COMPENSATION FOR THE DEGRADED RETINAL IMAGE WITHIN THE HUMAN VISUAL SYSTEM: AN INVESTIGATION OF CONTRAST CONSTANCY FOR SIMPLE AND COMPLEX STIMULI

A thesis presented to the graduate faculty of The New England College of Optometry in partial fulfillment of the requirements for the degree of Master of Science

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May, 2005

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This manuscript has been read and accepted by the
Thesis Examination Committee in satisfaction of the
thesis requirement for the degree of Master of Science

May 13, 2005
date

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Acknowledgements

I would like to thank my parents, Dr. Marvin B. Hendricks, and Helen P. T. Hendricks for providing me with the strong mental, spiritual, and intellectual foundation needed in order to accomplish this body of work. I especially thank my husband, Leonard H. Sutton, II for his unyielding love and support throughout the development and writing of this thesis. Many people worked on or contributed to much of this work, especially Hyunjeong (Jamie) Han, who helped with programming and generation of experimental stimuli. Special thanks also to committee members Drs. James P. Comerford, Frank Thorn, and Eli Peli for many years of advising and friendship and for fostering a rich, intellectual, and collaborative environment.

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Abstract

COMPENSATION FOR THE DEGRADED RETINAL IMAGE WITHIN THE HUMAN VISUAL SYSTEM: AN INVESTIGATION OF CONTRAST CONSTANCY FOR SIMPLE AND COMPLEX STIMULI

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Defocus and aberrations degrade the retinal image of high spatial frequency stimuli compared to low spatial frequency stimuli, resulting in decreased contrast sensitivity at high frequencies. However previous studies employing a contrast matching experimental paradigm have shown that contrast matching is not affected by the degraded retinal image; high contrast images in the environment subjectively appear to have high contrast despite the effects of defocus and aberrations on high spatial frequency stimuli – an effect called *contrast constancy*. Contrast constancy is presumed to be a form of neural compensation for the degraded retinal image.

In a series of experiments we explore the effect of contrast constancy as it relates to simple stimuli as well as more natural images. We have found that contrast constancy occurs in the presence of best corrected vision, as well as under conditions of induced spherical refractive defocus, and induced Gaussian blur. Our experiments have shown that the amount of induced refractive defocus that the visual system is exposed to does not directly predict the relative amount of compensation that occurs. Instead, contrast constancy appears to be absolute and equal across varying amounts of refractive defocus, as long as the stimuli

remain above contrast threshold. Contrast constancy is compromised for stimuli near contrast threshold. Contrast constancy is also shown to be generalizable to natural images. Based on our work as well as previous studies, relative gain control is suggested as a possible mechanism for contrast constancy.

Contrast constancy, as explored in this study, has important implications for the study of perceptual adaptation in low vision due to either optical or neural blur. For example, the presumed neural mechanisms underlying contrast constancy after exposure to refractive defocus may explain why the onset of myopia and cataracts are so well tolerated. Similarly, the mechanism responsible for contrast constancy after exposure to Gaussian-type blur (similar to the scatter blur experienced by individuals with cataracts) may be responsible for optimizing vision during age-related ophthalmic changes.

I. Introduction:

It is clear from studies of the human visual system, that high spatial frequencies in the retinal image are severely degraded relative to low spatial frequencies (Campbell & Green, 1965; Campbell & Robison, 1968). This degradation is due to defocus, optical aberrations, and limits set by cone density in the fovea, which result in a sharp decrease in contrast sensitivity at high frequencies. However, anecdotally, the perception of blur across a visual environment rich in low as well as high spatial frequencies tends to remain constant across the environment, despite the inherent sources of blur. This suggests that there is a mechanism within the human visual system responsible for compensating for these differences across the environment. Georgeson and Sullivan (1975) suggested that perceived clarity of the degraded retinal image is, in fact, restored by an active process of neural compensation. More specifically, it has been suggested that neural processing in the human visual pathway compensates for both optical degradation as well as intrinsic noise at the photoreceptor level. A model of neural adaptation to blur is implicated (Figure 6) as a possible mechanism for visual consistency of images despite the presence of intrinsic blur. (Georgeson & Sullivan 1975; Snyder & Srinivasan, 1979).

The research of Georgeson and Sullivan (1975) laid the foundation for many studies to come which sought to investigate, empirically, the basis behind the anecdotal findings of image invariance despite variations in sources of blur across the visual environment. Georgeson and Sullivan (1975) found that "patterns will match in apparent contrast when their physical contrasts are equal even though their thresholds may differ by a great deal". They

demonstrated that, for sine wave gratings, the perceived blur may be less than expected for high spatial frequency gratings relative to low spatial frequency gratings, even though the contrast sensitivities for high spatial frequencies are reduced relative to low spatial frequencies. They refer to this phenomenon as *Contrast Constancy*, and they have quantified it using a contrast matching technique. Contrast constancy has since been replicated (Kulikowski, 1976; Swanson, Georgeson, & Wilson, 1998) and has been shown to be independent of retinal image position (Georgeson & Sullivan, 1975; Kitterle & Corwin, 1979); stimulus size (Peli, 1995), and luminance (Peli, Arend, & Labianca, 1996); thus demonstrating a certain robustness of the phenomenon.

While Georgeson and Sullivan laid much of the ground work in researching contrast constancy as a model of neural adaptation to blur, others continue to build on this concept. Attempts have been made to generalize this phenomenon to different types of stimuli. For example, Tiippana et al (2000) compared contrast matching with achromatic gratings to contrast matching with chromatic gratings and demonstrated that isoluminant chromatic gratings exhibit contrast constancy at suprathreshold contrast levels in a similar manner as previously demonstrated for achromatic gratings. However, more research is needed in order to fully understand the scope and robustness of contrast constancy across stimuli of varying characteristics.

There is also a trend in current literature to build on the concept of contrast constancy and dynamic adaptability within the human visual system by exploring the effects of introducing

extrinsic blur into the visual system (such as inducing myopic defocus in an emmetropic visual system) and testing the visual performance as a function of exposure time to blur. This area of research was sparked by anecdotal findings that myopes of low degree commonly report that their vision seems poorer upon removal of their spectacles compared to that after a period of time without spectacle wear. Pesudovs and Brennan (1993) proposed several alternative hypotheses to explain this phenomenon: accommodative response to spectacles, sensory adaptation, or altered criteria for blur of psychological origin. They evaluated visual acuity and refractive error after a period of adaptation to myopic defocus, and found an improvement in acuity after a period of blur adaptation, without refractive shift. This would suggest a sensory adaptation to blur. However, the demonstrated change in visual acuity was found to be less than that which was subjectively reported; suggesting that there is in fact some psychological input to blur adaptation.

Subsequent studies have built upon the research of Pesudovs and Brennan, demonstrating larger, more genuine improvements in visual acuity after prolonged exposure to optical defocus. Mon-Williams et. al. (1998) conducted a study in which myopia was induced in emmetropes through +1.00 diopter ophthalmic lenses, while controlling for pupil size, accommodation, and refractive error. The results of their study demonstrated a significant improvement in the ability to detect and recognize letters following 30 minutes of exposure to optical defocus. They suggested that improvement was not due to optical factors such as change in accommodation or pupil size, but rather, a neural compensation for prolonged optical defocus. Similar studies have examined adaptation to myopic defocus and found

acuity improvements from 0.7 logMAR before adaptation to 0.49 logMAR after adaptation (Rosenfield & Abraham-Cohen, 1999); acuity improvements from 0.82 logMAR before adaptation to 0.61 logMAR after adaptation (Portello & Rosenfield, 2002); and acuity improvements from 0.68 logMAR before adaptation to 0.55 logMAR after adaptation (George & Rosenfield, 2002). Furthermore, studies have examined the decay of blur adaptation and showed that blur adaptation is persistant, extending for at least 48 hours following the adaptation period (Rosenfield et al, 2002); is not attenuated by brief intervening periods of clear vision (Portellow & Rosenfield, 2002); and does not alter the magnitude or dynamics of the blur driven accommodative response (George & Rosenfield, 2002).

There is a problem, however, in applying the above studies to the understanding of real-life visual experiences. Typically the human visual experience is not limited to the viewing of simple stimuli such as the sinusoidal grating, and Snellen letters used in the studies discussed so far. But rather, under normal circumstances, most human visual experience includes complex stimuli of varying spatial frequencies. Natural images have a characteristic distribution of spatial contrasts, as captured roughly by the 1/f amplitude spectra typical of natural scenes (in which amplitude falls in inverse proportion to increasing spatial frequency) (Burton & Moorehead, 1987; Field, 1987; Tolhurst, Tadmor, & Tang, 2002; Ruderman & Bialek, 1994; van der Schaaf & van Hateren, 1996). To understand how the visual system deals with the complexity of natural scenes, Brady and Field (1995) proposed a model predicting that perceived contrast will be approximately constant across scale for scenes

whose spectra fall as 1/f. Subsequent studies by Webster & Miyahara (1997) were among the first to show that contrast adaptation to natural images influences the spatial sensitivity of the visual system. More specifically, these studies suggested that the visual system may have the ability to selectively reduce the response of spatial frequency selective channels at low to medium frequencies, biasing contrast sensitivity/response toward higher frequencies. Further investigation showed that adaptation to unfocussed, complex images can profoundly and rapidly affect the actual perception of image focus, with significant but incomplete transfer of the adaptation across different images (Webster et al, 2002). However, one may question whether or not this effect represents a true adaptation within the visual system, versus a psychological recalibration of the concept of "focus" as a result of exposure to images with altered spatial statistics (e.g. blurred or sharpened images). Further investigation is needed in order to distinguish psychological recalibration from true physiological adaptation.

Being able to generalize the effects of contrast constancy in real-life situations and fully understand the mechanism by which this occurs is important. Contrast constancy has obvious implications for vision with uncorrected refractive error and may also be important for low vision patients (perhaps patients can have the perception of sharp contours despite low contrast optical and neural images). Therefore, there is a growing area of research exploring the more clinical application of contrast constancy and/or blur adaptation. Hess and Bradley (1980) introduced the idea of blur adaptation as a mechanism for compensation for low vision conditions such as amblyopia (a condition characterized by marked contrast

deficits for threshold stimuli, suggesting deficient contrast coding at and above threshold). They showed that there is no contrast coding abnormality in amblyopia in the suprathreshold high-contrast range that frequently exists in everyday vision; implying some sort of neural adaptation to suprathreshold blur in amblyopia. This implication was supported by a subsequent investigation which used contrast magnitude estimation to compare perceived contrast of the amblyopia and non-amblyopic eye (Loshin & Levi, 1983). The authors showed that while amblyopic eyes show large losses of contrast sensitivity at threshold, at suprathreshold contrast levels, perceived contrast is essentially normal in the amblyopic eye. They also introduced the idea of gain control as a basis for inconsistency between contrast sensitivity at threshold and suprathreshold perceived contrast, implying that the amblyopic eye has a higher contrast gain than the non-amblyopic eye. Investigators have also examined blur tolerance in persons with myopia as well as low vision, and have found that tolerance to defocus increases as magnitude of myopia increases and/or acuity decreases (Legge et al, 1987; Thorn et al, 1998; Rosenfield & Abaham-Cohen, 1999; Simmers et al, 2002).

Studies such as these show that there is growing interest in the area of neural compensation for optical defocus. The following general concepts have been demonstrated: contrast constancy with simple stimuli; improvement in visual acuity as a result of adaptation to optical blur; changes in perception of image focus after viewing defocused images; and increased blur tolerance in myopes as well as persons with low vision.

Many of the studies examining blur adaptation evaluate performance using letter acuity measures in the presence of refractive defocus; however, it has been shown that measuring

letter recognition in the presence of defocus may have many confounding variables. Learning effects and blur interpretation have been implicated as sources of confounding variables in letter recognition tasks. Furthermore, *spurious resolution* (in which phase-reversed gratings are readily detectable) has been suggested as a mechanism by which Snellen letters are more sensitive than gratings to refractive defocus (Thorn & Schwartz, 1990). This can be avoided by inducing Gaussian blur instead of refractive defocus when evaluating adaptation to blur.

While studies have repeatedly shown that contrast constancy holds true while viewing sinusoidal gratings under normal viewing conditions, few studies have examined whether or not contrast constancy holds true after exposure to induced blur of varying magnitude, and varying types. Furthermore, while numerous studies have examined contrast sensitivity and perceived image focus after exposure to complex stimuli with altered spatial statistics, little research has been done to evaluate contrast matching performance with complex, natural stimuli; or to compare contrast matching performance for different types of complex, natural stimuli.

The main aim of this paper is to further investigate aspects of contrast constancy which have more clinical and real life implications than that which has previously been explored. We will investigate the effect of exposure to mild versus moderate amounts of refractive defocus (as seen in myopia) on contrast constancy, as well as the effect of exposure to mild versus moderate amounts of Gaussian blur (as seen in cataracts) on contrast constancy.

Furthermore, we will evaluate contrast constancy for simple stimuli which are arguably unnatural (e.g. sinusoidal gratings) versus complex, natural stimuli which are frequently encountered in our visual environment (e.g. faces and trees). To this end, we conducted several experiments employing a matching technique similar to that of Georgeson and Sullivan (1975). In the first experiment, we examine contrast matching of sinusoidal gratings with observers wearing their best correction for refractive error. This serves as a replication of Georgeson and Sullivan's basic findings, laying the foundation for all subsequent experiments. In the second experiment, we repeat the contrast matching technique after exposure to refractive defocus similar to that found in myopic patients. The idea is that if contrast matching functions after exposure to defocus are similar to those obtained in the best-correction state, despite the change in the contrast sensitivity function, then there must be some form of compensation for blur that is responsible for the equivalent matching functions. Experiment three examines the generality (i.e. flexibility) of contrast constancy by comparing the contrast matching performance after exposure to +1.00 diopter of refractive defocus to contrast matching performance after exposure to +1.50 diopter of refractive defocus. While contrast sensitivity functions are expected to be significantly different for +1.00 diopter of refractive defocus, relative to +1.50 diopter of refractive defocus, contrast constancy is expected to be exhibited for all stimuli that remain above threshold. Contrast sensitivity functions with +1.00 and +1.50 diopters of refractive defocus are obtained, outlining the limits of resolution of the stimuli tested. Experiment four compares contrast matching performance after exposure to refractive defocus to matching performance after exposure to Gaussian blur. Gaussian-like blur, in this experiment, is induced by placing low-

pass filters over the observers' best correction. Gaussian blur is expected to degrade the contrast sensitivity function more than refractive defocus due to the effects of spurious resolution on sine wave gratings (i.e. in the presence of refractive defocus, spurious resolution may enhance the detection of sine wave gratings). However, once again contrast constancy is expected to be exhibited for all stimuli that remain above threshold. In an effort to generalize contrast matching results to more real-world situations, experiment five investigates contrast matching of complex stimuli whose amplitude spectrum is consistent with that found in natural scenes (i.e. a grayscale image of a face and a forest). If one were to propose that contrast constancy, much like other forms of physiological adaptation, is an evolutionary mechanism of dealing with the complexity of the environment in which we live, it is expected that contrast constancy would hold true for natural images as well as sinusoidal gratings. Finally, experiment six is a preliminary investigation of learning effect versus true adaptation after exposure to mild Gaussian blur. We will examine the effect of learning on a contrast matching task as a function of the number of repetitions of the task, and compare it to the effect of adaptation to blur on a matching task as a function of duration of exposure to blur. As with most psychophysical tasks, a learning effect is expected; however, if adaptation to blur is occurring in the presence of Gaussian blur, the improvement in performance over time, while adapting to Gaussian blur, should be larger than the improvement in performance over time of the same task in the absence of blur (i.e. in the blur condition, there should be a dual effect of adaptation and learning on performance).

2. Design and Methods:

Overview:

The subject population for the following experiments consisted mainly of NEWENCO students and faculty. Three non-NEWENCO affiliated subjects were used. All subjects used in this study had no known ophthalmic disease and had vision correctable to 20/20. All research followed the tenets of the Declaration of Helsinki, and informed consent was obtained from each subject after explanation of the experiments to be conducted, and full disclosure of the nature and possible consequences of the study.

In order to reduce the effects of accommodation, while still maintaining a distance at which the stimuli were viewable, all experiments were conducted at a test distance of 3 meters. All tests were performed binocularly. Ambient luminance was maintained at a constant dim illumination. Monitor calibrations were performed using a photometer (Spectra; Pritchard, Photo Research Corp., Burbank, CA). The Gamma of the system was maintained at a constant value of approximately 1.0. The Gamma was verified prior to experimentation using a photometer to measure the luminance of a grayscale stimulus of equiluminant RGB values ranging from 10 to 250, which was created in Power Point and presented on a 19-inch Samsung color monitor. Stimulus luminance, as measured by the photometer, was plotted as a function of screen RGB value, as specified on the monitor. The slope of this line (i.e. Gamma) was found to be 1 each time the monitor was calibrated.

