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ORIGINAL ARTICLE

Effects of Contour Enhancement on Low-Vision Preference and Visual Search

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ABSTRACT

Purpose. To determine whether image enhancement improves visual search performance and whether enhanced images were also preferred by subjects with vision impairment.

Methods. Subjects ($n = 24$) with vision impairment (vision: 20/52 to 20/240) completed visual search and preference tasks for 150 static images that were enhanced to increase object contours' visual saliency. Subjects were divided into two groups and were shown three enhancement levels. Original and Medium enhancements were shown to both groups. High enhancement was shown to group 1, and Low enhancement was shown to group 2. For search, subjects pointed to an object that matched a search target displayed at the top left of the screen. An "integrated search performance" measure (area under the curve of cumulative correct response rate over search time) quantified performance. For preference, subjects indicated the preferred side when viewing the same image with different enhancement levels on side-by-side high-definition televisions.

Results. Contour enhancement did not improve performance in the visual search task. Group 1 subjects significantly ($p < 0.001$) rejected the High enhancement, and showed no preference for Medium enhancement over the Original images. Group 2 subjects significantly preferred ($p < 0.001$) both the Medium and the Low enhancement levels over Original. Contrast sensitivity was correlated with both preference and performance; subjects with worse contrast sensitivity performed worse in the search task ($\rho = 0.77$, $p < 0.001$) and preferred more enhancement ($\rho = -0.47$, $p = 0.02$). No correlation between visual search performance and enhancement preference was found. However, a small group of subjects ($n = 6$) in a narrow range of mid-contrast sensitivity performed better with the enhancement, and most ($n = 5$) also preferred the enhancement.

Conclusions. Preferences for image enhancement can be dissociated from search performance in people with vision impairment. Further investigations are needed to study the relationships between preference and performance for a narrow range of mid-contrast sensitivity where a beneficial effect of enhancement may exist.

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Key Words: central vision loss, image enhancement, visual search, contrast sensitivity

Most people with impaired central vision report difficulty viewing television and other video and electronic displays.[1] Electronic image enhancement may be a viable vision rehabilitation approach. The increasing trend for electronic dissemination of information makes it important to develop and evaluate image enhancement techniques that can serve the needs of a growing population with vision impairments.[2,3] With rapid improvements in display and computer technologies and with the frequent releases of new consumer digital imaging products, ranging from hand-held devices to high-definition televisions (HDTVs), the application of this approach may be widespread and simple once an effective method is identified.

Image enhancement for vision rehabilitation was first proposed in the 1980s.[4,5] Since then, various approaches and enhancement algorithms have been applied to both static images[6–8] and videos.[9–14] Enhanced images were shown to be preferred to the originals by people with vision impairments for both static images[6,7] and videos.[9,12–14] Establishing preference for image enhancement may be the most important indication of its value, but it is also

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desirable to measure and, if possible, demonstrate functional (performance) benefits of this technology. Although tasks with clearly defined performance metrics, such as reading speed, have been shown to have improved with the use of image enhancement,[15–18] determining performance changes in passive viewing tasks is challenging.[19] Some studies have demonstrated performance benefits for image enhancement of static images, in face recognition[20,21] and in facial expression recognition tasks.[8] However, no performance benefit of the adaptive enhancement was found in the ability to describe the content of a TV program that was enhanced.[22]

In a recent study of preferences for adaptive image enhancement,[23,24] participants with normal vision had one of two types of preferences. One group of subjects ("Sharp") preferred higher enhancement than the original video for all images, whereas a majority of the subjects ("Smooth") preferred higher levels of enhancement only for videos that did not contain faces. For videos that predominantly contained faces, less (Sharp group) or no (Smooth group) enhancement was preferred compared with videos with other contents. Thus, both video content and individual differences determine how much enhancement is preferred. It could be expected that such variance in preferences could be found also among people with vision impairment. To investigate this effect in our study, we selected images with different contents (including faces).

Perceived image quality as a function of image enhancement levels is non-monotonic, as there is a level above which the enhanced images begin to look worse,[25] as found for people with normal sight.[12,14,23,24] In some studies of people with vision impairments,[9,12,14] the relationship between preference and enhancement level was monotonic, suggesting that the optimal enhancement level was higher than that used in those studies. Thus, when evaluating image enhancement, it is important to ensure that the relationship between enhancement and benefit is explored over a sufficient range to identify the inflection in the response to the enhancement, that inflection possibly being the optimal level or just above it.

The relationships between preferences and performances with image enhancement are not known. Performance could continue to improve above the inflection point in perceived image quality, as a high level of image enhancement, which the viewer does not subjectively prefer, may, nevertheless, produce better performance. Thus, one purpose of our study was to measure and compare preference and performance of subjects with impaired vision for wideband enhancement of the same static images. Wideband enhancement consists of finding edges or contours in images and modifying those features to enhance their contrast.[26] Preference for images with modest levels of enhanced edges was demonstrated for static images[27] and for video segments[13] among people with vision impairments. We measured performance using a visual search. We measured performance using visual search task with which we recently found improved performance[28] using a different enhancement method (JPEG-based enhancement[6,9]) that was also found to be preferred.[12] However, we did not compare the performance and preference in the same study or with the same subjects, as we report in the present manuscript. Image contrast was enhanced along semantically relevant object contours using a local edge detection method based on trained natural edge statistics.

