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Recommended Citation

Justin Laird, Mitchell Rosen, Jeff Pelz, Ethan Montag, Scott Daly, "Spatio-velocity CSF as a function of retinal velocity using unstabilized stimuli", Proc. SPIE 6057, Human Vision and Electronic Imaging XI, 605705 (3 February 2006); doi: 10.1117/12.647870; <https://doi.org/10.1117/12.647870>

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Spatio-Velocity CSF as a Function of Retinal Velocity using Unstabilized Stimuli

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ABSTRACT

LCD televisions have LC response times and hold-type data cycles that contribute to the appearance of blur when objects are in motion on the screen. New algorithms based on studies of the human visual system's sensitivity to motion are being developed to compensate for these artifacts. This paper describes a series of experiments that incorporate eye-tracking in the psychophysical determination of spatio-velocity contrast sensitivity in order to build on the 2D spatio-velocity contrast sensitivity function (CSF) model first described by Kelly and later refined by Daly. We explore whether the velocity of the eye has an additional effect on sensitivity and whether the model can be used to predict sensitivity to more complex stimuli. There were a total of five experiments performed in this research. The first four experiments utilized Gabor patterns with three different spatial and temporal frequencies and were used to investigate and/or populate the 2D spatio-velocity CSF. The fifth experiment utilized a disembodied edge and was used to validate the model. All experiments used a two interval forced choice (2IFC) method of constant stimuli guided by a QUEST routine to determine thresholds. The results showed that sensitivity to motion was determined by the retinal velocity produced by the Gabor patterns regardless of the type of motion of the eye. Based on the results of these experiments the parameters for the spatio-velocity CSF model were optimized to our experimental conditions.

Keywords: LCTV, CSF, Motion sensitivity

1. INTRODUCTION AND BACKGROUND

The motivation for this work was to understand how observers' contrast sensitivity changes with retinal velocity. If an object is perceived as having an unacceptable amount of blur when stationary then that object might be deemed acceptable if the image of the object moves across the retina. However, if observers track the object with their eyes making the retinal image stationary then the object can appear unacceptably blurred once again. This is because the perceptual threshold for blur tolerance increases for images in motion across the retina.

LCD devices are known to have temporal characteristics that lead to the appearance of blur due to relatively slow LC response times and hold-type data cycles. While there has been much effort in the industry applied toward the motion blur problem¹, a new possibility is to use algorithms that can predict where the observer will look and make adjustments to the image based on this knowledge. One requirement for such algorithms is to have a robust model of motion sensitivity. This model could report to the algorithm observer sensitivity based on the spatial frequency and velocity content of an image. Then the algorithm could predict the visibility of motion artifacts based on the observers' eye movements. An understanding of the interaction between image quality and motion blur, and the temporal response of LCTVs may lead to effective algorithm tradeoffs for reducing motion artifacts.

1.1. Motivation: LCTV Motion Artifacts

The new generation of LCTV panels using TFT thin film transistors, have the transistors arranged in a matrix format. Each pixel is addressed by turning on the appropriate row followed by a voltage sent down the appropriate column. Only the intended pixel is addressed since all other rows are turned off at that time. This is known as a "sample and hold" procedure² because the current pixel remains active until the next refresh cycle. This could be a problem when trying to show an object in motion because each image of the scene is only valid for a single instant in time and not for a complete frame. As a person is tracking an image across the screen his/her eye is in constant motion but if the image is held on the screen too long there is blurring across the person's retina. This is analogous to a person staring at a stationary object; if the person moves his/her eyes suddenly then the image of that object will be blurred because of the motion across the retina.

The speed of change for LCDs is slower than that for CRTs not only due to the sample-and-hold procedure and but also because of the response time of LCs. LCDs must apply a voltage to either twist or untwist the liquid crystals in

each subpixel in order to modulate the light passing from the backlight to the red, green or blue filters. Then the voltage is removed and the liquid crystals (LCs) must revert back to their original state. A CRT can refresh faster than an LCD can switch states. While the times reported for current LCTVs is increasing it is safe to say that they have not approached the speeds of CRTs.

1.2. Contrast Sensitivity Function

The human contrast sensitivity function (CSF) is a measure of visual sensitivity to contrast of different spatial and temporal patterns. The human visual system (HVS) is made up of components that detect and analyze the spatial pattern of light on the retina.³ By measuring the visual system's response to sine wave patterns it is possible to apply the results to more complex stimuli such as images. The spatial CSF reports sensitivity against spatial frequency of sine wave patterns and the temporal CSF reports sensitivity to temporal frequency of the patterns. These temporal CSF experiments have tended to rely on sinusoidal patterns undergoing counter-phase flicker. This flicker has been used as an attempt to understand how sensitive the HVS is to rapid fluctuations from such sources as television, movies and fluorescent lamps.⁴ In those studies a sine wave pattern was modulated at varying speeds, in order to determine the contrast at which perceived flicker is eliminated. The results from these studies are remarkably similar to those where only spatial frequency is modulated for a given temporal frequency.

Previous research^{5, 6, 7} has shown that for lower spatial and temporal frequencies the HVS channels are not independent. The interaction at low frequencies is due to the temporal behavior of the photo-receptor signal and the lateral inhibition of the receptors, which is affected by the spatial characteristics of the pattern.⁶ Sensitivity can thus be described as an interaction between temporal and spatial frequencies. A 2D spatio-temporal CSF is built showing a variety of spatial frequencies at a variety of temporal frequencies.

