

Laws of Visual Perception under Two-Dimensional Optical Stimulation

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Abstract

Human perception of stimuli is categorized into quantitative perception and qualitative perception. Both the Weber-Fechner logarithmic law of sensation and Stevens' power law of sensation describe the quantitative relationship between perceived magnitude and one-dimensional brightness stimuli. Images constitute stimuli characterized by two-dimensional brightness distributions. This study investigates the perception of quality for two-dimensional brightness stimuli, specifically the perception of the degree of goodness or badness of such stimuli. As the degree of goodness or badness constitutes a fuzzy psychological concept, we must employ fuzzy mathematical methods to quantify the degree of goodness or badness of perceived image visual quality, specifically by establishing a fuzzy membership function PQ to quantitatively represent the degree of goodness or badness of image visual quality.

Full Text

Visual Perception Law Under Two-Dimensional Optical Stimulation

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ABSTRACT

Human perception of stimulus quantity can be divided into quantitative perception and qualitative perception. Both Weber-Fechner's logarithmic law of sensation and Stevens' power function law of sensation describe the quantitative relationship between perceived magnitude and one-dimensional luminance stimuli. Images, however, constitute stimuli characterized by two-dimensional luminance distributions. This paper investigates the qualitative perception of two-dimensional luminance stimuli—specifically, the perception of image quality in terms of goodness or badness. Since goodness and badness are fuzzy psychological concepts, we employ fuzzy mathematics to quantify the degree of visual quality, establishing a fuzzy membership function PQ that quantitatively represents how good or bad an image's visual quality is.

Keywords: Two-dimensional optical stimulation, Perception law, Image visual quality assessment, Average luminance, Visual quality function

Human sensation is categorized into general sensation and special sensation. The traditional Weber-Fechner law of sensation was derived from experiments on pressure sensation under moderate stimulation intensity [?, ?], implicitly suggesting that the logarithmic law may not hold under higher or lower stimulation intensities. Debates between logarithmic and power laws have persisted in the literature [?]. The Weber-Fechner law examines the relationship between perceived magnitude P (perception) and physical aggregate stimulation S (stimulation), focusing on one-dimensional stimuli. It has not addressed sensation laws for two-dimensional stimuli with distributional characteristics (such as images), nor has it explored the relationship between perceived quality and stimulation distribution features. This work introduces a novel approach to sensation research: the perception of quality for two-dimensional stimuli (images) rather than the perception of stimulus magnitude. In essence, image quality perception is a perception of “quality” rather than quantity. For such distributional stimuli, magnitude (e.g., brightness) can only be characterized through first-order statistics—namely, the expected value. This study primarily investigates human visual perception of quality for two-dimensional stimuli (such as images) and quantifies this perception.

The foundation of image science lies in human vision. Light is merely a frequency band of electromagnetic waves; without vision, it would be just that—a frequency band of electromagnetic radiation. The most essential characteristic of an image is its luminance. Research shows that images that are too bright or too dark exhibit poor visual quality, making brightness the most fundamental metric for describing image visual quality. Since an image is a two-dimensional matrix of luminance values, only average luminance holds meaningful significance. This paper examines the quantitative relationship between average luminance and image visual quality, demonstrating that average luminance is an important and effective metric for image quality assessment and represents a technique for

quantifying psychological magnitude.

1. On Logarithmic and Power Function Laws of Sensation

Traditional sensation laws investigate the quantitative relationship between perceived magnitude and stimulus intensity. Two primary formulations exist: Weber-Fechner's logarithmic law [?, ?] and Stevens' power law [?]. The Weber-Fechner logarithmic law is expressed as:

$$P = k \cdot \log_a S \quad (a > 1) \quad (1)$$

where P represents perceived magnitude, S represents stimulus intensity, k is a constant dependent on unit selection, and a is the logarithmic base. This law applies across all sensory modalities, including vision, hearing, touch, temperature, taste, and olfaction.

Stevens' power law is expressed as:

$$P = k(S - S_0)^n \quad (2)$$

where P represents perceived magnitude, S represents stimulus intensity, S_0 represents the stimulus threshold, and n is the power exponent, which varies across different sensory modalities or stimulus types.