METHODS

Subjects

Twenty-four subjects with vision impairment that reduced central vision participated in this study. All subjects gave informed consent. The study was approved by the institutional review board of Schepens Eye Research Institute and adhered to the tenets of the Declaration of Helsinki. Single-letter visual acuity and letter contrast sensitivity (2.5° high letters) were measured for all subjects using electronic displays. The system used to measure letter contrast sensitivity display was calibrated and produces outcomes very similar to Pelli–Robson charts and Mars charts for letters of comparable visual angle. Subjects were divided into two groups (group 1 and group 2), depending on the image enhancement levels presented to them (Table 1). Two groups were used to enable testing four levels of enhancement, as only three levels were presented to each subject to limit the session duration. Sample size was determined based on data from a previous preference study.[23] There was no difference between the groups for visual acuity or letter contrast sensitivity (Mann–Whitney U test, $Z = 0.59$, $p > 0.6$).

Stimuli

High-quality digital images (1600 × 1200 pixels) were downloaded from flickr.com and images.google.com. Because image content was found previously to influence preference responses,[23,24] the images were categorized based on their content:

TABLE 1.
Visual characteristics of the two groups

Subjects	Group 1 (n = 10)	Group 2 (n = 14)
Image enhancement levels	Original, Medium, High	Original, Low, Medium
Visual acuity	20/96 (20/52–20/240)	20/115 (20/57–20/289)
Letter contrast sensitivity (log units)	1.20 (0.95–1.80)	1.33 (0.85–1.80)
Age (years)	49 (28–82)	57 (27–78)
Ocular diseases	AMD (3), JMD (1), glaucoma (1), myopic degeneration (1), and others (4)	AMD (2), JMD (4), glaucoma (1), myopic degeneration (2), and others (5)

Median and range (in parentheses) are shown for visual acuity, letter contrast sensitivity, and age.
Five subjects reported more than one disease conditions.
AMD, age-related macular degeneration; JMD, juvenile macular degeneration.

faces, indoors, or collections (examples are shown in Fig. 1 and in the appendix—available online at http://links.lww.com/OPX/A98). Face images were group photographs of sports teams or co-workers posing. In some, but not all, people in an image wore similar uniforms. Indoor images were photographs of kitchens, living rooms, bedrooms, and other living spaces, with no people. Collection images were photographs of a group of collected objects such as shells or toys. Face category was included because recognition of faces is a common complaint of people with vision impairment.[29,30] Although searching for objects within an indoor scene represents a common real-world search task, such searches are greatly influenced by top–down knowledge of where the searched-for object is likely to be located (e.g., a spoon is likely to be on a kitchen table). Thus, we used a third category, Collections, which had objects similar to the Indoor category, but provided no top–down information.

A total of 150 images (50 images per category) were used. Each image had 15 or fewer faces or objects in them. The same images were used in both performance and preference tasks. Although exposure to the images in the preference task may not affect visual search performance,[31] performance tasks preceded the preference tasks for all subjects. This pre-exposure to the content and the enhancement during the performance task provided familiarization with the range of enhancement levels. The combinations of the image category and enhancement levels were randomized independently for the performance and preference tasks.

When the 1600 × 1200 pixel images were displayed on the 1920 × 1080 pixel displays, they were shown at full resolution, so the bottom 120 pixels of each image were not visible. For the visual search task, the image was shown on the right side of the monitor, leaving a 320-pixel-wide black strip in which the search target was shown. For the preference task, the images were centered horizontally, leaving 160 pixel black strips on either side.

Image Enhancement

The contour enhancement algorithm used in this study was developed at the University of Southern California. Images were enhanced to increase the visual salience of object boundaries or contours. The enhancement was termed "semantic," as it was based on human observers' labeling of object boundaries in natural images, and only indirectly on local edge energy. The collection of the edge-present and edge-absent probability distributions was based on offline human labeling of extracts from 450 images from the COREL image database (http://kdd.ics.uci.edu/databases/CorelFeatures/CorelFeatures.data.html). These statistics once collected were incorporated into the local edge probability algorithm, which can be applied at any location in any image to automatically estimate the local oriented edge probability.[32] Bayes' rule was used to approximately compute

$$P(\text{edge @ } x,y,\theta | r_0, r_1 \ldots r_N), \tag{1}$$

where r_0 is the response of a "reference" linear filter at (x,y,θ), and r_i are the responses of other linear filters at (x_i,y_i,θ_i) in the vicinity of (x,y,θ). The neighboring filters ($n = 6$) used were chosen to satisfy two criteria: (1) low average correlation in natural images between all pairs of filters in the set and (2) high Chernoff distance[33] between edge-present and edge-absent distributions

$$P(r_i | \text{edge } \{\text{or } \sim \text{ edge}\} \text{@ } x,y,\theta), \tag{2}$$

where the existence of edges in images was as labeled by human observers as described earlier in the text. We modeled the joint distribution

$$P(r_0, r_1 \ldots r_N | \text{edge } \{\text{or } \sim \text{ edge}\} \text{@ } x,y,\theta), \tag{3}$$

based on simplifying assumptions about the dependencies between filter responses in the vicinity of an edge. The joint distribution was then used to determine the probability of a given pixel in the images being a semantic edge. Edge pixels forming contours were enhanced, as described later in the text.