In a break from the traditional spatiotemporal approach, D.H. Kelly investigated contrast sensitivity as a function of velocity across the retina.⁵ The results of his studies are more easily transferable to natural conditions because, in general, humans do not observe flickering objects; instead objects in motion move at some velocity across the retina or remain fixed on the fovea if a person is tracking an object. Kelly⁵ referenced prior work⁴ that showed motion sensitivities to be greater than flicker sensitivity. Furthermore, he states, "the fact that motion thresholds are lower than flicker thresholds suggests that moving gratings are somehow better matched to the characteristics of the visual process than are flickering gratings."⁵

An example of Kelly's 2D CSF is shown in Figure 1. This graph shows that as spatial frequency is increased from left to right while keeping temporal frequency constant, sensitivity increases to a peak and then quickly drops off. Likewise, if spatial frequency is held constant and temporal frequency increases from front to back there is also a peak reached followed by a quick falloff. The CSF plots in this paper are shown in terms of the temporal frequency corresponding to velocity relative to the retina

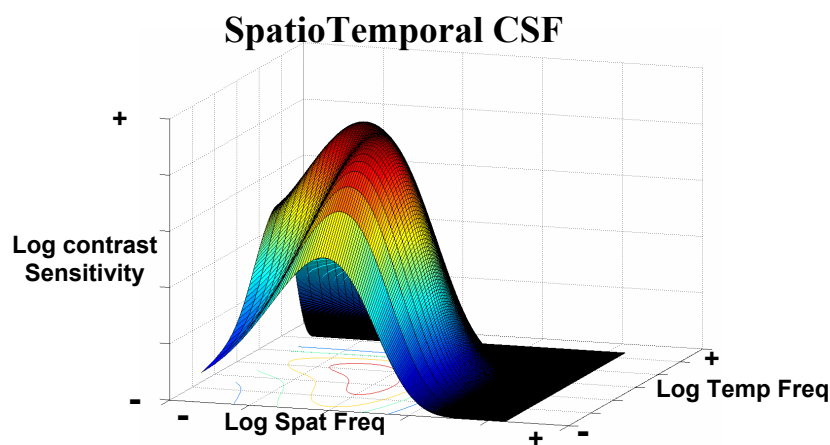


Figure 1 - Spatiotemporal CSF

Kelly⁵ modulated image velocity across the retina through retinal stabilization and could therefore induce movement or keep the stimulus stationary on the observer's retina. He held velocity constant and measured contrast sensitivity to a variety of spatial frequencies. He built a 2D CSF model by measuring contrast sensitivity at a variety of velocities and spatial frequencies. Kelly fit a model to his data using the formulas described in Section 3.1.

In 2001, Daly⁹ revised Kelly's model⁵ to incorporate retinal velocity that took into account smooth pursuit eye movements. It was found that observers can track an object up to a certain velocity and at faster velocities the person has to make "catch-up" saccades to keep up with the object. The exact velocity at which this happens is dependent on several variables. Daly incorporated retinal velocities with this limitation imposed on sensitivity to Kelly's model, among other changes. This distinction is important because during saccadic eye movements sensitivity drops to near zero. Daly also incorporated a minimum eye velocity into his revised model since it is known that observers do not keep their eyes still when fixated on a target.¹⁰ The shape of the curve from a traditional static stimulus CSF experiment is very similar to the shape of the same pattern moving at this minimum velocity. In other words, while sensitivity will drop to zero for fast velocities there will always be a response for minimum velocities.⁹

2. EXPERIMENTAL

2.1. Description of Experiments

There were a total of five experiments. The first experiment was a traditional spatial CSF experiment. Experiments 2 through 4 were used to investigate and populate the 2D spatiovelocity contrast sensitivity function (CSF). The fifth experiment was used to validate some aspects of the resulting 2D CSF model. For all five experiments observers were instructed to fix their gaze on a circular fixation point that was 4 pixels in diameter. Observers' eyes were tracked in all five experiments and the tracking data were used in the development of the 2D CSF model and also as a check that observers were in fact tracking the stimuli appropriately. There were on average 15 observers per experiment.

The stimuli for Experiments 1 through 4 were Gabor patterns of 2.46 visual degrees in diameter. Examples are seen in Figures 3-5. The stimulus for Experiment 5 was a disembodied edge, which is an edge windowed by a Gaussian, as seen in Figure 2. The edge stimulus was used for verification of the CSF model because it is an intermediate stimulus: more complex than a sine wave pattern yet simpler than a typical image.



Figure 2 - Example of disembodied edge

The experiments in this research used 2-interval forced choice designs (2IFC). The observer watched the screen over two timed intervals separated by audible beeps where the stimulus was randomly assigned to be present in one interval and absent in the other. The task of the observer was to determine in which interval the stimulus was present. Each experiment utilized the QUEST¹¹ routine run within the Psychophysics Toolbox¹² in Matlab to determine contrast thresholds. QUEST is used to dynamically adjust physical parameters within a judgment experiment in a search for a perceived psychological tolerance. Quest makes an initial threshold estimate for each new trial based on a particular psychometric function and knowledge of all previous trials. The initial threshold values were interpreted as contrast and used directly to modulate the Gabors for the next trial.

For Experiments 2 through 4, the independent variables were spatial frequency and velocity. There were a total of eight conditions, shown in Table 1. The spatial frequencies of the sine in the Gabor are on the left and the temporal frequencies are along the top. The velocity of the Gabor was changed in order to keep the temporal frequency constant and the particular velocity value, (in deg/sec), is seen in the corresponding cells. (A 16 CPD and 30 Hz stimulus was beyond the capability of the display system at our setup.)

