VISIBILITY OF DCT QUANTIZATION NOISE FOR HIGH DYNAMIC RANGE IMAGES

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ABSTRACT

VISIBILITY OF DCT QUANTIZATION NOISE FOR HIGH DYNAMIC RANGE IMAGES

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Discrete cosine transform (DCT) is one of the fundamental stages, which is widely used and studied in lossy image compression. This technique aims to generate a minimum visible distortion in an image with respect to human visual system (HVS). The studies until now propose DCT quantization matrices for low dynamic range (LDR) images to display on LDR monitors. In this thesis research, the visibility of DCT quantization noise is studied for high dynamic range (HDR) images. High luminance patterns for DCT quantization noise are formed with mean luminance levels of 100 $cd/m2$, 500 $cd/m2$, 1000 $cd/m2$ and 1500 $cd/m2$, for various DCT frequencies and amplitude levels. A novel rendering algorithm is proposed to generate the high luminance patterns for DCT quantization noise by using an HDR monitor (SIM2 HDR47). The visibility of DCT quantization noise is measured with psycho-visual experiments based on geometric search and QUEST methodologies. The estimated quantization levels with geometric search is utilized to form the initial statistics for the QUEST search. The quantization levels for each frequency are then obtained by fitting the QUEST results to a Weibull function. The experimental results first indicate that HVS is more sensitive to high DCT frequencies and high mean luminance levels. Second, although increased luminance levels cause increased quantization levels, they cause a decrease in contrast threshold values. Finally, both the geometric search and QUEST methodologies are observed to produce coherent results in the experiments.

Keywords: discrete cosine transform, quantization, contrast threshold, low dynamic range images, high dynamic range images, high dynamic range monitors, high luminance

ÖZ

YÜKSEK DİNAMİK ORANLI GÖRÜNTÜLER İÇİN AYRIK KOSİNÜS DÖNÜŞÜMÜ NİCEMLEME GÜRÜLTÜSÜNÜN GÖRÜNÜRLÜĞÜ

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Ayrık kosinüs dönüşümü (AKD), yaygın olarak kullanılan ve üzerinde çalışılan kayıplı görüntü sıkıştırmada temel aşamalardan biridir. Bu teknik, insan görme sistemine (İGS) göre görüntülerde minimum görünür bozulma oluşturmayı hedeflemektedir. Şu ana kadarki çalışmalar, alçak dinamik oranlı (ADO) monitörlerde gösterilmek üzere, ADO görüntüleri sıkıştırmak için gerekli AKD nicemleme matrislerini önermişlerdir. Bu tez çalışmasında, yüksek dinamik oranlı (YDO) görüntüler için AKD niceleme gürültüsünün görünürlüğü incelenmiştir. Yüksek parlaklıklı AKD gürültüsü içeren örüntüler ortalama parlaklık seviyeleri 100 $cd/m2$, 500 $cd/m2$, 1000 $cd/m2$ ve 1500 $cd/m2$ için ve farklı frekans ve genlik seviyelerinde oluşturulmuştur. Bu görüntülerin, YDO monitörde (SIM2 HDR47) oluşturulması için yenilikçi bir algoritma geliştirilmiştir. AKD nicemleme gürültülerinin görünülürlüğü geometrik arama ve QUEST metodolojisine dayanan psiko-görsel deneyler ile ölçülmüştür. QUEST araması için başlangıç istatistiklerini oluşturmak üzere geometrik arama ile tahmin edilen nicemleme seviyeleri kullanılmıştır. Deneysel sonuçlar ilk olarak İGS'nin yüksek frekans ve yüksek ortalama parlaklık değerlerine daha hassas olduğunu göstermiştir. İkinci olarak, artan parlaklık seviyeleri nicemleme seviyelerinin artmasına neden olsa da, kontrast eşik değerlerinin azalmasına neden olmaktadır. Son olarak, deneylerde geometrik arama ve QUEST yöntemlerinin uyumlu sonuçlar verdiği gözlemlenmiştir.

Anahtar Kelimeler: ayrık kösünüs dönüşümü, nicemleme, kontrast eşik değeri, düşük dinamik aralıklı görüntü, yüksek dinamik aralıklı görüntü, yüksek dinamik aralıklı monitör, yüksek parlaklık

To my family

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LIST OF ABBREVIATIONS

CFS	Contrast Sensitivity Function
DCT	Discrete Cosine Transform
HDR	High Dynamic Range
JND	Just Noticeable Difference
LCD	Liquid Crystal Display
LED	Light Emitting Diode
PSF	Point Spread Function
PNG	Portable Network Graphics
TMO	Tone Mapping Operator

CHAPTER 1

INTRODUCTION

1.1 Motivation and Problem Definition

Discrete Cosine Transform is one of the lossy image compression techniques. Using DCT, an image can be expressed as a summation of cosine functions that are calculated at different frequency levels. The reason for the DCT compression method being lossy is because high frequency levels can be omitted [2]. Due to absence of signal information, an error occurs in the decompressed image [3]. The visibility of the error needs to be minimum. Many studies have proposed the optimum quantization parameters. These studies are based on human psycho-visual system. Psycho-visual experiments are performed to detect the visibility of DCT quantization errors[1]. These studies are performed with LDR images. In this thesis, different than the previous studies working on LDR images, the visibility of DCT quantization noise for high dynamic range (HDR) images is studied for the next generation HDR displays, which can generate peak luminance levels up to 4000 cd/m^2.

HDR images are images which contain greater dynamic range of luminosity than traditional LDR images. This means a larger, more perceptible contrast between the brightest and darkest parts of an image. HDR images bring HDR monitor necessity with itself. Even though HDR images can be programmatically constructed, traditional displays, with their limited contrast ratio, are not able to display all the luminance levels. In this thesis, a SIM2 HDR47 HDR monitor is used to display HDR images. This monitor is constructed as a combination of two parallel screens, which are composed of LEDs and LCDs, respectively. In order to display quantization noise with this monitor, a rendering algorithm is developed for the HDR display, which accordingly determines the input values for the LEDs and LCDs to form the desired HDR image at the output. Experiment sets are generated by using this algorithm for different DCT frequencies at different mean luminance levels and amplitudes. The purpose of the psycho-visual experiments is to find the quantization level, where quantization noise is merely visible. Using the results of these experiments, just noticable quantization levels for each DCT frequency at different luminance levels can be determined.

1.2 Contributions

To sum up, the main contributions of this thesis are:

- formulating and forming the DCT quantization noise for high luminance images,
- a novel rendering algorithm to generate the DCT quantization noise for high luminance patterns on a HDR display,
- a psycho-visual experimental setup and methodology to measure the visibility of DCT quantization noise for high luminance patterns,
- revealing the just noticeable quantization levels for different DCT frequencies and mean luminance levels ranging from 100 $100cd/m^2$ to 1500 $1500cd/m^2$.

1.3 Outline of the Thesis

The outline of this thesis is as follows. In chapter 2, related studies for measuring DCT quantization levels for LDR images are presented, along with the proposed experiments based on human psycho-visual system. This section also explains the studies regarding HDR monitors, along with related psycho-visual studies for HDR images. Chapter 3 presents the proposed method for the construction and rendering of high luminance DCT patterns in detail. In chapter 4, psycho-visual experiments performed for measuring DCT quantization levels are explained. Chapter 5 reveals the results of these experiments. In chapter 6, Weibull function fitting to QUEST results is demonstrated, and finding just noticeable quantization levels is explained. Chapter 7 discusses the results according to various aspects. Finally, chapter 8 concludes the thesis.

CHAPTER 2

RELATED WORK

2.1 HDR Imaging

HDR images are formulated as a combination of photographs taken at different exposures. The same image can accommodate very bright and very dark pixels which gives high contrast ratio to the image. [4, 5, 6]

HDRI technology allows to imitate real-world luminance in captured images with a much extended dynamic range [7]. Greater range of colors and brightness levels in pixels makes HDR images more realistic. Compared to standard dynamic range images, HDR images are more appealing to human eye. For that reason future digital visual content will be highly affected by HDR imaging [8].

HDR image usage is expanding rapidly due to its high quality expression. Application areas like digital cinema, digital photography and next generation broadcast are using HDR image technology [9].

Since HDR images contain wider range of luminance levels, lighting researchers have been investigated this area quite a lot. Luminance levels perceived by human vision system can be captured with HDR imaging. Therefore, to obtain luminance data HDR imaging technique can be used. [10, 11, 12]. In addition to these areas, in computer graphics and 3D industries HDR imaging is being used. Since realism is important and realistic rendering takes too much time, HDR imaging technology took place in these fields [13].

2.2 Psycho-visual Studies for Low Dynamic Range Patterns

DCT is a standard image compression method. Briefly it works as follows[1, 14, 15]:

- Image is divided into 8x8 blocks.
- Each block is transformed into their 64 DCT basis functions, which is given in equation 21 for a NxN blocked size image.

$$F(i,j) = \frac{2}{N}C(i)C(j)\sum_{m=0}^{N-1}\sum_{n=0}^{N-1} f(j,k)cos(\frac{\pi m}{2N}[2j+1])cos(\frac{\pi n}{2N}[2k+1]) \quad (21)$$

  for $m = 0, ..., N-1$ and $n = 0, ..., N-1$

- Quantization is applied as dividing DCT matrix by quantization matrix.
- Results are rounded to the nearest integer.

Since human eye is less sensible for high frequencies, high frequency DCT coefficient are mostly zero. The higher the zero coefficients, the better the compressed images. However this means loss of data. When the images compressed using the DCT image compression method are reconstructed, an image distortion occurs because of data loss[16]. Difference between the original image and the reconstructed image is named as quantization error. In order to find out the quantization parameters that will ensure the minimum level of this quantization error, many studies have applied human vision system experiments [17, 18, 19]. The visibility of DCT quantization error can be measured with psycho-visual experiments [1]. For different DCT frequencies, luminance levels, viewing angles and distances, visibility threshold models are developed [16, 20, 21, 22] . Since display technologies allow up to certain luminance levels, these studies can not be investigated for high luminance patters. The compression methods for HDR images mostly include tone mapping[23, 24, 25, 26]. Tone mapping operators creates LDR images from HDR images while trying to maintain the image quality [27]. In order to measure visibility threshold for DCT quantization noises at high luminance images, display systems with high luminace values are required. In this thesis DCT quantization levels for compressing high luminance images are measured by experiments conducted using an HDR display.

CHAPTER 3

CONSTRUCTION AND RENDERING OF HIGH LUMINANCE DCT PATTERNS

In this chapter, the construction of high luminance discrete cosine transform (DCT) patterns are explained along with the rendering algorithms to display these patterns on an HDR display. The first section first gives the formulation for the construction of global cosine patterns, which is followed up with the construction of local DCT quantization noise. Then, Subsection 3.2 presents the proposed rendering algorithm for the visualization of DCT patterns.

3.1 Construction of Global and Local DCT Patterns

3.1.1 Forming Global Cosine Patterns

Global cosine patterns are formed at various frequency, average luminance and amplitude levels. The global cosine pattern at a certain frequency (f), average luminance (I_{DC}) and amplitude (A) is formulated as follows:

$$S_f(x, y) = I_{DC} + Acos(2\pi fx) \tag{31}$$

Figure 3.1 illustrates some global DCT quantization noise patterns. Figure 3.1 (a) formed with DC luminance level 100cd/m^2 and frequency level (0,3) with amplitude 100. Figure 3.1 (b) has the same DC luminance level and frequency with Figure 3.1 (a) but different amplitude level 300. Patterns shown in Figures 3.1 (c) and (d) are the same patterns with Figure 3.1 (a) and (b) in terms of frequency and amplitude but with different DC luminace level 1000cd/m^2. As another example, Figures 3.1 (e) and (f) show the global cosine patterns which have the same DC luminance level and amplitude with the patterns shown in Figures 3.1 (a) and (b) but with a different frequency (0,7).

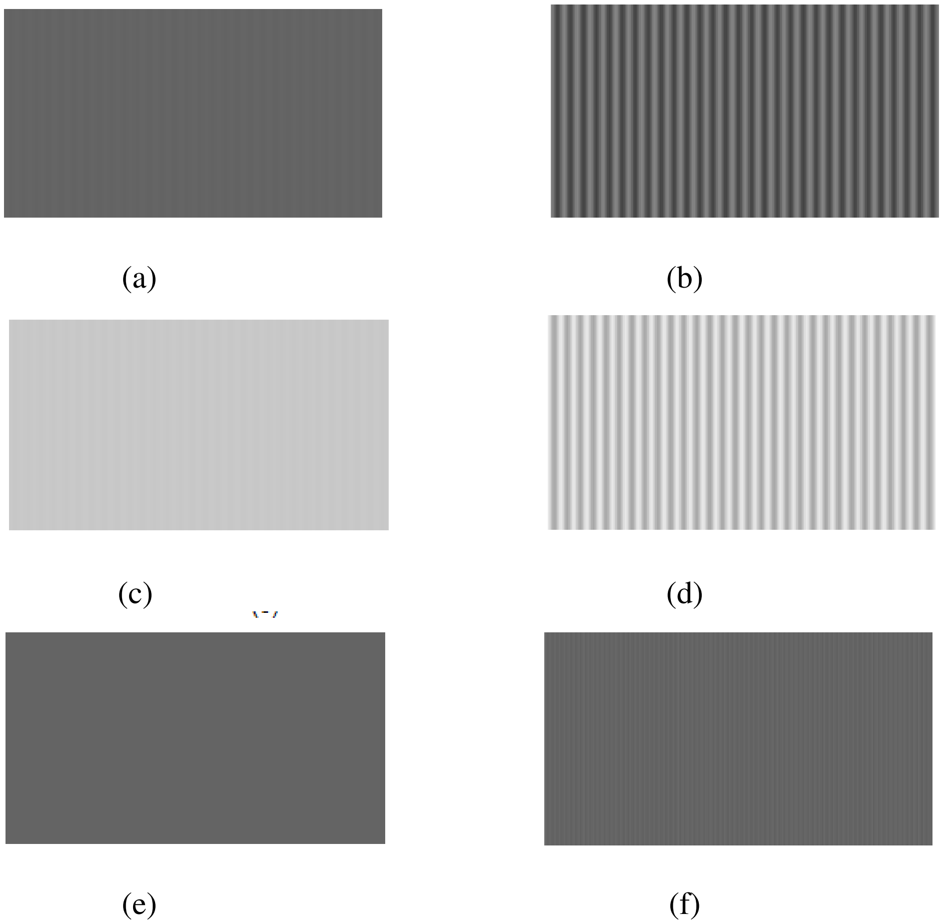


Figure 3.1: Examples for global DCT quantization noise

3.1.2 Forming Local Cosine Patterns

These patterns are formed according to the discrete cosine transform (DCT) image compression method [28].

The monitor used for the experiments has a 1920x1080 resolution. The whole image is divided into into 8x8 blocks, which results in 135x240 blocks. For a certain frequency, luminance, and amplitude level, a quantization error parameter Q_{error} is introduced [2]. This value is selected randomly between -Q and Q where Q is the selected amplitude level. Given the quantization error Q_{error}, the DCT quantization noise pattern for each block of image is generated by the following formula,

$$\mathbf{Q}_{error j,k} I_{j,k}. \tag{32}$$

In this formulation j and k values correspond to image coordinates. $I_{j,k}$ is the DCT basis function and formulated as follows:

$$I_{j,k} = c_{jm} c_{kn}, \tag{33}$$

where m and n values are correspond to frequency levels. Formulations of c_{jm} and c_{kn} are as follows:

$$c_{jm} = cos(\frac{\pi m}{2N}[2j+1]), \tag{34}$$

and

$$c_{kn} = cos(\frac{\pi n}{2M}[2k+1]). \tag{35}$$

Calculated quantization errors are added to the middle of the background image:

$$DCluminance + Q_{error} I_{j,k} \tag{36}$$

Background is plain gray level image at a selected luminance level. Not all 64 basis functions for 8x8 DCT are used to generate noise patterns. Figure 3.2 illustrates the 30 basis functions that are used at noise pattern generation.

X	X	X	X		X		X
X	X	X	X		X		X
X	X	X					
X	X		X		X		X
X	X		X		X		X
X	X		X		X		X

Figure 3.2: 8x8 DCT basis functions utilized for image generation.[1] .

For four different luminance levels (100, 500, 1000, 1500 cd/m^2) for each of the 30 frequency levels illustrated at Figure 3.2, images are formed with various amplitude levels. Figure 3.3 illustrates some of the examples of local DCT quantization noise patterns.