The image enhancement was based on the "Cornsweet illusion"[34] and was applied only to the luminance intensity channel of the original image. Image pixels along a contour were modulated in bipolar manner[35] such that the bright side of the contour was made brighter and the dark side was reduced in luminance intensity (Fig. 2 and in the appendix—available online at http://links.lww.com/OPX/A98). The enhancement level applied modified only the level of brightness change and not the selection of edge pixels. The enhancement levels used resulted in a maximum 40% increase or decrease of luminance on either side of the contour edge for the Low and Medium level of enhancement, and by maximum 60% increase for the High level of enhancement. The modulation diminished with distance from the edge, with an exponential falloff with distance from the edge (space constant was 1, 1.33, or 5 pixels for Low, Medium, and High levels, respectively). The unenhanced image is referred to as the Original level in this study. Subjects in group 1 saw Original, Medium, and High enhancements, and subjects in group 2 saw Original, Low, and Medium enhancements (Table 1).

FIGURE 1.

Sample images from the three categories (left) faces, (center) indoors, and (right) collections. For the visual search task, the search target was presented in the upper left corner of the image, and subjects were asked to point to the object that matched the search target. Additional examples are provided in the appendix (available online at http://links.lww.com/OPX/A98). A color version of this figure is available online at www.optvissci.com.

FIGURE 2.

Side-by-side image comparison for the preference task. The Original image is on the right and the enhanced (High) image is on the left. For easier appreciation of the enhancement, a small segment of each image is shown magnified. The contour enhancement makes the bright side of an edge brighter and the dark side to appear darker. Additional examples are provided in the appendix (available online at http://links.lww.com/OPX/A98). A color version of this figure is available online at www.optvissci.com.

Visual Search Task

Searching for objects is an everyday task that may improve if the object of that search is easier to see and distinguish from other potential objects. Visual performance was measured using a search task in which subjects identified a "target" object within an image. The target (an object copied from within the larger image) was displayed on the upper left corner of the image (Fig. 1) on a high-brightness 32 in LCD HDTV (Panasonic Viera TTC-LS32S1, 1920 × 1080 pixel native resolution, 70 cm by 39.5 cm, maximum luminance = 350 cd/m^2). The screen was fitted with a custom-made infrared touch screen frame (Mass Multimedia, Colorado Springs, CO). Subjects pointed to target's location in the image using a stylus that had a 7-mm-wide tip. Subjects sat centered to the screen and at a distance where they could easily reach all four corners of the screen. A table between the subject and the screen prevented the subject from leaning in. Viewing distance ranged from 45 to 55 cm for all subjects. At 50 cm distance, the horizontal screen spanned a horizontal visual angle of 55°.

Subjects had 17 practice trials with images that were not used in the study. For the experimental trials, 150 different images were presented in random order using a custom MATLAB (Mathworks, Natick, MA) and Psychophysics toolbox[36,37] program, counterbalanced for category and enhancement level. Reaction times and screen-touch locations were recorded. No feedback about the search performance was provided, and the next trial began immediately after the subject selected the target location, correct or otherwise. Breaks were enforced after every 30 trials, and subjects could request to take additional breaks at any time. The procedure lasted approximately 1 hour.

Reaction time was the interval between trial onset and response (screen touch). Targets varied from 44 to 372 pixels wide by 58 to 424 pixels high (illustrated in the appendix—available online at http://links.lww.com/OPX/A98), were on an average 1.7% of the image area, and, across the entire set of images, were distributed approximately evenly across the whole image area. A response was considered correct when the touch was within a rectangle that defined the target location, plus a surrounding 60-pixel-wide (22 mm, ~2.2°) rectangular annulus, to give some tolerance for touch placement errors and parallax (the mounted infrared touch frame was 20 mm in front of the HDTV screen). The distances of targets to nearest objects (potential targets) were all larger than the size of the buffer zone for touch error. Therefore, it is unlikely that an incorrect selection would be registered as a correct response.

Preference Task

Subjects indicated their preference between two versions of the same image with different enhancement levels displayed side by side (Fig. 2) on two comparable 42 in LCD HDTVs (Vizio, 1920 × 1080 pixel native resolution, maximum luminance = 300 cd/m^2). The instructions given to all the subjects for the preference task was read out from a script. In short, subjects were asked to choose the picture (preference) that looked better on the TV or if hung up on a wall. To minimize head movements required by the subjects to compare the two images, the HDTVs were angled (114°) toward each other. Subjects pressed the left or right button on a button box to select their preferred image, after which a confirmation screen on the selected side was displayed, and the subject pressed the button again to confirm or change the selection as needed. Subsequent trials began immediately after the subject indicated their preference for the right or left image.

