THE EFFECT OF CONTEXT LUMINANCE ON CONTRAST PERCEPTION

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ABSTRACT

THE EFFECT OF CONTEXT LUMINANCE ON CONTRAST PERCEPTION

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The present study has employed psychophysics and functional magnetic resonance imaging (fMRI) methodologies. The aim of the study is to investigate the role of bottom-up and top-down processing of luminance in contrast perception. In particular, since it is thought that visual illusions occur as a result of top-down processing by means of visual context, the present study investigates how luminance in context affects contrast perception by using brightness illusion. In other words, the purpose of the study is to understand whether physical or perceived properties of luminance dictate contrast perception. An illusory stimulus which was especially created for the present study was used in the experiments. Two psychophysical experiment series and one fMRI experiment series was conducted. In the first experimental series, brightness value of the illusory stimulus was measured with several methods and experimental designs to be sure that illusion is strong enough. In the second experiment series, contrast perception was measured by locating a rectified square-wave grating on the illusory stimulus. In the fMRI experiment series, neuronal correlates of psychophysical results were investigated. Results show that perceived properties of luminance has an effect on contrast perception. Furthermore, fMRI findings showed complicated results both favouring physical and perceptual properties in different conditions.

Keywords: Brightness illusion, Contrast perception, Luminance, Sensation, Context

ÖZ

KONTRAST ALGISININ BAĞLAMA GÖRE DEĞİŞİMİNİN ARAŞTIRILMASI

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Ağustos 2014, 86 sayfa

Bu çalışmada psikofizik ve işlevsel manyetik rezonans görüntüleme (iMRG) yöntemlerini kullanarak gerçekleştirilen deneylerden oluşmaktadır. Çalışmanın amacı, luminansın aşağıdan yukarı işlenmesinin ya da yukarıdan aşağı işlenmesinin kontrast algısı üzerindeki etkisini araştırmaktır. Literatürdeki mevcut bulgular görsel yanılsamaların bağlamın etkisiyle yukarıdan aşağı işlenme yoluyla oluştuğu görüşünü desteklemektedir. Bu nedenle, bu çalışmada parlaklık yanılsaması kullanılarak bağllamdaki parlaklığın kontrast algısına etkisinin araştırılması hedeflenmiştir. Bir başka deyişle, bu çalışma kontrast algısını luminansın fiziksel özelliklerinin mi yoksa algılanan özelliklerinin mi şekillendirdiği sorusunu cevaplamayı amaçlamaktadır. Deneylerde bu çalışma için özel olarak tasarlanmış, görsel yanılsama içeren bir uyaran kullanılmıştır. Bu çalışma için iki psikofizik, bir iMRG deney serisi uygulanmıştır. İlk deney serisinde yanılsamanın hangi koşullarda, ne kadar güçlü olduğunu görmek için farklı yöntemler ve tasarımlar kullanılarak yanılsamalı uyaranın parlaklık değeri ölçülmüştür. İkinci deney serisinde farklı yöntemler ve tasarımlarla kontrast algısı ölçümü yapılmıştır. iMRG deney serisi, elde edilen davranışsal sonuçların nöronal korelasyonlarını tespit etmek amacıyla yapılmıştır. Deneylerden elde edilen veriler, luminansın algılanan özelliklerinin kontrast algısını şekillendirdiğine işaret etmektedir. iMRG deneyi sonuçlarına göre kontrast algısı deneydeki koşullara bağlı olarak luminansın fiziksel özellikleriyle ya da algılanan özellikleriyle korelasyon göstermiştir.

Anahtar Kelimeler: Parlaklık yanılsaması, Kontrast algısı, Luminans, Duyum, Bağlam

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CHAPTER 1

INTRODUCTION

1.1. Sensation and Perception

The relationship between sensation and perception constitutes an important aspect of human cognition. Sensation refers to the detection of physical information about a stimulus whereas perception involves higher level processes that facilitate making sense of a sensory input (Purves, & Lotto, 2011). Earlier views on perception of sensory input assume that perception is a simple process of assembling elementary sensations in a cumulative way. Based on this idea, also known as the atomic claim, visual information is processed component by component (Palmer, 1999). Therefore, visual perception can be compared to operation of a camera from an atomic perspective. However, this analogy does not seem to be correct because a camera cannot capture what the visual system performs (Kandel, Schwartz, & Jessell, 2000). For instance, the visual system converts the two-dimensional image projected onto retina into a three-dimensional percept. The problem is not only about perceiving dimension but also about other cognitive abilities that are related to the visual system. Humans usually perceive an object as the same object under different physical conditions. For example, the physical information such as size, shape, or color reflected onto retina changes according to visual conditions such as distance, illumination or brightness. However, people perceive the object as the same object although the image on the retina is updated. People's ability to perceive an object's physical properties as constant demonstrates that the visual system does not simply record images passively like a camera, instead humans perceive differently than the sensory information serves. Because the atomic claim cannot give a full account of the ability of human perception, the so-called holistic view has been receiving more support recently (Kandel, Schwartz, & Jessell, 2000). The holistic claim indicates that perception is an active and creative process that involves more than the information provided by the retina (Palmer, 1999). Sensory input alone cannot explain human perception. It has also been claimed that there is too much sensory information in the environment to process at any particular moment. Therefore, the goal of perception does not seem to process all the sensory input, but to extract the information that matters at that moment (Smith, & Kosslyn, 2007). Based on these findings, studying the interaction between sensation and perception has a high potential to contribute to our understanding of human cognition.

Considering the difference between sensation and perception, studying fundamental physical qualities of a visual stimulus, such as luminance, color, contrast, shape, size and depth as isolated features and examining one physical quality at a time cannot fully explain the mechanism underlying human visual perception because such artificial experimental designs only deal with the sensory input. However, in real world situations people do not see only one physical quality at a time; instead they exposure many fundamental physical qualities are simultaneously. Therefore, the study of interaction between fundamental qualities by focusing on the perceptual outcomes is necessary to understand visual mechanism better (Kwon et al., 2009; Kilpeläinen, Nurminen, & Donner, 2011).

As far as today's scientific knowledge indicates vision cannot occur without luminance (Purves et al., 2008); and contrast is the most important property that enables human beings differentiate an object from its background. Therefore, among fundamental physical qualities luminance and contrast is a good place to start the research on visual perception.

The literature on luminance and contrast perception will be explained below in detail.

1.2. Luminance Perception

Luminance is defined as the measure of the intensity of light reflected from a surface. Luminance can be measured by a photometer and expressed in units such as candelas per square meter (Purves, & Lotto, 2011). Luminance is basically the measurement of a physical property; however, in terms of understanding perception considering just the physical properties is not enough. A perceptual measurement is also needed. **The perceptual measure of luminance is known as brightness.** In particular, brightness is the appearance of a surface; or visual experience of light and dark caused by different intensities of luminance (Blakeslee, & McCourt, 2012). Because the brightness value depends on the visual perception it is not subject to direct measurement. Therefore, it is usually measured by asking observers about their personal experience.

Because **brightness** is the correspondence of **perceived luminance**, a systematic interaction between luminance and brightness is expected. For instance, it may be predicted that changes in luminance consistently correlate with changes in brightness. The idea behind this prediction is that; increase in luminance level causes increase in the number of photons, and consequently photoreceptors are stimulated strongly. Therefore, it might be expected that increasing the luminance level causes an increase in the brightness level. Another expectation is that if the luminance value of two distinct stimuli is equal (if they reflect exactly the same amount of light), then these stimuli are perceived equally bright. However, brightness literature contradicts with these expectations (Purves, & Lotto, 2011; Blakeslee, & McCourt, 2004; Purves et al., 2008). Findings indicate that **luminance is not the only variable that affects brightness**; visual context has also a significant impact on it. This phenomenon might be observed in many visual illusions such as the *simultaneous brightness contrast effect*, and the *White Illusion* (Purves et al., 2008; Goldstein, 2010). In particular, when two distinct stimuli with equal luminance levels are represented on adjacent backgrounds with different luminance levels, they do not seem equally bright, rather they are perceived as different. The stimulus on the background which has relatively lower luminance value seems brighter compared to the stimulus on the background with relatively higher luminance value. Moreover, the effect strengthens if the stimulus contains information about real world conditions such as shadow and boundaries. Examples of the mentioned visual illusions are demonstrated below (see Figure 1.1; Figure 1.2; and Figure 1.3) (Adelson, 1995; Adelson, 2000).