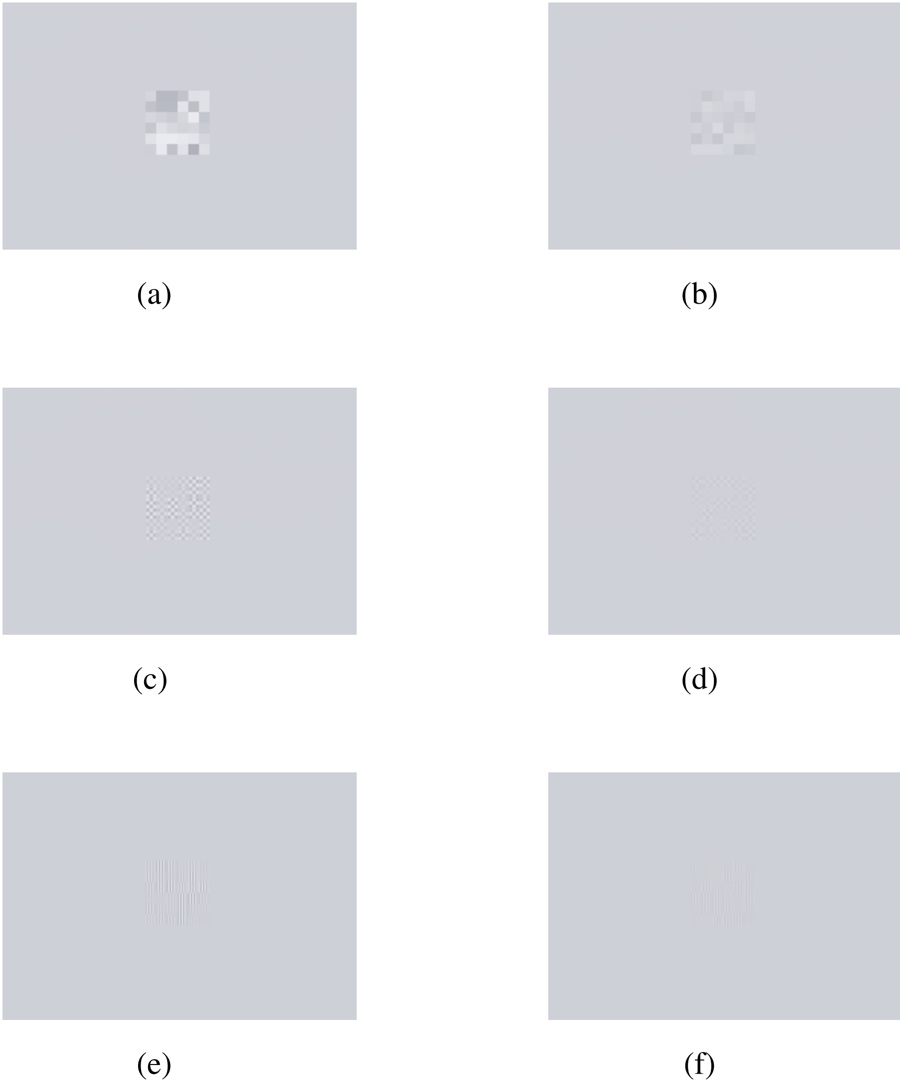


Figure 3.3: Some local DCT quantization noise examples that are constructed with luminance level $1000cd/m^2$. a) frequency(0,0) and amplitude 300, b) frequency(0,0) and amplitude 100, c) frequency(3,3) and amplitude 300, d) frequency(3,3) and amplitude 100, e) frequency(0,7) and amplitude 300, f) frequency(0,7) and amplitude 100.

Cosine patterns are constructed in Matlab environment. Resulting images are saved with HDR formatting. The monitor used for experiments (SIM2 HDR47 monitor) has its own algorithm to display images in HDR formats. However, for this purpose, images should be in PNG format. Therefore, images are transformed into special PNG format that SIM2 HDR47 monitor requires.

3.2 Proposed Rendering Method

The existing HDR image display systems are basically constructed with a combination of two layers. Layer that provides high resolution and low luminance placed in front of the layer that provides low resolution and high luminances. Using these layers one after the other provides both high luminance levels and contrast ratio. Contrast ratio is measured as multiplication of two systems. Back-mounted layer can give the desired luminance levels and front-mounted layer can give local contrasts. [29, 30].

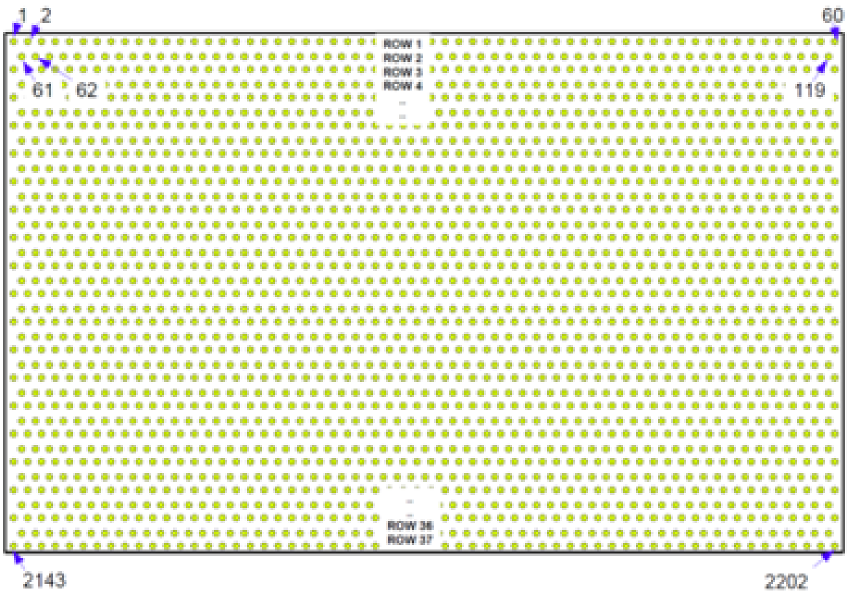


Figure 3.4: LED positions for SIM2 display

SIM2 monitors are produced with that principle. In the perceptual experiments SIM2 HDR47 monitor is used. In background, there are 2202 LEDs are placed diagonally. Each of these LEDs are adjusted independently. Figure 3.4 illustrates the LED positions on the SIM2 display. These LEDs provide high luminance levels. In the foreground there is an LCD layer with 1920x1080 full HD resolution.

SIM2 HDR47 monitor has two modes to display HDR images. One of these modes is the automatic rendering that display contains. The other mode is DVI+ mode, which takes LED and LCD values as inputs. In order to display the most accurate image with SIM2 HDR47 monitor, first the proposed algorithm in [31] is used.

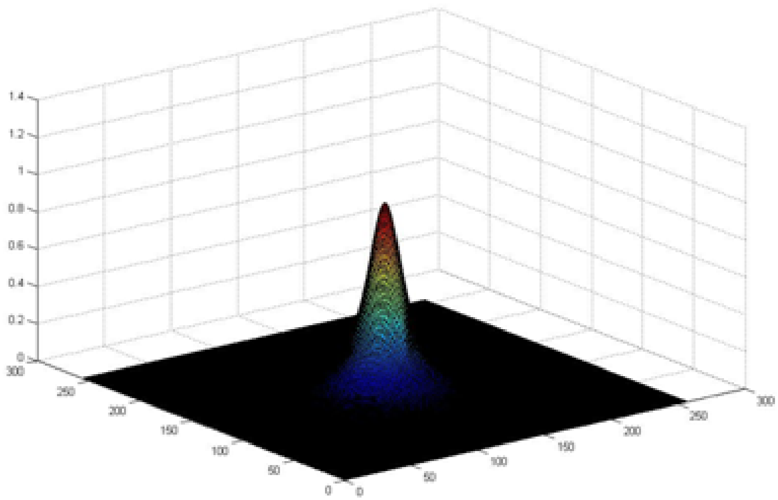


Figure 3.5: PSF for LEDs

Each LED in SIM2 HDR47 monitor has its own Point Spread Function (PSF) as shown in Figure 3.5. Each LED's radiance is a cumulative summation with its neighbour LEDs' radiance values. Algorithm described in [31] presents a solution for calculating the cumulative radiance of LEDs to give the desired luminance level and for finding the resulting LCD values. The main stages of this algorithm is as follows;

- Preprocessing
- Finding target backlight
- Iterative scaling
- Finding LCD values

As presented in Figure 3.6, this algorithm [31] gives an halo effect around the local noise patterns. The halo effect is a form of cognitive bias which causes one part to make the whole seem more attractive or desirable. For the perceptual experiments, making the noise more attractive is an unwanted situation. Since the question to the subject during the perceptual tests is whether a noise is noticed or not, there shouldn't be any eye catcher in the image.

Figure 3.6: Halo effect around the local noise pattern formed with frequency (3,3), DC luminance level 1000 cd/m^2, and amplitude 150.

For experimental purposes background luminance should be same in the whole image. For that purpose, the proposed algorithm in [31] is revised. Target backlight shouldn't be calculated but set to desired value. In order to find the desired backlight the following steps are done.

- While keeping the LCD values at 255, LED values are changed from 1 to 255.
- Luminance values of SIM2 HDR47 monitor are saved for each LED value.
- Search table is constructed with the obtained values.

Figure 3.7 illustrates the measured luminance values as a function of the LED values. LCD values are kept at 255 during the measurement. It is observed that the graph shows a linear increase until the LED values are approximately 100. It then proceeds in a linear manner. The reason for this graph is that led energies reach the maximum of the monitor after a point.

The step for finding LCD values is performed as defined in algorithm [31]. Halo effects are eliminated with the proposed approach. Sample images with the proposed algorithm are provided in Figure 3.8.

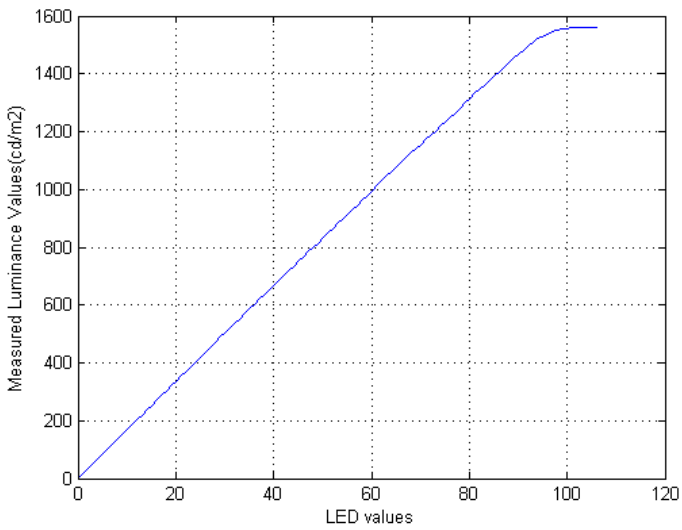


Figure 3.7: LED values vs. Luminance graph

Figure 3.8: Local noise pattern without halo effect formed with frequency (3,3), DC luminance level 1000 cd/m^2, and amplitude level 150.

CHAPTER 4

PROPOSED METHODOLOGY FOR PSYCHO-VISUAL EXPERIMENTS

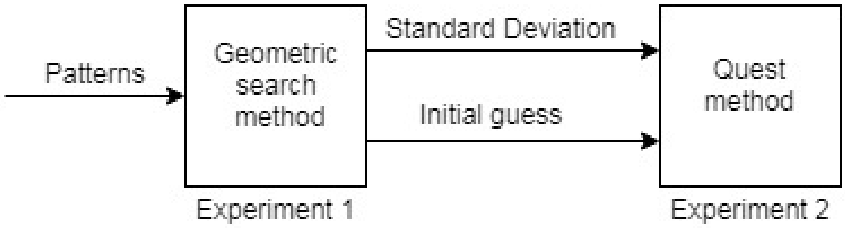


Figure 4.1: The overall experimental procedure

QUEST method, which is introduced by Watson and Pelli [32], a procedure that estimates the ideal threshold in a given number of sequential trials. QUEST method is generally used at psycho-visual experiments where subject is tested. According to the answers of the subject, probability density function for the estimated quantization level is recalculated [33]. In each trial of the experiment, the subject is asked a question. With each iteration, more information is obtained from the subject and thus more accurate estimations can be done. The experimental methodology, which is proposed by this thesis, also uses QUEST method.

QUEST method is provided in MATLAB environment by Psychtoolbox. However, in order to use this method, a prior threshold estimate and a standard deviation, which is assigned to that estimate, are required. With the purpose of estimating a threshold and a standard deviation, another experimental set up is implemented. In that experimental setup, geometric search is used. Figure 4.1 illustrates the whole experimental setup.

The images for the DCT quantization noise, as described in Chapter 3 (Construction And Rendering Of DCT Patterns), are used in the experiments. For four different luminance levels (100, 500, 1000, 1500 cd/m^2) for each of the 30 frequencies ((0,0), (0,1), (0,2), (0,3), (0,5), (0,7), (1,0), (1,1), (1,2), (1,3), (1,5), (1,7), (2,0), (2,1), (2,2), (3,0), (3,1), (3,2), (3,3), (3,5), (3,7), (5,0), (5,1), (5,2), (5,3), (5,5), (5,7), (7,0), (7,1), (7,2), (7,3), (7,5), (7,7)) the images for DCT quantization noise are formed. More specifically, the images are generated with an amplitude level from 1 to 70 for luminance level $100cd/m^2$. Accordingly, the images are generated up to an amplitude level 380 for $500cd/m^2$, whereas up to 500 for $1000cd/m^2$, and up to 700 for $1500cd/m^2$.

4.1 Geometric Search

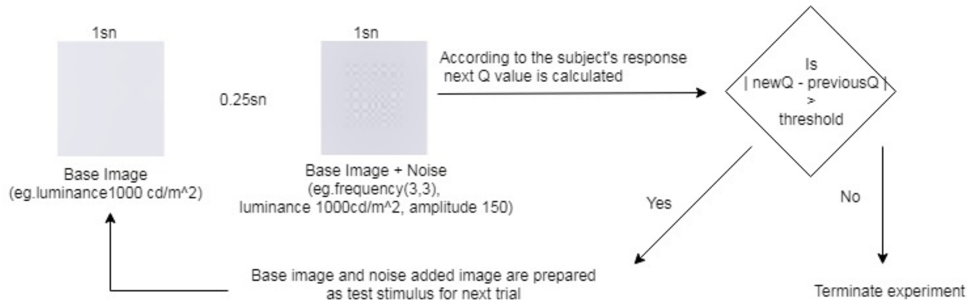


Figure 4.2: Psycho-visual experimental procedure with the geometric search

The aim of the experimental procedure with the geometric search is to determine an initial guess and a standard deviation for that guess for each DCT frequency pattern, which would be given as inputs to the QUEST procedure. Two alternative forced choice procedure [34] is used in this experiment. Two consecutive images are displayed, where one contains the test stimulus and the other one contains gray level base image. These images are displayed in a random order. Displaying two images and receiving the answer forms one trial. The amplitude of the DCT pattern to be displayed after each iteration is calculated by geometric search.

This experiment is completed for luminance levels 100,500,1000 and 1500 cd/m^2 and for each DCT frequency level, with three subjects.

The main stages of the geometric search are described as follows:

- Experiment starts with the highest amplitude of the given DCT pattern.

- Test stimulus which contains the noise and the base image which only contains gray level image are displayed consecutively in a random order for 1 second. Between two images there is a 0.25 second duration time.
- Subject is asked if any difference is observed between two images.
- Subject presses 'y' from the keyboard if any difference is observed. Otherwise subject presses 'n'.
- Next trial does not begin until a response is given.
- If the answer is yes then quantization value is decreased, if the answer is no then quantization value is increased.
- The amount of change in the quantization value is calculated as the half of the difference between subject's latest two trial's quantization values.
- When this difference is lower than a certain threshold, experiment is terminated.

The final Q value is considered as that subject's just noticeable quantization level for that experiment set.

Results of two subjects are used to calculate initial quantization value and standard deviation which is provided as inputs for Quest experiment sets. Initial guess is calculated as average of two subject's just noticeable quantization level for the given DCT pattern set. Standard deviation is calculated with respect to subjects's just noticeable quantization levels and their average.

4.2 Quest

In this experiment set the experimental procedure explained in the study [1] is extended for high luminance patterns. One trial consists of two temporal intervals and a feedback. Experiment terminates after forty trials. The main stages of the QUEST experiment set are described as follows:

- Experiment starts with the QuestCreate function call that Psychtoolbox provides. This function takes six arguments which are initial guess (tGuess), standard deviation (tGuessSd), threshold criterion(pThreshold), beta delta and gamma. tGuess and tGuessSd values are the findings obtained from experiments in which geometric search method is used. Since QuestCreate uses 'Weibull' cumulative distribution function, pThreshold, beta, delta and gamma values are used as defined in psychtoolbox. Return value of that call is a struct in which parameters required to calculate final threshold are stored.