2.1. Stimuli:

Simple Stimuli (gratings):

We used the *Morphonome Image Psychophysics Software for the Macintosh* for stimulus control and data collection. Stimuli were presented on a 13-inch Apple Monitor. Two horizontal sinusoidal gratings were presented in a rectangular envelope (11.5cm x 5.5cm in size) side by side; separated by 1.5cm (Figure 1). The number of grating cycles within the envelope varied as a function of spatial frequency. Contrast was adjusted using a continuous scale (0% to 100% contrast) provided within the Morphonome program. The contrast of the gratings was defined as (L max – L min)/(L max + L min), where L max and L min represent the maximum and minimum luminances of the grating, respectively. Overall, average luminance across stimuli remained constant. The background screen luminance was set to match the average luminance of the stimuli.

Complex Stimuli (face; forest):

Original 512 by 512 pixel grayscale images with spatial spectra most closely resembling that of natural scenes (1/f) were chosen (Figures 2 & 3). Reduced images were generated via Matlab software, by applying a Bicubic interpolation algorithm for image resampling (Carlson & Fritsch, 1989). Using this algorithm, RMS contrast remained constant for all sizes (bicubic interpolation does not alter spatial frequency or contrast). Bicubic interpolation generates each target pixel by interpolation from the nearest sixteen mapped source pixels. The value of an interpolated point is a combination of the values of the sixteen closest points. Two cubic interpolation polynomials, one for each plane direction, are used.

This method is piecewise bicubic, and produces a much smoother surface than bilinear interpolation. This algorithm yields a good balance between accuracy in detail preservation and smoothness for resampled images, while also allowing for satisfactory execution time and memory usage. RMS contrast of each image was calculated before the resampling process and compared to the calculated RMS contrast after resampling. The contrast remained unaffected by resampling. The Gamma of the monitor/computer system was verified prior to experimentation using the calibration procedure previously outlined (see Design and Methods: Overview), ensuring that the contrast of the images remained the same. Experimental stimuli were presented side by side on the monitor, with background screen luminance equal to the average luminance across stimuli (Figure 4).

2.2. Experiment 1: Contrast Matching with Best Corrected Vision

To evaluate contrast constancy, we used a matching technique similar to that of Georgeson and Sullivan (1975). While wearing their best correction for refractive error, twelve observers were presented with a 5cpd sinusoidal grating at contrasts of .03, .10, .30, and .80. The perceived contrast of these gratings was matched with gratings of 2.2, 5, 10.2, 15, and 23.6 cpd. Subjects were given the instructions, "adjust the contrast of the experimental image so that it matches the contrast of the standard image". Contrast was explained to the subjects as the "difference in brightness between the lightest parts of the image and the darkest parts of the image". Subjects were advised to scan the entire image while making judgments. Matching was determined using an ascending and descending method of limits.

Subjects responded verbally (i.e. experimenter asked: “do they match now”; subject responded “yes” or “no”).

Contrast sensitivity was also determined for the spatial frequencies of 2.2, 5, 10.2, 15, and 23.6 cpd. Contrast sensitivity functions were plotted from the thresholds obtained for each of the above special frequencies. Thresholds were found via a staircase, two alternative forced-choice experiment paradigm using the same stimuli that were used in the matching experiment (sine wave gratings). Each trial consisted of two presentations (a “test” and a “null”) separated by an inter-stimulus interval. The presentation shown first was determined at random. Subjects were required to indicate which was the test presentation by pressing either the left arrow (interval 1) or the right arrow (interval 2). When a response was entered, the program presented the next trial. The program continued presenting trials in a staircase procedure, with a step size of 0.05 log units, until a threshold value was determined. Threshold was defined as the moving average of the last set of trials. The staircase continued until the moving average became stable (i.e. the standard deviation was less than 1 staircase step or the number of trials reaches the maximum trial count).

2.3. Experiment 2: Contrast Matching after Exposure to +1 Diopter of Refractive Defocus

To evaluate contrast constancy after adaptation to blur, nine observers from “experiment 1” (after completing “experiment 1”) wore lenses (convex ophthalmic thin lenses placed in a trial frame) which induced +1 diopter of refractive defocus, and adapted to distance viewing for 15 minutes. During this adaptation period, subjects viewed a video taped movie at a distance of 3 meters on a 13 inch television screen. The purpose of the adaptation period was

to simulate a real-world visual experience in the presence of induced optical defocus. After adaptation, observers were retested with the same contrast matching technique described in "experiment 1", while wearing the +1 diopter lenses. Post-adaptation contrast sensitivity functions were also determined while wearing the +1 diopter lenses.

2.4. Experiment 3: Contrast Matching after Exposure to +1.5 Diopters of Refractive Defocus

To evaluate the robustness of contrast constancy, four observers who had previously participated in "experiment 1" and "experiment 2", wore lenses which induced 1.5 diopters of refractive defocus. These subjects adapted and were retested using the same technique as that which was described in "experiment 2".

2.5. Experiment 4: Contrast Matching after Exposure to Gaussian Blur

The goal of experiment 4 was to compare the effects of adaptation to refractive defocus to the effects of adaptation to Gaussian blur. Ten subjects who had previously completed experiment 1 were tested using the same procedure as outlined in experiment 2, except the type of adapting lens was varied. Rather than lenses which induce refractive defocus, subjects wore lenses which induce Gaussian blur during the adaptation period and contrast matching task. Gaussian blur was induced using diffusing filters (0.8 and 0.6 Bangerter Occlusion Foils; The Fresnel Prism and Lens Co., LLC). These foils have previously been shown to behave as low-pass filters, producing a reduction in modulation transfer function (MTF) similar to that found in various sources of scatter blur (e.g. cataracts) (Vera-Diaz et al, 2004). The relative changes in spatial contrast sensitivity produced by viewing through each

of these foils are illustrated in Figure8. The foils were placed over zero power trial lenses, which were worn over the subject's best correction. Two different levels of scatter blur were used. The 0.8 Bangerter Occlusion Foil, "Filter A", induced mild levels of blur (approximately 20/25 Snellen acuity), while the 0.6 Bangerter Occlusion Foil, "Filter B", induced moderate levels of blur (approximately 20/30 Snellen acuity).

2.6. Experiment 5: Contrast Matching with Complex Stimuli

To evaluate contrast constancy in complex stimuli, we used an experimental paradigm similar to that used in the previous matching experiments. Ten observers were presented with a grayscale image of a face (image 1) and a forest (image 2) at Michaelson contrasts of 0.075, 0.15, 0.30, and 0.60. The perceived contrast of the image was matched with the same image subtending different angular retinal sizes (2x, 1x, 0.5x, and 0.25x standard size image). Note, the "2x" image is not an expanded image, but rather, it is the original 512 pixel image from which all of the smaller images were created via bicubic interpolation. In using bicubic interpolation spatial contrast was preserved. The "2x" image subtended a visual angle of 2.86 degrees; the "1x" image subtended a visual angle of 1.43 degrees; the 1/2x image subtended a visual angle of 0.76 degrees; and the "1/4x" image subtended a visual angle of 0.38 degrees. The standard image and the experimental image were presented side by side on a 19 inch monitor. Subjects adjusted the experimental image to match the standard image in contrast by using the up/down arrows on a keyboard. An ascending and descending method of limits experimental paradigm was used.

2.7. Experiment 6: Evaluation of Learning Effect vs. Adaptation

A preliminary experiment was implemented to assess learning effect vs. adaptation. Image type and image contrast were kept constant [image type = "image 1"; image contrast = 0.60 Michaelson contrast] as 2 subjects performed a matching task as outlined in "experiment 5". The task was completed 10 times in a row (total of 10 trials); Accuracy of matching versus time was plotted. The amount and rate of improvement in accuracy was noted. In a second phase, we introduced a 0.8 Bangerter Occlusion Foil, "Filter A", which induced mild levels of scatter (approximately 20/25 Snellen acuity), and repeated the above procedure. Again, accuracy of matching vs. time was plotted, and the amount and rate of improvement in accuracy was noted. The improvement in accuracy in the best-corrected state was compared to the improvement in accuracy in the blur condition. It is assumed that the amount by which the improved accuracy over time in the blur condition exceeds the relative amount of improvement in best-corrected state represents the amount of "adaptation" to blur.

3. Results:

3.1. Experiment 1: Contrast Matching with Best Corrected Vision

In experiment 1, we found that while patients wearing their best refractive correction demonstrate a fall-off in contrast sensitivity at high spatial frequencies, their contrast matching as a function of spatial frequency is generally flat, thus demonstrating contrast constancy. Contrast constancy fails, however, when resolution is compromised by poor contrast sensitivity. Results were similar for all 10 subjects (Figure 7).

3.2. Experiment 2 and 3: Contrast Matching after Exposure to +1 vs. +1.5 Diopters of Refractive Defocus

With both +1D and +1.5D of refractive blur, all subjects tested exhibited a significant decrease in contrast sensitivity within the spatial frequency range that was tested ($p<0.0001$). Low contrast stimuli and high spatial frequency stimuli in many instances were not seen at all. In order to ensure that the stimuli were in fact reliably seen during the contrast matching task, we applied a rule that the stimulus must be at least 1/2 octave above threshold. For stimuli meeting our threshold criterion, contrast constancy still occurred for both the +1D and +1.5D blur conditions (Figure 8). Despite the fact that contrast sensitivity functions show an increase in threshold with blur, an ANOVA shows that there is no significant difference between the effect of the +1D and +1.5D lenses on contrast matching. Relative gain control functions were constructed from the CSF data and the contrast matching data. In this case, gain control is indicated by the difference in matching functions across different spatial frequencies. Apparent contrast relative to the 5 cpd standard was plotted against stimulus

contrast for each observer (Figure 9). These gain control functions quantify the relative amplification of apparent contrast that occurs equally across different spatial frequency stimuli. The assumption was made that at threshold, perceived contrast is equal for all spatial frequencies. Our data show individual differences in gain control functions. Some subjects show an increase in contrast gain (for low contrast stimuli) with blur adaptation, while others do not. Gain control functions were similar for +1 diopter and +1.50 diopter blur conditions.

3.3. Experiment 4: Contrast Matching after Exposure to Gaussian Blur

Results from experiment 4, in which the effect of Gaussian blur on contrast matching was examined, were similar to those of experiment 2 and 3, in which the effect of refractive defocus on contrast matching was examined. However, with Gaussian blur, low contrast images suffered more optical degradation and therefore exhibited less contrast constancy than was seen with refractive blur (Figure 8).

3.4. Experiment 5: Contrast Matching with Complex Stimuli

While contrast sensitivity functions showed a typical decrease in sensitivity at high spatial frequencies relative to lower spatial frequencies, contrast matching functions were unaffected by the high spatial frequencies represented in the ½ standard and ¼ standard images, relative to the lower spatial frequencies presented in the 1X and 2X standard images. Results for image 1 (face) and image 2 (trees) were similar. Subjects were not able to resolve the 1/4x size target at low contrast; therefore, contrast constancy was not demonstrated for that image. Results were similar between all 10 subjects (Figure 10).

3.5. Experiment 6: Evaluation of Learning Effect vs. Adaptation

Both subjects performed accurate contrast matching in the "best corrected" condition (experimental images were matched within 1 log unit of actual physical contrast of the standard image), with accuracy improving over time. Results were similar in the blur condition, except, there appeared to be a more dramatic improvement in accuracy over time, than that which was seen in the "best corrected" condition. Results for subject, "BH" are presented in Figure11.

4. **Discussion**

4.1. Overview:

By investigating contrast matching performance with and without exposure to refractive defocus, we have found that contrast constancy (compensation for optical defocus) occurs in the best corrected state as well as under conditions of induced spherical refractive blur (as predicted by the work of Georgeson and Sullivan, 1975). Furthermore, we have found that the amount of induced refractive defocus that the visual system is exposed to does not directly predict the relative amount of compensation that occurs. Instead, contrast constancy appears to be absolute and equal across the two different levels of refractive defocus tested, as long as the stimuli viewed are above threshold (as defined by the contrast sensitivity function). Contrast constancy is compromised for stimuli near contrast threshold. From previous studies, we also know that contrast constancy after exposure to blur is similar whether adapting under natural viewing conditions (i.e. walking around) or adapting while watching video taped images at a fixed distance.

In comparing contrast matching performance after exposure to refractive defocus (such as myopia) to matching performance after exposure to Gaussian blur (similar to that which is found as a result of light scatter secondary to ophthalmic disease such as cataracts) we have found that contrast matching functions are similar for both conditions. Refractive defocus and Gaussian blur of the amounts tested have little effect on the perception of high contrast gratings of any spatial frequency tested. Thus, contrast constancy occurs for each blur type.

In another phase of the investigation, in which contrast matching performance was evaluated for grayscale natural stimuli subtending varying retinal image sizes, we found that contrast constancy was exhibited for all stimuli that the observer was able to resolve (i.e. suprathreshold images). Thus contrast constancy is shown to be generalizable to natural images. Furthermore, our data show that observers showed more accurate contrast matching for the natural images, relative to the sine wave gratings. Therefore, this supports a preliminary observation that natural images have advantages compared to sine wave gratings in the assessment of contrast constancy. However, further statistical analysis is indicated.

The finding of contrast constancy for sinusoidal gratings as well as natural stimuli (1) in the best corrected condition, (2) after exposure to refractive defocus, and (3) after exposure to Gaussian blur, has important implications for the study of perceptual adaptation in low vision due to either optical or neural blur. Understanding the basis for contrast constancy may be pivotal in understanding how and why the onset of myopia, as well as certain age-related ophthalmic diseases (e.g. cataracts), is so well tolerated in many cases.

4.2. Contrast constancy for best optically corrected vision and induced blur:

Our findings of contrast constancy under conditions of best optical correction (within the limits imposed by threshold and resolution) are consistent with the original contrast matching work done by Georgeson and Sullivan (1975). However, contrast constancy (tested with a contrast matching technique) has not previously been demonstrated after exposure to blur. When testing visual performance after exposure to blur (i.e. blur adaptation), there is a trend

in current studies to test visual performance using letter acuity tasks (Pesudovs & Brennan, 1993; Mon-Williams et al, 1998; Rosenfield et al, 2002; Portello & Rosenfield, 2002; George & Rosenfield, 2002). However, letter acuity is a threshold task. The problem with this is that previous studies have shown that contrast constancy, as a form of adaptation to blur, only holds true for suprathreshold stimuli (Georgeson & Sullivan, 1975). Our reseach supports the finding that contrast constancy fails for stimuli near threshold. So, the exact mechanism that is responsible for improvement in letter acuity after prolonged exposure to blur, is not clear. It has been suggested that sensory adaptation to blur in combination with altered criteria for blur of psychological origin may play a role in the demonstrated change in visual acuity (Pesudovs & Brennan, 1993). Further research is needed in this area. Nevertheless, it is clear that contrast constancy can not be solely responsible, as it has not yet been shown to alter or increase contrast threshold. Our demonstration of contrast constancy via a contrast matching technique, in the presence of blur suggest that the blur adaptation mechanism which is responsible for the phenomenon of contrast constancy is flexible, and can recalibrate for different visual diets. Furthermore, it may function to provide a smooth invariant visual environment, rather than to actually improve threshold visual performance in the presence of blur.

4.3. Limitations of the experimental paradigm:

- In matching sinusoidal gratings in the presence of blur, if blur changes the contrast sensitivity for the reference 5cpd stimulus as much as it does the comparison 5cpd stimulus, little change would be expected in a test of contrast constancy. For some

observers, however, there was an unexpected effect on the reference stimulus. Although the effects of blur on the 5cpd reference stimulus were less than for some of the test stimuli, these effects were larger than we anticipated. A lower frequency reference stimulus would be ideal since low frequency stimuli are minimally affected by blur, however our present equipment makes it difficult to present them.

- Some observers apparently matched stimuli (successfully) that fall below threshold (as defined by their contrast sensitivity functions) in the best corrected condition. This result is most likely an artifact resulting from the use of two different experimental paradigms:

  (1) During the contrast matching procedure, stimuli were presented side by side and observers were allowed to scan both images while making their adjustments. Although observers were asked to make judgments as quickly as possible, there was no time limit imposed.