2. The Significance of Luminance

2.1 The Fundamental Importance of Luminance We first examine grayscale images. Light forms the basis of images; without light, there would be no image (though objective entities might exist, they cannot be visually perceived). Luminance is fundamental to image quality, as visual quality varies with changes in image brightness. Experiments demonstrate that visual quality initially increases with luminance, reaches a maximum, and then decreases with further luminance increase, as illustrated in [Figure 1: see original paper]. The grayscale images in the third row of [Figure 1: see original paper] are generated from the color images in the first row through the following transformation:

$$Im_G(i) = 0.3 \cdot RIm_C(i) + 0.6 \cdot GIm_C(i) + 0.1 \cdot BIm_C(i) \quad (3)$$

where $i = 1, 2, \dots, 6$ indexes the six images, $Im_G(i)$ represents the luminance of the transformed grayscale images (shown in subfigures g)-m) of [Figure 1: see original paper]), and $RIm_C(i)$, $GIm_C(i)$, $BIm_C(i)$ represent the red, green, and blue components of the original color images (subfigures a)-f) in [Figure 1: see original paper]), respectively. The physical unit of luminance is cd/m^2 (candela per square meter).

2.2 Incident Light and Reflected Light The relationship between reflected light intensity (received by the eye) and incident light intensity (illuminating the object surface) is described by:

$$I(c, x, y) = R(c, x, y) * E(c, x, y) \quad (4)$$

where $I(c, x, y)$, $R(c, x, y)$, and $E(c, x, y)$ represent reflected light intensity, object reflectance coefficient, and incident light intensity, respectively. The symbol “*” denotes the Hadamard product operator (element-wise matrix multiplication). In practice, $I(c, x, y)$ is the image perceived by humans. If $E(c, x, y)$ is spatially and temporally invariant, then:

$$I(c, x, y) \propto R(c, x, y) \quad (5)$$

This indicates that $I(c, x, y)$ carries information about the reflectance coefficient of the imaged object—the physical essence of an image. Normal vision perceives color images, while total color blindness perceives only grayscale images.

3. Quantification of Image Visual Quality Perception

3.1 Two-Dimensional Stimulus Quantity An image is a two-dimensional stimulus quantity. Human visual perception of image quality is no longer a simple perception of luminance (grayscale) magnitude, but rather a more complex perception of luminance distribution—a perception of two-dimensional stimulus characteristics. Clearly, an image with zero luminance is perceived as having poor quality because it contains no light and thus no luminance distribution. Similarly, an image with uniform luminance of 255 is also perceived as having poor quality because it lacks structure (or texture), meaning it has no distribution. Ultimately, image quality perception is a perception of luminance distribution: for grayscale images, it is perception of grayscale distribution; for color images, it is perception of chromatic distribution. For an image’s luminance, only the expected value (average) is meaningful.

3.2 Visual Threshold and Blinding Threshold The visual threshold is commonly known as JND (just noticeable difference). Experimental studies have shown that JND is a function of chromatic value and chromatic category, expressible as $JND(c, ch)$ [?], where c represents chromatic value and ch represents chromatic category. Considering that vision should also have threshold constraints, the luminance perception quantification formula (1) should be modified as:

$$P = k \cdot \log_a(S/S_0) \quad (6)$$

where S_0 is the JND. Equation (6) requires $S \geq S_0$; otherwise, no visual perception occurs. This formulation ensures that $(S/S_0) \geq 1$, guaranteeing $P \geq 0$

and avoiding the problematic negative perception values that could arise from equation (1).

Equation (6) can also be called the luminance (perception) level formula, where P represents the perceived luminance level—the logarithm of the ratio between a physical luminance S and the luminance threshold S_0 . Regarding units of P : when $a = 10$ and $k = 10$, the unit is decibel (dB); when $k = 1$, the unit is bel (Bell). In photometry, this is sometimes called a “Bril.” When $k = 1$ and $a = e$ ($= 2.7183$), the unit is nat (Nat). When $k = 1$ and $a = 2$, the unit is bit (Bit).