- Amplitude scaling factor is calculated. This factor is required because noised image and base image are displayed without any duration in between. In order to provide a smooth transition between niosed image and base image, noised image don't be displayed directly. Instead, it is displayed in 31 frames. Amplitude scaling factor is increased from $e^{-\pi}$ to 1 in the first 15 frames. At 16^{th} frame the desired quantization level is displayed. And from 16^{th} to 31^{st} frames the amplitude scaling factor is reduced back to $e^{-\pi}$.

- Experimental loop starts with the QuestQuantile function call that Psychtoolbox provides. Before each trial QuestQuantile is called and the intensity which is most appropriate for the trial is obtained.

- With the intensity value, that trial's amplitute value is calculated.

- For the duration of 31 frames then base image and for the duration of 31 frames noised image are displayed. Between two intervals a beep sound is given so as to let the subject know interval has changed.

- Subject is asked in which period of time he sees a noise.

- Response is saved as correct or wrong and a feedback is given to the subject in the format of beep sound if he answers wrong.

- With the answer of that trial QuestUpdate function is called. Historical data of subject's results and intensity values are updated with this call.

After fourty trials experiment is terminated. A modified Weibull distribution function is fed with QUEST results. The JND amplitute level of the given DCT pattern is obtained as a result of Weibull function.

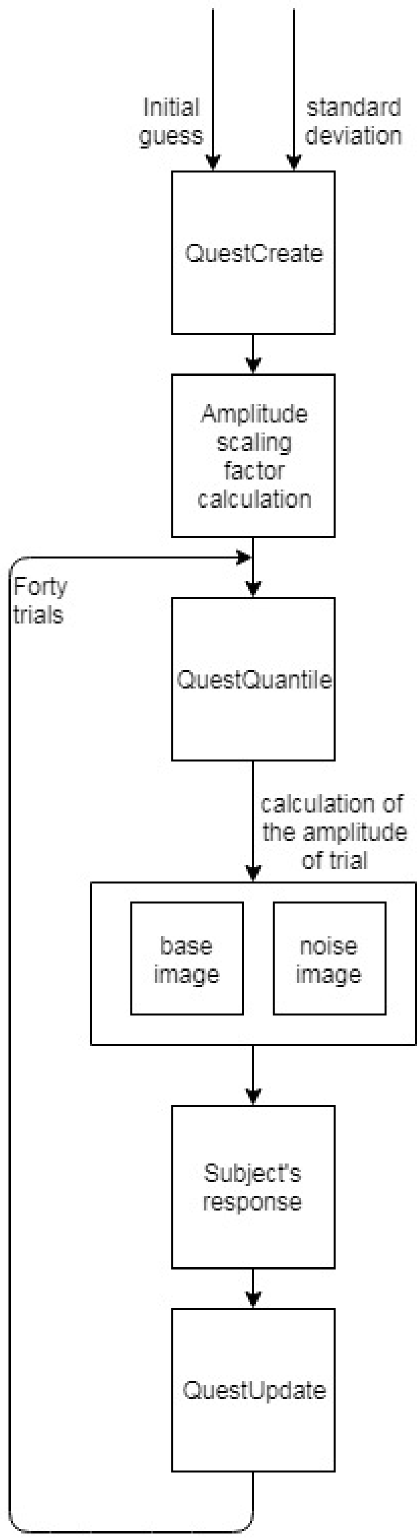


Figure 4.3: Experimental setup with QUEST

CHAPTER 5

EXPERIMENTAL RESULTS FOR THE PSYCHO-VISUAL TESTS

This chapter presents the experimental results for the developed psycho-visual tests. The experiments are performed for luminance levels 100 cd/m^2, 500 cd/m^2, 1000 cd/m^2 and 1500 cd/m^2 for the selected 30 frequencies shown in Figure 3.2. Three subjects participate in the experiments. Experiments are performed in a closed dark room which does not have any windows. Subjects are placed approximately 185 cm away from the HDR screen, which provides a viewing angle of 30 degree corresponding to 64 pixels/degree for a HD size monitor.

While the first part of this chapter gives the results for the geometric search, the second part presents the results for the QUEST methodology.

5.1 Experimental Results for Geometric Search

Figure 5.1 illustrates the experimental results performed at luminance level 100 cd/m^2 and for frequency level (7,7) for all three subjects. When generating DCT patterns for luminance level 100 cd/m^2, the maximum quantization level is selected as 70. For geometric search experiments, the quantization values converges to a level as the iteration continues. The just noticeable quantization level is reached after 7 iterations.

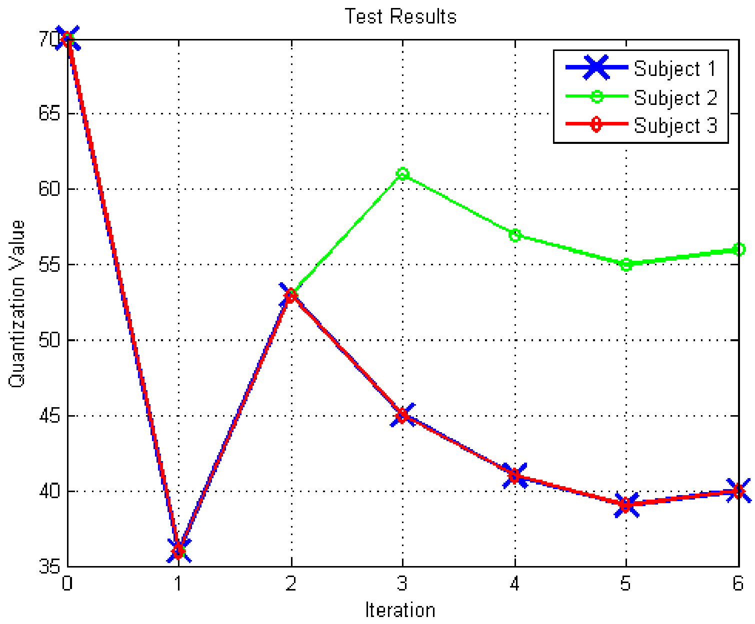


Figure 5.1: Quantization Value vs. Iteration for Luminance 100 cd/m^2 and frequency (7,7)

Tables 5.1, 5.2 and 5.3 show the ultimate quantization levels for the experiments performed at luminance level 100 cd/m^2 for all selected 30 frequencies for Subject 1, Subject 2 and Subject 3 respectively. Other frequencies are marked with 'X' sign. The quantization levels show a coherent behaviour for all the 3 subjects, while increasing for high frequencies.

4	4	4	4	X	4	X	8
4	4	4	4	X	6	X	14
4	4	4	X	X	X	X	X
4	4	X	4	X	12	X	20
X	X	X	X	X	X	X	X
4	6	X	8	X	16	X	24
X	X	X	X	X	X	X	X
6	12	X	16	X	28	X	40

Table 5.1: Quantization Levels for Luminance 100 cd/m^2 for Subject 1

4	4	4	4	X	4	X	6
4	4	4	4	X	4	X	12
4	4	4	X	X	X	X	X
4	4	X	4	X	6	X	20
X	X	X	X	X	X	X	X
4	6	X	10	X	18	X	30
X	X	X	X	X	X	X	X
10	18	X	18	X	46	X	56

Table 5.2: Quantization Levels for Luminance 100 cd/m^2 for Subject 2

4	4	4	4	X	4	X	10
4	4	4	4	X	6	X	18
4	4	4	X	X	X	X	X
4	4	X	4	X	10	X	18
X	X	X	X	X	X	X	X
4	8	X	6	X	10	X	34
X	X	X	X	X	X	X	X
10	18	X	28	X	34	X	40

Table 5.3: Quantization Levels for Luminance 100 cd/m^2 for Subject 3

Figure 5.2 illustrates the experimental results performed at luminance level 500 cd/m^2 and for frequency level (7,7) for all three subjects. When generating DCT patterns for luminance level 500 cd/m^2, the maximum quantization level is selected as 380. For geometric search experiments after 9 iterations just noticeable quantization level is reached.

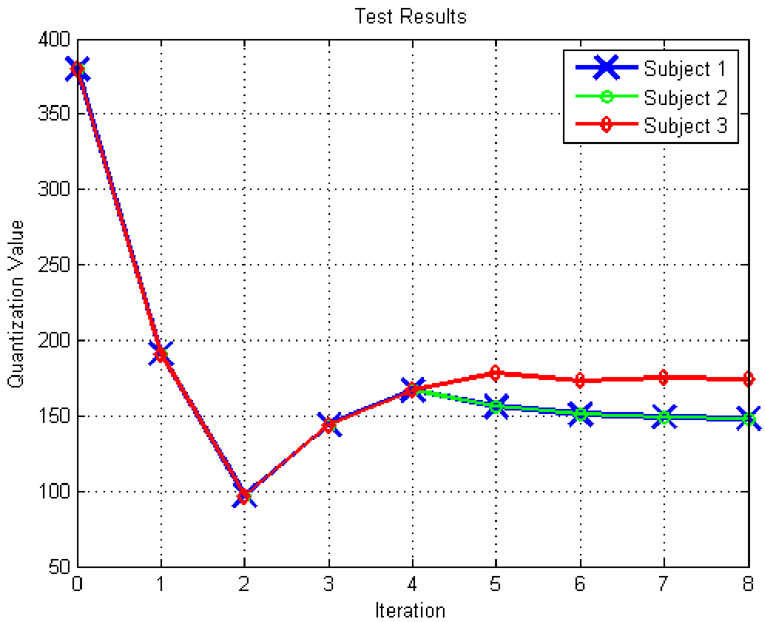


Figure 5.2: Quantization Value vs. Iteration for Luminance 500 cd/m^2 and frequency (7,7)

Tables 5.4, 5.5 and 5.6 show the quantization levels at luminance level $500cd/m^2$ for all selected 30 frequencies for Subject1, Subject2 and Subject3 respectively.

8	8	8	8	X	12	X	20
8	10	12	14	X	20	X	36
8	10	12	X	X	X	X	X
8	12	X	14	X	34	X	54
X	X	X	X	X	X	X	X
12	20	X	40	X	58	X	112
X	X	X	X	X	X	X	X
24	24	X	60	X	118	X	148

Table 5.4: Quantization Levels for Luminance 500 cd/m^2 for Subject 1

8	8	8	8	X	8	X	22
8	8	12	8	X	20	X	24
8	10	8	X	X	X	X	X
8	10	X	14	X	40	X	46
X	X	X	X	X	X	X	X
12	24	X	36	X	56	X	124
X	X	X	X	X	X	X	X
32	54	X	80	X	124	X	148

Table 5.5: Quantization Levels for Luminance 500 cd/m^2 for Subject 2

8	8	8	8	X	8	X	24
8	8	8	10	X	24	X	46
8	10	8	X	X	X	X	X
8	8	X	14	X	24	X	46
X	X	X	X	X	X	X	X
10	14	X	24	X	76	X	86
X	X	X	X	X	X	X	X
24	46	X	44	X	78	X	174

Table 5.6: Quantization Levels for Luminance 500 cd/m^2 for Subject 3

Figure 5.3 illustrates the experimental results performed at luminance level 1000cd/m^2 and for frequency level (7,7) for all three subjects. When generating DCT patterns for luminance level 1000 cd/m^2, the maximum quantization level is selected as 500. For geometric search experiments after 9 iterations just noticeable quantization level is reached.

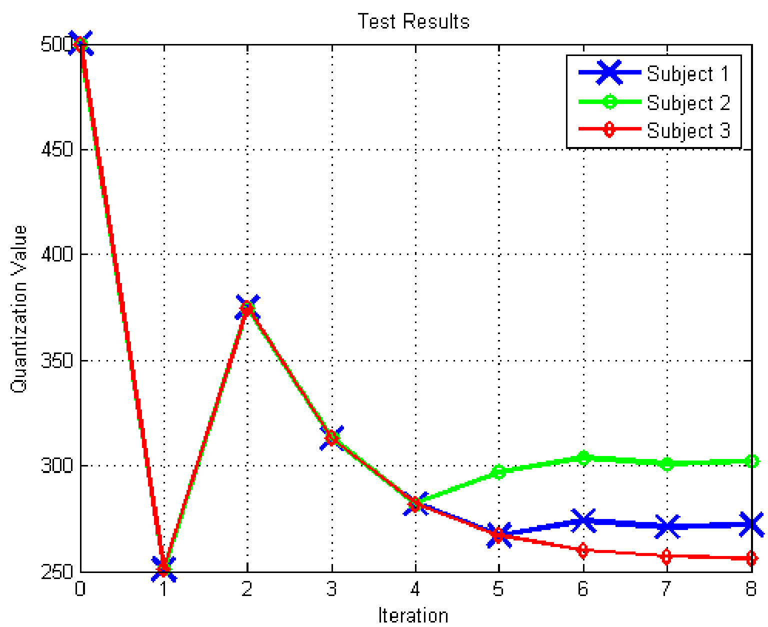


Figure 5.3: Quantization Value vs. Iteration for Luminance 1000 cd/m^2 and frequency (7,7)

Tables 5.7, 5.8 and 5.9 show the results for the experiments performed at luminance level 1000cd/m^2 for all selected 30 frequency levels for Subject1, Subject2 and Subject3 respectively.

8	10	10	14	X	14	X	24
8	14	22	30	X	30	X	70
8	16	24	X	X	X	X	X
10	16	X	30	X	46	X	92
X	X	X	X	X	X	X	X
14	28	X	40	X	132	X	176
X	X	X	X	X	X	X	X
30	60	X	100	X	140	X	272

Table 5.7: Quantization Levels for Luminance 1000 cd/m^2 for Subject 1

8	8	8	8	X	16	X	22
8	14	16	28	X	28	X	54
8	14	10	X	X	X	X	X
8	22	X	24	X	70	X	100
X	X	X	X	X	X	X	X
22	28	X	52	X	60	X	184
X	X	X	X	X	X	X	X
46	100	X	140	X	230	X	302

Table 5.8: Quantization Levels for Luminance 1000 cd/m^2 for Subject 2

10	8	8	8	X	14	X	30
8	10	8	10	X	16	X	60
8	10	10	X	X	X	X	X
8	10	X	16	X	16	X	60
X	X	X	X	X	X	X	X
16	16	X	16	X	30	X	122
X	X	X	X	X	X	X	X
30	58	X	86	X	122	X	256

Table 5.9: Quantization Levels for Luminance 1000 cd/m^2 for Subject 3

Figure 5.4 illustrates the experimental results performed at luminance level 1500cd/m^2 and for frequency level (7,7) for all three subjects. When generating DCT patterns for luminance level 1500 cd/m^2, the maximum quantization level is selected as 700. For geometric search experiments after 10 iterations just noticeable quantization level is reached.

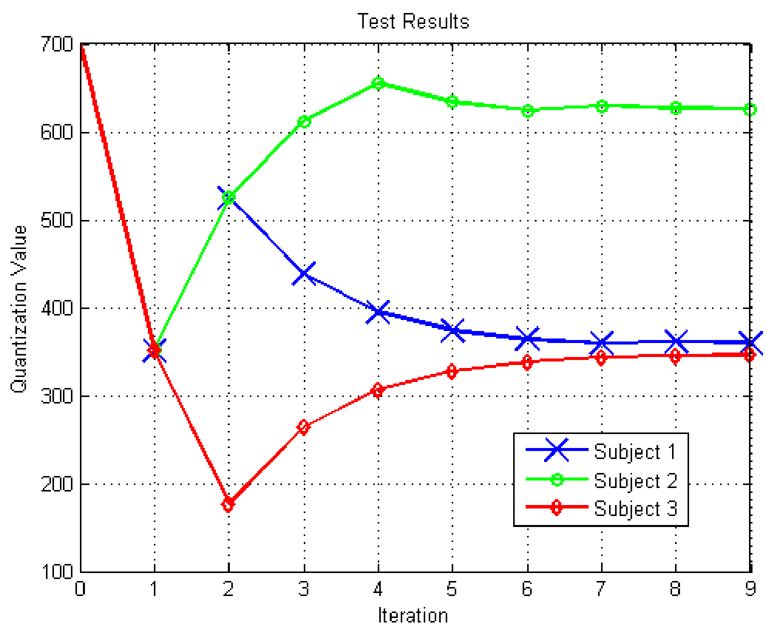


Figure 5.4: Quantization Value vs. Iteration for Luminance 1500 cd/m^2 and frequency (7,7)

Tables 5.10, 5.11 and 5.12 show the results for the experiments performed at luminance level $1500 cd/m^2$ for all selected 30 frequency levels for Subject 1, Subject 2 and Subject 3 respectively.

