, despite their poor vision. We can be sure that these filters would not result in improved perceived visibility. This indicates that the negative results with filters that were intended to enhance are genuine. The fact that the DoG gain <1 resulted in only a slight overall detriment in perceived visibility of is not unexpected, considering that the gain was 0.8, only slightly less than 1.

The second main finding of the current study is that, overall subjects, the unsharp masking and Peli adaptive enhancement (Peli et al.) provided significantly improved perceived visibility for some images. The RGB edge enhancer and the contrast stretch gave near-significant results for one image type each. Since the subjects showed bias towards anticipating improved visibility, these significant and near significant results were adjusted by subtracting the rating given to the original image by each subject. The unsharp mask for faces remained significant ($t = 2.976, p = 0.006$), while the unsharp mask for outdoors and the Peli et al. filter for faces became borderline significant ($t = 1.942, p = 0.063$ and $t = 1.875, p = 0.072$, respectively). The edge enhancer and the unsharp mask for face images, which were borderline before, reached significance with this adjustment ($t = 2.296, p = 0.03$ and $t = 2.596, p = 0.015$). When the subjects were divided into those with maculopathy/other disorders and those with central/peripheral field defects, the unsharp mask remained the filter that reached significance for perceived improvement for two image classes, with the Peli et al. giving significant improvement for one class of images for subjects with disorders other than maculopathy.

However, we must qualify these results, as they are based on subjective preference and not measures of performance, such as recognisability or ability to extract information. Whether preferred images would lead to better performance is not clear. In one study Peli et al. (1994b) were only able to measure improvements with the preferred filters in 3 out of 11 subjects and in other studies they have only measured improvements in face recognition in approximately half of their subjects (Peli et al., 1991). It is also noteworthy that the filters that were preferred gave only modest improvements (a score of 8.5–14.5 on a scale of 100 overall subjects). This is consistent with the findings of Peli (1999) who found modest improvements in subject's ratings of perceived image quality. It seems that the subjects find that these enhancements do not result in restoring clear or normal vision (which might be indicated by +100). Only a few subjects used scores as large as +90 or +100. However, it must be noted that subjects were not told what a value of 100 should represent. They were simply asked to give a value based on their perception of visibility. Since subjects may have used different scalings of their perception of visibility, the results were further analysed by normalizing each subject's responses by their largest response (whether positive or negative). The smallest maximum absolute score given by any subject was 50. Normalising each subject's responses did not result in smaller standard deviations with respect to the overall scale, or significantly different pattern of results regarding which filters were optimum.

The poor result with the custom multiplicative filter deserves some discussion, since this filter was derived from the individual vision loss experienced by each observer as derived from his or her contrast sensitivity. In fact this filter even under-compensates for the CS loss, as it was impossible to use the full gain required in most cases, since this resulted in gross distortion of the images. This outcome may be due to the non-linearity of the visual system (the calculation of the gains applied in this study assumed a linear relation between threshold loss and supra-threshold perception). It is known that suprathreshold perception does not relate linearly to threshold (Cannon, 1985; Georgeson & Sullivan, 1975) and that there may be differential gains in different channels, so that contrast constancy is achieved. It has also been shown that in people with vision loss due to a variety of ocular disorders, there is supra-threshold compensation for the contrast sensitivity loss. Supra-threshold perception behaves more normally than the threshold elevation would predict and this has been shown in a number of different pathologies (Dickenson & Abadi, 1992; Hess & Bradley, 1980; Leat & Millodot, 1990; Medjbeur & Tulunay-Keesey, 1986). There is evidence that this compensation for decreased sensitivity can change over time (Fine, Smallman, Doyle, & MacLeod, 2002).

Another factor which may have led to less preference for the custom multiplicative filter is the problem of saturation, which was addressed in this study by clipping. The clipping of the parts of image that exceed the dynamic range may have resulted in a loss or distortion of spatial frequency information. This may have been more excessive for the custom multiplicative filter than a number of the others, since larger gains were incorporated.