  (2) During contrast sensitivity testing, each experimental trial consisted of two presentations (a "test" and a "null") separated by an inter-stimulus interval. After both presentations were completed, observers were required to indicate which was the test and which was the null. This experimental paradigm has a larger attention and memory component than the matching paradigm.

  Furthermore, it has been suggested that, contrast sensitivity functions obtained using wide-band (1 octave) Gabor-patch stimuli are more relevant to the interpretation of form vision (Peli, et al, 1990 & 1991). The fact that our stimuli were not presented in this format may have contributed to the observed artifact.

- As is inherent in most psychophysical experiments, results may be confounded by the observer's interpretation of the phenomenon being tested. For example, in the matching paradigm, although observers are given explicit instructions regarding what criteria to use in selecting a match, different subjects may inadvertently use different criteria in determining the best match. It is difficult to control for the cognitive component of this experiment. For example, stimuli of different spatial frequency and/or different retinal image size may show varying levels of sharpness due to the decreased sensitivity for higher spatial frequencies relative to lower spatial frequencies. However, the task is to match the stimuli in contrast; not focus. Subjects must understand the difference between focus and contrast in order to use the correct criterion in selecting their match. Furthermore, some subjects may inherently have a more strict matching criterion than others whose criteria are more lax. Forced choice methodology and larger sample sizes, are necessary in order to fully control for this. These problems, which are common in psychophysical testing, may speak to a need for a more objective technique for determining contrast constancy.

- In matching natural stimuli, it was first determined whether observers were able to resolve the image by asking them to identify the image as well as features within the image. If observers were unable to identify the image, it was assumed that the overall image was subthreshold. However, it is clear that different features within the image are affected differently by blur. More objective measures are needed in order to establish contrast sensitivity for complex images, in the current study. It may be necessary to

calculate local band-limited contrast in the images and compare to each individual observer's contrast sensitivity function; However, even with this information, it is not clear whether or not it can be accurately predicted how well a complex image is discriminable to an observer (Peli, 2001). Perceived contrast may vary greatly across the image (Peli, 1990)

- It has previously been observed that objects that are further away appear to have lower contrast than near objects. This observation was confirmed by O'Shea et al (1994), who found that subjects reported that stimuli having lower contrast with their background appeared farther away than stimuli having higher contrast with their background. The authors suggested that contrast acts as an effective depth cue in the absence of any other depth information (the result was larger when viewing monocularly than binocularly). It follows that the converse is possible – distance may act as a cue for apparent contrast in our contrast matching technique, in which stimuli subtending different retinal sizes may appear to be at different distances from the observer. In presenting stimuli subtending different retinal image sizes, it was expected that relative distance cues (as well as relative cues to accommodation secondary to distance cues) would be controlled for by presenting different sized targets at the same distance from the observer (i.e. both targets on the same computer screen). However, when a small subset of subjects were asked to estimate the distance of each of the images presented, 2 out of 5 subjects estimated the 2x image to be at a greater distance relative to the 1x, 1/2x, and 1/4x size images. Therefore,

it is possible that presenting observers with stimuli of different retinal sizes may have introduced distance as a confounding cue for apparent contrast.

4.4. The limitations of contrast constancy:

Contrast constancy has been shown to be independent of retinal image position (Georgeson & Sullivan, 1975; Kitterle, 1979); stimulus size (Peli, 1995), and luminance (Peli, 1996). However, it is generally accepted that contrast constancy fails as stimuli approach threshold. Our findings coincide with this widely supported belief. However, Peli et al (1991) compared measured retinal contrast sensitivity at various spatial frequencies and eccentricities - using laser interferometry to bypass the optics of the eye – (Hilz & Cavonius, 1974) with their model which fits contrast thresholds for orientation identification over spatial frequencies of 1-16 cycles/deg and for retinal eccentricities of as much as 23 deg, and suggested that some (incomplete) compensation for the contrast reduction by the eye's optics occurs at threshold as well. So, whether or not contrast constancy operates at threshold visual function is an area open to further research.

4.5. Gain control as a mechanism for contrast constancy:

Significant amounts of compensation for blur have been shown to occur rapidly, and exhibit almost complete interocular transfer (Mon-Williams et al, 1998; Webster et al, 2002). Our study is consistent with others, showing that blur adaptation occurs after as little as 15 minutes of exposure to refractive defocus or scatter blur. Given the rapid nature of this

compensation, it is not surprising that a *dynamic* mechanism for *neural* compensation to blur has been implicated in phenomenon such as contrast constancy.

Many studies have shown that the visual system contains a large number of relatively independent channels which process the incoming information in parallel; each channel responding only to a limited band of spatial frequencies. Georgeson and Sullivan (1975) suggested that the channels adjust their gain (stimulus-response function) so as to flatten the over-all frequency response of the visual system. The result of this process would not affect the threshold function, but would correct the suprathreshold percept. This type of compensation leads to constancy in image perception despite the attenuated sensitivity to high spatial frequency features of the image. Georgeson and Sullivan suggested that this compensation process is local and could be adjusted to suit the particular conditions at different retinal loci, as well as changes in dioptric and retinal state. Our research supports this proposal.

The idea that the blur compensation mechanism is located in the visual cortex and is a property of the specific spatial frequency-selective channels is supported by several different studies. It has been shown that the slope of the function relating threshold elevation to adapting contrast is steeper at higher spatial frequencies (Blakemore & Campbell, 1969). In evaluating the correlation between the slope of adaptation and the unadapted contrast sensitivity for each spatial frequency, it was determined that the slope of adaptation increased from 0.27 at 10 cycles/deg to 0.47 at 20 cycles/deg, to over 0.7 at 28 cycles/deg (Georgeson

& Sullivan 1975). This suggests that the gain of high frequency-selective channels is boosted in direct proportion to the decrease in their contrast sensitivity (Blakemore et al, 1973; Graham, 1972; Tolhurst, 1972; Georgeson & Sullivan, 1975).

The proposed increase in gain of high frequency-selective channels may be an incomplete description of how neural adaptation occurs. It seems this would only account for the robustness of the compensation for blur if the gain of the high frequency-selective channels are initially low. Mon-Williams et al (1998) suggested that the mechanism for neural compensation for blur is most likely a combination of (1) an increase in gain for high spatial frequency-selective channels, and (2) a decrease in gain for low frequency-selective channels; thereby unmasking high frequency components.

Surprisingly, in our study, some observers showed an increase in contrast gain after exposure to blur, while others did not, suggesting that there may be individual differences in adaptability to blur. For example, in Figure 9 "Subject 1" showed a larger increase in gain, relative to "Subject 2". Previous studies have investigated "blur tolerance" in persons with myopia, as well as low vision, and found that "blur tolerance" increases as magnitude of myopia increases and/or acuity decreases. (Legge, 1987; Thorn et al, 1998; Rosenfield and Abaham-Cohen, 1999; Simmers, 2003). It is possible that the mechanism for "blur tolerance" is the same as that responsible for contrast constancy. If so, the question becomes are some individuals (e.g. myopes) actually more capable of adapting to blur than others (e.g. emmetropes) or are they simply more tolerant of blur because they have had a long term

experience of blur making them more adept at blur interpretation? Vera-Diaz et al (2004) examined accommodative response of myopes versus emmetropes after a period of blur adaptation . Compared to the pre-adaptation level, myopes showed a significant increase in the near accommodative response during and after just 3 minutes of blur adaptation, while emmetropes did not. This is consistent with previous studies of blur sensitivity, showing that myopes interpret and adapt to blur differently than emmetropes (Rosenfield & Abraham-Cohen; Oen, Lim, & Cheng, 1994; Wu, Lim, Seet, & Chew, 1997; Thorn, et al, 1998; Strang, Winn, & Bradley, 1998; Turatto et al., 1999). This is also suggestive that the nature of an individual's accommodative response to blur could be predictive of their adaptability to blur, and vice versa. Given that no differences have been found in the baseline accommodation levels for near viewing between myopes and emmetropes (Vera-Diaz et al, 2004), the mechanism underlying the finding of increased accommodative response of myopes with exposure to blur is not clear. Again the two possibilities are (1) myopes have an increased ability to adapt to blur relative to emmetropes, and/or (2) myopes are able to interpret blur more effectively than emmetropes. The inability of current studies to clearly distinguish between these two mechanisms shows that there is a growing dilemma of whether or not compensation for blur represents true cellular adaptation or rather a cognitive recalibration. This is an area in need of further research.

4.6. Applications to low vision

This area of research was originally sparked by anecdotal reports of myopes and persons with other sources of decreased acuity noticing improvements in "seeing" after prolonged periods

of exposure to blurred vision. The experience of "seeing" involves an ability to *detect* objects in our environment (usually involves threshold visual function); *discriminate* objects within the environment (which involves suprathreshold visual function as well as an ability to resolve objects); and *recognize* objects within the environment (which involves blur tolerance, blur interpretation, and cognitive function). Therefore, when a person notes that he/she has had an improvement in seeing, it is hard to know which of these functions has actually improved. Similarly, it is hard to isolate and/or distinguish between these functions when testing blur adaptation with psychophysical experiments. However, given that contrast matching techniques involve each of the above visual functions, studies of blur adaptation using contrast matching paradigms probably give the closest approximation to understanding real-world visual function. Therefore, contrast constancy, as explored in the current study as well as in previous studies, has important implications for the study of perceptual adaptation in low vision due to either optical or neural blur.

More specifically, the presumed neural mechanisms underlying contrast constancy after exposure to refractive defocus may explain why the onset of myopia and cataract are so well tolerated (Mon-Williams et al, 1998). Similarly the mechanism responsible for contrast constancy after exposure to Gaussian-type blur (similar to the scatter blur experienced by individuals with cataract changes) may be responsible for optimizing vision during age-related ophthalmic changes.

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Tables and Figures

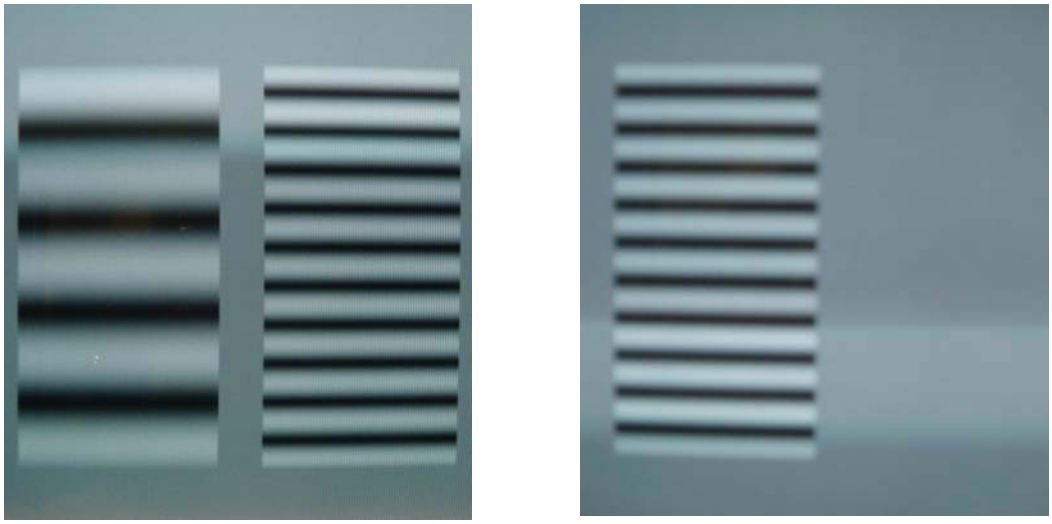
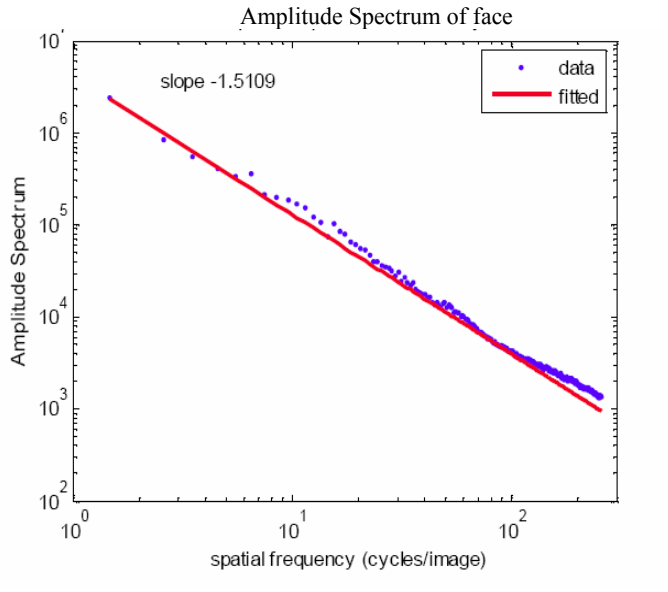


Figure 1: Digital photograph of grating stimuli used in experiments 1-4 for the contrast matching task (left) and contrast sensitivity testing (right).



Figure 2: Original (untouched) Image of face (left) and forest (right) used in experiments 5-6



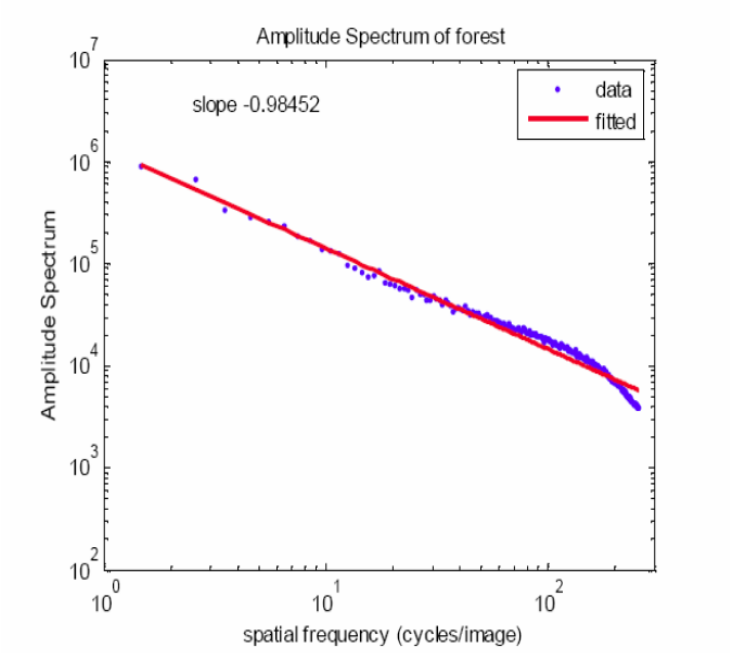
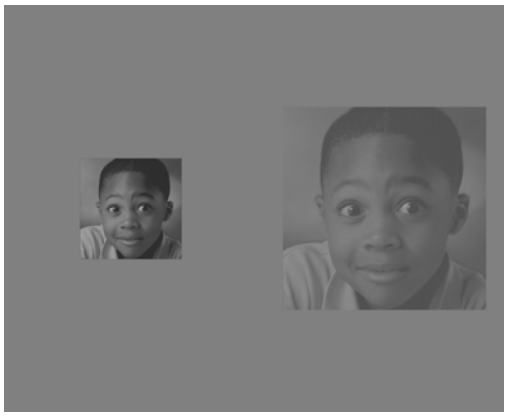
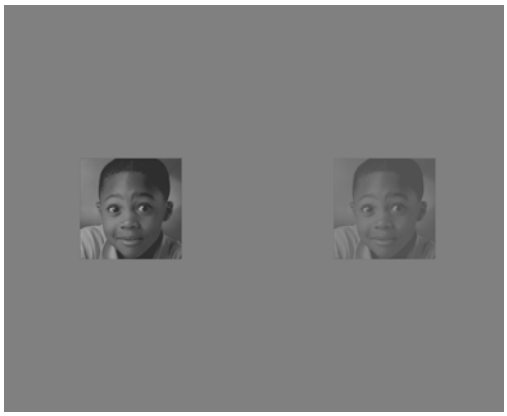


Figure 3: Amplitude spectrum plots for face (top) and forest (bottom).
Fourier Spectrum of natural images have a characteristic function:
$A(f) = cf^{\alpha}$ where A(f) is the amplitude spectrum and c and α are constants for a given image. In a loglog plot, amplitude spectrum becomes linear and α represents the slope of the line. Linear scale data were fit with the above equation and plotted in loglog scale, as this is more representative of how the human visual system functions than a linear log function.