14	18	14	18	X	32	X	54
18	22	22	24	X	56	X	82
10	30	30	X	X	X	X	X
14	24	X	54	X	84	X	128
X	X	X	X	X	X	X	X
10	38	X	74	X	110	X	168
X	X	X	X	X	X	X	X
28	50	X	118	X	230	X	360

Table 5.10: Quantization Levels for Luminance 1500 cd/m^2 for Subject 1

18	14	14	22	X	38	X	44
12	28	24	38	X	42	X	76
14	28	24	X	X	X	X	X
14	30	X	60	X	64	X	138
X	X	X	X	X	X	X	X
30	54	X	62	X	202	X	184
X	X	X	X	X	X	X	X
70	118	X	196	X	278	X	626

Table 5.11: Quantization Levels for Luminance 1500 cd/m^2 for Subject 2

14	10	14	14	X	24	X	44
10	24	24	14	X	24	X	86
10	28	14	X	X	X	X	X
14	24	X	42	X	24	X	86
X	X	X	X	X	X	X	X
24	44	X	66	X	166	X	274
X	X	X	X	X	X	X	X
94	106	X	86	X	172	X	346

Table 5.12: Quantization Levels for Luminance 1500 cd/m^2 for Subject 3

The experiment set with QUEST methodology requires two input arguments, one is the initial estimate for the just noticeable quantization value as an amplitude of the generated pattern and the other is the standard deviation for this estimate. The outputs of the geometric search experiment is utilized to obtain these input values. Initial estimate for the amplitude level is calculated as the average of just noticeable quantization values of two subjects Subject1 and Subject2. Standard deviation is selected from a range. Minimum value of this range is the difference between the average of two subjects and the value of either one. The maximum value of this range is big enough to say that DCT pattern can be certainly seen from anyone.

As an example, the just noticeable quantization level for Subject1 at frequency (7,7) at luminance level 100cd/m^2 is 40 as seen from Table 5.1. For Subject 2, it is 56 as seen from Table 5.2. The initial estimate is calculated as average of the two subjects Subject 1 and Subject 2 and set as 48 as seen from table 5.13. Standard deviation is selected in a range beginning from the difference of average and the subjects' results which is 8. The maximum value is selected big enough to cover many possible answers.

Table 5.13 presents the estimates for the just noticeable quantization values for 100 cd/m^2 for selected 30 frequencies out of total 8x8 DCT frequency levels. Table 5.14 gives the standard deviation values.

4	4	4	4	X	4	X	7
4	4	4	4	X	5	X	13
4	4	4	X	X	X	X	X
4	4	X	4	X	9	X	20
X	X	X	X	X	X	X	X
4	6	X	9	X	17	X	27
X	X	X	X	X	X	X	X
8	15	X	17	X	37	X	48

Table 5.13: Mean Quantization Levels for Luminance 100 cd/m^2

3	3	3	3	X	3	X	4
3	3	3	3	X	3	X	7
3	3	3	X	X	X	X	X
3	3	X	3	X	5	X	12
X	X	X	X	X	X	X	X
3	4	X	5	X	10	X	15
X	X	X	X	X	X	X	X
5	9	X	10	X	20	X	25

Table 5.14: Standard Deviation Levels for Luminance 100 cd/m^2

Table 5.15 presents the estimates for the just noticeable quantization values calculated for 500 cd/m^2 for selected 30 frequency levels out of total 8x8 DCT frequency levels. Table 5.16 gives the standard deviation values.

8	8	8	8	X	10	X	21
8	9	12	11	X	20	X	30
8	10	10	X	X	X	X	X
8	11	X	14	X	37	X	41
X	X	X	X	X	X	X	X
12	22	X	38	X	57	X	118
X	X	X	X	X	X	X	X
28	39	X	70	X	121	X	148

Table 5.15: Mean Quantization Levels for Luminance 500 cd/m^2

4	4	4	4	X	6	X	12
4	6	7	6	X	12	X	20
4	6	6	X	X	X	X	X
4	6	X	9	X	25	X	30
X	X	X	X	X	X	X	X
7	12	X	25	X	40	X	70
X	X	X	X	X	X	X	X
18	29	X	50	X	71	X	85

Table 5.16: Standard Deviation Levels for Luminance 500 cd/m^2

Table 5.17 presents the estimates for the just noticeable quantization values calculated for 1000 cd/m^2 for selected 30 frequency levels out of total 8x8 DCT frequency levels. Table 5.18 gives the standard deviation values.

8	9	9	11	X	15	X	23
8	14	19	29	X	29	X	62
8	15	17	X	X	X	X	X
9	19	X	27	X	58	X	96
X	X	X	X	X	X	X	X
18	28	X	46	X	96	X	180
X	X	X	X	X	X	X	X
38	80	X	120	X	185	X	287

Table 5.17: Mean Quantization Levels for Luminance 1000 cd/m^2

5	6	6	8	X	10	X	10
5	7	8	10	X	10	X	20
5	7	7	X	X	X	X	X
6	9	X	10	X	15	X	20
X	X	X	X	X	X	X	X
6	9	X	12	X	36	X	40
X	X	X	X	X	X	X	X
8	20	X	25	X	45	X	50

Table 5.18: Standard Deviation Levels for Luminance 1000 cd/m^2

Table 5.19 presents the estimates for the just noticeable quantization values calculated for 1500 cd/m^2 for selected 30 frequency levels out of total 8x8 DCT frequency levels. Table 5.20 gives the standard deviation values.

16	16	14	20	X	35	X	49
15	25	23	31	X	49	X	79
12	29	27	X	X	X	X	X
14	27	X	57	X	74	X	133
X	X	X	X	X	X	X	X
20	46	X	68	X	156	X	176
X	X	X	X	X	X	X	X
49	84	X	157	X	254	X	493

Table 5.19: Mean Quantization Levels for Luminance 1500 cd/m^2

6	6	6	10	X	20	X	30
6	15	14	19	X	30	X	40
6	18	18	X	X	X	X	X
6	18	X	35	X	40	X	60
X	X	X	X	X	X	X	X
10	30	X	39	X	70	X	80
X	X	X	X	X	X	X	X
30	45	X	70	X	100	X	200

Table 5.20: Standard Deviation Levels for Luminance 1500 cd/m^2

5.2 Experimental Results for QUEST

Pshyctoolbox in MATLAB environment is used for base functions regarding QUEST. These experiments consist of 40 trials. Figures starting from 5.5 to 5.16 shows the results for all three subjects at frequency level (7,7) for the mean luminance values 100 cd/m^2, 500 cd/m^2, 1000 cd/m^2 and 1500 cd/m^2 .

For the given realization, the initial estimate for the amplitude level, for frequency (7,7) at luminance level 100 cd/m^2 is given as 48 and standard deviation is given as 25 respectively, as given in Table 5.13 and 5.14. Likewise for luminance level 500 cd/m^2, the initial estimate and standard deviation values are selected as 148 and 85 respectively, as given in Table 5.15 and 5.16. For luminance level 1000 cd/m^2, the initial estimate and standard deviation values are selected as 287 and 50, respectively, as given in Table 5.17 and 5.18. Finally for luminance level 1500 cd/m^2, the initial estimate and standard deviation values are selected as 493 and 200, respectively, as given in Table 5.19 and 5.20.

Human eye sensitivity decreases at high frequencies, so it is hard to notice a noise in the image when frequency is higher. As seen from the Figures from 5.5 to 5.16, the curves converge to higher amplitude levels for higher frequencies. As observed, while the variation of the estimates is comparatively high in the initial iterations, it smoothly converges to a point in the later iterations.

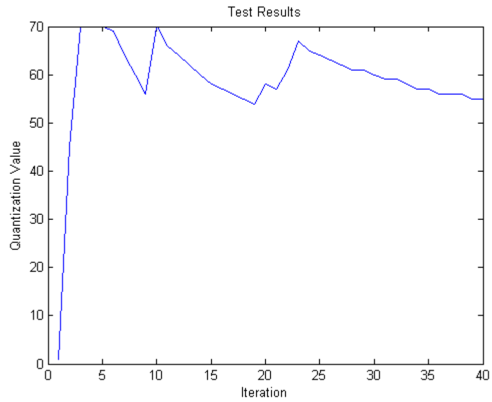


Figure 5.5: Quantization level vs. Iteration for Subject 1 at frequency level (7,7) and luminance level 100 cd/m^2

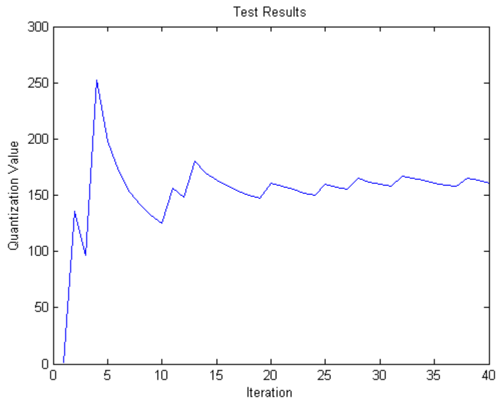


Figure 5.6: Quantization level vs. Iteration for Subject 1 at frequency level (7,7) and luminance level 500 cd/m^2

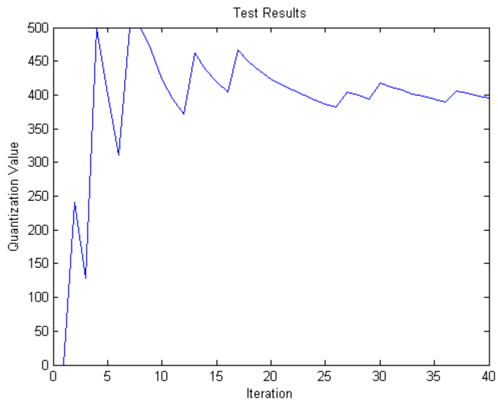


Figure 5.7: Quantization level vs. Iteration for Subject 1 at frequency level (7,7) and luminance level 1000 cd/m^2

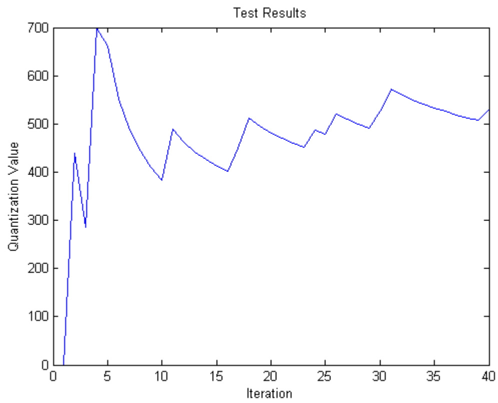


Figure 5.8: Quantization level vs. Iteration for Subject 1 at frequency level (7,7) and luminance level 1500 cd/m^2

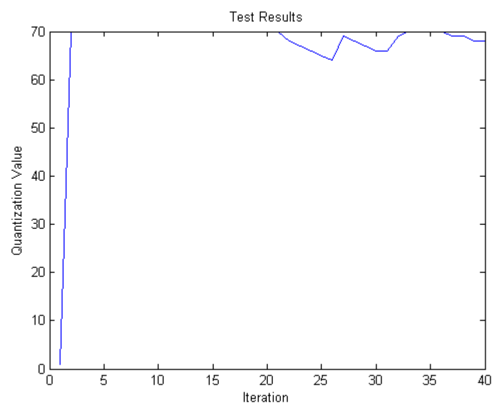


Figure 5.9: Quantization level vs. Iteration for Subject 2 at frequency level (7,7) and luminance level 100 cd/m^2

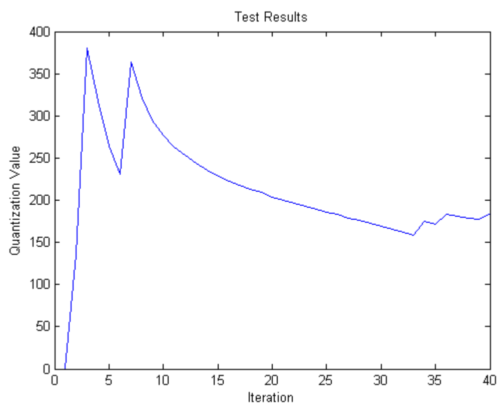


Figure 5.10: Quantization level vs. Iteration for Subject 2 at frequency level (7,7) and luminance level 500 cd/m^2

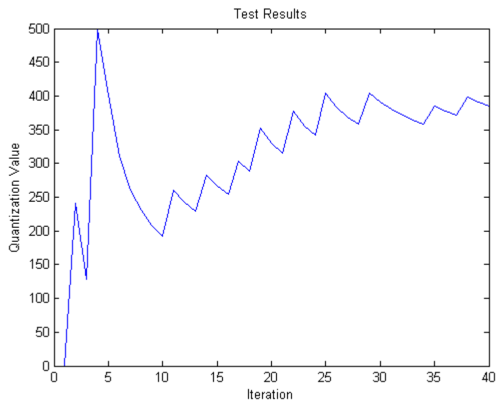


Figure 5.11: Quantization level vs. Iteration for Subject 1 at frequency level (7,7) and luminance level 1000 cd/m^2

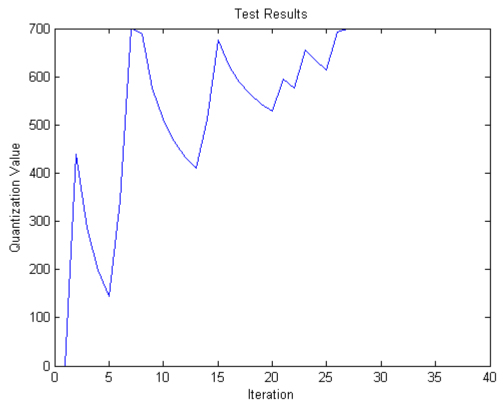
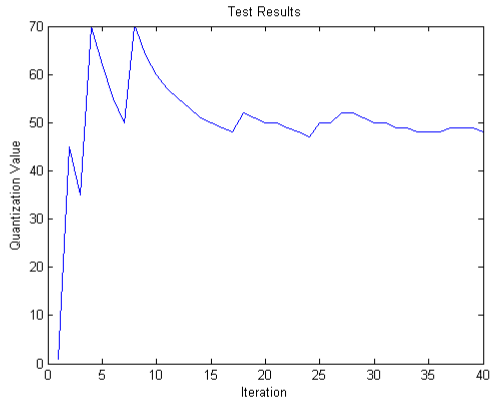


Figure 5.12: Quantization level vs. Iteration for Subject 2 at frequency level (7,7) and luminance level 1500 cd/m^2



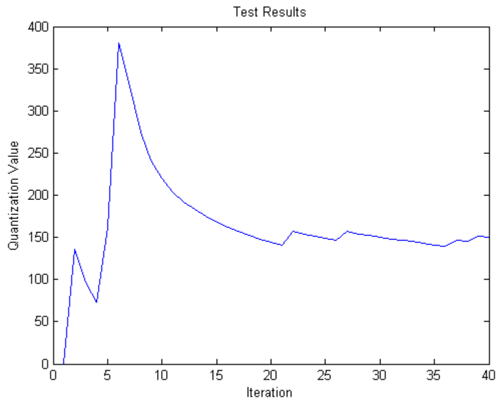
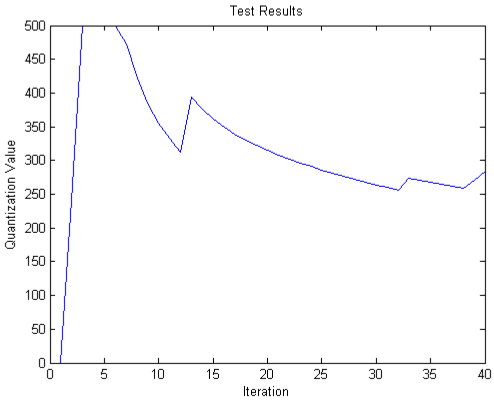


Figure 5.13: Quantization level vs. Iteration for Subject 3 at frequency level (7,7) and luminance level 100 cd/m^2

Figure 5.14: Quantization level vs. Iteration for Subject 3 at frequency level (7,7) and luminance level 500 cd/m^2



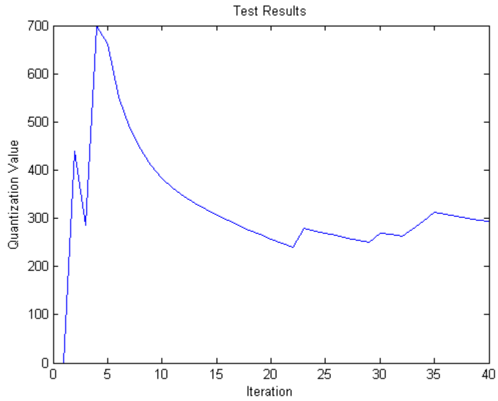


Figure 5.15: Quantization level vs. Iteration for Subject 3 at frequency level (7,7) and luminance level 1000 cd/m^2

Figure 5.16: Quantization level vs. Iteration for Subject 3 at frequency level (7,7) and luminance level 1500 cd/m^2

CHAPTER 6

CONTRAST THRESHOLD ESTIMATION

Contrast, in this study can be defined as the difference that makes a noise perceivable in luminance. Whereas, contrast sensitivity is the minimum level of noise that can be noticed from its background by the subject's eye [35, 36]. Having many subjects participated in the experiments, the visual capability of distinguishing quantization noise for frequency levels from (0,0) to (7,7) are measured for luminance levels 100 cd/m^2, 500 cd/m^2, 1000 cd/m^2 and 1500 cd/m^2.