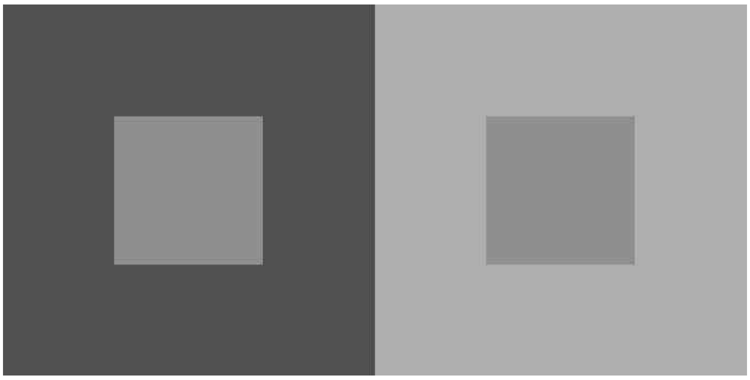


Figure 1.1. An example of simultaneous brightness contrast effect. Although the inner squares have equal luminance value, most observers have reported different brightness values (Adelson, 2000).

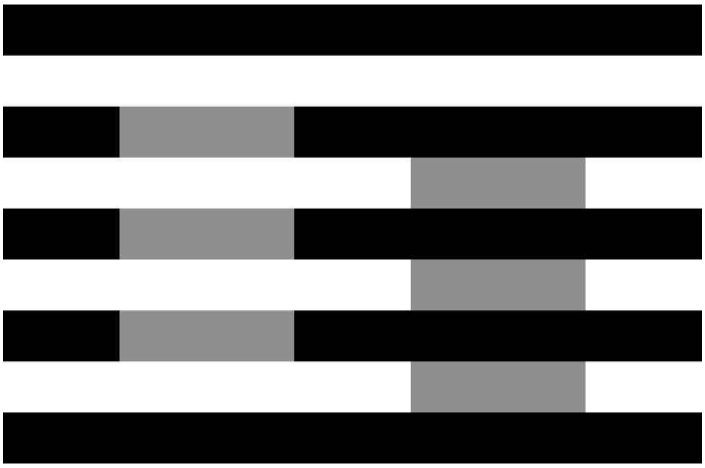


Figure 1.2. White Illusion. All the gray rectangles have same luminance value. However, the ones on the left of the stimulus seem brighter to most of observers (Adelson, 2000).

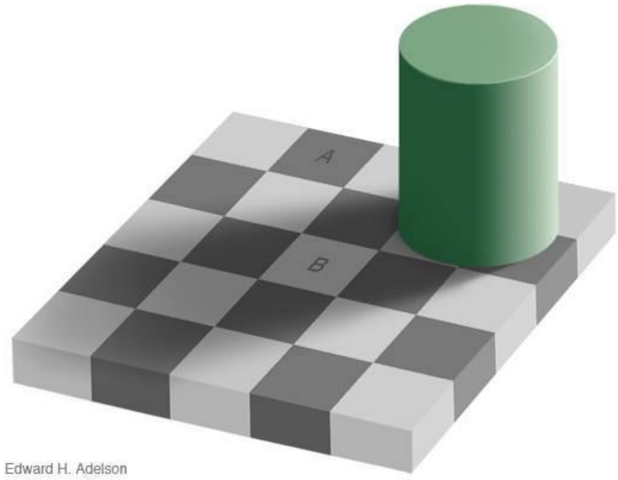


Figure 1.3. Adelson's checkershadow illusion. The squares on which "A" and "B" is written have exactly same luminance value; however they seem to have different brightness value. Moreover, the shadow caused by the green cylinder seems to enrich the illusion (Adelson, 1995).

The underlying mechanisms in those illusions have become the subject of research on visual perception. Until recently, researchers have attributed the effect to the adaptation property of neurons at the input level of the visual system. In other words, it has been claimed that during the retinal processing stimulation of ganglion cells and other lateral interactions generate the illusion (e.g., Attneave, 1954). However, such a mechanism could not explain all brightness illusions such as the White Illusion (Figure 1.2) (Blakeslee, & McCourt, 2004). Therefore, another explanation has been needed. Recently, the most widely accepted explanation is based on phylogenetic and the ontogenetic basis of visual perception. This idea indicates that the behavioural significance of a stimulus which is determined by visual context matters more than its physical properties, and significance is determined by past experience and evolutionary process of an observer.

1.3. Effect of Visual Context on Perception

The visual system relies heavily on parallel processing, and different brain areas perform their own specific information processes (Gleitman, Reisberg, & Gross, 2007). For instance, information coming from LGN is usually sent to primary visual cortex, V1. The processing of this visual information can be defined as bottom-up processing. Bottom-up processing, or data-driven processing, is determined largely by the incoming data about the stimulus (Palmer, 1999). Although bottom-up processing is essential for perception -because stimulation of receptors is usually necessary for perceptual process -the process cannot explain the perception by itself because the environment that humans perceive is not a perfect reflection of the physical world. For instance, although incoming data is the same, the perception of the data might be different as in the cases of visual illusions. Therefore, the difference in perception caused by the same stimulus is attributed to top-down processing of visual information (Smith, Kosslyn, 2007). Top-down processing, or knowledge-based processing, refers to the processing that is influenced by visual context. Visual context includes knowledge, beliefs, goals and expectations of a perceiver about the world. It has been claimed that because the world contains too much sensory stimuli to process at a particular time, humans use visual context to manage to interpret visual information. Figure 1.4. illustrates how knowledge and expectations shape perception. Although sensation caused by the symbol in the middle is the same, in the first row it is perceived as number 13 whereas it is perceived as the letter B in the second row. As it is demonstrated in the figure, the visual system uses problem solving short-cuts constituted by the help of visual context for making inferences from the information it receives. It can be said that perception is the result of these inferences.

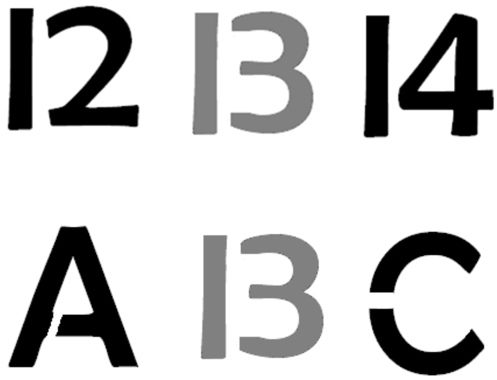


Figure 1.4. The effect of visual context on perception. Although both symbols in the middle are same they are perceived as different because of the surrounding symbols.

It has been claimed that the visual illusory effects are also caused by top-down processing. In other words, visual illusions do not occur through low level perceptual mechanisms such as retinal neuron adaptation, but it occurs at a higher perceptual level in which visual context matters. According to this claim, while human brain processes visual information, it takes the real world situations and expectancies into account; and perceives the stimulus accordingly (Hillis & Brainard, 2007; Purves, et. al, 2008).