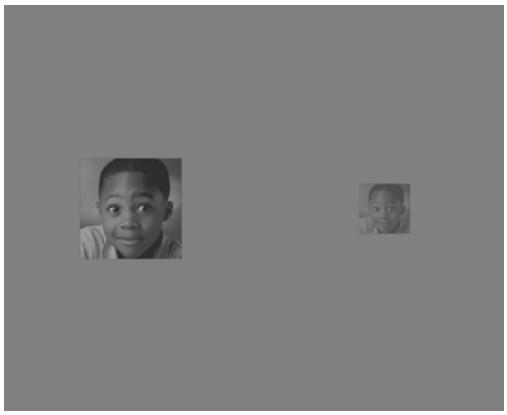
Note: Image resampling (generation of stimuli for experiments 5 and 6) was performed by Hyunjeong (Jamie) Han, who also assisted in image analysis.



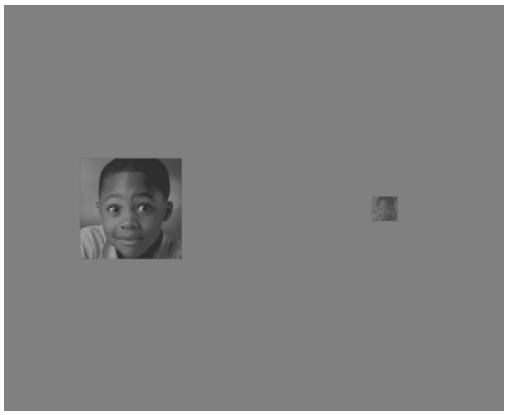
1x standard (left) and 2x experimental stimulus (right)



1x standard (left) and 1x experimental stimulus (right)

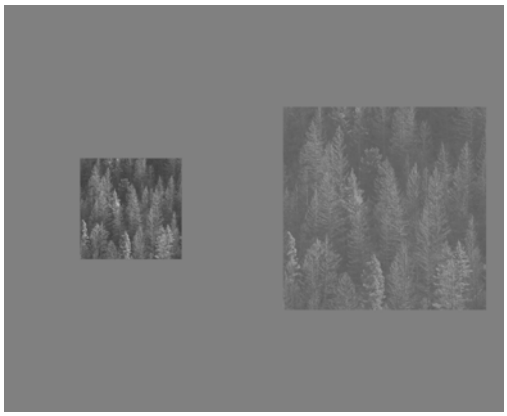


1x standard (left) and 1/2x experimental stimulus (right)

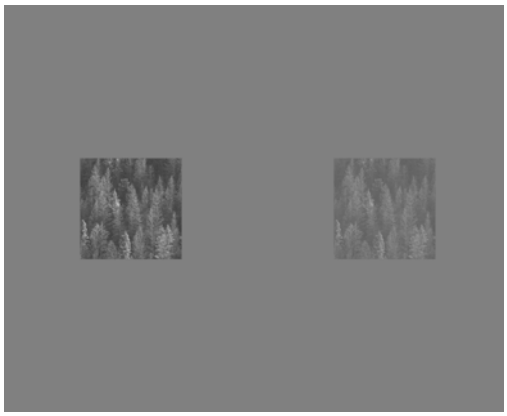


1x standard (left) and 1/4x experimental stimulus (right)

Figure 4: Experimental presentation of a natural image (face) used in the contrast matching procedure (experiments 5-6)



1x standard (left) and 2x experimental stimulus (right)



1x standard (left) and 1x experimental stimulus (right)



1x standard (left) and 1/2x experimental stimulus (right)



1x standard (left) and 1/4x experimental stimulus (right)

Figure 5: Experimental presentation of a natural image (face) used in the contrast matching procedure (experiments 5-6). Observers were asked to match the contrast of the standard image to that of the experimental image. The anglular size of the experimental image varied in each trial (2x, 1x, 1/2x, and 1/4x, with "x" being the size of the standard image); while the contrast of the standard image varied in each set (7.5%, 15%, 30%, and 60% Machaelson contrast, which corresponds to approximately 2, 5, 11, and 22 RMS contrast, respectively).

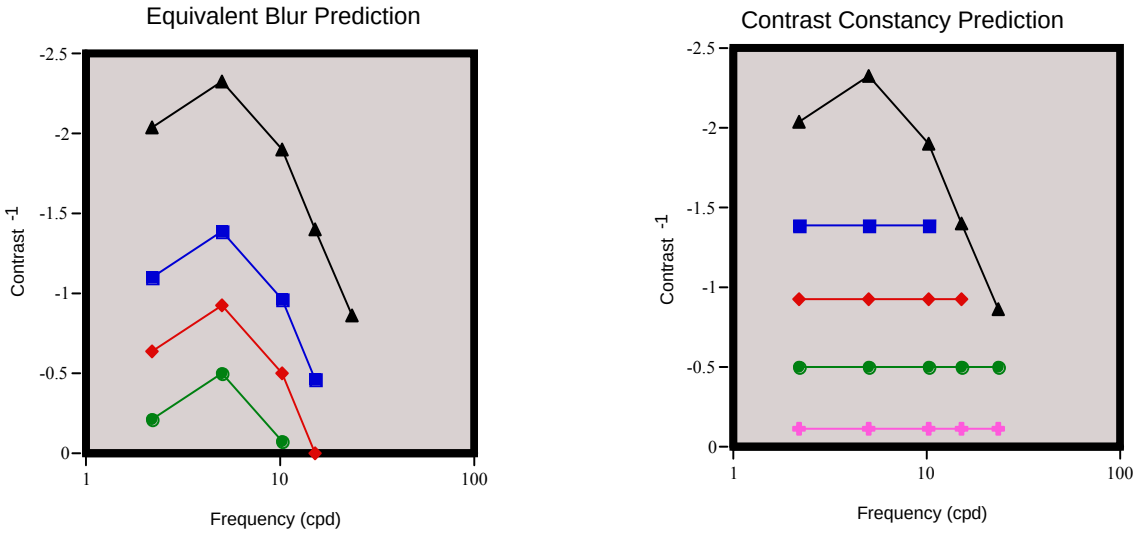


Figure 6:
Predictions for two models of contrast matching for stimuli varying from 2.2 to 23.6 cpd when compared with a 5 cpd standard in which contrast varies from .03 to .8. One model demonstrates the expected result if Contrast Constancy occurs: Contrast matching depends on the contrast of the stimulus in the environment and is not affected by optical or neural blur. The second model, Equivalent Blur, demonstrates the expected result if optical and neural blur modify stimulus contrast to affect the subject's contrast matching performance.

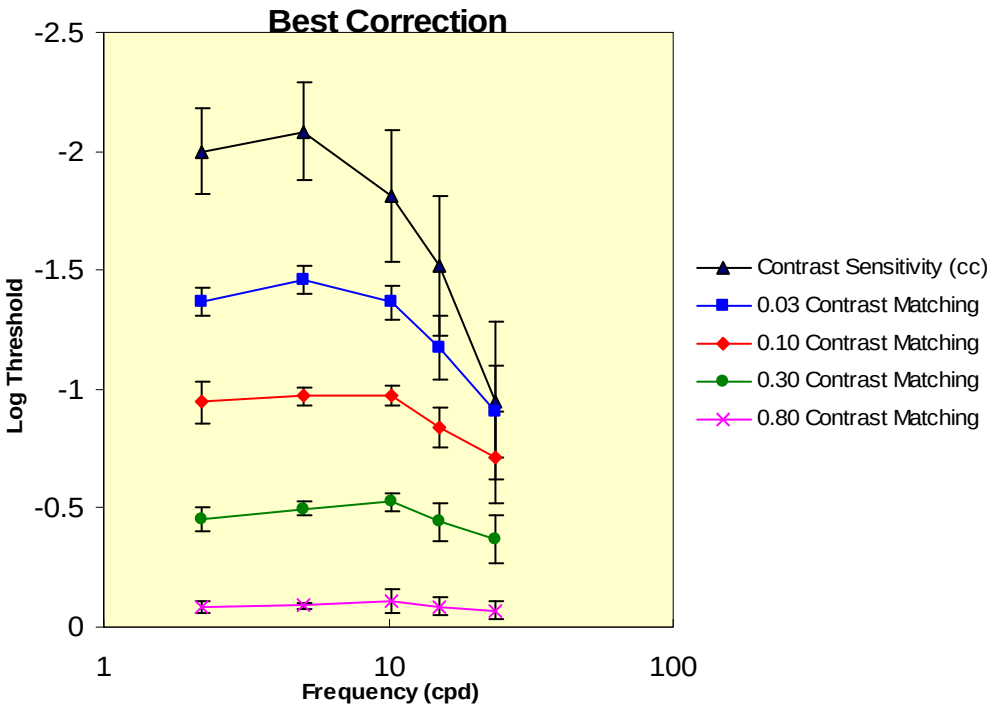


Figure 7: Averaged contrast matching performance is shown for observers with their best refractive correction. Results are similar to that which is predicted by the Contrast Constancy model (Figure 6).

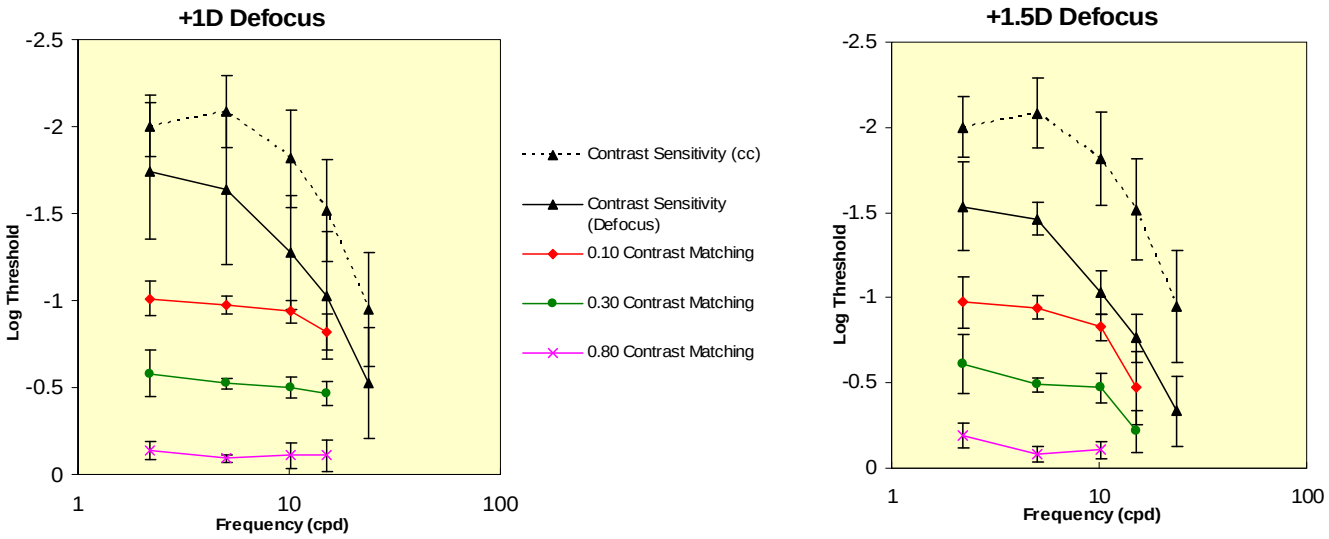


Figure 8:
Contrast matching performance is shown for conditions in which observers have +1D refractive defocus (top left), +1.5D refractive defocus (top right), mild scatter blur (bottom left), and moderate scatter blur (bottom right). Observers were tested after 15 minutes of adaptation to blurred vision.

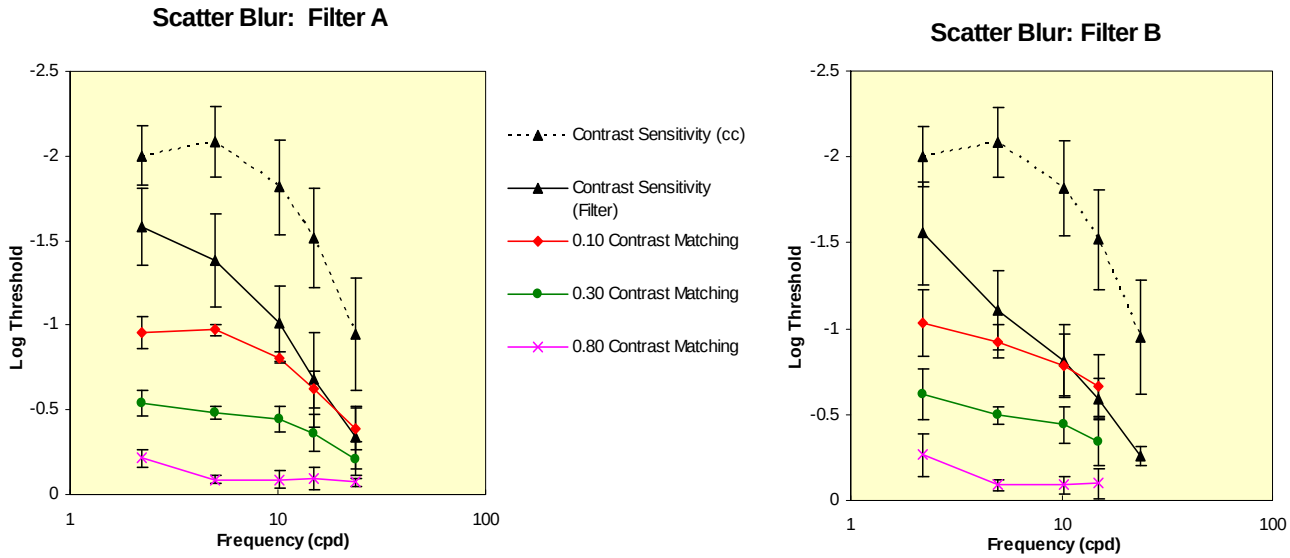
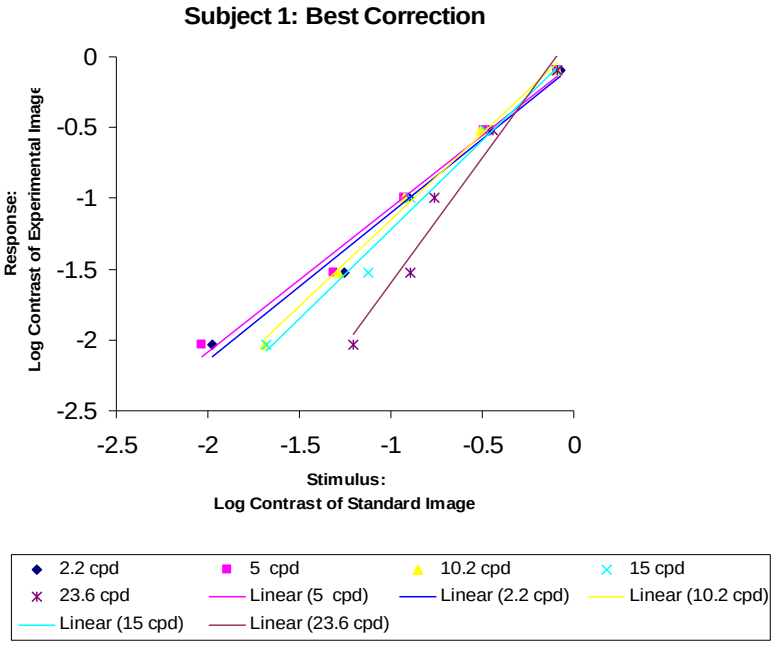


Figure 9: Contrast Gain plots for individual subjects: Contrast Gain is shown as a function of relative matching functions for 2.2, 5, 10.2, and 15 cpd sinusoidal stimuli. Matching experiment was performed (a) wearing best correction; (b) after exposure to +1 diopter of refractive defocus; and (c) after exposure to +1.5 diopters of refractive defocus. Flatter functions indicate lower relative gain, while steeper functions indicate increased relative gain.