6.1 Weibull Function Fitting

Weibull distribution function is fitted with a maximum likelihood to quantization value vs. iteration results for each psychometric experiment set at each luminance level [37, 38]. The total number of correct and wrong answers are calculated for each amplitude level shown for each experiment. The desired percentage for the correct answers is set to 82$\%$. The maximum and minimum values are provided as the maximum and minimum amplitudes displayed at each experiment.

Figures from 6.1 to 6.24 illustrate the quantization levels and iteration for QUEST and fitted Weibull functions for all three subjects at each luminance levels for the frequency level (7,7).

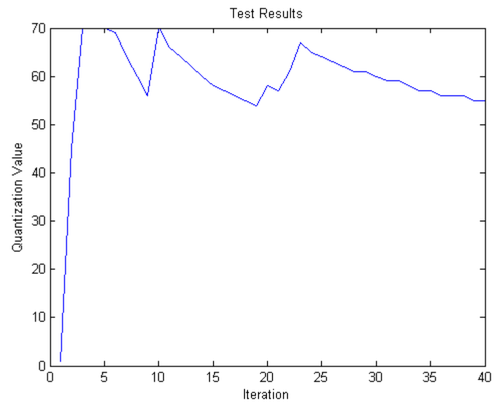


Figure 6.1: Quantization level vs. Iteration for Subject 1 at frequency level (7,7) and luminance level 100 cd/m^2

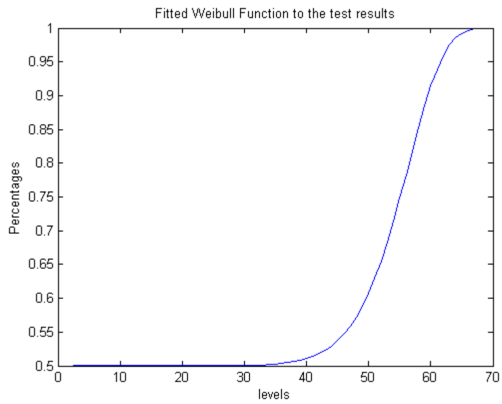


Figure 6.2: Fitted Weibull function for Subject 1 at frequency level (7,7) and luminance level 100 cd/m^2

Figure 6.1 illustrates the displayed quantization levels per iteration for QUEST experiment at frequency (7,7) and mean luminance level 100 cd/m^2 for Subject1. Figure 6.2 is the fitted Weibull function for this result set. X axis gives the quantization values and Y axis is the correctness percentage at those quantization levels. The quantization level, where the correct response rate is 82 percent, is chosen as the just noticeable quantization. Table 6.1 is the just noticeable quantization values for Subject 1 at mean luminance level 100 cd/m^2. As seen from Table 6.1 57.07 is the just noticeable quantization value for subject 1 for frequency (7,7) for luminance level 100 cd/m^2.

1.98	2.00	2.05	2.03	X	3.99	X	15.77
3.23	6.59	8.29	12.40	X	7.01	X	14.40
3.65	3.55	11.46	X	X	X	X	X
2.15	7.33	X	7.97	X	12.76	X	18.41
X	X	X	X	X	X	X	X
3.52	10.87	X	11.31	X	28.60	X	39.60
X	X	X	X	X	X	X	X
6.58	13.54	X	40.02	X	35.23	X	57.07

Table 6.1: Quantization Levels for Luminance 100 cd/m^2 for Subject 1

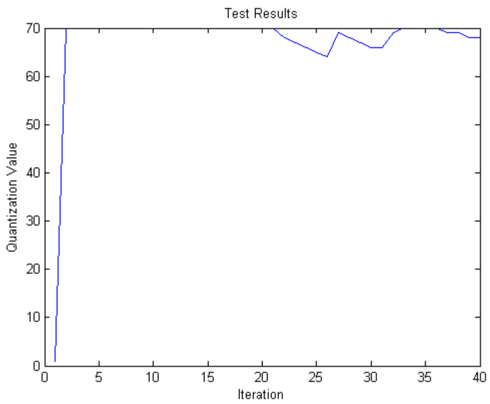


Figure 6.3: Quantization level vs. Iteration for Subject 2 at frequency level (7,7) and luminance level 100 cd/m^2

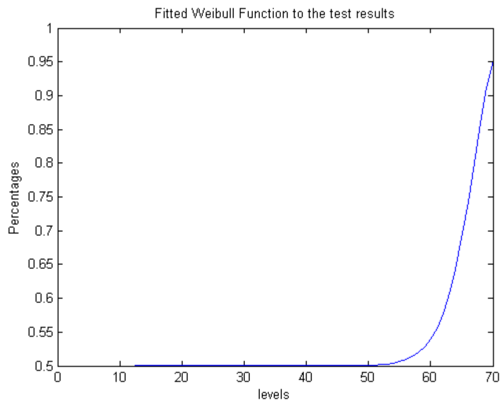


Figure 6.4: Fitted Weibull function for Subject 2 at frequency level (7,7) and luminance level 100 cd/m^2

1.08	1.13	2.51	1.95	X	4.00	X	16.77
1.21	1.98	2.01	3.84	X	9.13	X	23.40
2.55	2.04	2.00	X	X	X	X	X
3.84	2.00	X	6.60	X	12.04	X	22.21
X	X	X	X	X	X	X	X
3.85	12.30	X	13.55	X	31.12	X	53.29
X	X	X	X	X	X	X	X
12.87	22.19	X	39.59	X	48.55	X	67.33

Table 6.2: Quantization Levels for Luminance 100 cd/m^2 for Subject 2

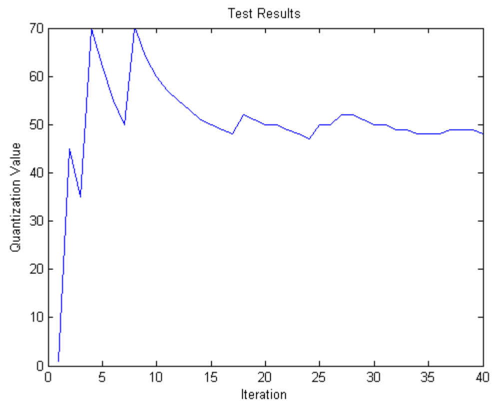


Figure 6.5: Quantization level vs. Iteration for Subject 3 at frequency level (7,7) and luminance level 100 cd/m^2

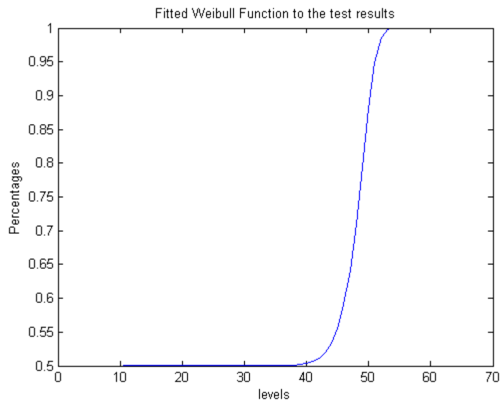


Figure 6.6: Fitted Weibull function for Subject 3 at frequency level (7,7) and luminance level 100 cd/m^2

1.96	1.11	1.71	1.96	X	3.00	X	8.01
1.70	2.85	3.08	4.13	X	40.61	X	7.86
1.76	2.98	4.43	X	X	X	X	X
1.97	3.01	X	3.48	X	7.02	X	16.13
X	X	X	X	X	X	X	X
3.86	6.09	X	8.89	X	29.02	X	28.14
X	X	X	X	X	X	X	X
10.96	9.98	X	22.27	X	40.78	X	49.29

Table 6.3: Quantization Levels for Luminance 100 cd/m^2 for Subject 3

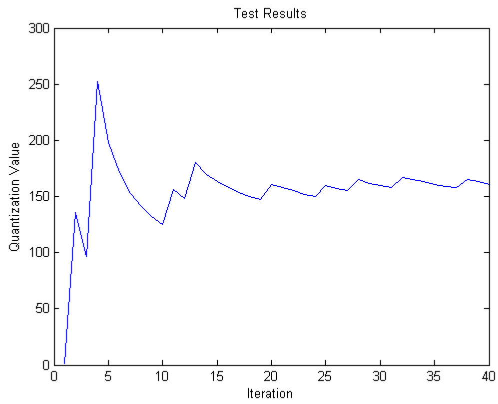


Figure 6.7: Quantization level vs. Iteration for Subject 1 at frequency level (7,7) and luminance level 500 cd/m^2

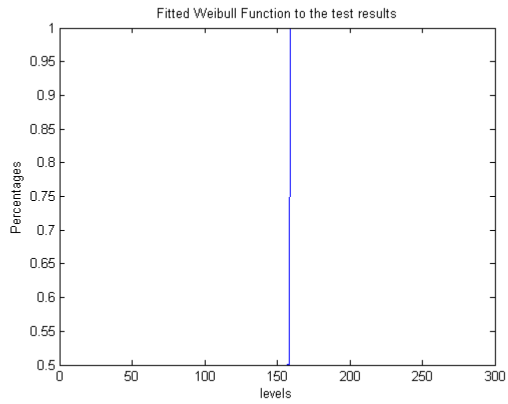


Figure 6.8: Fitted Weibull function for Subject 1 at frequency level (7,7) and luminance level 500 cd/m^2

31.13	6.76	8.46	9.28	X	19.98	X	42.31
7.73	23.75	12.92	30.39	X	30.08	X	57.45
11.95	24.23	23.73	X	X	X	X	X
16.11	16.78	X	32.21	X	55.57	X	93.21
X	X	X	X	X	X	X	X
26.88	41.82	X	56.07	X	65.30	X	126.65
X	X	X	X	X	X	X	X
37.37	63.84	X	109.11	X	141.61	X	158.80

Table 6.4: Quantization Levels for Luminance 500 cd/m^2 for Subject 1

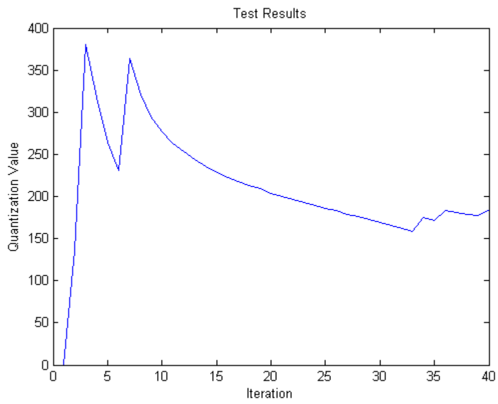


Figure 6.9: Quantization level vs. Iteration for Subject 2 at frequency level (7,7) and luminance level 500 cd/m^2

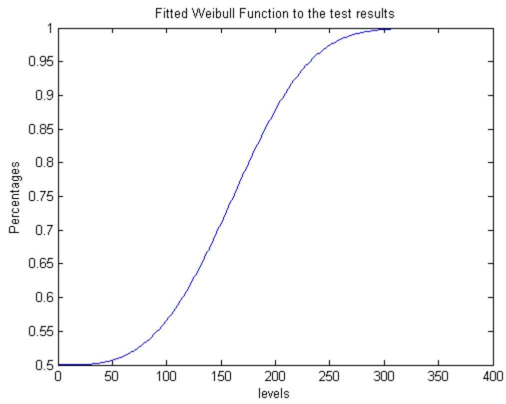


Figure 6.10: Fitted Weibull function for Subject 2 at frequency level (7,7) and luminance level 500 cd/m^2

25.18	10.58	7.36	7.42	X	13.23	X	26.16
4.42	8.71	12.58	11.04	X	26.72	X	51.86
3.93	8.37	9.03	X	X	X	X	X
3.93	28.90	X	22.52	X	69.46	X	87.12
X	X	X	X	X	X	X	X
20.26	29.74	X	52.82	X	91.05	X	96.39
X	X	X	X	X	X	X	X
29.66	59.62	X	38.28	X	132.76	X	181.06

Table 6.5: Quantization Levels for Luminance 500 cd/m^2 for Subject 2

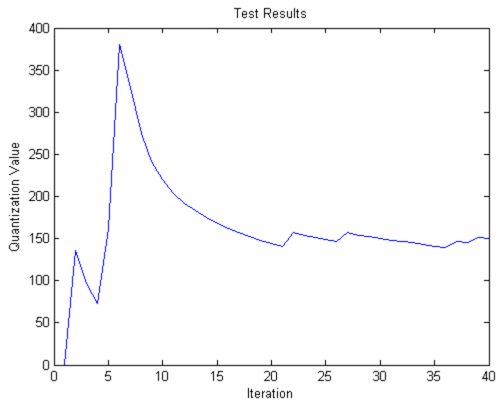


Figure 6.11: Quantization level vs. Iteration for Subject 3 at frequency level (7,7) and luminance level 500 cd/m^2

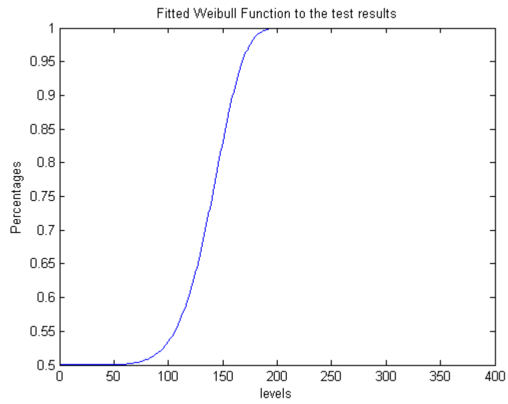


Figure 6.12: Fitted Weibull function for Subject 3 at frequency level (7,7) and luminance level 500 cd/m^2

6.06	8.29	2.70	3.81	X	9.53	X	15.29
3.13	8.91	8.95	13.59	X	26.99	X	69.28
4.98	15.98	8.93	X	X	X	X	X
10.71	4.64	X	20.71	X	33.99	X	75.69
X	X	X	X	X	X	X	X
10.63	18.56	X	22.19	X	39.78	X	93.08
X	X	X	X	X	X	X	X
35.03	85.97	X	71.90	X	184.63	X	148.57

Table 6.6: Quantization Levels for Luminance 500 cd/m^2 for Subject 3

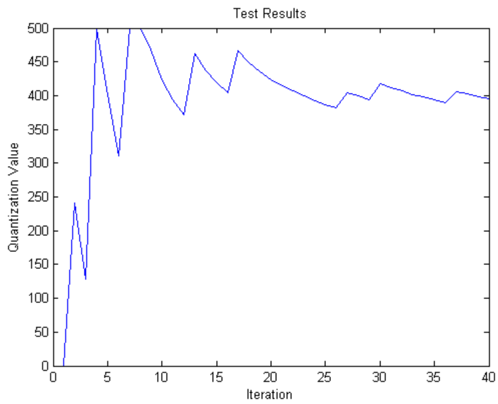


Figure 6.13: Quantization level vs. Iteration for Subject 1 at frequency level (7,7) and luminance level 1000 cd/m^2

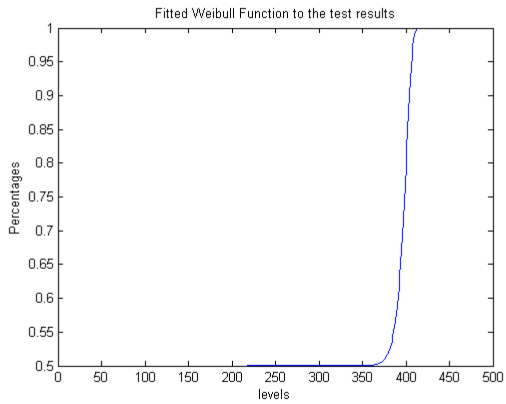


Figure 6.14: Fitted Weibull function for Subject 1 at frequency level (7,7) and luminance level 1000 cd/m^2