The study of the underlying mechanisms in those illusory effects is beyond the scope of the present study. On the other hand, the presence of such effects gives us an opportunity to test the perceptual mechanisms of vision because, for example, by using the brightness illusion we can change the perceptual properties by keeping the physical qualities constant. This gives us the opportunity to investigate the human visual perception mechanism, and the differences caused by visual sensation and visual perception (Blakeslee, & McCourt, 2012).

1.4. Contrast Perception

There exist numerous formulas and definitions of contrast. In its most basic terms, contrast can be defined as a difference in light intensity between dark and light regions of a visual stimulus; or a measure of differences in luminance between bright and dark regions compared to the mean luminance in an image (Peli et al., 1991; Kwon et al., 2009). Although the most significant property of a visual stimulus is luminance, Hubel and Wiesel (1960s) have shown that central neurons ignore the intensity of a light stimulus, rather the contrast between the light and dark regions are much more important for visual perception because some features of a visual stimulus such as shape, texture and size are determined via contrast within the object or between the object and background (Purves et al., p. 122). Therefore, such claims make research on the contrast perception desirable.

In contrast perception literature, one of the most preferred ways of research is to use sinusoidal or square-wave Gabor grating which is a two-dimensional pattern whose luminance varies according to a sine wave or square wave over one spatial dimension and is constant over the perpendicular dimension. Figure 1.5 shows examples of various gratings. Because Gabor gratings have characteristics that match the fundamental physical qualities of a visual stimulus such as spatial frequency, contrast, size and orientation it is a preferred stimulus in vision research.

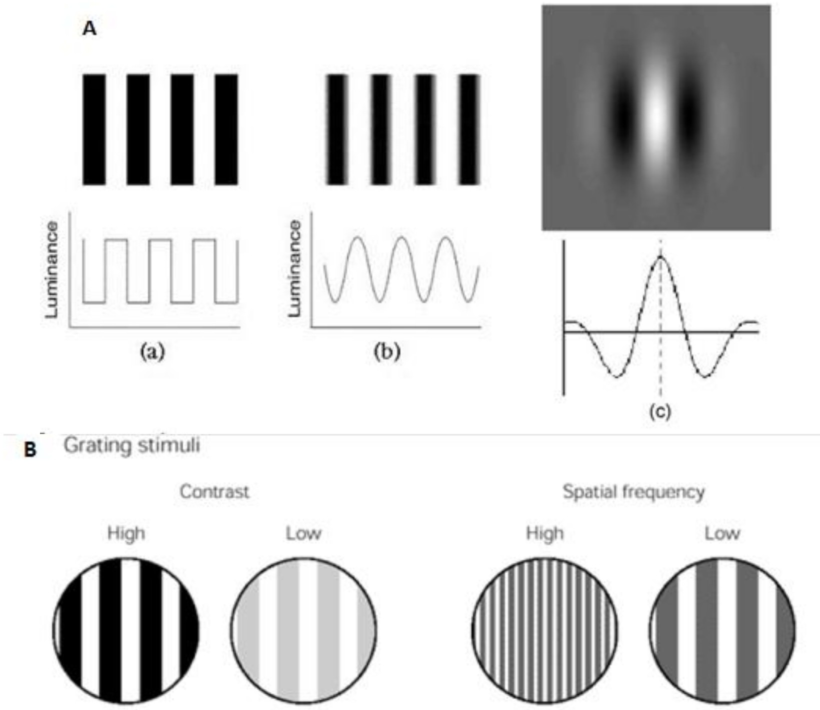


Figure 1.5. Different versions of gratings. A. (a) Square wave grating: square wave modulation of light intensity (b) Sinusoid wave: sinusoid modulation of light intensity (c) Gabor function modulation of light intensity. Gabor functions allow for subtle modulation of light contrast and spatial frequency (retrieved February 23, 2013 from http://read.uconn.edu/PSYC3501/Lecture03/). B. Examples of grating stimuli with different contrast and spatial frequency levels (Kandel, Schwartz, & Jessell, 2000).

Because contrast is based on the difference in light intensity between dark and light regions of a visual stimulus, luminance variation in Gabor grating enables measuring contrast perception easily and accurately. Therefore, Gabor patches are widely used in contrast perception studies as well as research on other fundamental physical qualities of a visual stimulus.

Humans' contrast perception can be measured by psychophysical methods. Psychophysics focuses on the relationship between physical properties of the stimuli and the perceptual responses to these stimuli (Kingdom, & Prins, 2009). There are several ways of measuring perception. Description of what it is perceived or recognition of a stimulus by naming can be shown as the indicators of perception. However, they are not quite helpful to measure the effect caused by the small differences in stimuli. Therefore, it is useful to build a quantitative relationship between the stimulus and perception. One way of doing this is using threshold methods. Absolute threshold or difference threshold can be measured quantitatively. Absolute threshold, also known as detection threshold, refers to the smallest amount of stimulus energy necessary to detect a stimulus whereas difference threshold, also known as discrimination threshold, can be defined as smallest difference between two stimuli that a person can detect. If two threshold methods are compared, reporting detection threshold is easier especially for naïve subjects. Therefore, in vision science, detection threshold (henceforth, threshold-level) studies are very commonly applied. As a result, in early studies, contrast perception had been mostly studied at threshold level. Threshold-level studies have mostly indicated that contrast perception depends on some visual properties and viewing conditions such as spatial frequency, background luminance, and distance. Therefore, such conditions alter the form of contrast sensitivity function (CSF) [1] (Georgeson, & Sullivan, 1975; Van nes, & Bauman, 1966; Chubb, Sperling, & Solomon, 1989; Peli, Arend, & Labianca, 1996; Robilotto & Zaidi, 2004; Peli et al., 1991). Although it is important to know the mechanism of contrast perception at threshold level, high-contrast objects are more commonly found in naturalistic visual environments. Besides, literature indicates significant differences between visual processing near threshold and above threshold (Stephens, & Banks, 1985). Therefore, it is crucial to understand the

[1] The contrast sensitivity function is basically a measure of sensitivity to gratings of different spatial frequencies. Spatial frequency is the thickness of bars in a grating and it is usually defined in terms of number of cycles per degree of visual angle. Sensitivity here can be defined as the reciprocal of the minimum contrast required to detect gratings with different spatial frequencies (George, & Sullivan, 1975; Stephens, & Banks, 1985).

processes of the visual system in relation to suprathreshold contrast perception[2]. Based on this need, Georgeson and Sullivan conducted a research whose findings were seminal on suprathreshold contrast perception literature (Georgeson, & Sullivan, 1975). They showed by using contrast matching technique[3] that on the suprathreshold level of contrast, CSF is not affected by background luminance, spatial frequency or distance. In other words, when the contrast value is above detection threshold, difference in some visual qualities such as spatial frequency or luminance do not damage matching the apparent contrast of two patterns successfully although significant differences are observed in contrast matching studies at the threshold level. As a result they concluded that, suprathreshold contrast perception is independent of some factors such as luminance, spatial frequency and the position on the retina, and called this new phenomenon *contrast constancy*.

Although findings of many research have supported the results of Georgeson and Sullivan (1975), other researchers have had doubts on the phenomenon of contrast constancy. For instance, Peli and his colleagues claimed that different spatial frequencies with the same luminance values cause contrast constancy, however whether different luminance values with the same spatial frequency affect contrast perception or not is not known (Peli et al., 1991). Although researchers including Georgeson and Sullivan tested the same question, Peli et al. thought that because those studies demonstrating contrast constancy were done under *unnatural viewing conditions* such as dichoptic viewing; they may not be applicable to more natural viewing conditions. Therefore, they conducted a study on suprathreshold contrast perception by using free viewing condition. Their results showed that contrast constancy is affected by luminance on suprathreshold levels. They demonstrated that

[2] The term suprathreshold is used to mean that physical properties of a stimulus are above detection threshold.