Subjects were 71 cm from the center of each HDTV; thus, each HDTV spanned a horizontal visual angle of 53°, comparable with the visual angle in the performance task. The three enhancement levels compared were the same as that used in the performance study. All possible pairings of the three enhancement levels were presented five times for each image category, but we presented comparisons of closer image enhancement levels (e.g., Original vs. Medium, Medium vs. High) twice as often as more distant levels (e.g., Original vs. High), for 50 comparisons per image category. The 150 trials lasted approximately 45 min, and subjects did the preference task after a short break after the performance (visual search) task.

Data Analysis

Because subjects may trade off speed for accuracy (i.e., may try to search for the target quickly, compromising accuracy) or vice versa, we applied a novel measure that accounts for any time–accuracy trade-off. Integrated search performance,[28] illustrated in Fig. 3, is based on the cumulative proportion of correct responses with increasing search time. Integrated search performance is the area under the curve generated by this cumulative function. Generally, a higher final number of correct responses and shorter search times will result in a larger area under the curve, which represents better search performance. A single search performance measure allows simpler performance quantification and outcome interpretation under time–accuracy trade-off conditions, as could occur in our task. For the area under the curve computation, for each individual, the search time range between the fastest response and the slowest response for all the testing conditions was normalized to 1. Thus, integrated search performance can range from 0 to 1.

Binary logistic regression was performed on preference data (every image enhancement level combination was either preferred or not preferred, a binary outcome). This approach produces a measure that is similar to Thurstone scaling for pairwise comparisons, with the additional benefit of determining the statistical significance of differences (e.g., between enhancement levels).[24,38] The binary logistic regression coefficients are the relative preferences for those conditions. The range of the coefficients was normalized to a range of 1, and the relative preference for the Original image was set to 0. Relative preference can range from -1 to $+1$.

Repeated-measures ANOVA was used for analyses of search performance and relative preference. Statistical significance of $\alpha = 0.05$ was set as the threshold for all analyses. Because the sample sizes were small, we also note effects that approached significance ($0.05 < \alpha \leq 0.10$).

RESULTS

All subjects in both groups (Table 1) were able to complete all the 150 search trials and the 150 pair-wise comparisons for the preference task. Letter contrast sensitivity, and not visual acuity, was correlated with visual search performance. Letter contrast sensitivity, and to a lesser extent, visual acuity, were correlated with the relative preference for the Medium enhancement (Table 2). Visual acuity was correlated with letter contrast sensitivity ($\rho_{24} = -0.46$, $p = 0.02$), and did not improve models of the data that were corrected for letter contrast sensitivity. Therefore, only letter con-

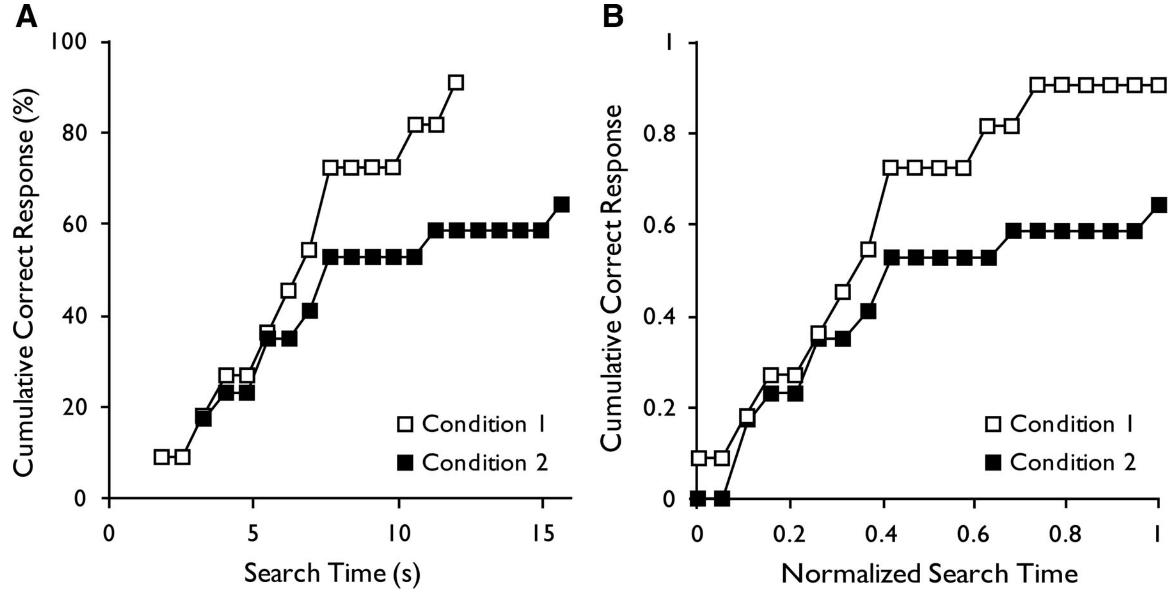

FIGURE 3.