Table 1- Gabor pattern data

Spat Freq (Cyc/Deg)	Temporal Freq (Hz)		
	10	20	30
4	2.5	5.0	7.5
8	1.25	2.5	3.75
16	0.625	1.25	

Figures 3-5 show how each experiment differed and in each figure the arrow represents an increase in time moving back to front. The first experiment (Figure 3) was a traditional CSF experiment and is considered a control experiment, which allowed comparisons to be made between results in this research with those in the literature. The Gabors in this experiment were completely stationary. Experiment 2 was similar to Experiment 1 except the sine wave pattern inside the Gabor was in motion while the window itself and fixation mark remained centered on the monitor.

This is intended to generate retinal velocities without eye movements. In Experiment 3 (Figure 4), the sine wave pattern was stationary relative to the Gabor but the Gabor itself moved left to right across the screen while the observer remained fixated on a stationary point centered on the display. Experiment 4 (Figure 5) was similar to Experiment 3 except the fixation point was in motion along with the Gabor.

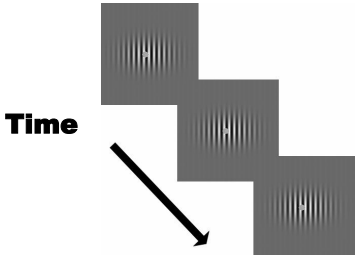


Figure 3 - Exp 1, Completely Stationary Gabor: window stationary and sine pattern stationary. Fixation point remains in center of stimulus.

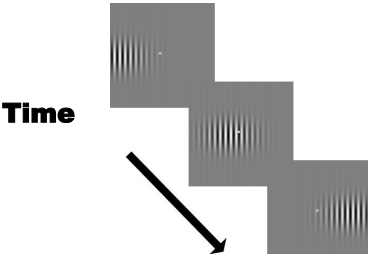


Figure 4 - Exp 3, Gabor in motion, eyes fixated: window in motion, sine stationary with respect to window. Fixation point remains centered on screen.

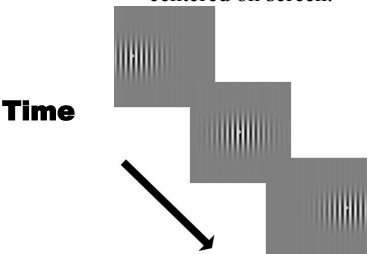


Figure 5 - Exp 4, Gabor in motion, eyes tracking: window in motion, sine stationary with respect to window. Fixation point remains centered on window as it moves across the screen.

The fifth and final experiment utilized a disembodied edge. The experiment was also a 2IFC and the experimental design was the same as in Experiment 4 but the independent variables in this experiment were velocity and contrast. There were three contrast levels used at four velocities, shown in Table 2. There was a stimulus present in both trials; in one interval there was a sharp edge and in the other there was a blurred edge. Convolution of a sharp edge with a Gaussian filter blurred the edge. The velocities were chosen from those used in experiments 2 through 4 (see Table 2). The contrast values were chosen based on those used by Hamerly & Dvorak¹³, with the exception that the maximum contrast value possible was 0.4 for our setup. As in Experiment 4, the observers tracked the moving edge. The question posed after each trial was; “In which interval was the edge sharper?” in order to determine the blur threshold and thus sensitivity to edge-sharpness detection. The value returned by QUEST was used to modulate the amount of blur.

Table 2 - Parameters of Experiment 5

Velocity (deg/sec)	Contrast (Michelson)
0	0.05
1.25	0.25
3.75	0.4
7.5	

2.2. Experimental Setup

The setup for each experiment consisted of a Sony Trinitron MultiScan G420 CRT monitor, an eyetracker and a chinrest. Observers were seated a fixed distance from the monitor using a chinrest. The CRT was used because of its fast

refresh times, which reduced motion artifacts. However, in order to relate sensitivities from experiments on the CRT to the much brighter LCD, the brightness of the CRT was set as high as possible.

A characterization was performed on the CRT monitor. Measurements were made with an LMT Colorimeter C1210. The model was verified using measurements of 2000 randomly selected RGB colors. The average CIEDE2000 between the measured and calculated values was 0.31 with a maximum value of 1.91. Other tests performed included a channel and spatial independency test¹⁴. Table 3 below shows the settings for the CRT.

Mean Lum. of screen	60 cd/m ²
Horiz. span of screen	23.95°
Dist Obs. from Screen	84 cm

An ASL Series 504 remote eyetracker, seen in Figure 6, was run using ASL’s proprietary data acquisition package. This system monitors eye position without any contact with the subject by imaging the eye through a desk-mounted camera. The lens is surrounded by infrared light emitting diodes (IRLEDs) providing illumination aligned with the optical axis. This infrared, video-based eyetracker determines the point-of-gaze by determining the center of the subject’s pupil and a first-surface reflection on the cornea. This is known as bright pupil technology because the illumination is coaxial with the axis, resulting in a back-illuminated pupil. The effect is the same as “red eye” and it simplifies thresholding to track the eye.

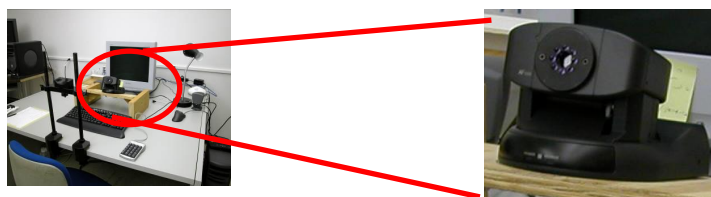


Figure 6- ASL Series 504 Remote eye tracker

Prior to each experiment, the eyetracker was calibrated to the observer using ASL’s software and a calibration target. The calibration process sets a relationship between known distances, in centimeters, between points on the monitor to distances the observer’s eye moved between those points. The position recorded by ASL can be converted to visual degrees if the distance between observer and the monitor is known. This calibration provided accurate position of the tracked eye as long as the observer was at the same distance from the monitor throughout the experiment. The accuracy of the eyetrack record is approximately 1° or 16 cm on the display.