[3] The contrast matching technique is a psychophysical method used to measure perceived contrast. In this technique, a standard contrast level of a grating is defined, and participants are asked to match the contrast of another grating with the standard grating.

especially in low luminance values the contrast perception is affected by the luminance level of background which is also equal to mean luminance of grating. Their figures of results are represented below (see Figure 1.6 and Figure 1.7) (Peli et al., 1991).

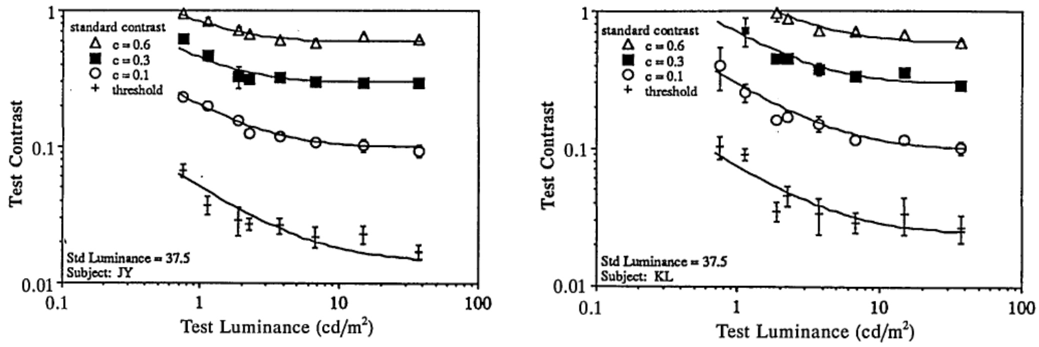


Figure 1.6. The results of Peli et al. (1991) from two participants. Contrast matching paradigm was used in the study. The figure shows that changes in mean luminance cause changes in perceived contrast.

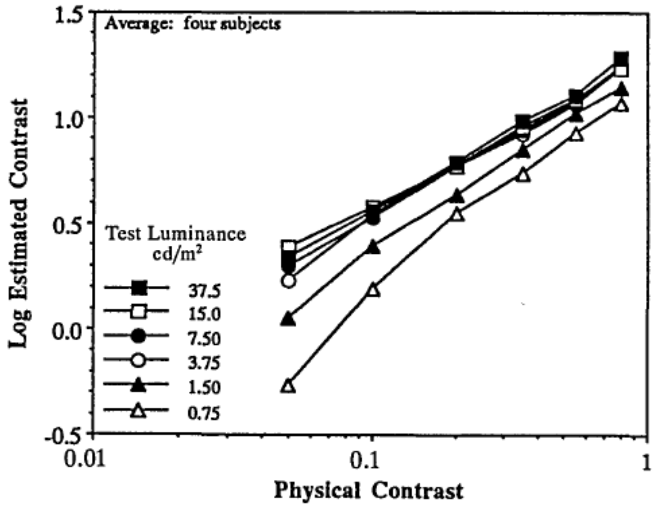


Figure 1.7. Results of Peli et al. (1991) from the avarage values of four participants.

Figure shows the effect of luminance on contrast perception. It indicates that the difference between physical and perceived contrast increases in lower luminance and contrast levels.

More detailed results have been obtained by Peli et al. (1996) in which spatial frequency was also used as a variable in addition to luminance and contrast. Their results demonstrated that in terms of contrast perception high-frequency gratings are much more affected by changes in luminance value compared to the low-frequency gratings (Figure 1.8) (Peli, Arend & Labianca, 1996).

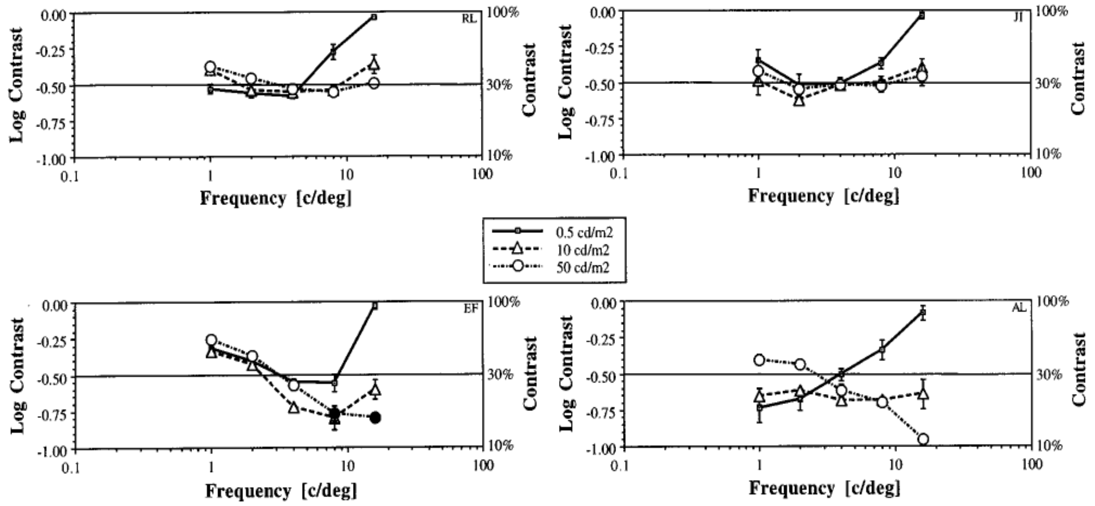


Figure 1.8. The results of Peli et al. (1996) obtained from four participants. The figure shows the effect of spatial frequency and luminance on contrast perception. Y axis refers to the perceived contrast of stimulus with 30 per cent of constant contrast. The figure demonstrates that the greatest difference between the high and low spatial frequencies is observed for the lowest luminance value.

Peli and his colleagues' findings have been reproduced by other researchers (e.g. Kilpeläinen, Nurminen, & Donner, 2011; Kilpeläinen, Nurminen, & Donner, 2012). Studies have shown that contrast constancy approach may not reflect the underlying mechanism of the visual system under natural viewing conditions; instead it is the result of some unnatural experimental techniques used in vision research. As a result, later evidence has suggested that suprathreshold contrast perception is affected by physical luminance value; and the combination of luminance value and the spatial frequency.

1.5. Scope of the Present Study

The present study aims to investigate the role of bottom-up and top-down processing of luminance in contrast perception. In particular, since it is thought that visual illusions occur as a result of top-down processing by means of visual context, the present study investigates how luminance in context affects contrast perception by using a brightness illusion. Because luminance and contrast values influence visual performance on various tasks, we should first figure out how these properties are processed and how they interact to understand relatively complex visual processes. By doing this, due to the inconsistency between sensory input and perception, studying with isolated gratings alone is not sufficient to understand the mechanism. Therefore, we should investigate the luminance and contrast perception in visual context. Although effects of context on luminance perception are widely studied in literature, there are much fewer studies investigating context effects on contrast perception. Therefore, our aim is to demonstrate whether contextual (top-down processing) or stimuli-based changes (bottom-up processing) affect contrast perception. To investigate this, we chose luminance as the variable because with the help of context it is easy to create perceptual differences by using the same physical values as mentioned above. In other words, generating stimuli that have the same luminance but different brightness value is easier. Moreover, we know the effect of physical luminance on contrast perception from the study of Peli et al. However, we do not know whether (perceived) brightness or (physical) luminance dictates contrast perception because in previous studies only the physical value of the luminance has been manipulated and brightness value has changed accordingly. Brightness has not been taken into account in a controlled way. Therefore, the proposed study aims to fill this gap in the literature. As a result the research question of the present study is whether luminance value or the brightness value causes changes in perceived contrast.