The fact that subjects with maculopathy appeared to gain less overall subjective improvement than subjects with other disorders is interesting. The majority of the subjects in the maculopathy group had a diagnosis of age-related maculopathy. In ARMD, in addition to loss of photoreceptor function, a number of studies have suggested dysfunction within the amacrine and horizontal cells, resulting in a loss of local luminance adaptation and disturbances of gain control within the retina (Brown & Garner, 1983; Brown & Lovie-Kitchin, 1983; Brown, Zadnik, Bailey, & Colenbrander, 1984; Enoch, 1978). Since the image processing techniques used in this study invariably resulted in increases in local contrast within the image (increase in contrast of some spatial frequency components), it is possible that the inability to adapt to these local increases in contrast may have offset the expected improvements due to increased contrast. However, this does not explain the reverse finding, that many patients with ARMD appreciate a closed circuit TV for reading, which also increases local contrast. Neither does it explain why subjects with diabetic retinopathy or glaucoma obtain more subjective improvement. Diabetic retinopathy and glaucoma are also likely to affect the activity of the inner retina including horizontal and amacrine cells (Frishman et al., 2000; Hood et al., 1999; Park et al., 2003).

When the subjects were divided according to visual field loss, the unsharp mask was the filter that was significantly preferred by both groups of subjects. The unsharp mask enhances the higher spatial frequencies. Certainly it can be understood why this would be beneficial to those with central field loss, who are relying on eccentric retinal function, which has lower resolution and lower contrast sensitivity, particularly at higher spatial frequencies, than the fovea. Thus, enhancing the higher spatial frequencies would have an obvious advantage to these subjects. Subjects with peripheral field defects would tend to include those with a diagnosis of glaucoma, retinitis pigmentosa and diabetic retinopathy. It must be noted that all subjects in this study, including those with peripheral field defects, had some acuity loss (see Table 1), that is the fovea was also affected. In retinitis pigmentosa, once visual acuity is compromised, contrast sensitivity is invariably reduced for all spatial frequencies, and this loss is greatest for high spatial frequencies (Alexandra, Barnes, Fishman, Pokorny, & Smith, 2004). Similarly in diabetes prior to retinal involvement and glaucoma, contrast sensitivity is reduced for all spatial frequencies, with greater losses at higher frequencies (Ansari, Morgan, & Snowden, 2002; Lopes de Faria, Katsumi, Cagliero, Nathan, & Hirose, 2001). This may explain why subjects with central field loss (who rely on eccentric retina) and those with peripheral loss, who also have greater reductions of the higher frequencies, perform similarly with respect to their preference for filters. In both cases there is greatest loss of sensitivity for high frequencies, and the unsharp mask enhances these.

Lastly, the assumption made in this study is that all spatial frequencies are equally important for image recognition and that the aim is to restore the input contrast to a "normal" level or to that prior to vision loss. Previous studies have indicated that this may not be the case, although there is some dispute over which are the most critical frequencies for recognition. There is some inconsistency in the present study in terms of the frequencies which subjects preferred being enhanced. For example, there was some inconsistency between the results for the Peli and the unsharp masking filters, the former being more frequently preferred with a larger mask size (which would result in more emphasis of the high and middle spatial frequencies) and the latter with a smaller mask (emphasis at the higher frequencies and little change at the low and medium frequencies). The Peli et al. filter, which was preferred while the modified Peli was not, had larger mask sizes and lower gains, resulting in emphasis at the medium and higher spatial frequencies, with less attenuation of a narrower band of lower frequencies. Alternatively, the contrast stretch emphasizes all spatial frequencies equally (except when the pixel values exceed the dynamic range). The DoG filter (which was not rated to give significant improvement overall), was most frequently preferred with emphasis at lower spatial frequencies. The DoG filters with the emphasis at higher spatial frequencies gave rise to high frequency noise in the image, which subjects could detect and did not like (i.e., they commented on it). Overall, it seems that the filters which were most often preferred were those that give high and medium frequency emphasis, without too much attenuation of lower frequencies. This is again in agreement with Peli et al. (1994b) who found that subjects preferred filtered images of faces with gains at higher frequencies (approximately 16 cycles/face), although it must be noted that they found the opposite when using simulations of low vision with normal observers; enhancement of low spatial frequencies improved face recognition.