3. RESULTS AND DISCUSSION

The results for Experiment 1 are compared to Experiment 4 further down this section. The results from Experiment 2, where the sinusoid moved within the stationary Gaussian window with a stationary fixation point, are shown in Figure 7 where the each line is the average sensitivity for all observers. It is shown that as temporal frequency increased for a given spatial frequency, sensitivity decreased for the range of temporal frequencies used in the study. Likewise, Figure 8 shows that as spatial frequency is increased for a given temporal frequency sensitivity decreased. Again, this was the expectation based on previous research⁷ and what was already known about the HVS. The perceived contrast and sensitivity of high spatial frequency targets is reduced due to neural and optical effects.³ It is also known that center-surround retinal ganglion cells in the retina are less sensitive to high spatial frequencies.⁴ Watson has discussed in more detail physiological reasons for lower sensitivity at higher spatial and/or temporal frequencies.⁴ The errorbars in all graphs are ± 2 SEM. The corresponding velocities are shown along the top in Figure 8 and 11.

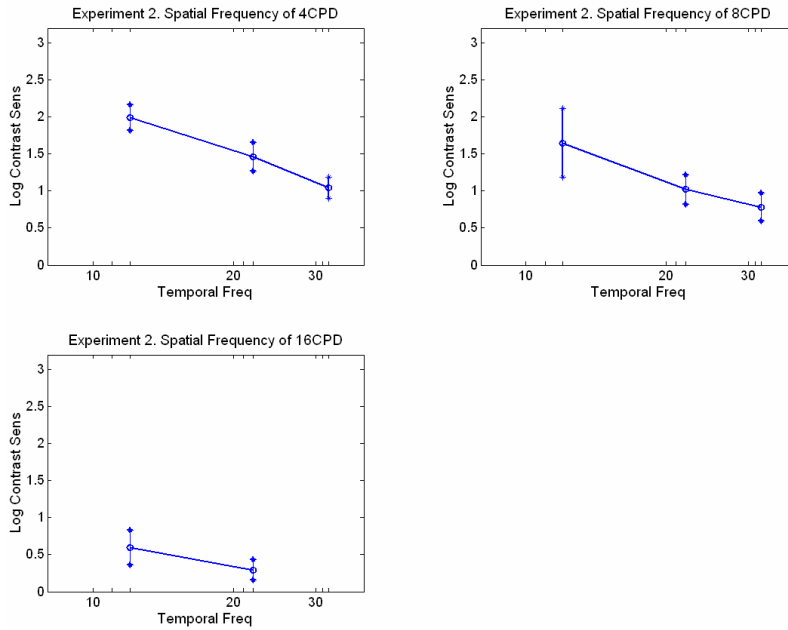


Figure 7 - Experiment 2; plot of contrast sensitivity for each spatial frequency as a function of temporal frequency.

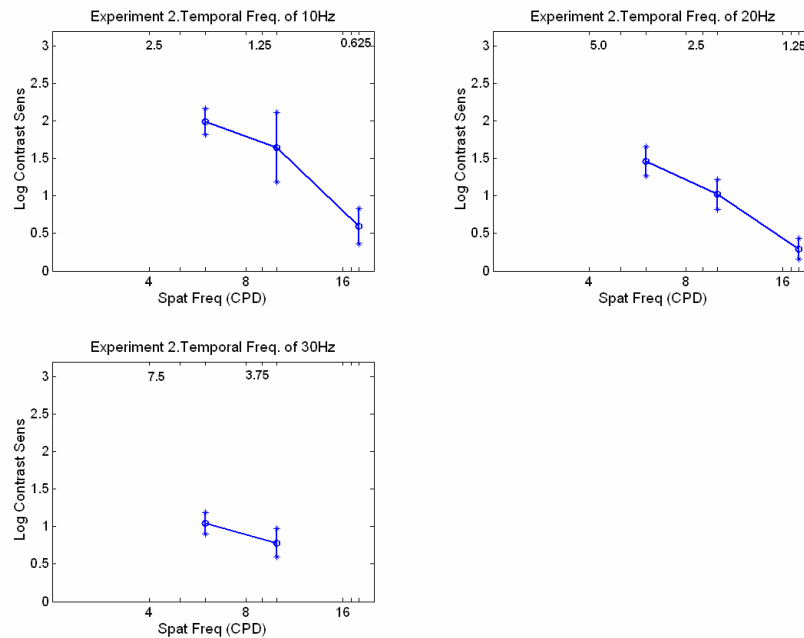


Figure 8 - Experiment 2; plot of contrast sensitivity for each temporal frequency as a function of spatial frequency.

The motion in Experiment 3 was different than Experiment 2 in terms of the movement along the screen. Unlike Experiment 2, temporal frequency for this was the actual movement of the Gabor across the screen. The difference is that the Gabor is moving across a larger section of the retina in Experiment 3 and for higher velocities the Gabor moves into and out of the field of view of the observer while in Experiment 2 the motion was always in the central fovea of the observer. This could affect the results because the peripheral retina, with lower spatial resolution, may be contributing even though the observers are fixating the center of the screen and movement of the Gabor could induce involuntary eye tracking despite the stationary fixation mark. In order to reduce high temporal frequency artifacts, the contrast of the Gabor was gradually increased from the background level to full contrast. This effectively put the Gabor at full contrast

within the same region on the screen as when the Gabor was stationary. If the motion on the retina was the same then observers were able to hold a steady fixation point despite “object” motion and there should be no difference between the results of Experiments 2 and 3 in terms of sensitivity. Indeed, the results are statistically the same between both experiments as seen from Figure 9. Each plot in the figure is a different spatial frequency and within each graph the results for Experiments 2 and 3 are plotted together for comparison. Additionally, the table in the lower right of the figure has the sensitivity values with the standard deviation for both experiments. This indicates that the visual system responds equivalently to moving sinusoids within a stationary window (relative to screen) and stationary sinusoids in a moving Gabor as long as the temporal and spatial frequencies are the same at the retina.