Moreover, previous research has shown that luminance and contrast are processed via different networks in the brain (Dai & Wang, 2012; Geisler, Albrecht, & Crane, 2007; Mante, Frazor, Bonin, Geisler, & Carandini, 2005; Kilpeläinen, Nurminen, & Donner, 2011). However, if changes in one of them affect the perception of the other as mentioned above, then these networks should interact somewhere in the process of visual perception. This interaction may occur in lower levels like retina or LGN or in higher levels of the perception process. Depending on the literature findings, if luminance has an effect on contrast perception, then the same contrast value on the backgrounds, whose luminance values are equal, but brightness values are different, should be perceived as same, and should not be affected by changes in brightness. Consequently, the interaction between the contrast and luminance networks occurs in a lower level of perception process because neuronal activations in lower levels like retina and LGN respond mostly to physical properties of a light stimulus, not perceived properties (Kandel, Schwartz, & Jessell, 2000 p.533). However, if brightness has an effect on contrast perception, then the perceived contrast of gratings on the target squares should be different. If this would be the case, then it indicates that the interaction between the networks occur in higher perceptual levels because despite the equal luminance values differences in brightness seems to occur in higher level process (Pollen, 1999). In literature, there are some experiments conducted and computational modelling studies aimed to clarify this interaction. However, any direct measurement could not have been carried out so far. Therefore, the present research is the first study in the literature, as of our knowledge, in terms of directly measuring the interaction between the contrast and luminance networks and researching on the effect of brightness on contrast perception.

The present study has employed psychophysics and functional magnetic resonance imaging (fMRI) methodologies. Three experiment series have been performed. An illusory picture which was created especially for this study has been used to manipulate luminance and brightness at the same time. The illusory picture gave the opportunity to create some patches (context squares) on the stimulus which have exactly the same luminance values but perceived differently. Therefore, the first experimental series were intended to measure brightness values of the context squares (CS) with several psychophysical methods based on subjective judgment. In the second experimental series, square-wave gratings have been used as a visual stimulus to measure to the perceived contrast. Gratings were placed on the context squares and the perceived contrast across participants has been measured based on subjective judgment. This experimental design allowed us to see how perceived contrast is affected by changes in brightness value. Afterwards, isolated backgrounds whose luminance is determined per observer based on the results of the first experimental series were created. This provided an opportunity to compare the effect of the same brightness values on contrast in context and in isolated environment. In the third experimental series, fMRI was conducted to see whether the difference in brightness correlate with any changes in brain activity in a particular brain region. Each experiment series will be explained in detail as separate chapters below.

CHAPTER 2

EXPERIMENT SERIES I

BRIGHTNESS MEASUREMENT OF CONTEXT SQUARES

The purpose of this measurement was to define which overall image luminance and contrast values make the illusion strongest. According to this, increase in the difference of perceived brightness between the context squares means the illusion is getting stronger. To understand this, four experiments with two different psychophysical methods were conducted by using different procedures which are mostly preferred in previous studies. Because of the variety in methods and procedures in literature to investigate the brightness in context, it is intended to compare results from different designs and psychophysical methods to see the consistency among methods. Therefore, method of adjustment (MoA) and two-alternative forced-choice (2AFC) method were used in the measurement. The details are explained below.

METHOD

Participants

Three male and five females participated in the luminance adjustment experiments. All participants were familiar with the vision research and the concept of luminance and contrast. They were also aware of the brightness illusion in the present stimulus; however, being aware of such a brightness illusion cannot help to suppress it. In addition, the hypothesis about the effect of illusion on contrast perception and expectations were not declared to them. Therefore, participant's awareness was not considered likely to be a confound. They participated in the study voluntarily. The mean age was approximately 23.4 and the range was from 21 to 26. Each participant provided informed consent and the experimental protocol was approved by the Ethics Committee of Bilkent University.

Stimuli and Apparatus

The experiments were conducted in the psychophysics laboratory which is dedicated to visual research experiments of UMRAM (National Magnetic Resonance Research Center) located in Bilkent University. The stimuli were represented on a computer screen. Special software was designed by using an open source package, which is created by Huseyin Boyacı, on the Java programming platform (www.bilkent.edu.tr/˜hboyaci/PsychWithJava/index.html) for the present study. For every participant, a PC and CRT monitor that is 22" were used to run the software. The monitor was calibrated using a Cambridge Research Systems Ltd. SpectroCAL colorimeter. The screen was viewed from a distance of 75 centimeter on a chair in front of the table on which CRT monitor is located. A chin rest was used in order to hold the participant's head steady. Responses were taken via a keyboard.

Procedure

An illusory stimulus which was generated specially for the present study is used in all experimental series (see Figure 2.1). There are two squares on the illusory stimulus (context squares) whose brightness values have been perceived as different by all observers despite their luminance values were exactly the same. Therefore this illusory stimulus gave the opportunity to investigate the consequences of contrast perception caused by difference in brightness by keeping luminance constant. The height and width of the original version of the illusory stimulus were 512 pixels (12.2 degrees visual angle).

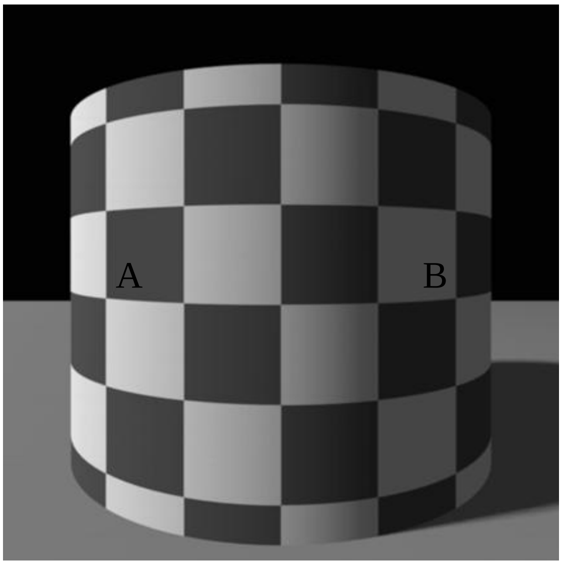


Figure 2.1. The illusory stimulus used in the study. Squares on which A and B (context squares) is written have the same physical luminance value.

Eleven different stimuli with different overall image contrast and luminance values were used in the study. Actual luminance values of the context squares are ranged from 1.64 to 26.15 candelas per square meter. Examples of stimulus are shown below (see Figure 2.2). Only the version that light comes from the left side was used throughout the experiments. Therefore, the right context square was always perceptually brighter than the left context square.

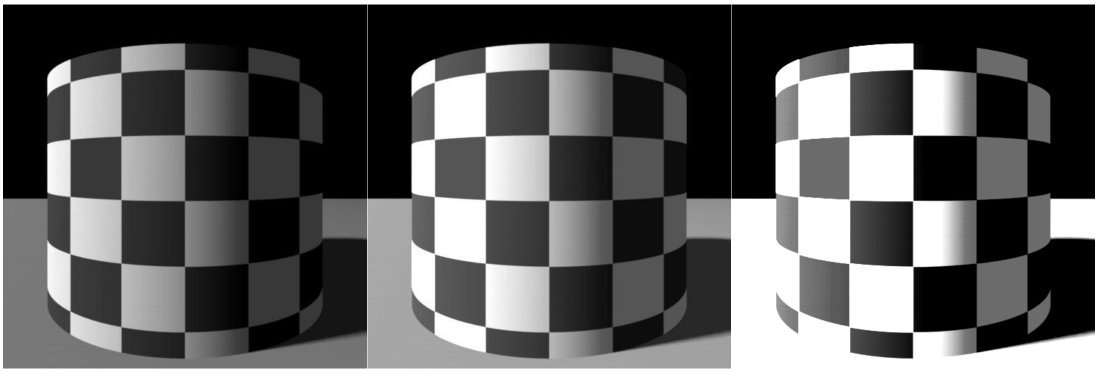


Figure 2.2. Examples of stimulus with different overall image luminance (in cd/m^2) and contrast values.