8.59	13.27	14.77	12.34	X	17.69	X	26.39
12.13	16.42	22.53	18.13	X	37.55	X	71.36
9.73	22.00	25.38	X	X	X	X	X
11.45	24.84	X	56.86	X	87.48	X	171.88
X	X	X	X	X	X	X	X
15.99	73.36	X	105.61	X	161.04	X	231.88
X	X	X	X	X	X	X	X
47.23	75.35	X	280.76	X	495.65	X	400.90

Table 6.7: Quantization Levels for Luminance 1000 cd/m^2 for Subject 1

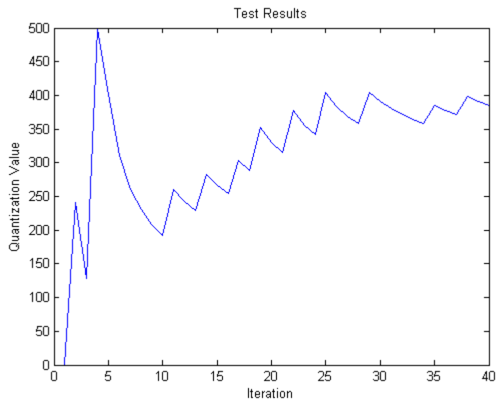


Figure 6.15: Quantization level vs. Iteration for Subject 2 at frequency level (7,7) and luminance level 1000 cd/m^2

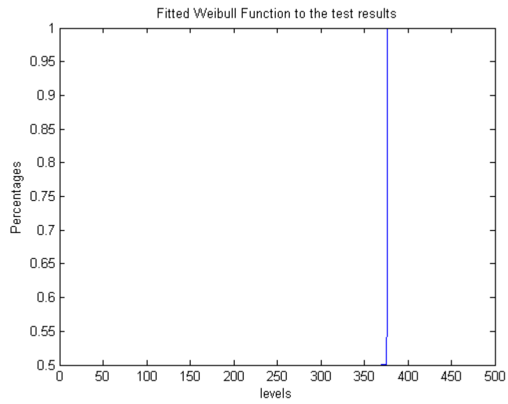


Figure 6.16: Fitted Weibull function for Subject 2 at frequency level (7,7) and luminance level 1000 cd/m^2

13.40	9.86	10.92	4.12	X	26.70	X	97.74
27.38	23.12	18.95	22.04	X	42.73	X	70.72
12.47	28.96	28.39	X	X	X	X	X
15.08	32.77	X	41.30	X	81.05	X	140.36
X	X	X	X	X	X	X	X
17.94	46.89	X	62.47	X	162.42	X	236.63
X	X	X	X	X	X	X	X
85.98	126.38	X	164.75	X	245.58	X	376.38

Table 6.8: Quantization Levels for Luminance 1000 cd/m^2 for Subject 2

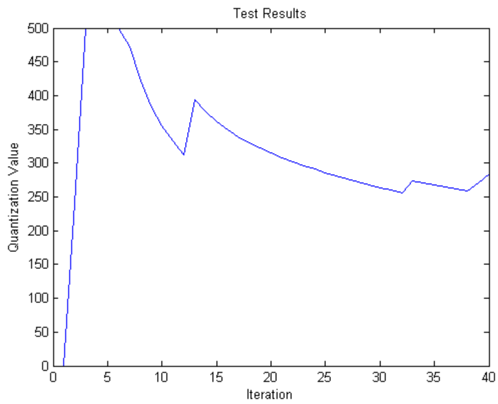


Figure 6.17: Quantization level vs. Iteration for Subject 3 at frequency level (7,7) and luminance level 1000 cd/m^2

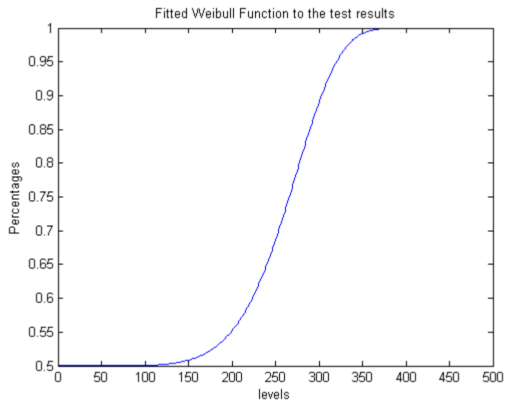


Figure 6.18: Fitted Weibull function for Subject 3 at frequency level (7,7) and luminance level 1000 cd/m^2

48.98	16.16	13.84	38.35	X	24.30	X	57.47
481.46	39.04	20.76	41.98	X	37.19	X	82.16
15.69	18.98	37.49	X	X	X	X	X
9.75	16.77	X	48.74	X	269.32	X	225.72
X	X	X	X	X	X	X	X
17.84	50.18	X	53.56	X	63.00	X	175.97
X	X	X	X	X	X	X	X
39.44	67.86	X	104.96	X	149.70	X	282.23

Table 6.9: Quantization Levels for Luminance 1000 cd/m^2 for Subject 3

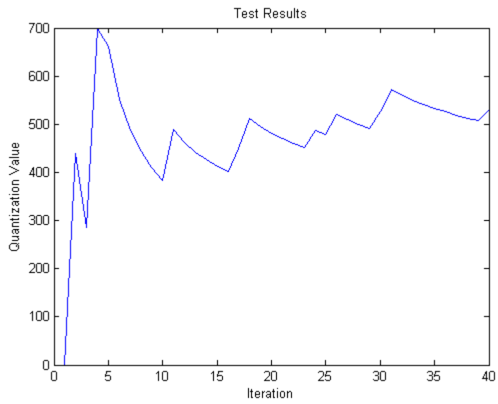


Figure 6.19: Quantization level vs. Iteration for Subject 1 at frequency level (7,7) and luminance level 1500 cd/m^2

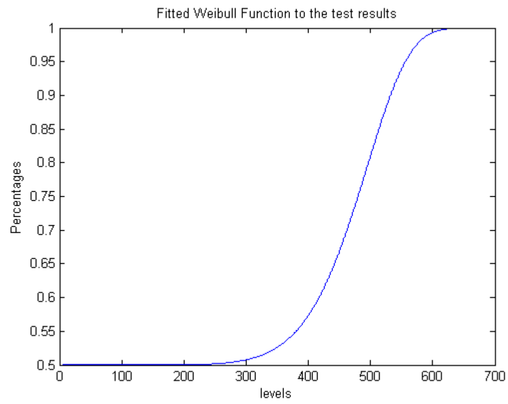


Figure 6.20: Fitted Weibull function for Subject 1 at frequency level (7,7) and luminance level 1500 cd/m^2

14.05	16.20	23.01	16.14	X	28.77	X	62.31
35.36	33.27	38.43	56.70	X	129.20	X	107.13
28.25	56.56	39.17	X	X	X	X	X
89.32	47.06	X	203.02	X	133.27	X	127.65
X	X	X	X	X	X	X	X
45.80	85.04	X	125.88	X	185.57	X	528.91
X	X	X	X	X	X	X	X
64.93	47.90	X	259.49	X	423.56	X	502.88

Table 6.10: Quantization Levels for Luminance 1500 cd/m^2 for Subject 1

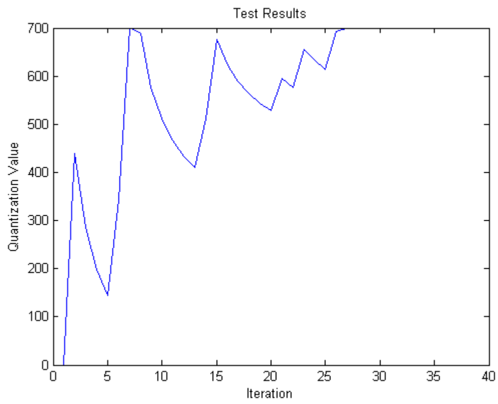


Figure 6.21: Quantization level vs. Iteration for Subject 2 at frequency level (7,7) and luminance level 1500 cd/m^2

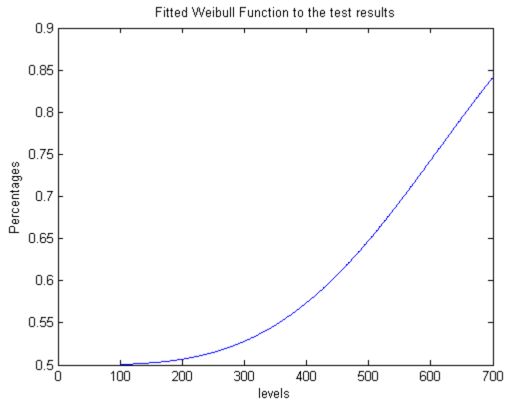


Figure 6.22: Fitted Weibull function for Subject 2 at frequency level (7,7) and luminance level 1500 cd/m^2

13.48	18.21	16.71	30.51	X	92.55	X	77.13
17.76	29.76	23.67	28.92	X	56.63	X	144.58
22.00	25.62	41.52	X	X	X	X	X
21.51	44.94	X	62.20	X	109.96	X	143.88
X	X	X	X	X	X	X	X
85.43	68.69	X	163.29	X	122.85	X	226.18
X	X	X	X	X	X	X	X
91.53	145.86	X	336.82	X	400.14	X	677.13

Table 6.11: Quantization Levels for Luminance 1500 cd/m^2 for Subject 2

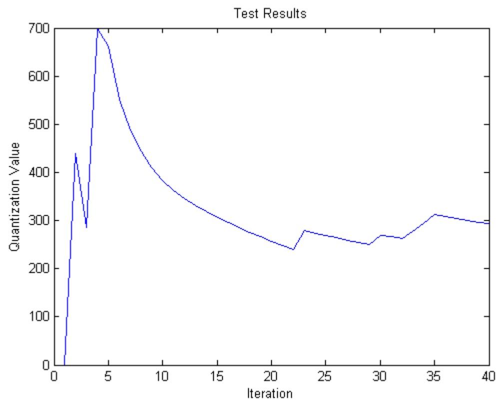


Figure 6.23: Quantization level vs. Iteration for Subject 3 at frequency level (7,7) and luminance level 1500 cd/m^2

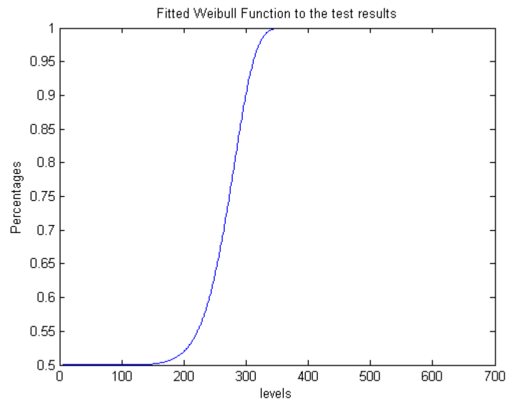


Figure 6.24: Fitted Weibull function for Subject 3 at frequency level (7,7) and luminance level 1500 cd/m^2

13.32	25.99	20.03	22.42	X	24.02	X	246.02
13.99	17.20	21.50	81.06	X	48.45	X	73.94
18.27	30.88	6.08	X	X	X	X	X
14.42	27.63	X	34.85	X	62.12	X	98.02
X	X	X	X	X	X	X	X
16.97	39.27	X	67.47	X	65.56	X	206.68
X	X	X	X	X	X	X	X
10.20	77.23	X	478.82	X	229.46	X	284.68

Table 6.12: Quantization Levels for Luminance 1500 cd/m^2 for Subject 3

CHAPTER 7

EXPERIMENTAL COMPARISONS

In this chapter, experimental results obtained by geometric search and QUEST methodology are compared with respect to various aspects.

- While keeping vertical frequency constant at 7 and horizontal frequency increases from 0 to 7, quantization levels found by quest methodology for all three subjects are compared for each mean luminance. This comparison is done for all four mean luminance levels which are $100cd/m^2$, $500cd/m^2$, $1000cd/m^2$ and $1500cd/m^2$. This comparison is also performed for increasing vertical frequency levels while keeping horizontal frequncy constant at 7.
- For increasing frequency levels, quantization levels found with quest methodology for different mean luminance levels are compared for each subject. This comparison is performed for all three subjects.
- Quantization levels found by both geometric search methodology and quest methodology for same frequency levels are compared. This comparison is performed for all four mean luminance levels for only Subject 1.

7.1 Changes in Quantization Levels with respect to Frequency

In Figures 7.1, 7.2, 7.3 and 7.4, the results of the QUEST at increasing frequency levels, are shown for psychometric experiment sets with luminance levels of $100cd/m^2$, $500cd/m^2$, $1000cd/m^2$ and $1500cd/m^2$ respectively. While the vertical frequency is kept constant at 7 and the horizontal frequency is increased from 0 to 7. Each figure displays the results for all three subjects.

Figures 7.5, 7.6, 7.7, 7.8 shows the QUEST results for increasing vertical frequencies where horizontal frequency is kept constant at 7.

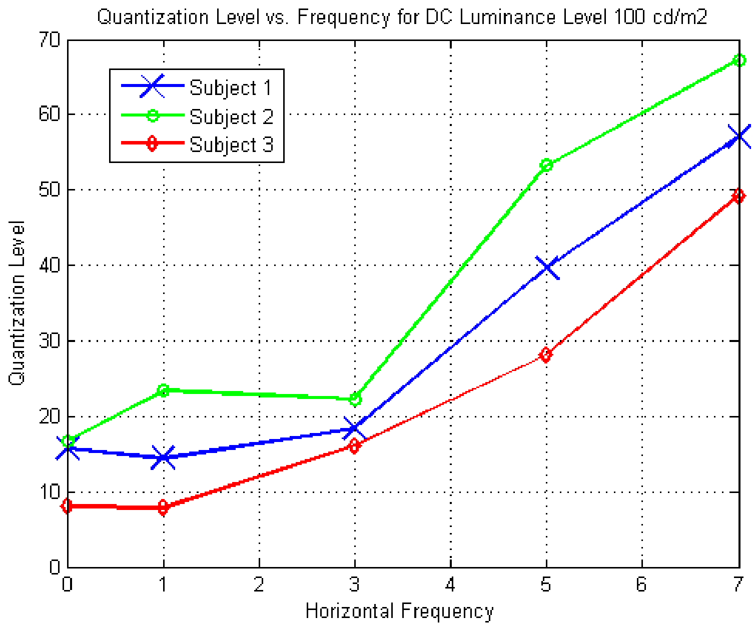


Figure 7.1: Quantization levels for increasing horizontal frequency levels at vertical frequency 7 and luminance level $100cd/m^2$ for all subjects.

Figure 7.1 shows QUEST results for all three subjects Subject 1, Subject 2 and Subject 3 at mean luminance level 100 cd/m^2 for increasing horizontal frequency levels where vertical frequency is kept at 7. It is seen from the Figure 7.1 that quantization level is increasing while the frequency of DCT pattern increases. This increase can be observed from all three subjects.

For Subject 1 at frequency (1,7), we observe a decrease in quantization level when compare to (0,7). Likewise for Subject 2 at frequency (3,7), we observe a decrease in quantization level when compare to (1,7).

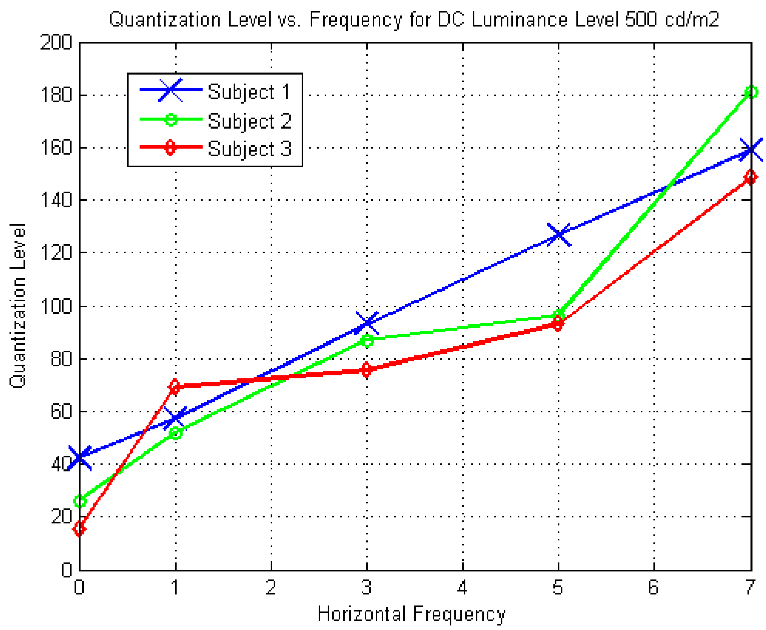


Figure 7.2: Quantization levels for increasing horizontal frequency levels at vertical frequency 7 and luminance level $500cd/m^2$ for all subjects.