Cumulative correct responses over time for two conditions to be compared are plotted. (A) For each condition, the curve starts from the shortest correct responses, and ends at the longest correct responses. (B) For the integrated search performance computation, the cumulative response curves are first extended to the shortest and longest correct response time across the two conditions, and then the search time range is normalized from 0 to 1.

trast sensitivity was included as a covariate in the repeated-measure ANOVAs for all search task analyses (i.e., ANCOVA) and in the logistic regressions (relative preference).

To examine whether the two groups had similar responses, analyses were conducted on data for the Original and Medium levels of enhancement only, as these were common for the two groups. For these two enhancement levels, there was no difference in search performance between the two groups ($F_{1,21} = 0.05$, $p = 0.83$). However, there was a significant difference in the relative preference between the two groups ($p < 0.001$). Therefore, and because the groups experienced different sets of enhancements (on the same images), the results for the two groups are presented separately later in the text. Effects of image category were considered within those analyses.

Visual Search Task

Search performance (Fig. 4A) declined with increasing enhancement for group 2 ($F_{2,26} = 5.17$, $p = 0.01$), but enhancement level did not affect search performance of group 1 ($F_{2,18} = 0.86$, $p = 0.44$). Image category had a significant effect on search performance for group 1 ($F_{2,18} = 8.91$, $p = 0.002$) and group 2 ($F_{2,26} = 6.77$, $p = 0.004$). Subjects had worst performance on face images and best performance on collections images. There were no significant interactions between image category and enhancement (group 1: $F_{4,36} = 0.77$, $p = 0.56$; group 2: $F_{4,52} = 0.15$, $p = 0.96$) in either group.

Preference Task

For both groups, there were significant differences in preference between the enhancement levels (Fig. 4B), demonstrating that these people with reduced central vision could discriminate the enhancement levels. For group 1, High enhancement was strongly rejected over Original and Medium enhancement level ($p < 0.001$). Preference for the Medium enhancement level was not significantly different from Original ($p = 0.79$). At the High enhancement level, the collection images had higher relative preference for enhancement when compared with face images ($p = 0.02$) and indoor images ($p = 0.06$). In contrast, group 2 showed a significantly higher relative preference for the tested enhancement levels, Low (not shown to group 1) and

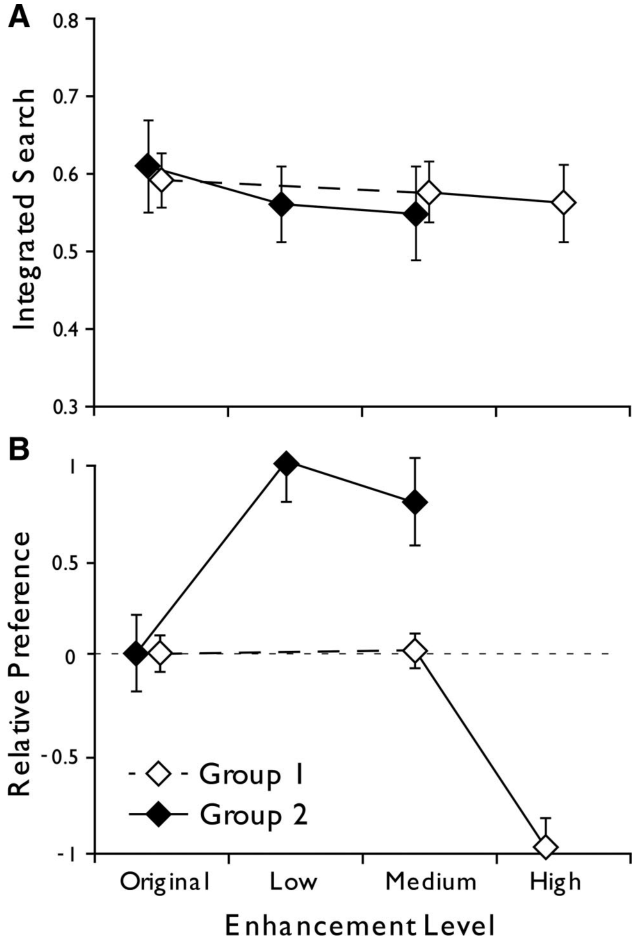

FIGURE 4.

(A) Integrated search performance and (B) relative preference for the tested enhancement levels for group 1 (open symbols) and group 2 subjects (filled symbols). Higher values denote better search performance (possible range: 0 to 1), and greater preference for a given enhancement level over the Original (possible range: −1 to 1). Original level is fixed to zero for the relative preference. Error bars denote 95% within-subject confidence intervals.

TABLE 2.