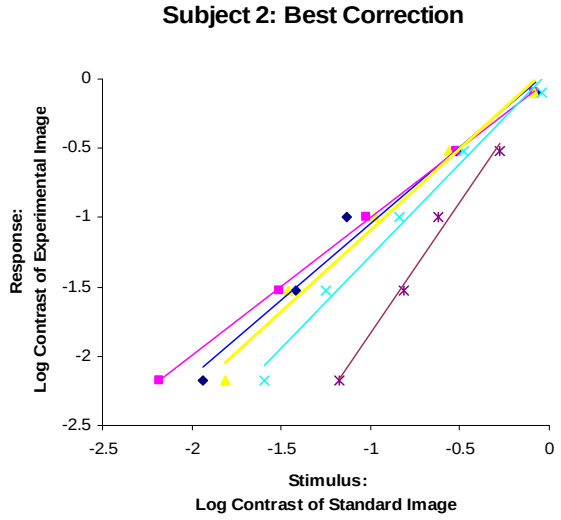
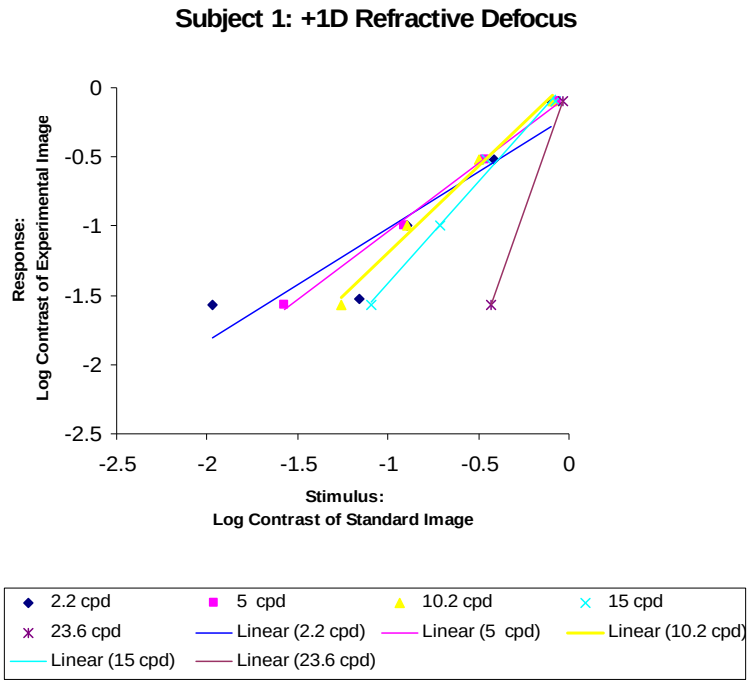


Figure 9a:


Subject 1: +1D Refractive Defocus
Response:
Log Contrast of Experimental Image
0
-0.5
-1
-1.5
-2
-2.5
-2.5
-2
-1.5
-1
-0.5
0
Stimulus:
Log Contrast of Standard Image
2.2 cpd
5 cpd
10.2 cpd
15 cpd
23.6 cpd
Linear (2.2 cpd)
Linear (5 cpd)
Linear (10.2 cpd)
Linear (15 cpd)
Linear (23.6 cpd)

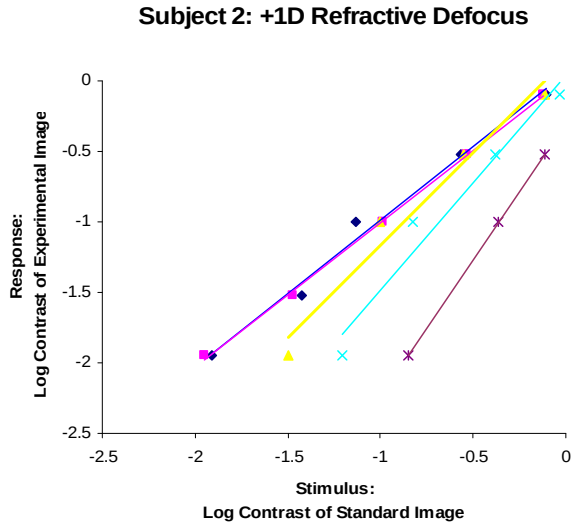
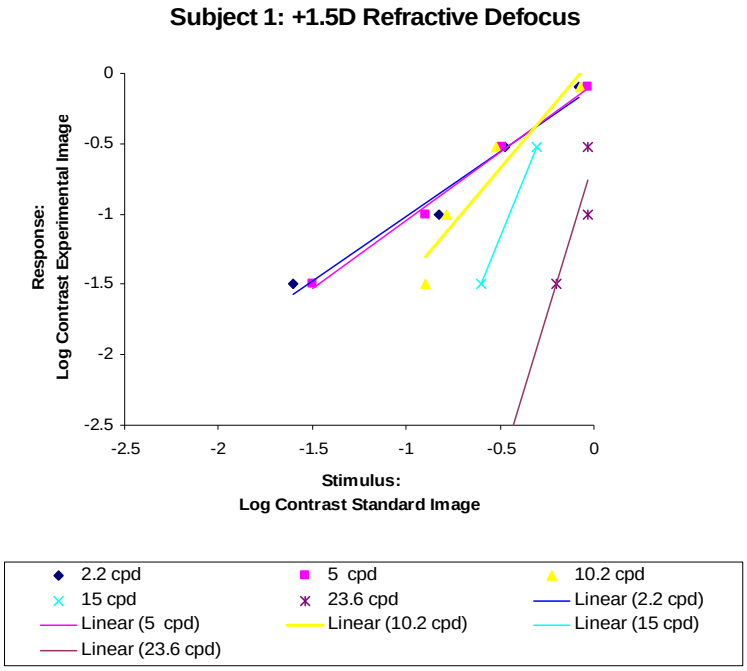

Subject 2: +1D Refractive Defocus
Response:
Log Contrast of Experimental Image
0
-0.5
-1
-1.5
-2
-2.5
-2.5
-2
-1.5
-1
-0.5
0
Stimulus:
Log Contrast of Standard Image

Figure 9b


Subject 1: +1.5D Refractive Defocus
Response:
Log Contrast Experimental Image
0
-0.5
-1
-1.5
-2
-2.5
-2.5
-2
-1.5
-1
-0.5
0
Stimulus:
Log Contrast Standard Image
2.2 cpd
5 cpd
10.2 cpd
15 cpd
23.6 cpd
Linear (2.2 cpd)
Linear (5 cpd)
Linear (10.2 cpd)
Linear (15 cpd)
Linear (23.6 cpd)

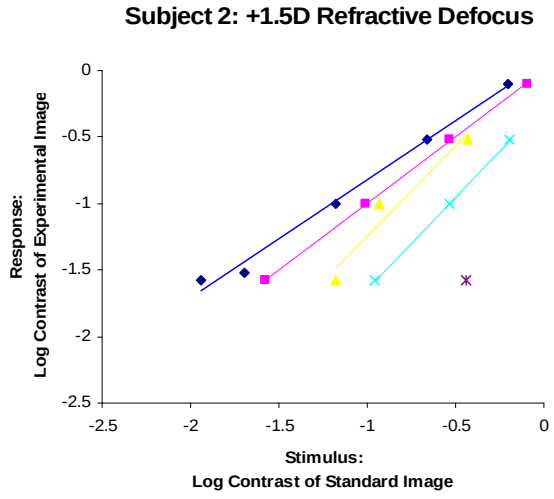

Subject 2: +1.5D Refractive Defocus
Response:
Log Contrast of Experimental Image
0
-0.5
-1
-1.5
-2
-2.5
-2.5
-2
-1.5
-1
-0.5
0
Stimulus:
Log Contrast of Standard Image

Figure 9c

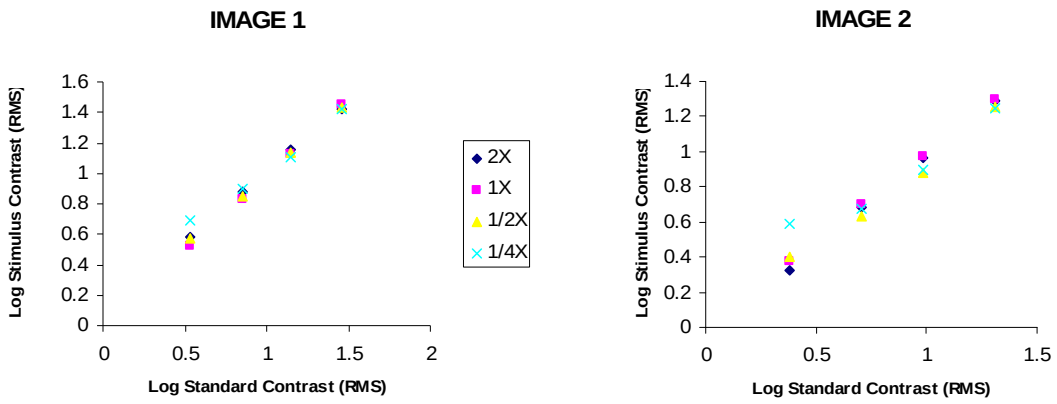


Image 1:

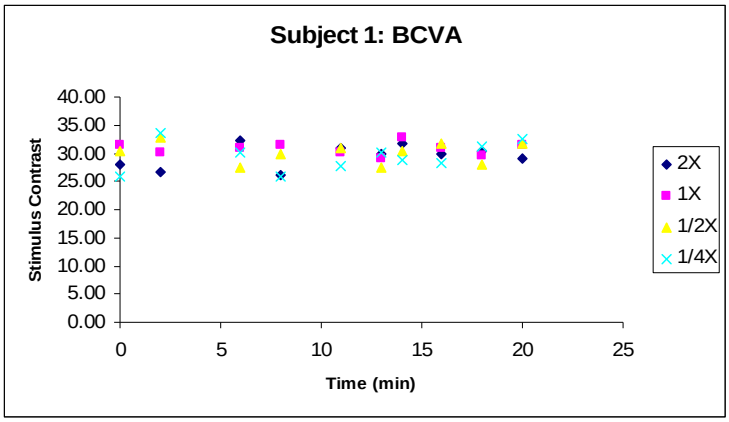
Log Standard Contrast	**0.53021**	**0.84887**	**1.150504**	**1.459323**
Log Stimulus Contrast (2x)	0.582724	0.876127	1.158239	1.426995
Log Stimulus Contrast (1x)	0.523825	0.834349	1.12856	1.448606
Log Stimulus Contrast (1/2x)	0.575475	0.851872	1.132917	1.429867
Log Stimulus Contrast (1/4x)	0.692674	0.899404	1.101663	1.421393

Image 2:

Log Standard Contrast	**0.377923**	**0.708756**	**0.987147**	**1.310457**
Log Stimulus Contrast (2x)	0.323661	0.681187	0.96661	1.292989
Log Stimulus Contrast (1x)	0.379542	0.70212	0.971393	1.294917
Log Stimulus Contrast (1/2x)	0.397765	0.627881	0.882882	1.254339
Log Stimulus Contrast (1/4x)	0.589256	0.670719	0.89302	1.247725

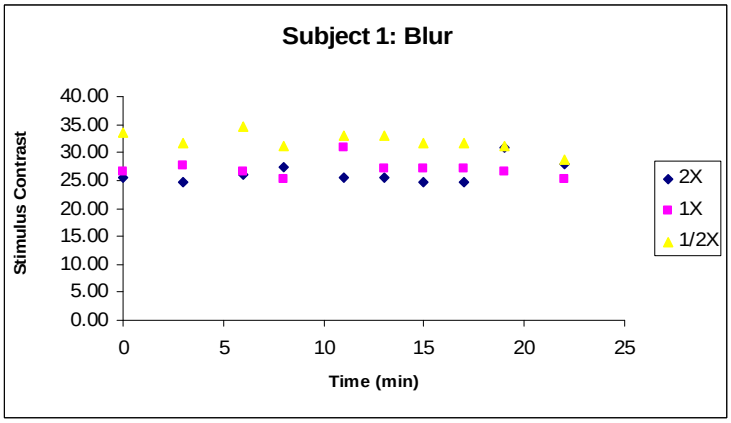
Figure 10: Averaged contrast matching data for experiment 5: Contrast matching for natural images.
"Image 1" = face; "Image 2" = forest

note: subjects were not able to resolve the 1/4x size image at low contrast; therefore contrast constancy was not demonstrated for that image.



minutes	0	2	6	8	11	13	14	16	18	20
Stimulus (2x)	27.89	26.65	32.23	26.03	30.99	29.75	31.61	29.75	30.37	29.13
Variable (1x)	31.44	30.20	30.82	31.44	30.20	28.97	32.67	30.82	29.59	31.44
Variable (1/2x)	30.45	32.89	27.41	29.84	31.06	27.41	30.45	31.67	28.02	31.67
Variable (1/4x)	25.89	33.72	30.10	25.89	27.70	30.10	28.90	28.30	31.31	32.51

standard contrst = 30.88



minutes	0	3	6	8	11	13	15	17	19	22
Stimulus (2x)	25.41	24.79	26.03	27.27	25.41	25.41	24.79	24.79	30.99	27.89
Variable (1x)	26.50	27.74	26.50	25.27	30.82	27.12	27.12	27.12	26.50	25.27
Variable (1/2x)	33.50	31.67	34.71	31.06	32.89	32.89	31.67	31.67	31.06	28.62
Variable (1/4x)	27.70	43.35	45.16	41.54	39.74	40.34	34.32	34.32	37.93	37.93

standard contrast = 30.88

Figure 11: Individual Subject Data for observer 1
Experiment 6: Evaluation of Learning Effect vs. Adaptation
Best Corrected condition (top); Mild Gaussian blur condition (bottom)

Appendix A: Individual Subject Data

S1

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.42	-0.917	-0.432	-0.097
5 cpd	-1.469	-0.939	-0.486	-0.097
10.2 cpd	-1.42	-0.947	-0.565	-0.123
15 cpd	-1.161	-0.848	-0.476	
23.6 cpd	-0.812	-0.82	-0.375	-0.032

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.05	0.06	-1.979
5	0.89	0.06	-2.051
10.2	0.9	0.05	-2.046
15	2.54	0.23	-1.595
23.6	7.76	0.52	-1.11

S2

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.432	-0.996	-0.498	-0.056
5 cpd	-1.488	-0.996	-0.452	-0.072
10.2 cpd	-1.347	-1.02	-0.563	-0.097
15 cpd	-1.184	-0.912	-0.373	-0.056
23.6 cpd	-0.828	-0.704	-0.362	-0.045

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	0.87	0.05	-2.06
5	0.7	0.03	-2.155
10.2	1.43	0.1	-1.845
15	1.63	0.09	-1.788
23.6	7.56	0.55	-1.121

S3

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.415	-0.859	-0.423	-0.049
5 cpd	-1.488	-0.965	-0.512	-0.087
10.2 cpd	-1.481	-0.977	-0.538	-0.087
15 cpd	-1.256	-0.894	-0.498	-0.112
23.6 cpd	-1.046	-0.759	-0.402	-0.082

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	0.48	0.03	-2.319
5	0.31	0.02	-2.509
10.2	0.51	0.02	-2.292
15	1.17	0.09	-1.932
23.6	3.2	0.19	-1.495

S4

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.328	-0.808	-0.412	-0.092
5 cpd	-1.481	-0.934	-0.481	-0.068
10.2 cpd	-1.347	-0.989	-0.522	-0.068
15 cpd	-1.432	-0.759	-0.442	-0.068
23.6 cpd	-1.218	-0.919	-0.422	-0.061

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	0.89	0.08	-2.051
5	1.3	0.07	-1.886
10.2	3.31	0.23	-1.48
15	5.68	0.34	-1.246
23.6	24.32	1.53	-0.614

S5

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.415	-1.137	-0.52	-0.077
5 cpd	-1.509	-1.027	-0.523	-0.087
10.2 cpd	-1.462	-0.973	-0.563	-0.087
15 cpd	-1.248	-0.839	-0.481	-0.04
23.6 cpd	-0.812	-0.623	-0.274	

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.16	0.07	-1.936
5	0.66	0.04	-2.18
10.2	1.54	0.07	-1.812
15	2.55	0.17	-1.593
23.6	6.64	0.42	-1.178

S6

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.252	-0.905	-0.457	-0.077
5 cpd	-1.31	-0.923	-0.491	-0.092
10.2 cpd	-1.288	-0.93	-0.511	-0.092
15 cpd	-1.119	-0.896	-0.481	-0.102
23.6 cpd	-0.896	-0.762	-0.441	-0.087

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.05	0.08	-1.979
5	0.93	0.04	-2.032
10.2	2.06	0.15	-1.686
15	2.1	0.16	-1.678
23.6	6.26	0.39	-1.203

Table 1: Individual Subject contrast matching data for Experiment 1: Contrast Matching with Best Corrected Vision

S7

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.26	-0.915	-0.382	-0.07
5 cpd	-1.45	-0.959	-0.462	-0.087
10.2 cpd	-1.362	-0.994	-0.502	-0.097
15 cpd	-1.18	-0.82	-0.453	-0.056
23.6 cpd	-1.011	-0.75	-0.311	-0.069

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	0.75	0.06	-2.125
5	0.32	0.02	-2.495
10.2	0.6	0.04	-2.222
15	1.21	0.09	-1.917
23.6	7.53	0.52	-1.123