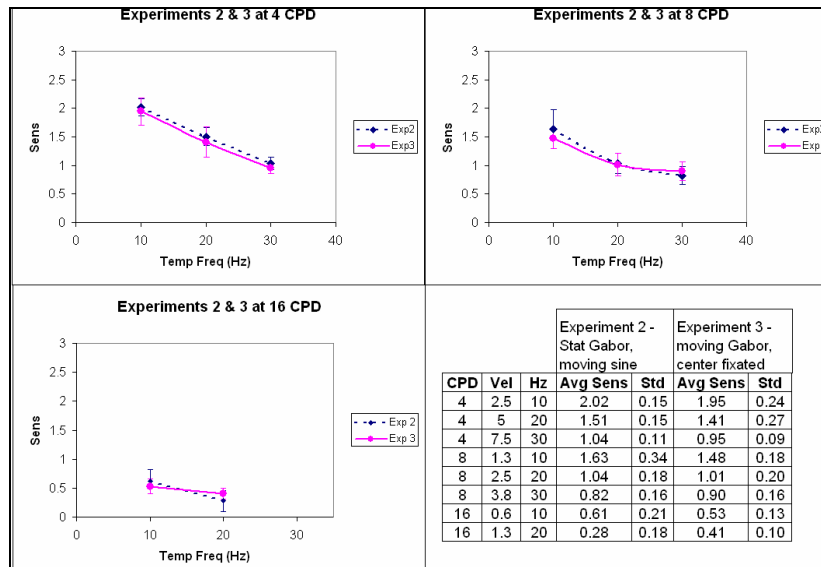


Figure 9 - Comparison of results for Experiments Two & Three

The results for Experiment 4, shown in Figure 10, are different from those of Experiments 2 and 3. While the stimulus motion was the same in Experiment 4 as in 3, the difference was that observers were fixated on the screen center in Experiment 3 and tracking the Gabor in Experiment 4. As the temporal frequency increases (measured relative to the screen position), the sensitivity does not decrease for Experiment 4 as it does for Experiments 2 and 3.

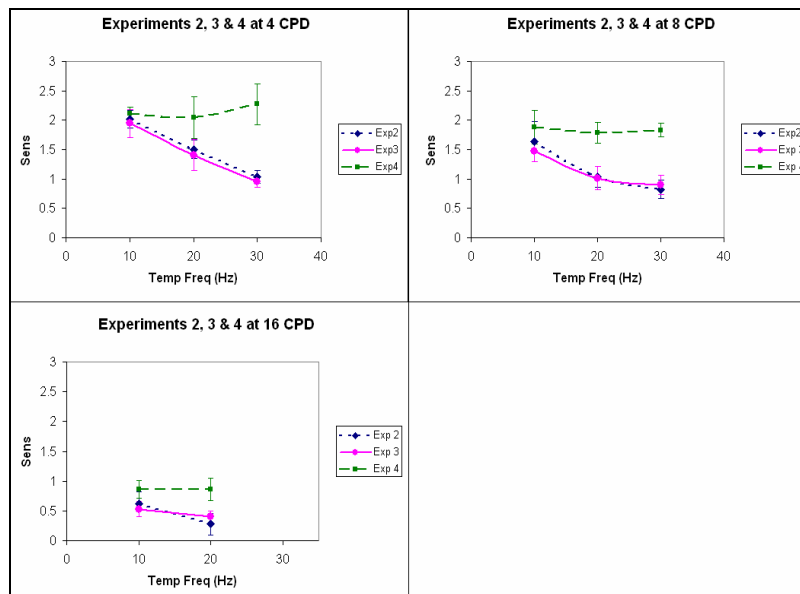


Figure 10 - Comparison between results for Experiments 2 & 3 and those in Experiment 4

Furthermore, results for Experiment 4 show that as spatial frequency increases for a given temporal frequency, sensitivity decreases, similar to Figure 7. However, the graphs in Figure 11 show there is no decrease in sensitivity as temporal frequency is increased. This indicates that observers were doing a good job tracking the Gabor and that there is no substantial retinal velocity. Furthermore, it was found that eye movements did not affect contrast sensitivity in these experiments. This will be further discussed in section 3.2 when the results of observer eyetracking are discussed. Furthermore, Figures 10 and 11 show that contrast sensitivity was the same in this experiment as in the control experiment, the stationary Gabor in Exp. 1.