Spearman correlations (ρ) for visual acuity and letter contrast sensitivity with median integrated search performance and relative preference

Enhancement	Original	Low	Medium	High
Visual acuity (logMAR)				
Search performance	$\rho_{23} = -0.26$ $p = 0.23$	$\rho_{13} = -0.39$ $p = 0.17$	$\rho_{23} = -0.23$ $p = 0.28$	$\rho_{9} = +0.01$ $p = 0.99$
Relative preference		$\rho_{13} = -0.02$ $p = 0.96$	$\rho_{23} = +0.41$[a] $p = 0.047$[a]	$\rho_{9} = +0.15$ $p = 0.68$
Letter contrast sensitivity (log units)				
Search performance	$\rho_{23} = +0.80$[a] $p < 0.001$[a]	$\rho_{13} = +0.92$[a] $p < 0.001$[a]	$\rho_{23} = +0.77$[a] $p < 0.001$[a]	$\rho_{9} = +0.78$[a] $p = 0.01$[a]
Relative preference		$\rho_{13} = +0.02$ $p = 0.94$	$\rho_{23} = -0.47$[a] $p = 0.02$[a]	$\rho_{9} = -0.31$ $p = 0.38$

The relative preferences for the Original level are zero, and hence there is no variability between subjects.

[a] Significant ($p \leq 0.05$) correlations.

Medium (shown to group 1), over the Original ($p < 0.001$). Low was also significantly preferred to the Medium enhancement level ($p = 0.01$). Similar to group 1, the collection images had higher relative preference at Low enhancement when compared with face images ($p = 0.03$) and indoor images ($p = 0.02$), and higher relative preference at Medium enhancement when compared with indoor images ($p = 0.05$), but not face images ($p = 0.59$; Fig. 4B). Similarly, in a previous study,[23,24] subjects with normal vision had lower preference to enhancement of videos that contained more faces.

By using self-reported preference criteria,[23] we separated subjects into two preference subgroups. The "Sharp" preference subgroup ($n = 2$ in group 1; $n = 8$ in group 2) preferred more clarity and scrutinized the clarity of small details in the image, whereas the "Smooth" preference subgroup ($n = 8$ in group 1; $n = 6$ in group 2) preferred smoother and more natural appearance of images. Because for group 1, only three subjects were in the "Sharp" subgroup, no subgroup analysis was performed for group 1. For group 2, Sharp and Smooth subgroups were indeed significantly different ($p < 0.001$) at Low and Medium enhancement levels (Fig. 5). That difference between the subject-report–defined subgroups (Sharp and Smooth) was not found for search performance (ANCOVA accounting for contrast sensitivity, $F_{(1,11)} = 1.23$, $p = 0.29$).

Correlations between Visual Search and Preference

Correlations between integrated search performance and relative preference were computed controlling for contrast sensitivity for the enhancement levels (Low, Medium, and High). Integrated search performance was computed for all images (from the three image categories), as relative preference for each image category was not computed for each subject owing to the small sample size (only 25 images were seen with each enhancement level for each category). In group 1, no significant correlations were found between search performance and preference for either the Medium ($p = 0.50$) or High ($p = 0.31$) levels of enhancement. Similarly, in group 2, no significant correlations were found for either the Low ($p = 0.77$) or Medium ($p = 0.06$) levels of enhancement. Fig. 6 shows the relationship between the performance improvement (Medium enhancement over the Original) and contrast sensitivity or relative performance for all 24 subjects.

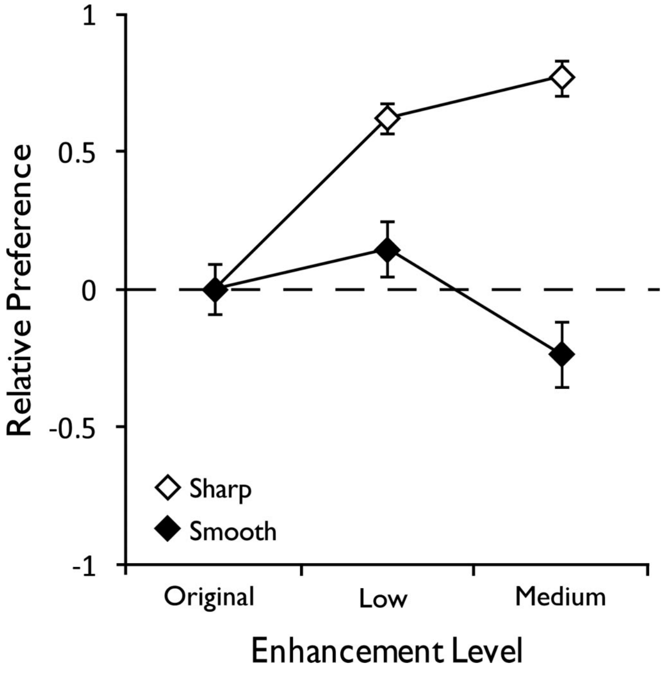

FIGURE 5.

Subjects in group 2 were categorized as Sharp and Smooth using self-reported preference criteria. Sharp and Smooth subgroups were significantly different at Low and Medium enhancement levels ($p < 0.001$). Error bars denote 95% within-subject confidence intervals.