For luminance, besides the lower visual threshold (JND), there exists an upper blinding threshold. Vision is a cascade of photochemical and electrochemical processes. Blinding can be temporary or permanent. Temporary blinding occurs when light intensity is so high that rhodopsin is depleted and can no longer respond to light changes; normal vision recovers after the intense light is removed. Permanent blinding results from organic damage to visual cells caused by intense light, leading to irreversible vision loss.

The luminance region between the lower visual threshold and upper blinding threshold is called the visual area. The Weber-Fechner law no longer holds at luminance values approaching either end of this region. The most comfortable luminance for human eyes is 120 lx–150 lx (median 135 lx). Luminance exceeding 10,000 lx generally causes temporary blinding. Computer screen luminance, defined as the brightness of an all-white screen, is approximately 300 lx. The range 0–300 lx represents a sub-region of the visual area where computer image processing operates. For 8-bit systems, this is divided into 256 luminance levels (0–255). One luminance level on a computer screen corresponds to approximately 1 lx.

3.3.1 Absence of Logarithmic Law for Image Quality Perception In digital image processing, computer screen luminance range is typically set to 0–255 for comfortable viewing, with level 255 corresponding to approximately 300 cd/m². This range (0–300 cd/m²) is suitable for prolonged human observation without causing significant discomfort. Computer screen brightness can be adjusted within a small range to accommodate different observers. For two-dimensional stimuli like images, only average luminance can describe the visual system’s luminance perception. Throughout the entire visual domain of 0–255, the relationship between perceived image quality and average luminance does not follow a logarithmic law, as shown in [Figure 1: see original paper] and . Instead, it exhibits a maximum-value functional relationship.

3.3.2 Boundary Conditions for Image Quality Perception Image quality perception has two boundary conditions: when average luminance AL is less than or equal to ALO , perceived quality PQ is zero; and when AL is greater than or equal to ALE , PQ is also zero. These are described as follows:

First boundary condition: Let ALO be the left boundary value of the visual

perception range. Then:

$$PQ(AL \leq ALO) = 0 \quad (7)$$

Second boundary condition: Let ALE be the right boundary value of the visual perception range. Then:

$$PQ(AL \geq ALE) = 0 \quad (8)$$

These are called the first (lower) and second (upper) boundaries, respectively:

$$ALO = JND_O - 1 \quad (9)$$

$$ALE = 255 - (JND_E - 1) \quad (10)$$

where JND_O and JND_E represent the JND values at the beginning and end of the image-defined luminance range. JND (just noticeable difference) denotes the just-perceptible luminance difference; JND-1 becomes just-imperceptible. If JND_E = JND_O, this is called a symmetric JND boundary condition; otherwise, it is asymmetric.

3.3.3 Image Perception Quality Equation The equation satisfying these boundary conditions is called the image perception quality equation, characterized by:

$$PQ(AL) = CC \cdot (AL - ALO) \cdot (ALE - AL) \quad (11)$$

where AL represents average luminance, PQ(AL) represents perceived quality as a function of AL, and CC is a color constant. For grayscale images, CC = 1:

$$PQ_{Gray}(AL) = (AL - ALO) \cdot (ALE - AL) \quad (12)$$

For color images, CC = 3. The factor $PQ_{\{CORE\}}(AL) = (AL - ALO) \cdot (ALE - AL)$ is called the core factor, which is also the perception quality equation for grayscale images.

As shown in [Figure 1: see original paper] and , for a series of captured images, there exists an optimal average luminance ALOPT corresponding to the best perceived quality. By setting the first derivative of equation (11) to zero to find the extremum:

$$ALOPT = (ALE + ALO)/2 \quad (13)$$

where ALE and ALO represent the end and start values of the screen's visual region. For symmetric JND boundaries where $ALO = JND - 1$ and $ALE = 255 - (JND - 1)$:

$$ALOPT = 127.5 \quad (14)$$

For asymmetric JND boundaries with lower JND_O and upper JND_E:

$$ALOPT = (225 - JND_E + JND_O)/2 \quad (15)$$

If JND_O = 5 and JND_E = 1, then ALOPT = 129.5, which rounds to ALOPT = 130. This indicates a rightward shift (increase) along the average luminance axis. shows ALOPT values and corresponding PQ values for three boundary condition combinations.