S8

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.357	-0.985	-0.478	-0.11
5 cpd	-1.469	-0.979	-0.537	-0.115
10.2 cpd	-1.333	-0.919	-0.521	-0.134
15 cpd	-0.987	-0.884	-0.502	-0.094
23.6 cpd	-0.845	-0.619	-0.478	-0.036

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.51	0.1	-1.821
5	1.02	0.06	-1.991
10.2	2.15	0.14	-1.668
15	3.4	0.17	-1.469
23.6	12.56	0.92	-0.901

S9

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.357	-0.996	-0.472	-0.12
5 cpd	-1.409	-0.973	-0.493	-0.087
10.2 cpd	-1.276	-1.068	-0.568	-0.249
15 cpd	-1.167	-0.803	-0.268	-0.159
23.6 cpd	-0.884	-0.82	-0.434	-0.153

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.59	0.1	-1.799
5	0.92	0.06	-2.036
10.2	1.58	0.2	-1.801
15	8.21	0.8	-1.086
23.6	24.4	1.66	-0.613

S10

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.393	-0.854	-0.395	-0.105
5 cpd	-1.42	-0.934	-0.511	-0.097
10.2 cpd	-1.244	-0.961	-0.44	-0.045
15 cpd	-0.977	-0.758	-0.381	-0.049
23.6 cpd	-0.674	-0.366	-0.102	-0.032

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.1	0.07	-1.959
5	1.01	0.05	-1.996
10.2	1.66	0.08	-1.78
15	3.255	0.23	-1.487
23.6	22.73	1.87	-0.643

S11

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.403	-0.923	-0.453	-0.049
5 cpd	-1.509	-1.043	-0.487	-0.092
10.2 cpd	-1.415	-0.985	-0.541	-0.097
15 cpd	-1.347	-0.965	-0.547	-0.077
23.6 cpd	-1.252	-1.022	-0.472	-0.056

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	0.41	0.03	-2.387
5	0.57	0.03	-2.244
10.2	0.45	0.02	-2.347
15	0.81	0.06	-2.092
23.6	2.17	0.18	-1.664

S12

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.372	-1.041	-0.548	-0.07
5 cpd	-1.53	-0.994	-0.547	-0.102
10.2 cpd	-1.387	-0.915	-0.467	-0.12
15 cpd	-1.056	-0.66	-0.384	-0.134
23.6 cpd	-0.631	-0.387	-0.352	-0.123

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.13	0.07	-1.947
5	1.26	0.11	-1.9
10.2	2.19	0.17	-1.66
15	3.81	0.2	-1.419
23.6	9.68	0.59	-1.014

Table 1 (continued): Individual Subject contrast matching data for Experiment 1: Contrast Matching with Best Corrected Vision

Freq	0.03	0.1	0.304	0.809
2.2 cpd	**-1.367**	**-0.945**	**-0.456**	**-0.081**
5 cpd	**-1.461**	**-0.972**	**-0.499**	**-0.09**
10.2 cpd	**-1.363**	**-0.973**	**-0.525**	**-0.108**
15 cpd	**-1.176**	**-0.836**	**-0.44**	**-0.086**
23.6 cpd	**-0.909**	**-0.712**	**-0.369**	**-0.071**

Freq	Mean Threshold (% Michelson)	%Error (+/-)	log threshold
2.2 cpd	0.999166667	0.0666667	-2
5 cpd	0.824166667	0.0491667	-2.084
10.2 cpd	1.531666667	0.1058333	-1.815
15 cpd	3.030416667	0.2191667	-1.518
23.6 cpd	11.23416667	0.7783333	-0.949

Table 2: Averaged data for Experiment 1: Contrast Matching with Best Corrected Vision

Freq	0.03	0.1	0.304	0.809
2.2 cpd	**0.06**	**0.091**	**0.05**	**0.024**
5 cpd	**0.059**	**0.038**	**0.028**	**0.013**
10.2 cpd	**0.073**	**0.044**	**0.041**	**0.05**
15 cpd	**0.135**	**0.083**	**0.076**	**0.038**
23.6 cpd	**0.192**	**0.193**	**0.104**	**0.039**

Freq	Mean Threshold (%Michelson)	%Error (+/-)	log threshold
2.2 cpd	0.353642303	0.0226969	0.177
5 cpd	0.32185424	0.0253909	0.206
10.2 cpd	0.840311991	0.0711539	0.2772
15 cpd	2.12445978	0.1991554	0.2932
23.6 cpd	8.049570805	0.5845407	0.33

Table 3: Standard deviations for Experiment 1: Contrast Matching with Best Corrected Vision

S1

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.225	-0.949	-0.457	-0.073
5 cpd	-1.367	-0.959	-0.512	-0.065
10.2 cpd	-1.393	-1.007	-0.467	-0.099
15 cpd	-1.053	-0.865	-0.427	-0.061
23.6 cpd	-0.945	-0.849	-0.513	-0.064

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.17	0.08	-1.932
5	1.83	0.14	-1.738
10.2	1.98	0.11	-1.703
15	3.88	0.26	-1.411
23.6	14.83	1.04	-0.829

S2

	-1.523	-1	-0.517	-0.092
2.2 cpd		-1.081	-0.724	-0.249
5 cpd		-0.973	-0.55	-0.094
10.2 cpd		-0.965	-0.483	-0.056
15 cpd		-0.824	-0.489	-0.087
23.6 cpd		-0.287	-0.156	

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	2.42	0.17	-1.616
5	3.48	0.23	-1.458
10.2	7.71	0.43	-1.113
15	20.96	1.03	-0.679
23.6	55.84	3.11	-0.253

S3

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.276	-0.994	-0.542	-0.105
5 cpd	-1.42	-0.967	-0.502	-0.087
10.2 cpd	-1.28	-0.854	-0.453	-0.087
15 cpd	-1.086	-0.741	-0.539	-0.047
23.6 cpd	-0.799	-0.548	-0.483	-0.032

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	0.77	0.05	-2.114
5	0.64	0.05	-2.194
10.2	1.83	0.09	-1.738
15	3.44	0.21	-1.463
23.6	10.45	0.47	-0.981

S4

	-1.523	-1	-0.517	-0.092
2.2 cpd		-0.959	-0.553	-0.154
5 cpd		-1.092	-0.539	-0.112
10.2 cpd		-1.027	-0.487	-0.121
15 cpd		-0.912	-0.551	-0.186
23.6 cpd		-0.487	-0.522	-0.092

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	15.23	1.33	-0.817
5	13.99	1.08	-0.854
10.2	13.72	0.94	-0.863
15	23.49	1.18	-0.629
23.6	71.14	2.74	-0.148

S5

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.42	-1.134	-0.568	-0.105
5 cpd	-1.469	-0.989	-0.533	-0.117
10.2 cpd	-1.393	-1.007	-0.547	-0.112
15 cpd	-1.14	-0.824	-0.377	-0.032
23.6 cpd	-0.93	-0.366	-0.115	

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.24	0.09	-1.907
5	1.13	0.05	-1.947
10.2	3.21	0.19	-1.493
15	6.18	0.54	-1.209
23.6	14.09	0.77	-0.851

Table 4: Individual subject data for Experiment 2: Contrast Matching after Exposure to +1 Diopter of Refractive Defocus

S6

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.161	-0.896	-0.413	-0.102
5 cpd	-1.342	-0.907	-0.463	-0.063
10.2 cpd	-1.208	-0.891	-0.5	-0.087
15 cpd	-1.043	-0.712	-0.452	-0.077
23.6 cpd	-0.8	-0.677	-0.388	-0.032

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.08	0.09	-1.967
5	2.68	0.16	-1.572
10.2	5.53	0.37	-1.257
15	8.04	0.61	-1.095
23.6	37.17	2.24	-0.43

S7

	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.403	-1.158	-0.805	-0.153
5 cpd	-1.319	-0.998	-0.507	-0.094
10.2 cpd	-1.288	-0.907	-0.41	-0.036
15 cpd	-1.097	-0.848	-0.347	-0.032
23.6 cpd	-1.015	-0.761	-0.303	

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.04	0.05	-1.983
5	0.82	0.08	-2.086
10.2	4.57	0.32	-1.34
15	5.11	0.34	-1.292
23.6	18.51	1.62	-0.733

S8

	-1.523	-1	-0.517	-0.092
2.2 cpd		-1.029	-0.683	-0.174
5 cpd		-0.957	-0.559	-0.077
10.2 cpd		-0.868	-0.561	-0.087
15 cpd		-0.658	-0.507	-0.163
23.6 cpd				

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.51	0.06	-1.821
5	2.02	0.14	-1.695
10.2	7.01	0.54	-1.154
15	9.19	0.48	-1.037
23.6	48.6	3.38	-0.313

S9

	-1.523	-1	-0.517	-0.092
2.2 cpd		-0.884	-0.466	-0.115
5 cpd		-0.926	-0.531	-0.112
10.2 cpd		-0.928	-0.597	-0.287
15 cpd		-0.991	-0.493	-0.303
23.6 cpd		-0.744	-0.509	-0.294

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	2.9	0.29	-1.538
5	6.8	0.43	-1.167
10.2	15.34	1.19	-0.814
15	35.86	3.51	-0.445
23.6	62.07	2.98	-0.207

Table 4 (continued): Individual subject data for Experiment 2: Contrast Matching after Exposure to +1 Diopter of Refractive Defocus

Freq (cpd)	-1.523	-1	-0.517	-0.092
2.2	-1.297	-1.009	-0.579	-0.137
5	-1.383	-0.974	-0.522	-0.092
10.2	-1.312	-0.939	-0.501	-0.108
15	-1.084	-0.819	-0.465	-0.11
23.6	-0.898			

Frequency (cpd)	Mean Threshold (% Michelson)	%Error (+/-)	log threshold
2.2	3.04	0.2455556	-1.744
5	3.71	0.2622222	-1.635
10.2	6.766666667	0.4644444	-1.275
15	12.90555556	0.9066667	-1.029
23.6	36.96666667	2.0388889	-0.527

Table 5: Averaged data for Experiment 2: Contrast Matching after Exposure to +1 Diopter of Refractive Defocus

Freq (cpd)	-1.523	-1	-0.517	-0.092
2.2	0.539	0.0987	0.132	0.053
5	0.5673	0.0525	0.029	0.02
10.2	0.5404	0.0645	0.058	0.072
15	0.4438	0.103	0.07	0.091
23.6	0.3764			

Frequency (cpd)	Mean Threshold (%Michelson)	%Error (+/-)	log threshold
2.2	4.624289135	0.4138874	0.3919
5	4.289000466	0.3281683	0.4317
10.2	4.861679237	0.3759026	0.3303
15	11.28245996	1.0305581	0.3647
23.6	23.30967771	1.0959179	0.3203

Table 6: Standard deviations Experiment 2: Contrast Matching after Exposure to +1 Diopter of Refractive Defocus

S2

Freq	-1.5229	-1	-0.517	-0.092
2.2 cpd		-0.923	-0.839	-0.218
5 cpd		-1	-0.43	-0.134
10.2 cpd		-0.848	-0.563	
15 cpd		-0.69	-0.303	
23.6 cpd		-0.148	-0.082	

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	4.2	0.55	-1.377
5	4.49	0.29	-1.348
10.2	11.7	0.85	-0.932
15	17.57	1.47	-0.755
23.6	23.6	3.03	-0.627

S5

Freq	-1.5229	-1	-0.517	-0.092
2.2 cpd	-1.699	-1.18	-0.665	-0.206
5 cpd	-1.4949	-1.011	-0.531	-0.092
10.2 cpd	-1.2757	-0.93	-0.432	
15 cpd	-0.9686	-0.532	-0.196	
23.6 cpd	-0.3284			

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.15	0.06	-1.939
5	2.63	0.31	-1.58
10.2	6.67	0.32	-1.176
15	11	0.7	-0.959
23.6	36.03	3.46	-0.443

S6

Freq	-1.5229	-1	-0.517	-0.092
2.2 cpd	-1.2518	-0.828	-0.472	-0.082
5 cpd	-1.2557	-0.896	-0.491	-0.032
10.2 cpd	-1.1079	-0.789	-0.517	-0.073
15 cpd	-0.7055	-0.478	-0.308	
23.6 cpd	-0.4782	-0.032	-0.032	

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	2.41	0.09	-1.618
5	3.16	0.08	-1.5
10.2	11.43	0.11	-0.942
15	24.02	0.28	-0.619
23.6	65.28	1.69	-0.185

S8

Freq	-1.5229	-1	-0.517	-0.092
2.2 cpd		-0.961	-0.476	-0.246
5 cpd		-0.87	-0.502	-0.07
10.2 cpd		-0.752	-0.369	-0.139
15 cpd		-0.183	-0.052	
23.6 cpd				

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	3.89	0.27	-1.41
5	3.46	0.24	-1.461
10.2	7.29	0.38	-1.137
15	16.3	1.34	-0.788
23.6	60.15	2.66	-0.221

Table 7: Individual subject data Experiment 3: Contrast Matching after Exposure to +1.5 Diopters of Refractive Defocus

Freq (cpd)	-1.5229	-1	-0.517	-0.092
2.2	-0.7377	-0.973	-0.613	-0.188
5	-0.6876	-0.944	-0.488	-0.082
10.2	-0.5959	-0.83	-0.47	-0.106
15	-0.4185	-0.471	-0.215	
23.6	-0.2016			

Frequency (cpd)	Mean Threshold (%Michelson)	%Error (+/-)	log threshold
2.2	2.9125	0.2425	-1.536
5	3.435	0.23	-1.464
10.2	9.2725	0.415	-1.033
15	17.2225	0.9475	-0.764
23.6	46.265	2.71	-0.335

Table 8: Averaged data for Experiment 3: Contrast Matching after Exposure to +1.5 Diopters of Refractive Defocus

Freq (cpd)	-1.5229	-1	-0.517	-0.092
2.2	0.31619	0.1491	0.1752	0.073
5	0.1691	0.0717	0.0424	0.043
10.2	0.11867	0.0776	0.0868	0.047
15	0.18601	0.2118	0.1201	
23.6	0.10596			

Frequency (cpd)	Mean Threshold (%Michelson)	%Error (+/-)	log threshold
2.2	1.410918731	0.225	0.2586
5	0.782581199	0.1042433	0.0967
10.2	2.661508031	0.3122499	0.1279
15	5.35092749	0.5579352	0.1395
23.6	19.7722103	0.7544976	0.2065

Table 9: Standard deviations for Experiment 3: Contrast Matching after Exposure to +1.5 Diopters of Refractive Defocus

S3

Freq	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.268	-1.027	-0.562	-0.212
5 cpd	-1.456	-1.022	-0.462	-0.073
10.2 cpd	-1.164	-0.849	-0.393	-0.032
15 cpd	-1.152	-0.792	-0.364	-0.04
23.6 cpd	-0.641	-0.532	-0.218	

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	0.97	0.06	-2.013
5	0.95	0.06	-2.022
10.2	3.16	0.2	-1.5
15	4.29	0.24	-1.368
23.6	16.81	1.33	-0.774

S2

Freq	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.516	-1.102	-0.577	-0.243
5 cpd	-1.456	-1.007	-0.493	-0.065
10.2 cpd	-1.347	-0.767	-0.315	-0.087
15 cpd	-1.032	-0.539	-0.278	
23.6 cpd	-0.729	-0.43	-0.266	

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.84	0.1	-1.735
5	2.59	0.13	-1.587
10.2	9.86	0.57	-1.006
15	17.41	1.14	-0.759
23.6	39.4	1.91	-0.405

S4

Freq	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.42	-0.912	-0.548	-0.205
5 cpd	-1.488	-0.961	-0.513	-0.107
10.2 cpd	-1.347	-0.777	-0.427	-0.04
15 cpd	-1.146	-0.551	-0.268	
23.6 cpd	-0.786	-0.502	-0.092	

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	5.05	0.49	-1.297
5	4.27	0.67	-1.37
10.2	6.5	0.5	-1.187
15	27.5	1.92	-0.561
23.6	37.65	1.83	-0.424

S6

Freq	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.475	-0.834	-0.421	-0.115
5 cpd	-1.42	-0.949	-0.447	-0.068
10.2 cpd	-0.937	-0.845	-0.452	-0.073
15 cpd	-0.862	-0.732	-0.393	
23.6 cpd	-0.525	-0.251		

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	2.82	0.17	-1.55
5	4.28	0.27	-1.369
10.2	10.44	0.67	-0.981
15	30.39	3.39	-0.517
23.6	54.47	3.29	-0.264