DISCUSSION

The major findings of our study for people with reduced central vision are that relative preferences were non-monotonic, individual preferences varied widely, contrast sensitivity was related to search performance and image enhancement preference, and importantly, search performance was not related to preference. The non-monotonic change in relative preference with increasing enhancement, with subjects liking moderate (e.g., Low and Medium), but not high, levels of enhancement, is consistent with previous studies of people with low vision[6,7,9,12] and normal sight.[14,23] Approximately, 30% of the subjects with normal sight in a previous study of a contrast enhancement[23] and 46% of the subjects with impaired vision in the current study (11 of 24) reported a Sharp preference. As with subjects with normal sight,[23] our subjects with low vision in the Sharp subgroup had higher relative preferences than those in the Smooth subgroup (Fig. 5). These between-subject differences in preferences for the amount of image enhancement indicate that these differences were not abolished by impairment of vision. Thus, these between-subject differences should be considered in the development of image enhancement algorithms and in their use for vision rehabilitation. Because people with impaired vision know their preference, it may be possible to recommend different technologies to different people or to recommend the technology only to those who are likely to appreciate it.

Although moderate levels of contour enhancement resulted in increased relative preference (Fig. 4B), no level of enhancement improved the visual search performance of our subjects (Fig. 4A). The lack of an improvement (actually, a decrement for group 2) was not a failure of this rehabilitation paradigm because, for a different image enhancement, an improvement in search performance of subjects with reduced central vision was found using the same images and task.[28] The lack of improvement in visual search contradicts the finding of Kwon et al.,[39] who found a performance improvement (faster reaction times) with the same enhancement using the same images in a similar visual search task (we did not find improvement in the search time measure). Their normally sighted subjects performed the search task with simulated scotomas using a gaze-contingent display. The different outcome may indicate a problem with the scotoma simulation (e.g., an update lag that allowed a preview[40]). Such preview may help performance with the enhanced images more than in the unenhanced images. If so, such studies need to be conducted with subjects with reduced central vision until a simulation of impaired central vision that yields similar results is available. Another possible explanation is the greater brightness (350 cd/m^2) of our monitor (100 cd/m^2 for Kwon et al.[39] and 190 cd/m^2 for Luo et al.[28]) and higher magni-

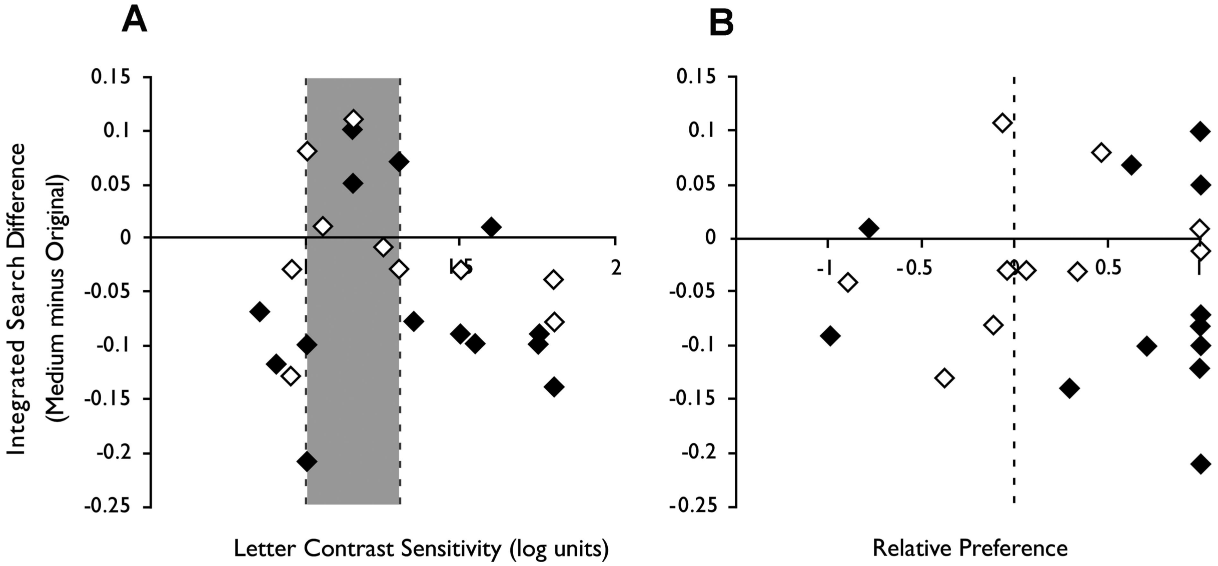

FIGURE 6.