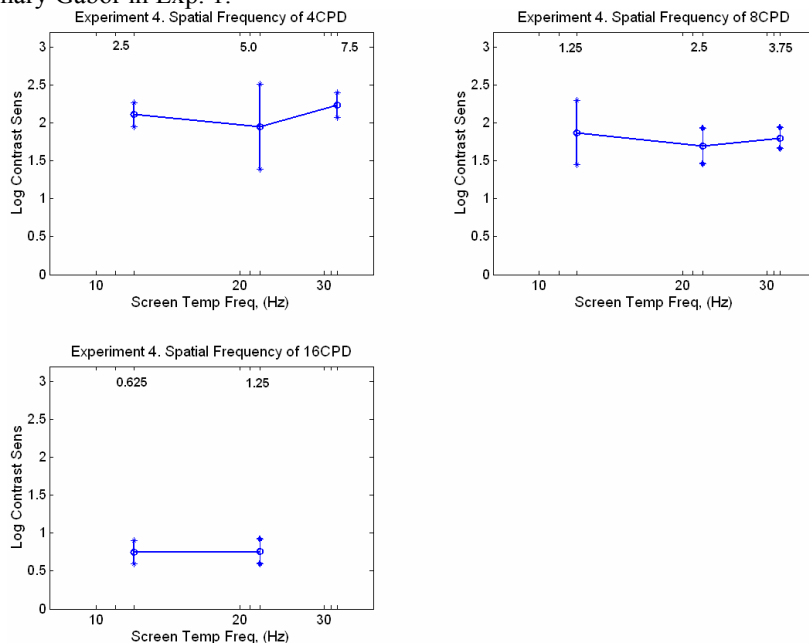


Figure 11 - Experiment 4; plot of contrast sensitivity for each spatial frequency as a function of temporal frequency

The results of Experiment 1, the control experiment, compare favorably to results in the literature where increasing spatial frequency decreases sensitivity in the region tested. As seen in Figure 12 the overlap in the errorbars, which represent ± 2 SEM, at each point and similarity in curve shape reveal similar visual processing. In order to test the hypothesis that sensitivity results would be the same for stationary Gabors as for tracked Gabors the results from Experiment 1 were compared to those from Experiment 4. Experiment 1 is considered a traditional spatial CSF experiment in the sense that there is no motion involved. In Figure 12, the bottom dashed line represents average sensitivity from all observers for Experiment 1 and the middle dashed and top solid lines are from Experiment 4 and represent average contrast sensitivity for observers tracking a Gabor moving along the screen at corresponding temporal frequencies of 10, 20 and 30 Hz respectively. It is evident from Figure 12 there was not significant differences.

There does appear to be a slight trend, although not statistically significant, for higher sensitivities for eyes in motion, especially at lower spatial frequencies. It is plausible that eye movements slightly increase sensitivity for low spatial frequencies but as spatial frequency increases these slight eye movements, which result in retinal velocity, become less important. The idea that eye movements actually increase contrast sensitivity have been shown by Kelly⁵ and in the research described here the fact that retinal velocity decreases sensitivity will be discussed in more detail later. Nevertheless, Robson shows that sensitivity to gratings at low temporal frequencies is modulated by spatial frequency and also that low sensitivity to low spatial frequency is modulated by temporal frequency. For small eye movements that result in small retinal velocities it is plausible that contrast sensitivity increases slightly at low spatial frequencies^{9, 10}.

The results from Experiment 3, (the Gabor in motion with observers fixated on the center of the screen), will be used in the parameterization of the 2D spatiovelocity CSF model. The results from this experiment are useful because they indicate how sensitivity changes with retinal velocity and better relate to natural eye movements. The results from Experiment 1 are also referred to in the 2D spatiovelocity CSF development.

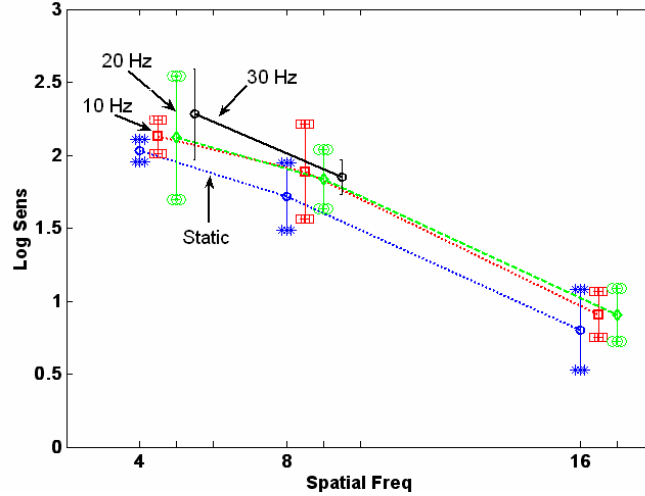


Figure 12 - Contrast sensitivity data for static Gabor compared to Gabor tracked across screen. The horizontal offset of each data point is for clarity. In actuality these points are plotted at 4, 8 and 16 cpd..

3.1. Parameterizing and Verifying the Spatiovelocity CSF Model

3.1.1. Parameterizing CSF Model

As stated previously the model from Kelly², modified by Daly³, is used as the 2D spatiovelocity model. Daly's modification adds constants c_0 , c_1 and c_2 to Kelly's model. The Kelly-Daly equation is found in Equations 1-3:

$$CSF(\rho, v_R) = k \cdot c_0 \cdot c_1 \cdot c_2 \cdot v_R \cdot (c_1 2\pi\rho)^2 \exp\left(-\frac{c_1 4\pi\rho}{\rho_{\max}}\right) \quad (1)$$

$$\text{where } k = s_1 + s_2 \cdot \left| \log\left(\frac{c_2 v_R}{3}\right) \right|^3 \quad (2)$$

$$\text{and, } \rho_{\max} = \frac{p_1}{(c_2 v_R + 2)}, \quad (3)$$

where $s_1=6.1$, $s_2=7.3$ and $p_1=45.9$ and are the original constants provided by Kelly. The variable v_R is velocity, which for purposes in this paper is actually retinal velocity. Daly's constants allow the model to be fit based on a particular experimental setup primarily to address high sensitivity and bandwidth at higher light adaptation levels than used in Kelly's apparatus. The constant c_0 can be adjusted for peak sensitivity, c_1 for maximum spatial frequency cutoff and c_2 for the maximum critical flicker frequency⁹. If these values are set to 1 then Kelly's model is produced. The variable ρ is spatial frequency in cycles per degree and v is the velocity for which the contrast sensitivities were tested at a variety of spatial frequencies. The scale factor k is responsible for the vertical shift of sensitivity and is dependent on velocity, where in general at lower velocities there is simply a vertical offset in sensitivity^{5, 9, 4, 15}, and p_{\max} is responsible for the horizontal shift of the peak sensitivity. Both of these scale factors account for the separability of the spatial and temporal components of the CSF at higher frequencies.