Table 10: Individual Subject Data: Filter A (mild Gaussian blur)
Experiment 4: Contrast Matching after Exposure to Gaussian Blur

S12

Freq	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.629	-1.036	-0.652	-0.249
5 cpd	-1.502	-0.951	-0.507	-0.115
10 cpd	-1.301	-0.811	-0.491	-0.105
15 cpd	-0.912	-0.522	-0.401	-0.097
23.6 cpd	-0.321	-0.279	-0.134	-0.065

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.75	0.1	-1.757
5	2.45	0.16	-1.611
10.2	6.15	0.39	-1.211
15	15.1	1.17	-0.821
23.6	36.03	2.12	-0.443

S13

Freq	-1.523	-1	-0.517	-0.092
2.2 cpd		-0.888	-0.46	-0.18
5 cpd		-0.971	-0.425	-0.07
10.2 cpd		-0.839	-0.562	-0.183
15 cpd		-0.682	-0.565	-0.187
23.6 cpd		-0.479	-0.374	-0.099

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	2.63	0.2	-1.58
5	5.7	0.3	-1.244
10.2	15.46	1.42	-0.811
15	16.25	0.8	-0.789
23.6	54.1	2.77	-0.267

S14

Freq	-1.523	-1	-0.517	-0.092
2.2 cpd		-0.915	-0.562	-0.288
5 cpd		-0.937	-0.518	-0.115
10.2 cpd		-0.777	-0.458	-0.092
15 cpd		-0.542	-0.279	-0.056
23.6 cpd		-0.268	-0.192	-0.056

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.55	0.12	-1.81
5	5.72	0.36	-1.243
10.2	10.24	1.07	-0.99
15	19.24	1.59	-0.716
23.6	54.29	3.71	-0.265

Table 10 (continued): Individual Subject Data: Filter A (mild Gaussian blur)
Experiment 4: Contrast Matching after Exposure to Gaussian Blur

Freq (cpd)	-1.523	-1	-0.517	-0.092
2.2	-1.044	-0.959	-0.54	-0.213
5	-1.046	-0.971	-0.481	-0.088
10.2	-0.871	-0.809	-0.443	-0.087
15	-0.729	-0.623	-0.364	-0.095
23.6	-0.429	-0.392	-0.213	-0.074

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	2.606666667	0.1966667	-1.584
5	4.168333333	0.315	-1.38
10.2	9.775	0.77	-1.01
15	20.98166667	1.6683333	-0.678
23.6	45.99	2.605	-0.337

Table 11: Averaged Data: Filter A (mild Gaussian blur)
Experiment 4: Contrast Matching after Exposure to Gaussian Blur

Freq (cpd)	-1.523	-1	-0.517	-0.092
2.2	0.133	0.0965	0.0767	0.056
5	0.032	0.0317	0.0362	0.023
10.2	0.174	0.0355	0.0775	0.05
15	0.132	0.1101	0.1055	0.066
23.6	0.185	0.1217	0.1001	0.023

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.338540428	0.1456839	0.2275
5	1.784109755	0.2017778	0.2763
10.2	3.965648329	0.4199773	0.2232
15	8.588639229	1.0053002	0.2793
23.6	13.83589104	0.8592383	0.1811

Table 12: Standard Deviations: Filter A (mild Gaussian blur)
Experiment 4: Contrast Matching after Exposure to Gaussian Blur

S3

Freq	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.415	-0.859	-0.423	-0.049
5 cpd	-1.488	-0.965	-0.512	-0.087
10.2 cpd	-1.481	-0.977	-0.538	-0.087
15 cpd	-1.256	-0.894	-0.498	-0.112
23.6 cpd	-1.046	-0.759	-0.402	-0.082

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.03	0.07	-1.987
5	4.12	0.36	-1.385
10.2	8.33	0.58	-1.079
15	23.07	1.63	-0.637
23.6	44.39	2.34	-0.353

S4

Freq	-1.523	-1	-0.517	-0.092
2.2 cpd		-1.149	-0.652	-0.372
5 cpd		-1.092	-0.526	-0.078
10.2 cpd		-0.923	-0.514	-0.082
15 cpd		-0.79	-0.52	-0.045
23.6 cpd				

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	2.6	0.13	-1.585
5	9.56	0.55	-1.02
10.2	24.27	1.7	-0.615
15	35.1	2.42	-0.455
23.6	55.67	2.98	-0.254

S5

Freq	-1.523	-1	-0.517	-0.092
2.2 cpd		-1.177	-0.777	-0.346
5 cpd		-0.973	-0.548	-0.159
10.2 cpd		-0.646	-0.347	-0.032
15 cpd		-0.614	-0.264	
23.6 cpd		-0.168		

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	2.38	0.15	-1.623
5	6.01	0.31	-1.221
10.2	15.44	0.69	-0.811
15	26.93	1.63	-0.57
23.6	65.36	3.09	-0.185

S6

Freq	-1.523	-1	-0.517	-0.092
2.2 cpd		-0.728	-0.435	-0.094
5 cpd		-0.879	-0.495	-0.036
10.2 cpd		-0.457	-0.267	-0.056
15 cpd		-0.326	-0.134	-0.032
23.6 cpd				

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	3.1	0.1	-1.509
5	6.69	0.51	-1.175
10.2	23.93	1.59	-0.621
15	33.86	2.7	-0.47
23.6	61.23	2.8	-0.213

S7

Freq	-1.523	-1	-0.517	-0.092
2.2 cpd		-1.046	-0.64	-0.293
5 cpd		-0.91	-0.554	-0.078
10.2 cpd		-0.739	-0.347	-0.087
15 cpd		-0.554	-0.196	-0.047
23.6 cpd				

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	0.9	0.05	-2.046
5	3.94	0.19	-1.405
10.2	6.65	0.55	-1.177
15	18.25	1.61	-0.739
23.6	58.5	2.83	-0.233

Table 13: Individual Subject Data: Filter B (moderate Gaussian blur)
Experiment 4: Contrast Matching after Exposure to Gaussian Blur

S10

Freq	-1.523	-1	-0.517	-0.092
2.2 cpd		-1.337	-0.78	-0.323
5 cpd		-0.767	-0.435	-0.095
10.2 cpd		-0.981	-0.479	-0.04
15 cpd		-0.783	-0.342	
23.6 cpd		-0.373	-0.131	

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	2.51	0.16	-1.6
5	12.02	0.79	-0.92
10.2	18.7	1.19	-0.728
15	27.08	1.48	-0.567
23.6	51.53	3.57	-0.288

S11

Freq	-1.523	-1	-0.517	-0.092
2.2 cpd	-1.475	-1.039	-0.728	-0.311
5 cpd	-1.337	-0.991	-0.474	-0.087
10.2 cpd	-1.043	-0.849	-0.533	-0.115
15 cpd	-0.959	-0.747	-0.452	-0.265
23.6 cpd	-0.724	-0.573	-0.434	-0.172

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	1.75	0.13	-1.757
5	4.34	0.28	-1.363
10.2	9.54	0.61	-1.02
15	15.41	1.01	-0.812
23.6	48.56	2.6	-0.314

S13

Freq	-1.523	-1	-0.517	-0.092
2.2 cpd		-0.951	-0.511	-0.321
5 cpd		-0.84	-0.406	-0.082
10.2 cpd		-0.726	-0.482	-0.205
15 cpd		-0.628	-0.326	-0.097
23.6 cpd		-0.199	-0.077	-0.056

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	8.04	0.59	-1.095
5	15.75	0.77	-0.803
10.2	16.89	0.76	-0.772
15	25.01	2.73	-0.602
23.6	58.64	3.29	-0.232

Table 13 (continued): Individual Subject Data: Filter B (moderate Gaussian blur)
Experiment 4: Contrast Matching after Exposure to Gaussian Blur

Freq (cpd)	-1.523	-1	-0.517	-0.092
2.2	-0.361	-1.036	-0.618	-0.264
5	-0.353	-0.927	-0.494	-0.088
10.2	-0.316	-0.787	-0.438	-0.088
15	-0.277	-0.667	-0.341	-0.1
23.6	-0.221			

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	2.78875	0.1725	-1.555
5	7.80375	0.47	-1.108
10.2	15.46875	0.95875	-0.811
10.2	25.58875	1.90125	-0.592
23.6	55.485	2.9375	-0.256

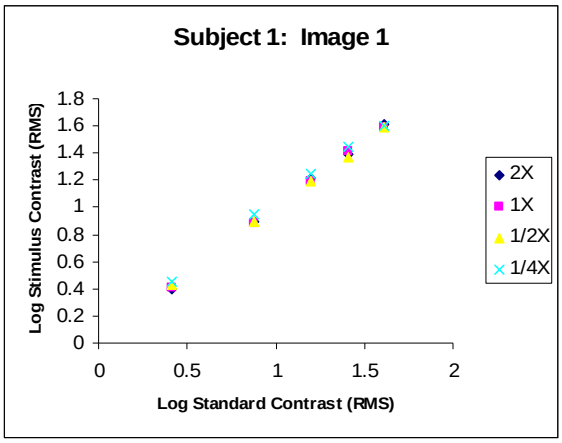
Table 14: Averaged Data: Filter B (moderate Gaussian blur)
Experiment 4: Contrast Matching after Exposure to Gaussian Blur

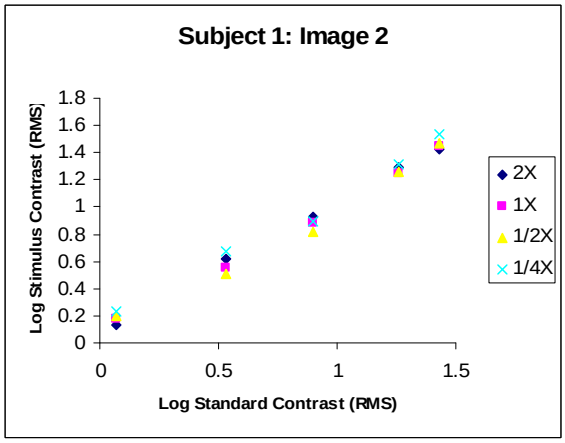
Freq (cpd)	-1.523	-1	-0.517	-0.092
2.2	0.0427	0.192	0.1455	0.121
5	0.1067	0.1	0.0526	0.034
10.2	0.3098	0.182	0.1029	0.055
15	0.2101	0.177	0.1409	0.087
23.6	0.2278			

Frequency (cpd)	Mean Threshold (%Michaelson)	%Error (+/-)	log threshold
2.2	2.258080332	0.17293682	0.297
5	4.292155428	0.2244358	0.227
10.2	6.818029538	0.4698461	0.213
15	6.835239441	0.63219431	0.123
23.6	6.931252206	0.38743663	0.056

Table 15: Standard Deviations: Filter B (moderate Gaussian blur)
Experiment 4: Contrast Matching after Exposure to Gaussian Blur

Figures 12-21:
Individual subject data for Experiment 5: Contrast Matching with Complex Stimuli





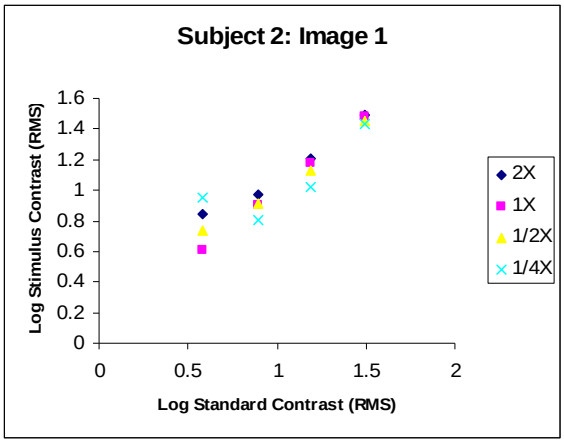
Subject 1 Image 1:

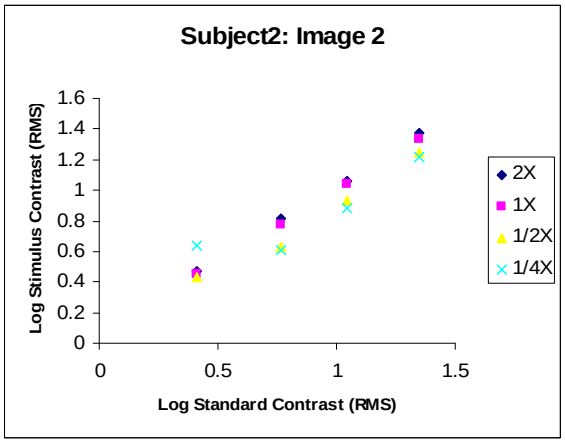
Log Std Ctr	**0.410423**	**0.880196**	**1.198278**	**1.41237**	**1.610118**
Log Stim 2x	0.393067	0.889304	1.21136	1.396856	1.612844
Log Stim 1x	0.405152	0.879134	1.187536	1.412734	1.591723
Log Stim 1/2x	0.43386	0.899209	1.193698	1.372559	1.586007
Log Stim 1/4x	0.456498	0.946592	1.247647	1.448823	1.597858

Subject 1 Image 2:

Log Std Ctr	**0.072728**	**0.532525**	**0.900591**	**1.259219**	**1.427884**
Log Stim 2x	0.136059	0.620892	0.92605	1.288688	1.429007
Log Stim 1x	0.175848	0.552556	0.880688	1.242505	1.44112
Log Stim 1/2x	0.194307	0.508696	0.814299	1.25437	1.463463
Log Stim 1/4x	0.234509	0.676775	0.895785	1.309441	1.537829

Figure 12





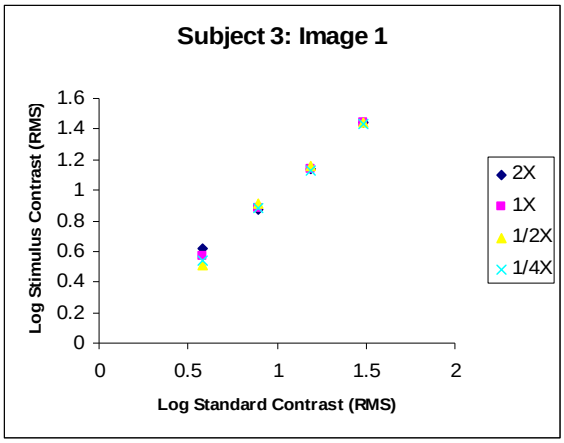
Subject 2 Image 1:

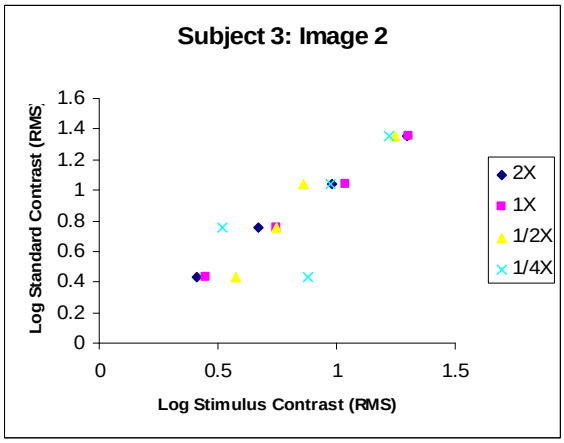
Log Std Ctr	**0.580377**	**0.895931**	**1.187538**	**1.493013**
Log Stim 2x	0.846634	0.974768	1.2077	1.496431
Log Stim 1x	0.609695	0.905892	1.175062	1.480843
Log Stim 1/2x	0.734444	0.909049	1.132514	1.44801
Log Stim 1/4x	0.947828	0.806943	1.023386	1.428526

Subject 2 Image 2:

Log Std Ctr	**0.410727**	**0.767957**	**1.044387**	**1.348644**
Log Stim 2x	0.47523	0.81718	1.063566	1.370344
Log Stim 1x	0.453553	0.779722	1.039784	1.337649
Log Stim 1/2x	0.436606	0.629894	0.932863	1.246832
Log Stim 1/4x	0.638538	0.608027	0.879827	1.218794

Figure 13





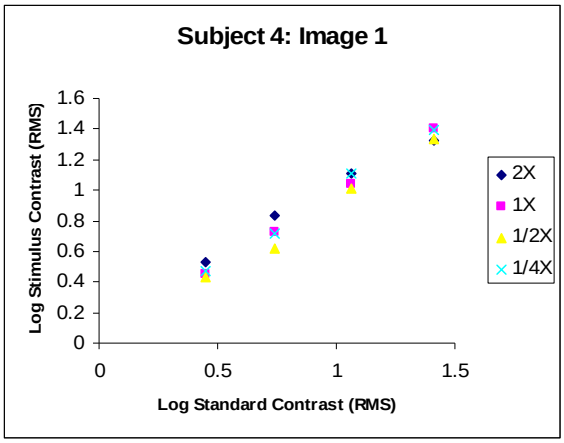
Subject 3 Image 1:

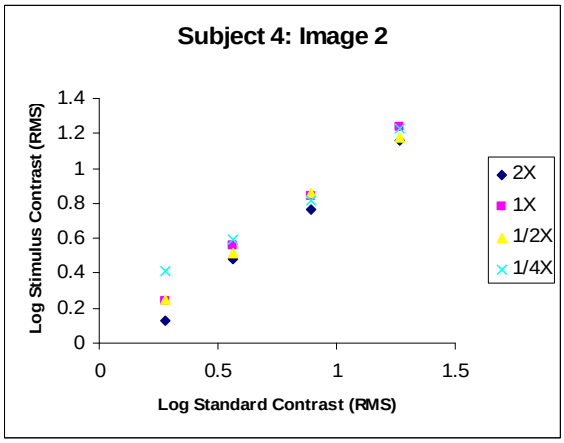
Log Std Ctr	**0.580377**	**0.895931**	**1.186626**	**1.48921**
Log Stim 2x	0.616074	0.877674	1.141381	1.445796
Log Stim 1x	0.567876	0.879773	1.1341	1.443386
Log Stim 1/2x	0.511474	0.909049	1.161889	1.447728
Log Stim 1/4x	0.539754	0.882831	1.128773	1.428331

Subject 3 Image 2:

Log Std Ctr	**0.434713**	**0.754218**	**1.044387**	**1.350769**
Log Stim 2x	0.412307	0.670598	0.977937	1.296228
Log Stim 1x	0.452282	0.748942	1.035374	1.300746
Log Stim 1/2x	0.578945	0.74443	0.862575	1.246786
Log Stim 1/4x	0.878347	0.517968	0.977835	1.218652

Figure 14





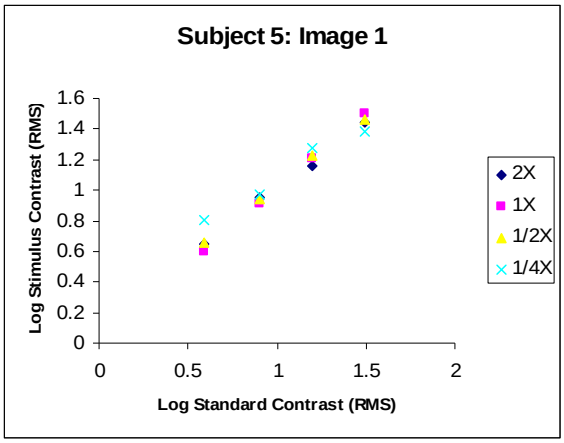
Subject 4 Image 1:

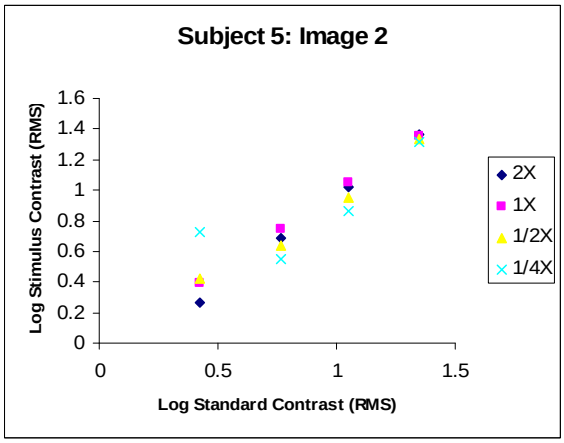
Log Std Ctr	**0.45174**	**0.740513**	**1.06271**	**1.410173**
Log Stim 2x	0.53058	0.834676	1.105967	1.325106
Log Stim 1x	0.448845	0.72869	1.038392	1.400627
Log Stim 1/2x	0.432975	0.622107	1.01315	1.334955
Log Stim 1/4x	0.473593	0.718734	1.113881	1.391614

Subject 4 Image 2:

Log Std Ctr	**0.27699**	**0.56234**	**0.891616**	**1.263986**
Log Stim 2x	0.126787	0.480035	0.767541	1.157905
Log Stim 1x	0.23782	0.555398	0.843437	1.238425
Log Stim 1/2x	0.251113	0.511759	0.858948	1.179258
Log Stim 1/4x	0.412377	0.594923	0.815229	1.230394

Figure 15





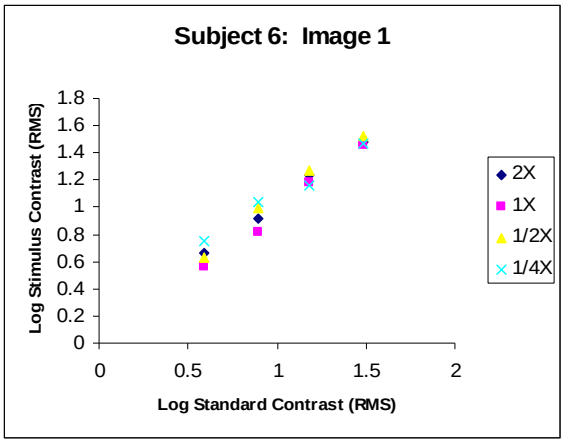
Subject 5 Image 1:

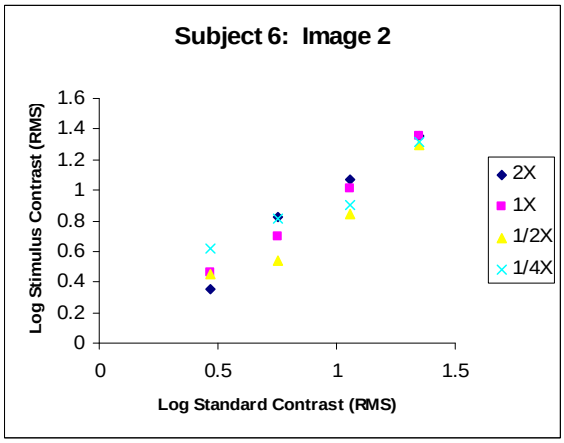
Log Std Ctr	**0.594724**	**0.901796**	**1.197115**	**1.493013**
Log Stim 2x	0.652743	0.948166	1.161924	1.446021
Log Stim 1x	0.602425	0.908864	1.210201	1.50259
Log Stim 1/2x	0.656315	0.940544	1.230749	1.466618
Log Stim 1/4x	0.807451	0.973179	1.275593	1.381879

Subject 5 Image 2:

Log Std Ctr	**0.42341**	**0.767957**	**1.050674**	**1.349854**
Log Stim 2x	0.267686	0.683641	1.016855	1.361384
Log Stim 1x	0.397536	0.744609	1.046517	1.351116
Log Stim 1/2x	0.418225	0.635158	0.949467	1.335148
Log Stim 1/4x	0.723351	0.550035	0.863994	1.314324

Figure 16





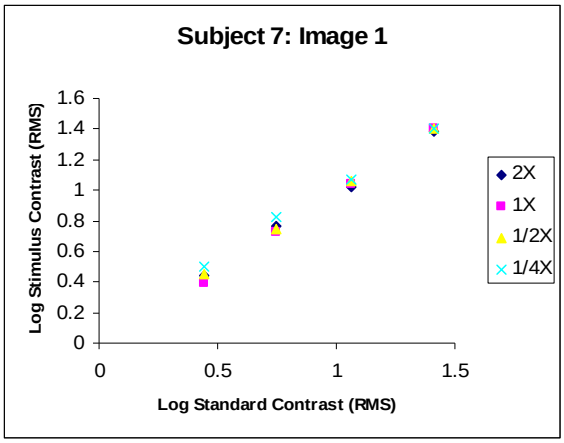
Subject 6 Image 1:

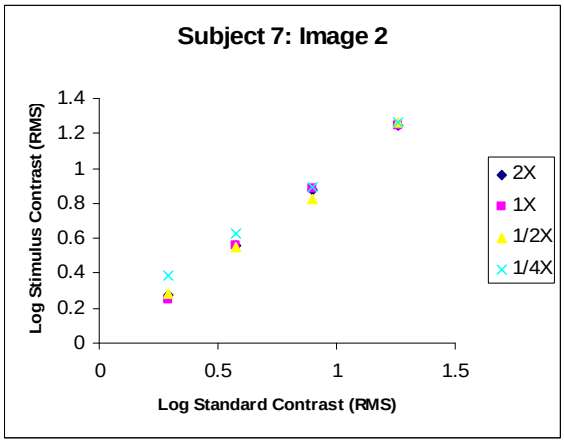
Log Std Ctr	**0.591465**	**0.89089**	**1.183426**	**1.486756**
Log Stim 2x	0.662237	0.91999	1.24129	1.48237
Log Stim 1x	0.566551	0.817614	1.181975	1.452658
Log Stim 1/2x	0.624391	0.996927	1.270185	1.524688
Log Stim 1/4x	0.750173	1.03636	1.163003	1.469762

Subject 6 Image 2:

Log Std Ctr	**0.470455**	**0.754218**	**1.054586**	**1.348644**
Log Stim 2x	0.348961	0.82492	1.07429	1.356485
Log Stim 1x	0.464052	0.693362	1.013914	1.350808
Log Stim 1/2x	0.455039	0.541886	0.842916	1.293108
Log Stim 1/4x	0.618656	0.815745	0.906738	1.314134

Figure 17





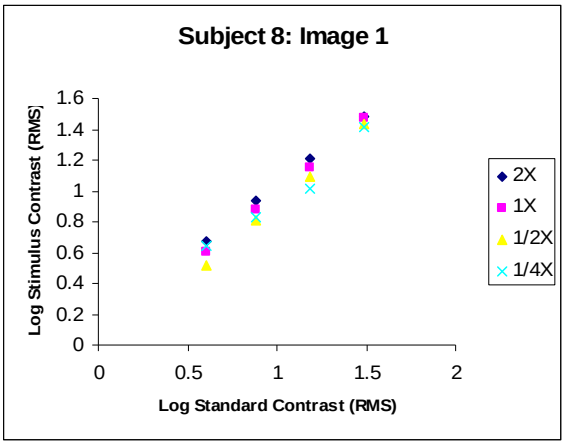
Subject 7 Image 1:

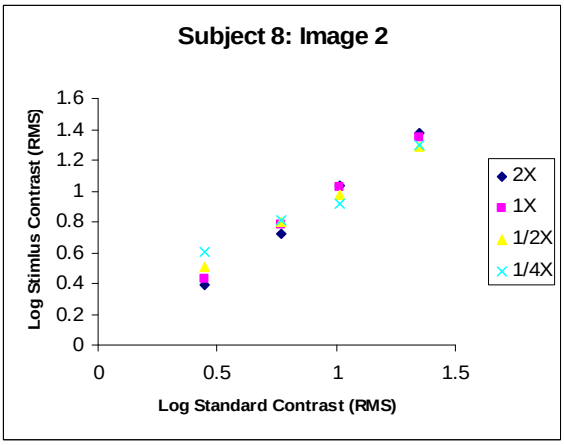
Log Std Ctr	**0.444981**	**0.749837**	**1.06271**	**1.414024**
Log Stim 2x	0.436954	0.763224	1.018558	1.380008
Log Stim 1x	0.391888	0.728278	1.038392	1.399118
Log Stim 1/2x	0.45521	0.744044	1.063143	1.401196
Log Stim 1/4x	0.50382	0.824309	1.070222	1.400011

Subject 7 Image 2:

Log Std Ctr	**0.291036**	**0.57671**	**0.896763**	**1.260987**
Log Stim 2x	0.272127	0.557275	0.873257	1.24373
Log Stim 1x	0.247131	0.560003	0.884932	1.249653
Log Stim 1/2x	0.281524	0.550896	0.824175	1.265648
Log Stim 1/4x	0.384326	0.629703	0.890089	1.266789

Figure 18





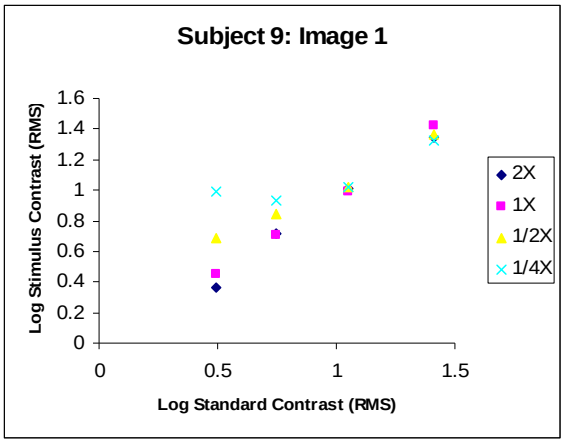
Subject 8 Image 1:

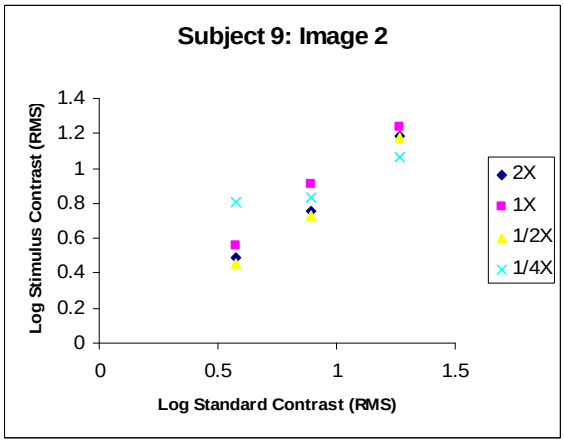
Log Std Ctr	**0.60181**	**0.881659**	**1.186626**	**1.488783**
Log Stim 2x	0.672004	0.938229	1.212688	1.482702
Log Stim 1x	0.605745	0.882405	1.148551	1.475839
Log Stim 1/2x	0.520513	0.811217	1.087822	1.433269
Log Stim 1/4x	0.648118	0.826126	1.012888	1.413401

Subject 8 Image 2:

Log Std Ctr	**0.444544**	**0.769495**	**1.014175**	**1.34802**
Log Stim 2x	0.386873	0.720257	1.033384	1.374734
Log Stim 1x	0.427657	0.776505	1.026498	1.344924
Log Stim 1/2x	0.509128	0.797905	0.977812	1.288648
Log Stim 1/4x	0.605618	0.808988	0.914661	1.293193

Figure 19





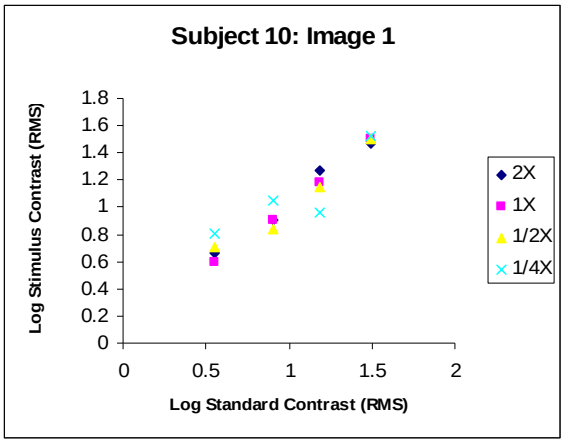
Subject 9 Image 1:

Log Std Ctr	**0.492229**	**0.746393**	**1.053382**	**1.41237**
Log Stim 2x	0.35887	0.711713	1.014798	1.349538
Log Stim 1x	0.447192	0.70299	0.986503	1.419803
Log Stim 1/2x	0.683299	0.84212	1.023306	1.367909
Log Stim 1/4x	0.992253	0.933746	1.022141	1.322407

Subject 9 Image 2:

Log Std Ctr	**0.57671**	**0.893384**	**not tested**	**1.263986**
Log Stim 2x	0.486923	0.755882		1.187404
Log Stim 1x	0.560003	0.90798		1.238425
Log Stim 1/2x	0.455002	0.730309		1.179258
Log Stim 1/4x	0.807584	0.834305		1.063804

Figure 20



Subject 10 Image 1:

Log Std Ctr	**0.553968**	**0.905553**	**1.186626**	**1.493519**
Log Stim 2x	0.658081	0.903527	1.266723	1.46512
Log Stim 1x	0.59288	0.90985	1.18489	1.498461
Log Stim 1/2x	0.702266	0.844452	1.152713	1.501745
Log Stim 1/4x	0.807248	1.045217	0.959092	1.529173

Subject 10 Image 2:

Not Tested

Figure 21