Details about the different psychophysical designs and experimental procedures are explained below separately.

A. Method of Adjustment on a Distant Background: In this experiment, an adjustable patch that is isolated from the illusory stimulus was presented on the screen. The size of the patch was approximately the same with the size of the context squares. The patch was located on a noisy-pattern rectangle (See Figure 2.3). The luminance value of the patch could be adjusted; and its starting luminance was determined randomly at the beginning of each trial. The task of the participant was to match the brightness of the patch with the brightness of the one of the context squares. Instructions about which context square should be considered in that particular trial was given by writing "left" or "right" on the noisy rectangle. In this experiment every illusory stimulus which has different luminance values was represented five times for the left context square and five times for the right context square. As a result, a single run of the experiment contains 110 trials which contain representation of 11 stimuli for 10 times of each.

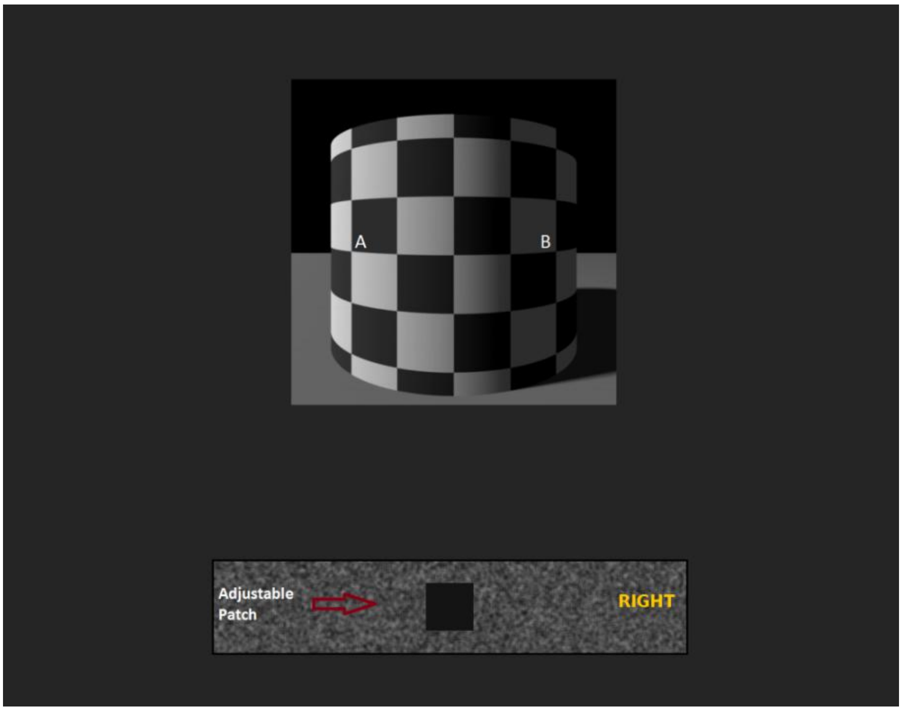


Figure 2.3. Experimental design used in method of adjustment on distant background. The arrow; the letters A, and B; and the writing of adjustable patch were not shown on the screen during the experiment. If it is written left on the screen, luminance of adjustable patch was matched with the context square A, whereas right corresponded to context square B.

B Method of Adjustment on Contextual Background: In this step, two experiments with different designs and psychophysical methods were applied, and participants were asked to match the brightness of patches with the context squares' brightness. Differently from the Experiment 1.1, comparison patch was also on the context square in this design. Therefore, the adjustment patch could also be affected by context. A single run of the experiment contains 110 trials which contain representation of 11 stimuli for 10 times of each. Details of experiments are explained below.

Method of Adjustment with a circular patch: A circular patch whose luminance value can be adjusted was located on one of the context squares (see Figure 2.4). On which context square adjustable patch is located was decided pseudo-randomly.

Participants' task was to perceptually equalize the brightness of circular patch to the brightness of the other context square which the patch was not located on. For example, if the circular patch is on the left context square, participant should match the brightness of the circular patch with the brightness of the right context square.

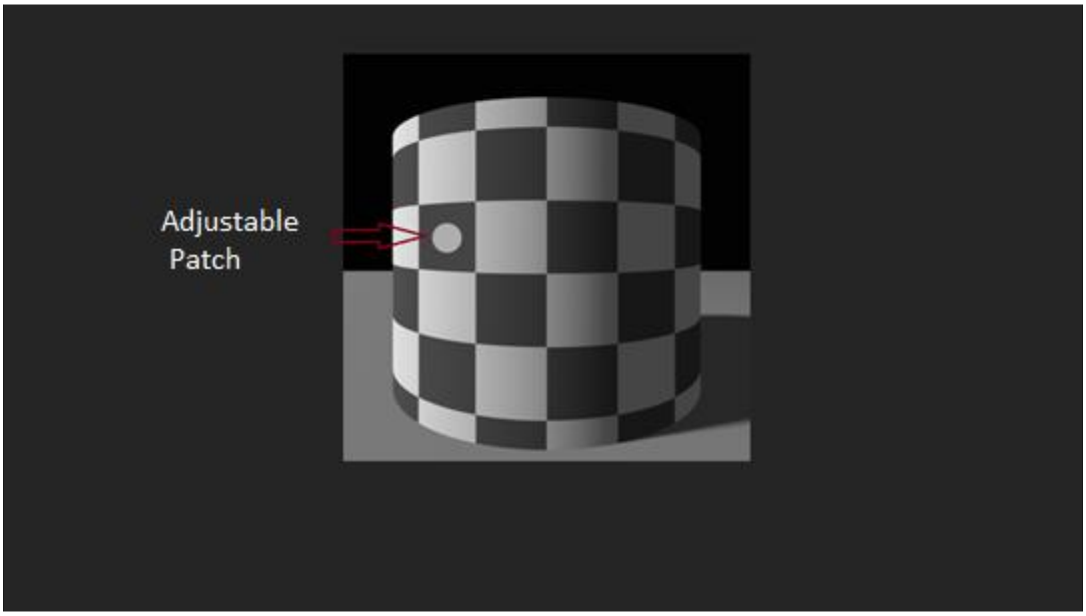


Figure 2.4. Method of adjustment task with a circular patch. The arrow and the writing of adjustable patch are just for demonstration; actual experimental screen does not consist of them. The patch is pseudo-randomly placed on one of the context squares. The task is to match the luminance of the patch with the luminance of the context square on which patch is not placed.

Method of Adjustment with whole covering patch: This experiment was similar to the Experiment 1.2.A. However, instead of a circular, an adjustable patch covering one of the context squares completely was used. In other words, the patch covered the context square; and it seemed like the luminance of one of the context square can be adjusted. In each trial, which context square the patch is located on was decided pseudo-randomly. Participants' task was to perceptually equalize the brightness of the context square to that of the patch (see Figure 2.5). A single run of the experiment contains 110 trials which contain representation of 11 stimuli for 10 times of each.