The constants c_0 , c_1 , c_2 were optimized in the following way. A nonlinear least-square routine was run in MATLAB in which the sensitivity values from the model were fit to the experimental results corresponding to the spatial frequency and velocity data points. Values of the constants were modified until the differences between the model and the experimental results were minimized. These values found by fitting the model to our experimental results are as follows: $c_0 = 0.6329$, $c_1 = 0.8404$, and $c_2 = 0.7986$. In Figure 13 below the 2D CSF model was built from the optimized constants. There was a maximum cut-off spatial frequency of approximately 20 CPD. Because of viewing distance and parameters of the CRT there were 41 pixels-per-degree and because there is a minimum of 2 pixels for 1 cycle there was a maximum of 20.5 CPD available in these experiments.

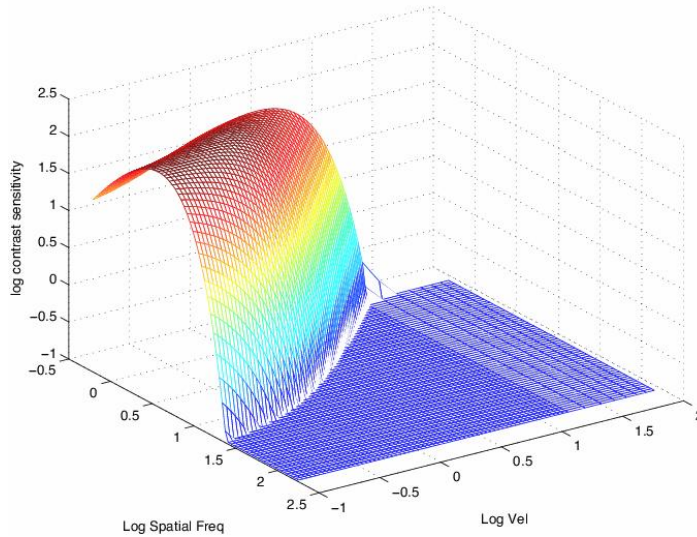


Figure 13 - Spatial-velocity CSF model found after optimization of Daly-constants

3.1.2. Verifying the model

The final experiment was used to verify the prediction results from the model. In this case a moving disembodied edge was shown at three contrast levels and four velocities. The results from this experiment, shown in Figure 14, show how sensitivity to edge sharpness changes with different contrast and velocities. The abscissa represents the three contrast levels tested and the ordinate is sensitivity to edge-blur. Each line in the graph represents a different velocity that the edge moved. The results showed no change in sensitivity to the edge blur as velocity increased. However, the minimum contrast level had the lowest sensitivity while the middle and high contrast level had the same sensitivity, which was higher than the lowest contrast level. The results in Figure 14 show no difference in the results for the different velocities indicating good eyetracking performance. Sensitivities to the two higher contrast levels are statistically identical. The error bars for each velocity overlap each other, indicating zero retinal velocity at each contrast level. These results will be compared to the model predictions. Due to good tracking of the moving edges indicated by overlapping error bars in Figure 14 and the eye tracking records, data from the 2D CSF model corresponding to 0 retinal velocity was used for verification.

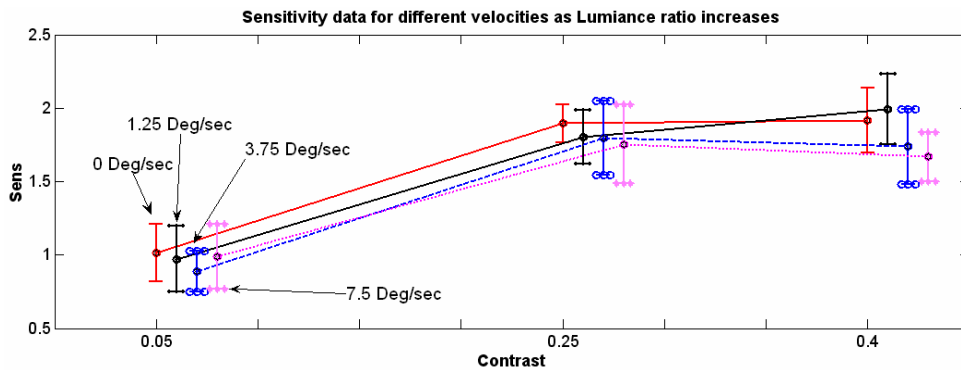


Figure 14 - Results of Experiment 5 where each line represents a different velocity.

For verification, the CSF was normalized to between 0 and 1. Then, the blurred edge 1D Fourier transform was multiplied by the normalized CSF data for zero velocity followed by integration. Because the results from the experiment are in terms of threshold, the values are different than the values from the above process. Therefore, both the experimental and model results are normalized and plotted together. Figure 15 below shows the similarities.