Perceived quality PQ exhibits convex characteristics as average luminance AL increases. PQ values for each AL can be calculated using equation (11). [Figure 2: see original paper] illustrates PQ versus AL for the three boundary condition examples from . Equation (15) and demonstrate that the greater the difference between lower JND_O and upper JND_E, the further the optimal average luminance deviates from 127.5.

The quantification of image quality perception given by equation (11) clearly exhibits polynomial (quadratic trinomial) characteristics. However, different boundary conditions yield different perceived quality values for the same image, necessitating standardized boundary conditions to enable comparison across studies. To avoid this issue, a maximum-value normalized perception quality quantification method can be employed, yielding the normalized visual perception quality equation:

$$NPQ(AL) = \frac{(AL - ALO) \cdot (ALE - AL)}{(ALOPT - ALO) \cdot (ALE - ALOPT)} \quad (16)$$

The domain of equation (16) is [0, 1], making it a fuzzy membership function. When equation (16) equals 1, the image has optimal quality. A value of 0.9 indicates the image quality is 90% of optimal. Equation (16) is a functional expression because its argument $AL = f(x, y, c)$ is a function of image plane coordinates x, y and color parameter c.

The normalized perception function NPQ(AL) for two-dimensional stimuli is dimensionless, but like information entropy or intensity levels (which use units such as bits or bells), it can be assigned units such as "Qual." A unit ten times smaller is the deci-qual, and a unit one hundred times smaller is the centi-qual.

3.3.4 Perception Quality Distance The distance DNPQ between an image' s normalized visual perception quality NPQ(AL) and the normalized optimal visual perception quality NPQ(ALOPT) is defined as:

$$DNPQ(AL) = \beta \cdot (NPQ(ALOPT) - NPQ(AL)) \quad (17)$$

where β is a unit-dependent constant. When $\beta = 1$, DNPQ' s unit is qual; when $\beta = 10$, it is deci-qual; when $\beta = 100$, it is centi-qual. NPQ(ALOPT) = 1.0000, and NPQ(AL) ranges between 0 and 1.

A smaller perception quality distance indicates better image quality. Images with large perception quality distances require technical improvement, either by adjusting aperture size or lighting conditions during capture, or through image enhancement methods.

3.4 Significance of Normalized Image Quality Perception

1. The normalized perception quality of an optimally captured image is 1.
2. A normalized perception quality less than 1 indicates the image can be further enhanced.
3. A normalized perception quality less than 1 also indicates suboptimal capture conditions, providing a basis for intelligent optimization of shooting conditions.
4. The converse—that an image with normalized perception quality of 1 is optimally captured—does not hold unless the image is restricted to being a natural image.
5. The perception function is polynomial, not Weber-Fechner' s logarithmic function nor Stevens' power function. The luminance range in image science work is not the entire visual region but a comfortable sub-region.

3.5 Fuzzification of Image Visual Perception Quality In practice, image quality perception is fuzzy: terms like “good,” “better,” “excellent,” and “optimum” reflect actual visual observation. Therefore, the numerical perception quality results PQ from equation (11) must be transformed into fuzzy concepts FPQ, as shown in . The fuzzy evaluations for the image series in [Figure 1: see original paper] and [Figure 2: see original paper] are listed in the FPQ rows of and .

3.6 Additional Examples of Quantified Image Visual Perception Quality An example set of captured images named “Patio” (P1-P6) is provided in [Figure 3: see original paper]. Subfigures a)-f) show color images, while g)-m) show corresponding grayscale images transformed using equation (3). presents calculated average luminance AL values for [Figure 3: see original paper] and derived perception quality PQ, normalized perception quality NPQ, and normalized perception quality distance DNPQ values.

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