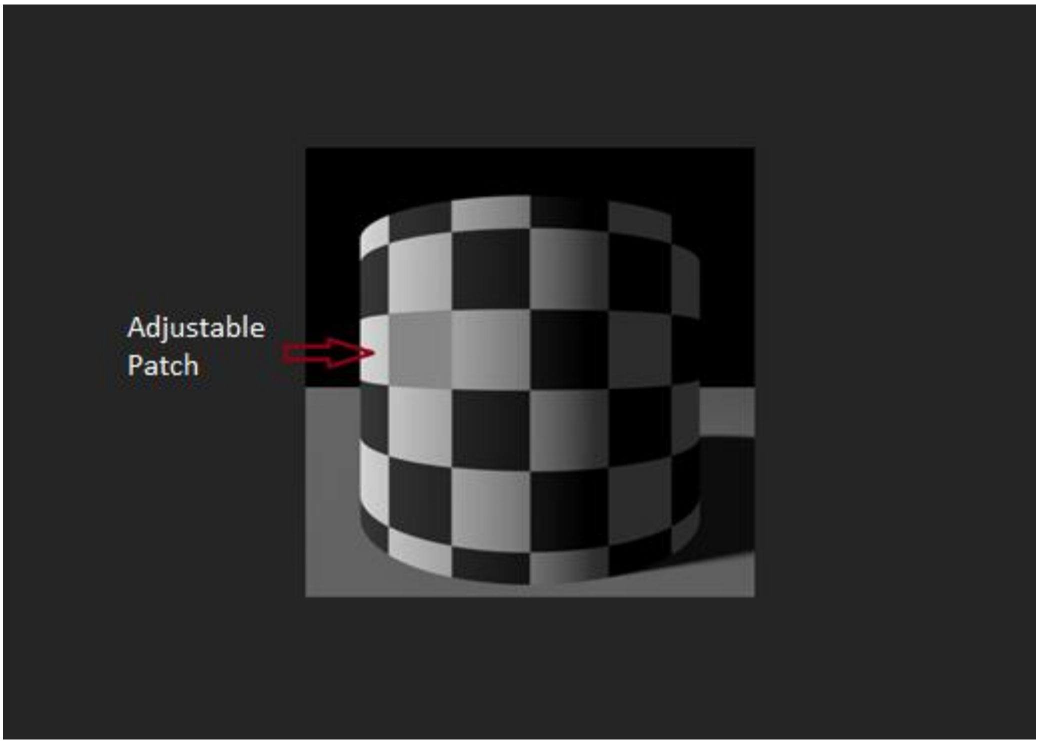


Figure 2.5. Method of adjustment task with a covering patch. The arrow and the writing of adjustable patch are not shown on the actual experiment screen. The adjustable patch is exactly covered one of the context squares randomly. The task is to match the luminance of patch with the luminance of uncovered context square.

C. Adaptive two-alternative forced-choice (2AFC): Two experiments were conducted in four sessions by using 2AFC method. In the first experiment a circular patch; in the second experiment a covering patch was used. Actually, design of the experiments was very similar with the Experiment 1.2.A and 1.2.B. However, luminance value of patches was not adjustable in these experiments; these patches (test patch) had pre-defined luminance value. Participants were asked to decide whether the test patch or the context square is darker. For example, if the test patch is on the left context square, it was asked whether the test patch or the right context square is darker. In the first session, test patch was always on the left context square;

and in the second session the circular patch was always on the right context square. In the third session, covering patch was located on the left context square; and in the fourth session it was located on the right context square; as in Experiment 1.2.B. Although all of the 11 stimuli with different luminance values were used in previous studies; in these 2AFC experiments two of the eleven stimuli which lead to stronger illusion were used. The physical luminance values of the context squares in the used stimuli were 2.86 and 17.4 cd/m^2. Although both of the two selected stimuli are represented randomly in a session, two different one up – one down staircases were applied for each of them. At the beginning of a session, luminance values at which staircases start were decided based on the perceived brightness values of context squares obtained from the results of the experiments 1.1 and 1.2. If participant had given the correct answer, the difference between the luminance values of the test patch and the context squares were decreased by approximately 0.5 cd/m^2 whereas it was increased by 0.5 cd/m^2 as a result of a wrong answer. There were 30 trials for each staircase; therefore one session consisted of 120 trials due to four staircases.

As a result of all the experiments mentioned above, the brightness values of the context squares can be defined and the difference in brightness values caused by various designs and methods can be observed if there is. Therefore, the results of the present study contribute also the brightness perception literature by comparing different methodologies.

RESULTS

The data obtained from the brightness measurement and contrast perception measurement experiments were converted for each participant to a divergence score by extracting physical value of the stimulus from its perceived value. Analysis was implemented by using these scores. Therefore, the value “0” corresponds to the physical value of the stimulus. If perceived value is negative, it means that perceived value of the stimulus is lower than its physical value. If perceived value is positive, then it means that perceived value is higher than its physical value. The same rationale is valid for the figures below.

MoA with contextual and distant backgrounds data were analysed by using repeated measures ANOVA and Bonferroni corrected pairwise comparisons in SPSS. Threshold analysis for the 2AFC data was implemented in OCTAVE; and t-test analysis was conducted in SPSS. The analysis of the brightness measurement experiments was performed on mean divergence scores based on subjective judgment results across eight participants. There were three factors of the experiment which are method (three levels), luminance (11 levels), and the position of CS (two levels). 2AFC data were analysed separately. Data obtained from different experimental designs (MoA on distant background, MoA with circular patch, and MoA with covering patch) were compared. Results show that the experimental design has an effect on brightness (main effect of method: $F(2,14)=51.78$, $p<0.001$). Bonferroni corrected pairwise comparisons demonstrated that all the methods used in the study have yielded significantly different results compared to each other. When MoA with distant background (M = 0.16, SD = 0.54) was used (see Figure 2.6) the difference between the brightness of context squares was smallest compared to both MoA tasks with contextual background. The difference was significantly increased due to the MoA task with circular patch (M = 6.07, SD = 0.94) (see Figure 2.7), and more with covering patch (M = 11.43, SD = 1.3) (see Figure 2.8). In addition, data obtained from 2AFC task with circular patch have resulted in similar results with MoA with circular patch; and the results of 2AFC task with covering patch were similar to those with MoA task with covering patch (see Figure 2.9., and Figure 2.10.) In other words, the difference between the brightness values of context squares was biggest for the 2AFC task with covering patch and MoA with covering patch method compared to other methods.

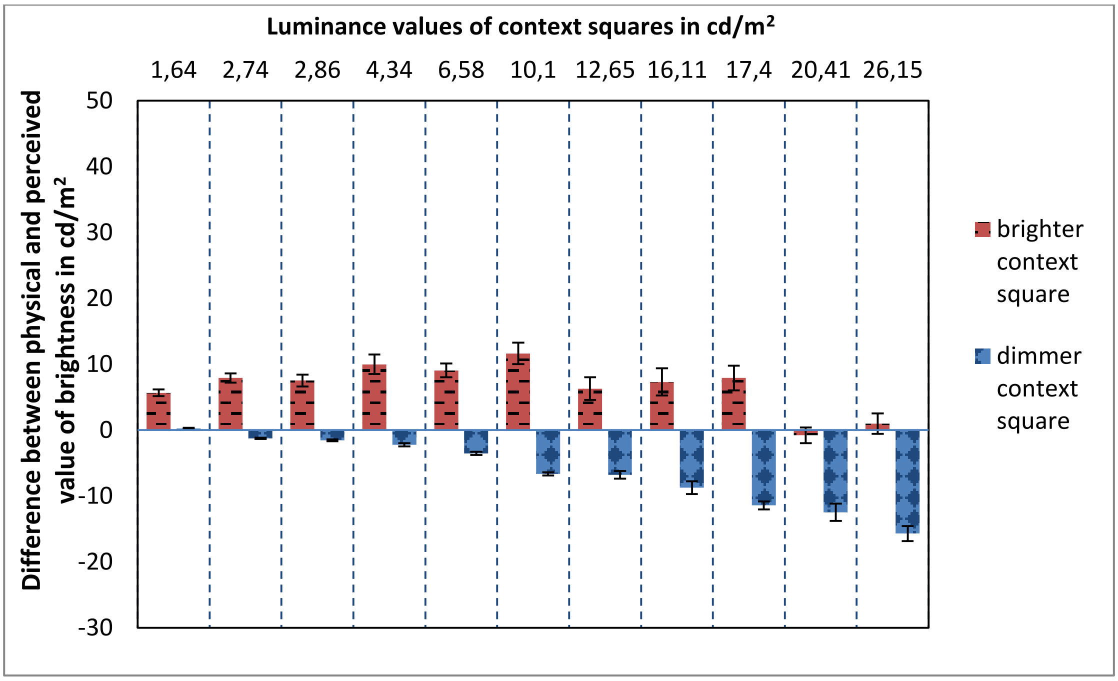


Figure 2.6. Mean divergence scores of brightness values through MoA on distant background. The value "0" corresponds to exact match with the luminance value of the context squares. Error bars show +/-1 SE.