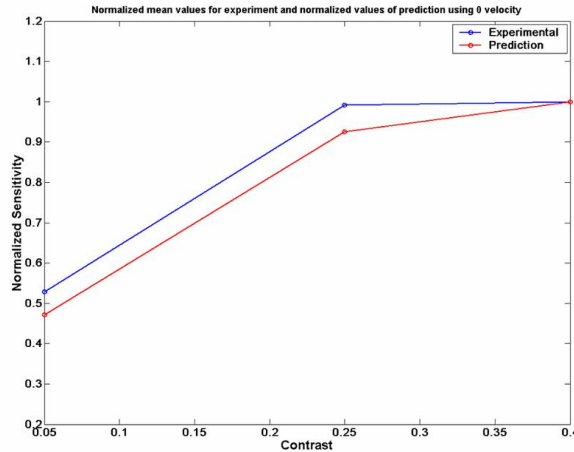


Figure 15 - Model results (on bottom) compared to experimental results (on top).

3.2. Eyetrack Analysis

Observers' eye movements were tracked for the main purpose of calculating their gains and actual velocities. The metric of how well they track a stimulus is referred to as gain. If observers track something perfectly then their gain would be 1 and if they did not track at all it would be 0. If the observers move their eye faster than the object, their gain is greater than 1, and if eye movements are slower than the object, their gain is less than 1.¹⁶ The method for calculating gain was to first calculate the eye velocity and then divide this by the target velocity. For example, if an observer's calculated eye velocity is 11.41 and 11.35 for interval 1 and 2 respectively then the average calculated gain between the two intervals would be 1.07 for a target velocity of 10.59 cm/sec. Note that this gain value is for a single trial out of a total of 50 for this condition. There are several possible reasons why the gain metric would not accurately report tracking: there could be noise in the eyetracker, the person could be looking away from the screen, they could be lagging behind the stimulus and then making "catch up" saccades. All these were accounted for prior to calculating velocity and gain values by eliminating erroneous records. However, it was expected from the psychophysical results that most observers would have gains near 1 since it was already shown that the sensitivities did not change with different velocities. It was hypothesized that as gain approaches 1, sensitivity approaches a maximum for that particular condition.

Through Experiment 3, where the Gabor pattern moved across the observer's retina while his/her eyes were fixated, it was shown that sensitivity decreased with increasing retinal velocity. Through Experiment 4, where the observer tracks the Gabor across the screen, it was shown that contrast sensitivity did not change. This result shows that eye movements did not affect contrast sensitivity. This was expected but could not be extrapolated from the Kelly retinal velocity experiments. Therefore, it can be inferred that gain was not affected and that observers tracked very well. It can also be inferred that if the gain value deviates from 1 then there will be retinal velocity and most likely a change in sensitivity.

To determine which factors in Experiment 4 affected gains an ANOVA was performed on the eyetrack data and the calculated gains for each observer. The ANOVA results are in terms of an average gain across 50 trials since there is only a single sensitivity value that is calculated from all 50 trials. Some interesting results of the ANOVA were examined. First, the average gain over all observers was 0.956 +/- 0.017. Gains for a spatial frequency of 16 CPD were higher and statistically different than those for 4 and 8 CPD. Likewise the gains for the slowest velocities (0.625, 1.25 & 2.5 deg/sec) were statistically different than those at the medium and fast velocities. In this case as velocity (which equates to eye velocity) increased the gains decreased. This indicates that there is an interaction between spatial frequency and velocity, where overall there was a decrease in gain for increasing velocity but as the spatial frequencies increased the gain increased. This may indicate that for the regions tested observer's track better for higher spatial frequencies at higher velocities and therefore were more sensitive to these patterns. However, these trends are small compared to the overall results.

It was seen that the majority of gains were close to 1 with a few exceptions. The majority of observers tracked the stimuli acceptably and their data were included in the development of the 2D spatial-velocity CSF model, which, because of the use of non-stabilized retinal images is a more natural model for human contrast sensitivity than previous models. Furthermore, it can now be said that observers' contrast sensitivity is the same for tracked targets as when the target is stationary up to the angular speeds studied in this paper.

4. CONCLUSION

Results from all experiments show that observers did a good job tracking the stimuli and so their results were used to populate the spatiovelocity CSF model. Proper eyetracking was important because, from Experiment 3, it was shown that sensitivity is determined by retinal velocity and the eyetrack records demonstrated that eye movements did not affect contrast sensitivity. Because the majority of observers' eye movement gains were close to 1 it was determined that they were tracking the stimuli quite well. This inference was supported by the analysis of eye movement records and further reinforced from the sensitivity data from Experiment 4 where observers tracked moving Gabors.

A spatiovelocity CSF model was fit using the data from Experiment 1, static Gabors, and Experiment 3, fixated observers with moving Gabors. Aspects of the model were verified with results from Experiment 5 in which an edge moved at several different velocities while observers followed the moving edges. The predictions from the model agreed favorably with experimental results and observer tolerances were shown to be the same as the static stimuli. The experiments only measured 11 points in the spatiovelocity space, so further experiments should be used to better refine the model and should also include edges whose images move across the retina. Additionally, these experiments have shown that contrast sensitivity is the same for a moving sinusoid inside a stationary Gaussian window or the Gabor pattern moving across the field of view. This agrees well with the idea that at low levels of visual processing, the visual system is responding to both temporal variation and spatial pattern of the light without regard to the type of pattern motion. The practical implication is that a model can be built using stimuli with natural motion.

From the eyetrack records it was shown that observers did an acceptable job of tracking the stimuli since the average gain for all observers was close to 1. This allowed the use of calculated retinal velocities in the 2D spatiovelocity CSF model from the observed data without complicated eyetracking devices. Although it was good for building the CSF model, using lower velocities did not probe the limits of smooth pursuit. Observers had no trouble tracking a Gabor moving at 7.5 deg/sec, (which was the fastest speed in these experiments). Future experiments should test the limit of smooth pursuit. The results of that experiment could be used to further develop the spatiovelocity CSF model.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Sharp Labs of America, sponsor of this project.

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