Figure 7.2 shows QUEST results for mean luminance level $500cd/m^2$. Quantization levels are increasing with the frequency for all subjects. Increase rate varies between the subjects.

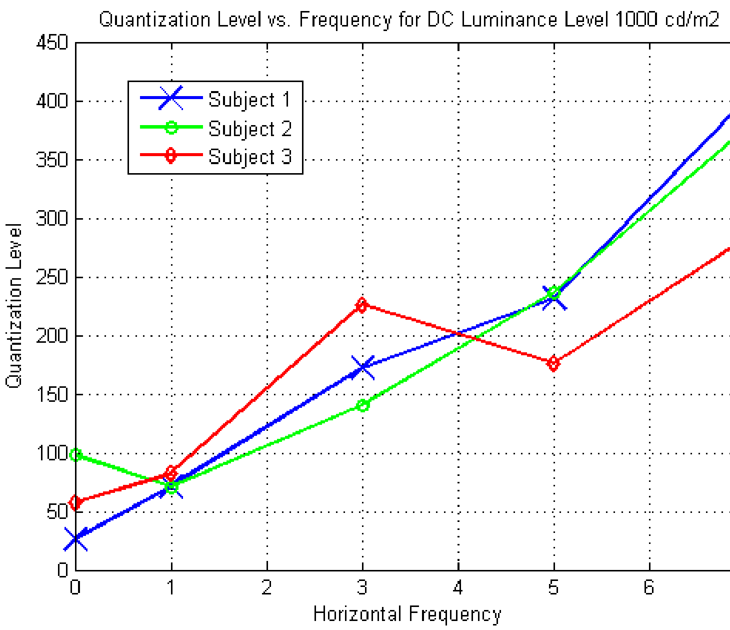


Figure 7.3: Quantization levels for increasing horizontal frequency levels at vertical frequency 7 and luminance level $1000cd/m^2$ for all subjects.

Figure 7.3 shows QUEST results for mean luminance level $1000cd/m^2$. A complete increase in the results of the Subject 1 is observed. For Subject 2 there is decrease at frequency (1,7) and for Subject 3 frequency (3,7) can be said to be an outlier.

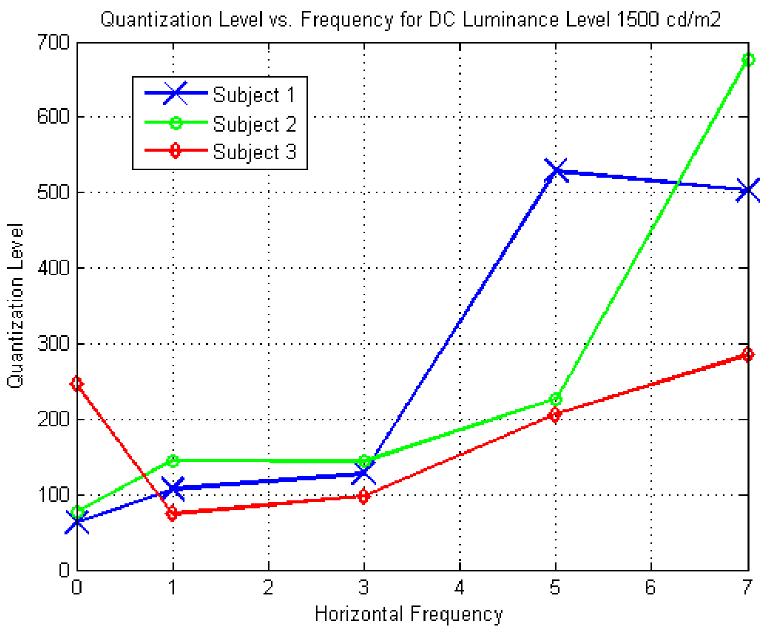


Figure 7.4: Quantization levels for increasing horizontal frequency levels at vertical frequency 7 and luminance level $1500cd/m^2$ for all subjects.

Figure 7.4 shows QUEST results for mean luminance level $1500cd/m^2$. For Subject 1 frequency level (5,7) and for Subject 3 frequency level (0,7) can be labeled as outliers.

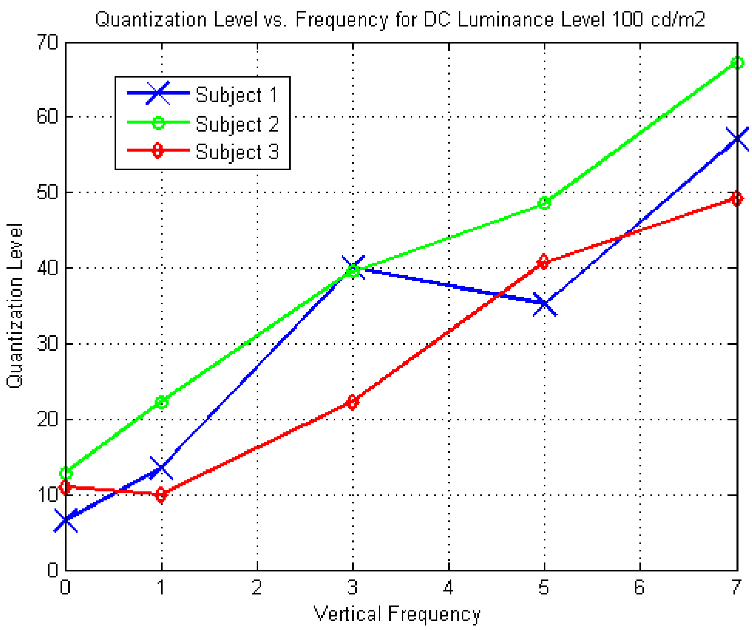


Figure 7.5: Quantization levels for increasing vertical frequency levels at horizontal frequency 7 and luminance level 100 cd/m^2 for all subjects.

Figure 7.5 shows QUEST results for all three subjects Subject 1, Subject 2 and Subject 3 at mean luminance level $100cd/m^2$ for increasing vertical frequency levels where horizontal frequency is kept at 7. It is seen from the Figure 7.5 that quantization level is increasing in general while the frequency of DCT pattern increases. For Subject 1, frequency level (7,5) can be called as outlier.

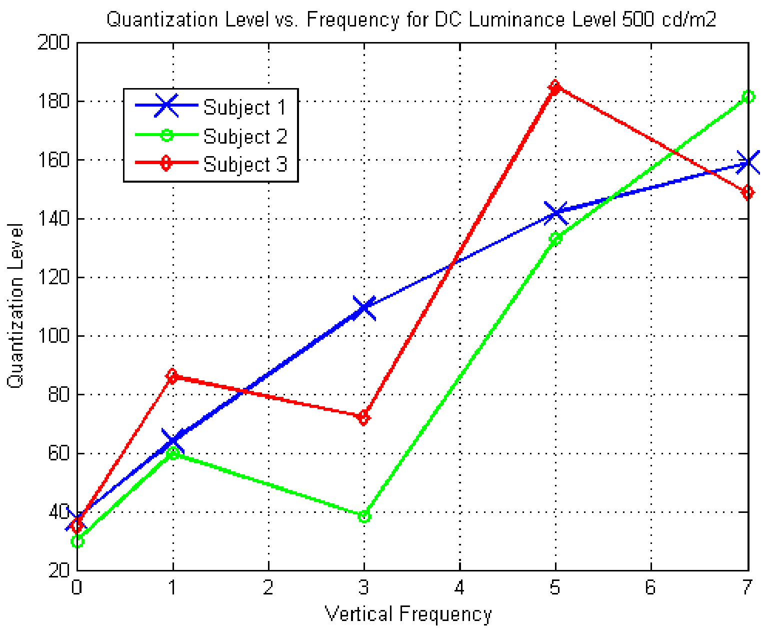


Figure 7.6: Quantization levels for increasing vertical frequency levels at horizontal frequency 7 and luminance level $500cd/m^2$ for all subjects.

Figure 7.6 shows QUEST results for mean luminance level $500cd/m^2$. As the frequency increases, the expected change in the quantization levels is also an increase. However for Subject 3 a decrease is observed at frequency levels (7,3) and (7,5). Likewise for Subject 2 at frequency level (7,3) a decrease is observed. These frequencies can be called as outliers.

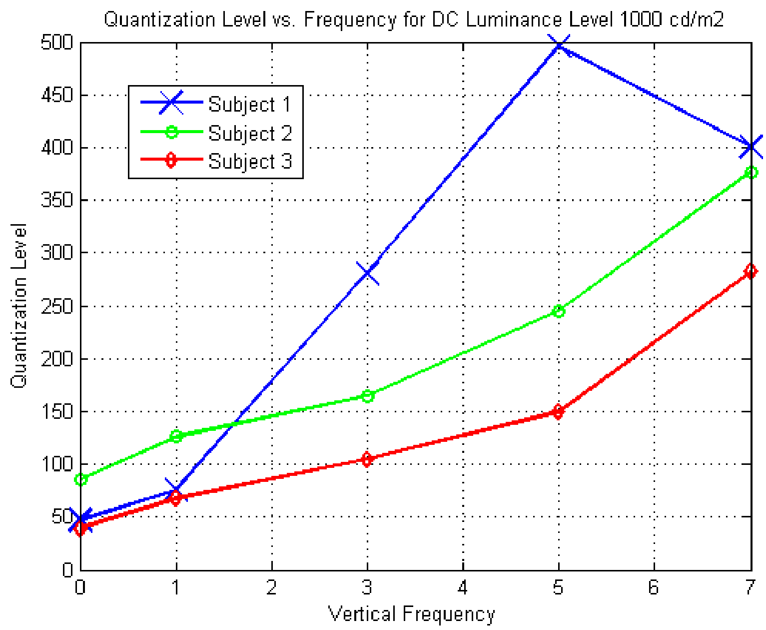


Figure 7.7: Quantization levels for increasing vertical frequency levels at horizontal frequency 7 and luminance level $1000cd/m^2$ for all subjects.

Figure 7.7 shows QUEST results for mean luminance level $1000cd/m^2$. For Subject 1, frequency level (7,5) can be called as outlier.

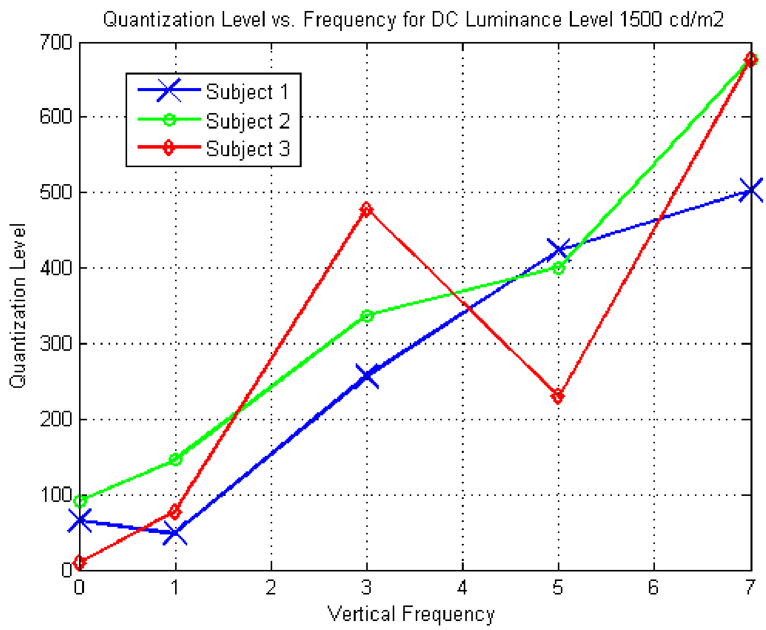


Figure 7.8: Quantization levels for increasing vertical frequency levels at horizontal frequency 7 and luminance level $1500cd/m^2$ for all subjects.

Figure 7.8 shows QUEST results for mean luminance level $1500cd/m^2$. For Subject 3, frequency level (7,3) can be called as outlier.

In general, when the frequency increases, the quantization levels also increase for all subjects. As human eye sensitivity increases with the increasing frequency levels, this is an expected result. However there are a few outliers that break that rule for the QUEST tests.

7.2 Changes in Quantization Levels with respect to Background Luminance

In Figures 7.9, 7.10 and 7.11, the results of the QUEST at increasing frequency levels, are shown for psychometric experiment sets with subject 1, subject 2 and subject 3 respectively. While the vertical frequency is kept constant at 7, the horizontal frequency is increased from 0 to 7. Each figure displays the results for all four luminance levels.

In Figures 7.11, 7.12 and 7.13 contrast threshold values are shown instead of quantization levels. Contrast thresholds are calculated as dividing quantization levels to current mean luminance level and taking its logarithm.

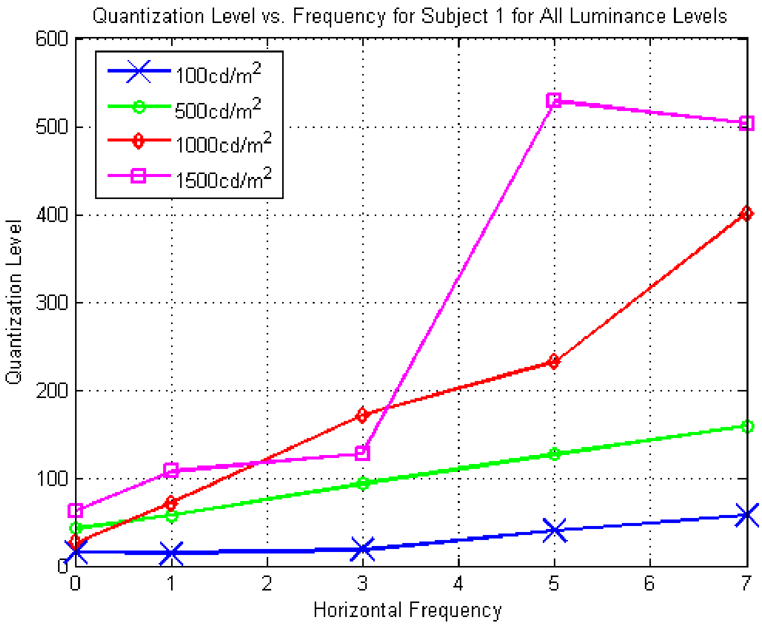


Figure 7.9: Quantization levels for increasing horizontal frequency levels at horizontal frequency 7 for all luminance levels for Subject 1

Figure 7.9 shows QUEST results for Subject 1 for all mean luminance levels. In general it is observed that as luminance level increases, quantization levels are also increasing. For frequency level (3,7), the quantization level for the luminance level $1500cd/m^2$ is lower than the quantization level for luminance level $1000cd/m^2$. As human eye sensitivity increases with the increasing luminance levels, this case can said to be an outlier.

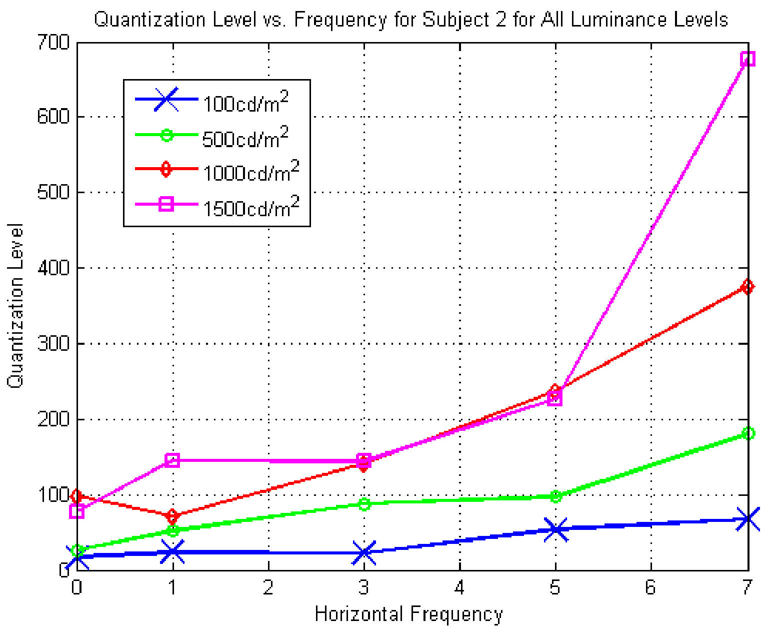


Figure 7.10: Quantization levels for increasing horizontal frequency levels at horizontal frequency 7 for all luminance levels for Subject 2

Figure 7.10 shows QUEST results for Subject 2 for all mean luminance levels. In general the results are as expected.