Relationship between the effects of Medium enhancement on integrated search performance (Medium compared with the Original enhancement) with (A) letter contrast sensitivity and (B) relative preference. Six of the seven subjects that showed improved search performance (above zero on y-axis) had letter contrast sensitivities within a narrow range (illustrated with gray). Most subjects preferred Medium enhancement (positive values on x-axis of panel B), including five of the seven subjects who showed improvement in performance. Subjects in group 1 are shown with open symbols.

fication (55° wide) provided by our monitor (40°[39] and 41°[28]) could have reduced the potential benefits of the enhancement. Although visual search was found to vary with another image enhancement,[28] and visual search is an activity of daily living (e.g., looking for your keys), visual search, as implemented, may not be the best measure to detect changes in performance with enhancement. Other functional vision performance tasks, such as facial expression recognition,[8] may have improved with our enhancement and may better correlate with the preference pattern. Although it may be tempting to argue that a (objective) performance measure is a better measure of the benefit of image enhancement than (subjective) preference, if a user does not like the appearance, particularly for leisurely activities such as TV viewing, the user is unlikely to use the enhancement or to purchase a device that provides that enhancement. Therefore, we feel that preference remains a very important measure of the impact of image enhancements. Ideally, image enhancements should both improve performance of relevant tasks and be preferable in appearance to the viewer.

The reason for the difference between the two groups in their preference for the Medium enhancement (Fig. 4B) is not clear owing to the study design. Our study design cannot distinguish between an effect of the accompanying enhancement level, a "context" effect (i.e., Medium paired with High for group 1 and paired with Low for group 2), and a between-groups effect, reflecting real differences between these two small samples. Group 2 had a higher proportion of sharp preference (57%) than group 1 (30%), which could have caused the higher preference for Medium enhancement by group 2. Alternatively, as the subject responses were obtained after completion of the preference task, the experience of the "excessive" High enhancement by group 1 may have lead to more Smooth responses in group 1. Exposure to enhancement could result in a "sharp adaptation," making the Original image look blurred and the enhanced images appear "normal" or "sharper."[41] This could have occurred for group 2. Once the enhancement becomes "excessive," these high enhancements would produce less apparent blurring of the original image,[42] which may have occurred with the High level of enhancement presented to group 1. This may explain the lack of a preference for the Medium level by group 1. Subjects with reduced central vision exhibit such adaptation, and their adaptation extends to higher levels of the adapting stimuli than normally sighted subjects.[43] A future study should examine this possible enhancement context effect. Such a study could use a cross-over design, with the same group of subjects performing search tasks in the two groups of enhancement.

Letter contrast sensitivity emerged as an important predictor of responses to the image enhancements (Table 2). Contrast sensitivity was significantly correlated with both performance and preference measures. Subjects with worse contrast sensitivity preferred the enhancement (Medium) more than subjects with better contrast sensitivity, as was found in two previous studies.[12,14] In our study, subjects with better contrast sensitivity also had better visual search performance. Interestingly, six of the seven subjects whose visual search performance improved with Medium enhancement had contrast sensitivity in a narrow range (1 to 1.3 log units; Fig. 6A). Of those six subjects, five also preferred the Medium enhancement (over Original; Fig. 6B). With this small sample ($n = 24$), this apparent effect could be due to chance, but it is broadly consistent with the prediction of the model underlying the concept of contrast-based image enhancement for people with low vision.[25] Considering the non-linear (threshold) character of contrast sensitivity, it is expected that performance improvement will occur only when critical image features transition across the observer's sensitivity threshold.[44] The contour enhancement applied here is wideband in nature,[27] enhancing a wide band of frequencies. Letter contrast sensitivity probes only a limited range of spatial frequencies.[45,46] Perhaps, for a small portion of our subjects, their reduction in contrast sensitivity was a better match for the spatial frequencies enhanced by our contour enhancement, so some details important for the task performance changed from invisible to visible, making the task easier to perform. Although consistent with these speculations, our study was not designed to test that hypothesis directly. Direct testing could involve changing some characteristics of the images (e.g., observation distance[47]) or the enhancement levels, and testing the predicted response distributions across the subjects' contrast sensitivity range. If the effect is confirmed, our contour wideband enhancement will be most effective (at least for performance) by being individually tuned for the subject. The normally sighted subjects tested by Kwon et al.[39] had improved search performance. Although their contrast sensitivity was not measured under the simulated-scotoma condition, the 10° diameter artificial scotoma would reduce vision to approximately 20/100[48] and contrast sensitivity (gratings) to approximately 1.4 log units[49] in a healthy retina. This is consistent with the contrast sensitivity range that was related to improved visual search performance in our subjects. Thus, it is possible that the specific image enhancement with the specific parameters used will be beneficial (both for performance and for preference) for a small subset of subjects with vision impairment that can be determined by their contrast sensitivity. This, however, needs to be investigated further.

CONCLUSIONS

In conclusion, mild to moderate levels of our contour image enhancement were significantly preferred by subjects with vision impairment. The value of visual search as a measure of benefit from image enhancement requires further study. We have identified some factors that should be considered in the development of enhancement systems for people with impaired vision and their evaluation. Methods to implement image enhancement as a rehabilitation strategy need to be explored further.

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APPENDIX

The appendix is available online at http://links.lww.com/OPX/A98.

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