There is considerable variation in the results of studies of the critical frequencies for face recognition. There are many variables in face recognition experiments which would impact the exact results e.g., the exact psychophysical task and the degree of control of the hairline or other non-facial information. There are two common approaches for face recognition; the predictive value of contrast sensitivity (for either normal or low vision observers) and the effects of band-pass/low/high pass filtering. Owsley and Sloane (1987) found that contrast sensitivity for 6 cycles/deg was the best predictor of face discrimination. Bullimore, Bailey, and Wacker (1991) found that in subjects with low vision, facial expression recognition was best predicted by visual acuity rather than contrast sensitivity for an edge. It must be noted that Bullimore et al. were using a threshold distance for the threshold of facial expression recognition, so that the correlation with VA rather than CS is not unexpected—effectively it becomes a visual acuity test. Fiorentini et al. (1983) determined that the higher spatial frequencies (above 5 cycles/face) were most important for recognition, and that performance was only slightly decreased with only higher frequencies (above 8 cycles/face) included. In other words, the high frequencies are used in face recognition and low spatial frequencies are not required. In a study using band-pass filtering and the addition of narrow-band spatial noise, Näsänen (1999) found that spatial frequencies around 8–13 cycles/face were most critical for face recognition, but that there was at least some contribution of higher and lower spatial frequencies. Gold, Bennett, and Sekuler (1999) found that at least a two octave band-width is required, faces being virtually unrecognisable by the human observer with one only octave band-pass filtering. With two octave filters, recognition was most efficient at 6.2 cycles/face. Alternatively, Schuchard and Rubin (1989) concluded that there was no particular critical band width and that contrast sensitivity did not predict face recognition for people with low vision (Rubin & Schuchard, 1989). Using low pass filters, Peli et al. (1994b) found that the lowest band of frequencies which was sufficient for recognition was centred at 8 cycles/face height (4 cycles/face width). Thus, although there is some variability, most studies conclude that medium to high frequencies (in terms of cycles/face) are most critical for face recognition. The faces in the current study were large, subtending the majority of the screen. Each face for the "face" image subtended approximately 21 deg. Thus, 5–15 cycles/face would be approximately 0.23–0.69 cycles/deg, respectively. Yet subjects generally preferred emphasis at even higher frequencies, particularly for face images, as seen by the preference for large mask sizes in Table 2. This may not be so much for purposes of recognition as subjects may already be able to detect the low frequencies sufficiently for recognition of faces that subtend such a large angle. It may be that subjects prefer enhancement of higher frequencies for a subjectively clearer view.

It is interesting to note that recently developed electro-optical devices for people with low vision have incorporated digital image enhancements which appear to be similar to two of those found to be borderline effective in this study. The Jordy (supplied by Enhanced Vision Systems) is a head-mounted video display unit incorporating magnification and image processing. The first generation of the Jordy was called the V-Max. Although the technical details of the filter are not published our observations indicate that it appears to be similar to the contrast stretch filter in this study. Similarly, the VisAble video telescope (Betacom), which is a hand held device with magnification, appears to use a similar contrast enhancement feature. The NuVision (Keeler Instruments Inc.) is also a head-borne magnifying video device which incorporates a filter similar to edge enhancement. However, none of the currently marketed devices appear to use an unsharp mask filter.

5. Conclusion

The results of this study show that a number of generic image enhancement algorithms have potential for improving the visibility of images for low vision observers and were, indeed, better than our custom devised filters. It was initially assumed that low vision subjects would prefer as much enhancement as possible within the dynamic range of the display, due to their severe contrast sensitivity loss. Therefore the initial selection of filters included those that gave maximum enhancement. However, high gain values resulted in highly exaggerated cartoon-like images, which were not preferred by most of the subjects. In light of these results, a range of filters with lower gains could be investigated. Overall, it seems that the filters which were most often preferred were those that give high and medium frequency emphasis, without too much attenuation of lower frequencies. Additionally, more study is required on the custom-devised filters, which in theory should be able to more accurately compensate for contrast sensitivity loss.

It would appear that it may not be possible to provide an optimum filter for all possible images and image sizes. There was an effect of image type, the face, faces and outdoor type of images being most frequently improved. Sports images were not significantly improved by any filter used here. The present results indicate that there are generic filters that could be incorporated into devices for people with visual impairment. The results of this study indicate that the generic filter, unsharp masking, was the most consistently preferred, and this preference remained for certain image types when the subjects were analysed according to ocular disorder and central versus peripheral field loss. The Peli et al. adaptive enhancement, the edge enhancer and the contrast stretch also appeared worthy of future study.

However, it is unlikely that image processing will be a substitute for magnification. The majority of people with visual impairment experience visual acuity loss, and therefore will still require a magnified image, in order to improve resolution. However, this study indicates that there is a benefit to be gained from image enhancement used together with magnification to give a more usable and preferred perceptual image for many people with low vision.

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