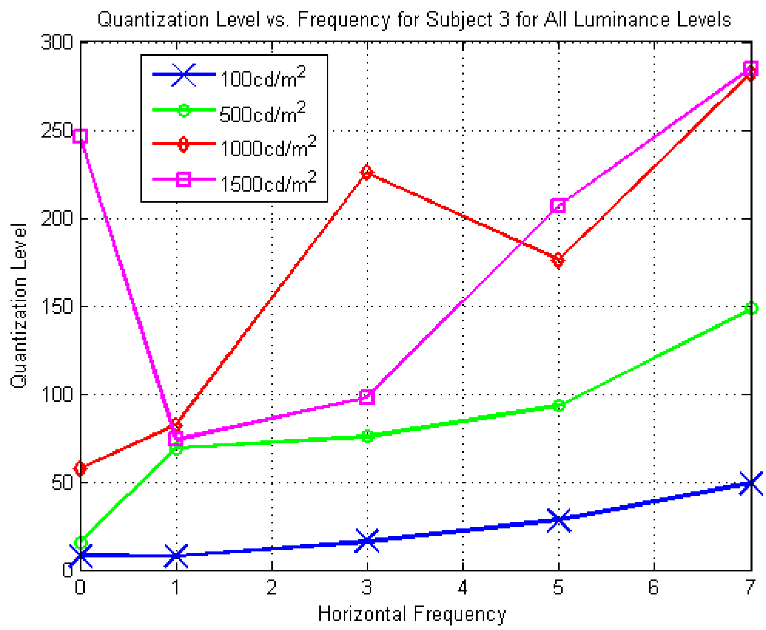


Figure 7.11: Quantization levels for increasing horizontal frequency levels at horizontal frequency 7 for all luminance levels for Subject 3

Figure 7.11 shows QUEST results for Subject 3 for all mean luminance levels. For frequency level (3,7), quantization level for luminance level $1500cd/m^2$ is lower than the quantization level for luminance level $1000cd/m^2$.

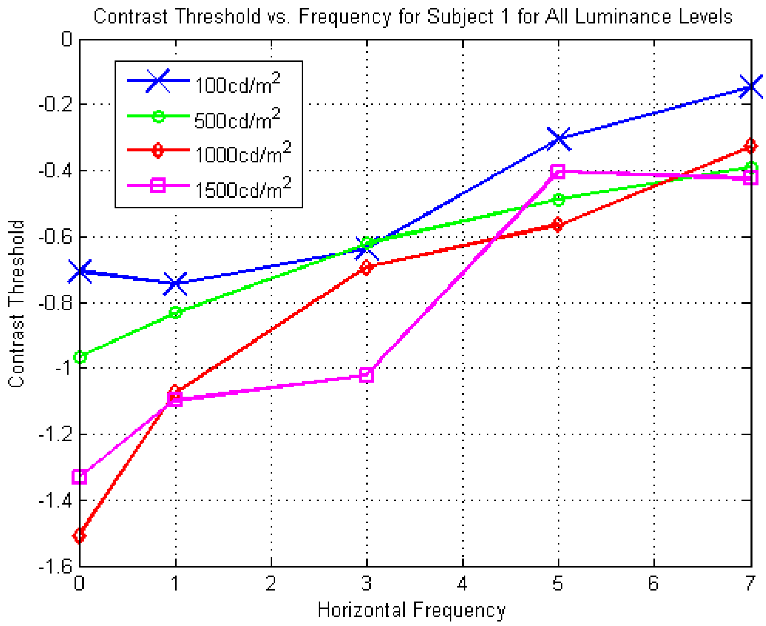


Figure 7.12: Contrast Threshold for increasing horizontal frequency levels at horizontal frequency 7 for all luminance levels for Subject 1

Figure 7.12 shows QUEST contrast threshold values for Subject 1 for all mean luminance levels. In general contrast threshold values are decreasing while luminance is increasing. It is also observed that as frequency levels increase, contrast threshold values also increase. Figure 7.13 and 7.14 show the results for Subject 2 and Subject 3 respectively. Similar results are observed.

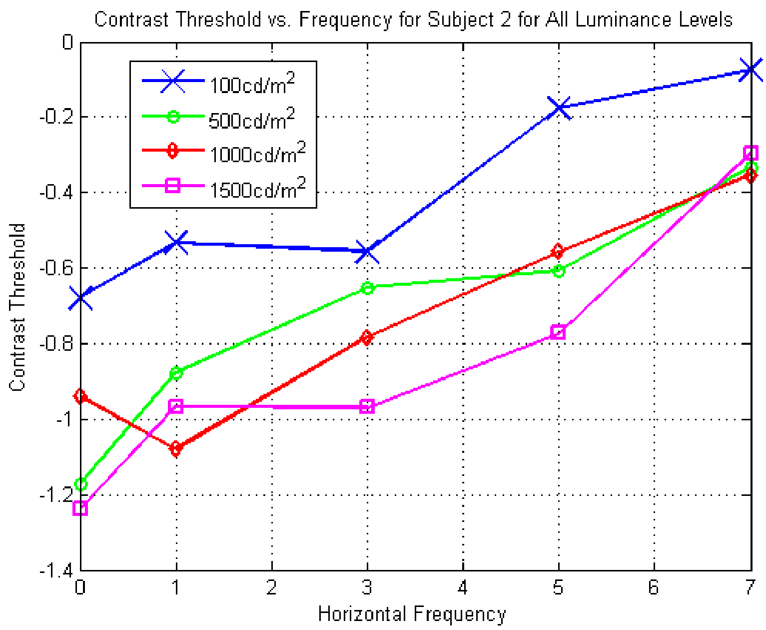


Figure 7.13: Contrast Threshold for increasing horizontal frequency levels at horizontal frequency 7 for all luminance levels for Subject 2

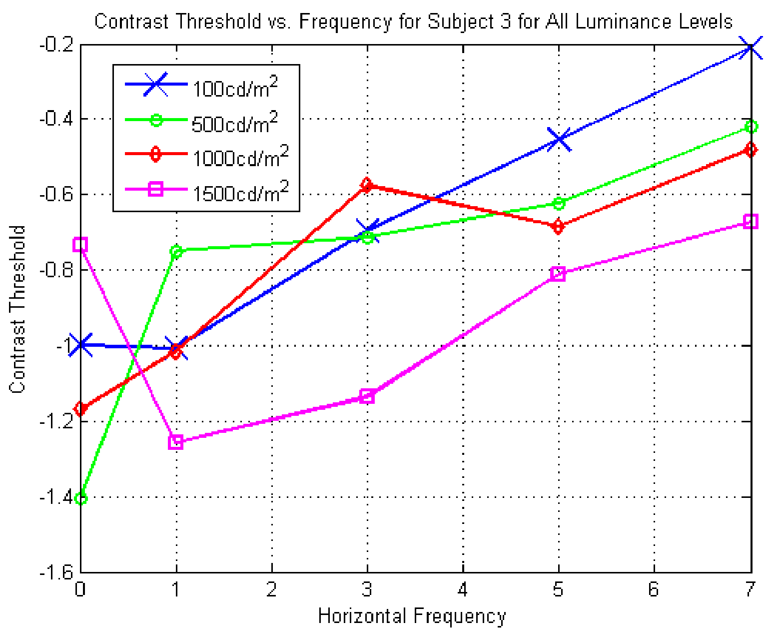


Figure 7.14: Contrast Threshold for increasing horizontal frequency levels at horizontal frequency 7 for all luminance levels for Subject 3

7.3 Comparison of QUEST and Geometric Search Results

In Figures 7.15, 7.16, 7.17 and 7.18 the results of psychometric experiments in which geometric search and the QUEST methodologies are applied are shown with increasing frequency levels. Results are given only for Subject 1. Similar behaviors are also observed for the other subjects. Psychometric experiment sets with luminance levels $100cd/m^2$, $500cd/m^2$, $1000cd/m^2$ and $1500cd/m^2$ are shown respectively. While the vertical frequency is kept constant at 7, the horizontal frequency is increased from 0 to 7.

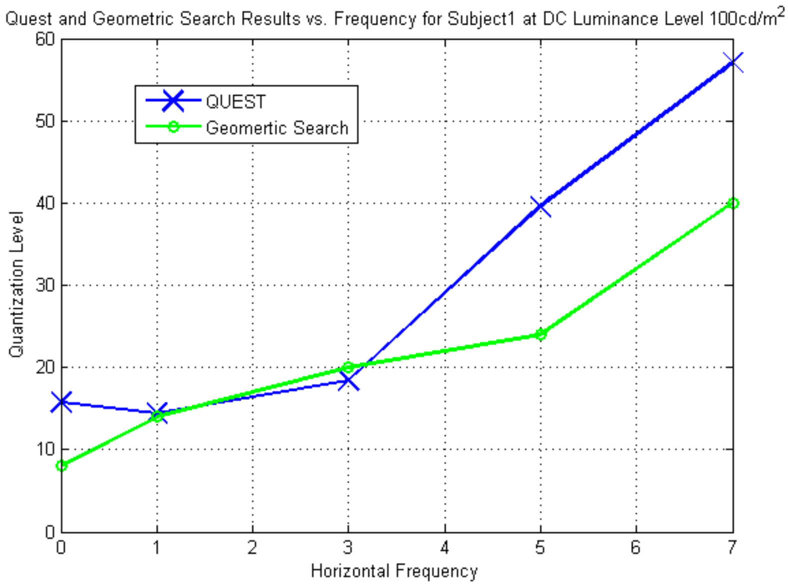


Figure 7.15: Quantization levels found with both geometric search and Quest for increasing horizontal frequency levels at vertical frequency 7 at luminance level $100cd/m^2$

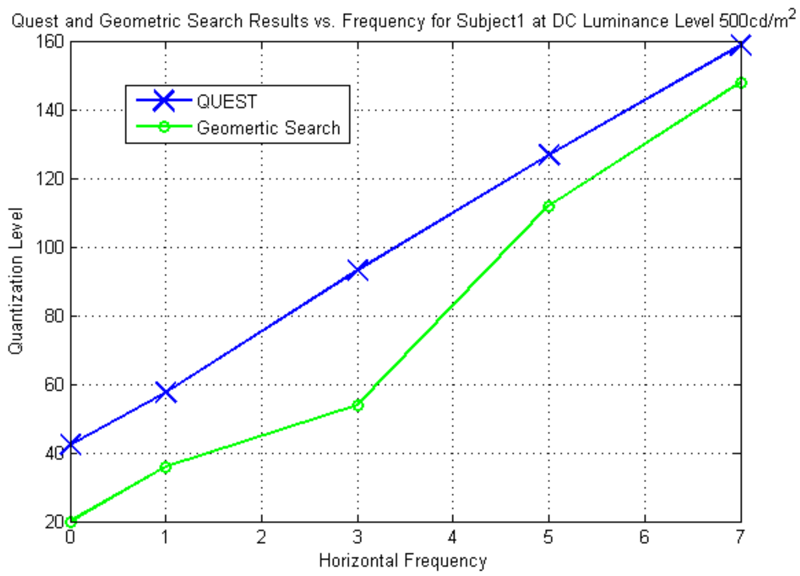


Figure 7.16: Quantization levels found with both geometric search and Quest for increasing horizontal frequency levels at vertical frequency 7 at luminance level $500cd/m^2$

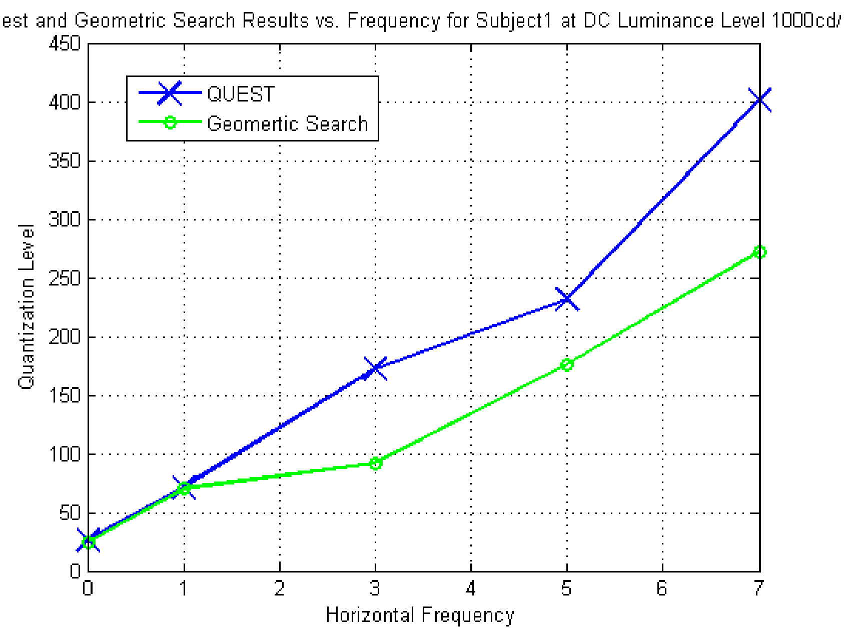


Figure 7.17: Quantization levels found with both geometric search and Quest for increasing horizontal frequency levels at vertical frequency 7 at luminance level $1000cd/m^2$

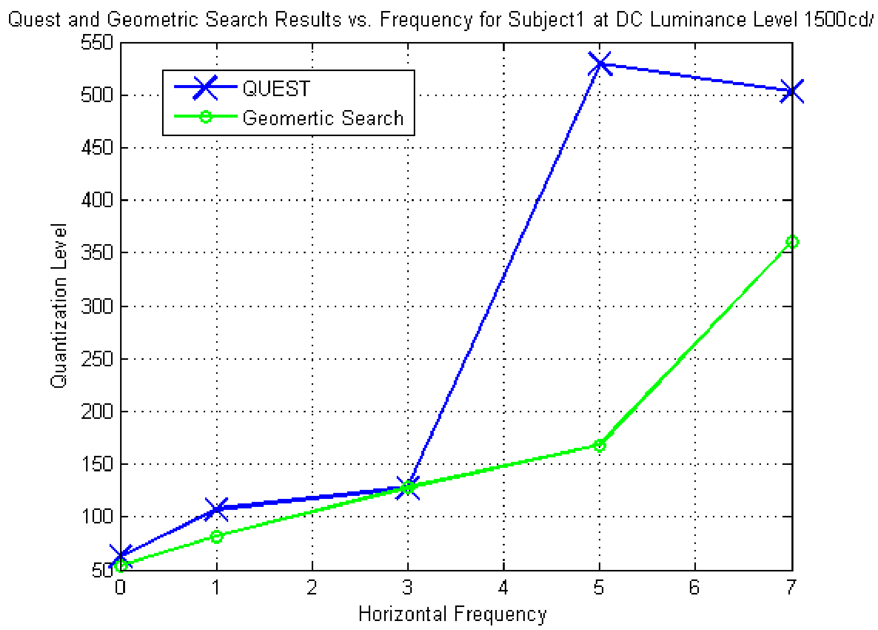


Figure 7.18: Quantization levels found with both geometric search and Quest for increasing horizontal frequency levels at vertical frequency 7 at luminance level $1500cd/m^2$

It can be said that geometric search and quest results show a parallel behavior. It is observed that just noticeable quantization levels found with geometric search are lower than QUEST. Results obtained by QUEST may have outliers. On the other hand, this situation is not occurred with geometric search.

CHAPTER 8

CONCLUSIONS

In this study for HDR image rendering, the algorithm defined in [31] is followed and it is observed that this algorithm caused a halo effect around patterns. In order to eliminate the halo effect, the step for calculating the LED values is modified. Screen luminance is measured, while leaving LCD values constant at 255 and changing LED values from 0 to 120. The LED value, which gives the desired luminance level, is selected for pattern rendering.

Psycho-visual test results reveal that HVS is more sensitive for high frequencies. Just noticeable quantization levels are higher for high frequencies. Likewise, for high luminance levels, just noticeable quantization levels are higher than for low luminance levels. So HVS is more sensitive for high luminance levels. It is also observed that although just noticeable quantization levels are higher for high luminance values, contrast thresholds are lower. The two psycho-visual test methods applied in this study, namely geometric search and QUEST, reveal similar results.

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