Figure 2.6. shows the results obtained from MoA on distant background task across eight participants. Mean divergence scores for luminance adjustment of context squares are displayed across 11 illusory stimuli which have different luminance values. It can be seen in the figure that although both context squares have the same physical luminance values, they were perceived as significantly different (main effect of context squares: $F(1,7)=159.52$, $p<0.001$). For all the luminance values, separate Student t-test was implemented for brighter and dimmer CSs. Results show that brightness of CSs are significantly different than each other for all of the luminance values (see Appendix 1 for detailed t-test results). Although the difference between the brighter and dimmer CS is significant, MoA on distant background task has resulted in the smallest difference compared to other methods. In other words, results of the present study indicate that MoA on distant background task is the less affected method from the illusory context.

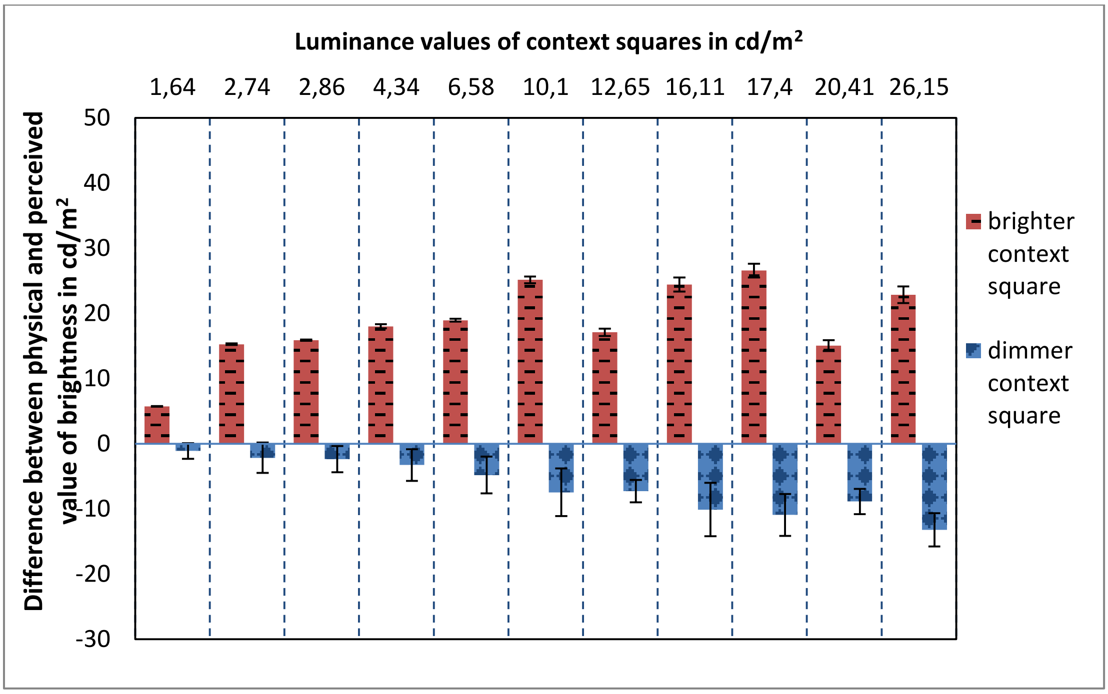


Figure 2.7. Mean divergence scores of brightness values through MoA with circular patch. The value "0" corresponds to exact match with the luminance value of the context squares. Error bars show +/-1 SE.

Figure 2.7. shows the results obtained from method of adjustment task with circular patch. The figure demonstrates the mean divergence scores for luminance adjustment of context squares of 8 participants across 11 luminance levels. Pairwise comparison results demonstrate that the difference between brightness values of two CSs are significantly greater than previous task (M = 6.07, SD = 0.94, $p<0.001$). Also, separately implemented Student t-test results indicate that brightness of CSs is significantly different than each other for all of the luminance values (see Appendix 1 for detailed t-test results).

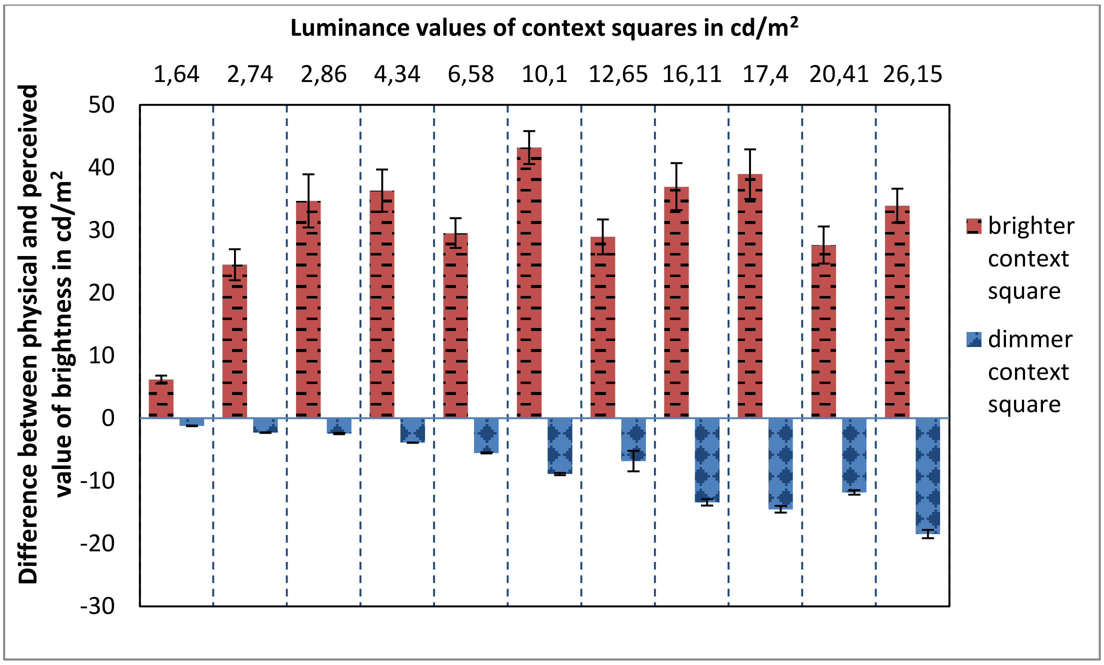


Figure 2.8. Mean divergence scores of brightness values through MoA with covering patch. The value "0" corresponds to exact match with the luminance value of the context squares. Error bars show +/-1 SE.

Figure 2.8. shows the results obtained from method of adjustment task with covering patch. The figure displays the mean divergence scores of brightness values of CSs for 8 participants. It can be seen that difference between brightness values of context square are significantly greater than previous two tasks (*M* = 11.43, *SD* = 1.3, $p<0.001$). For all the luminance values, separate Student's t-test was implemented for brighter and dimmer CSs. Results show that difference between the brightness values of brighter and dimmer CSs are significantly different than each other for all of the luminance values (see Appendix 1 for detailed t-test results).

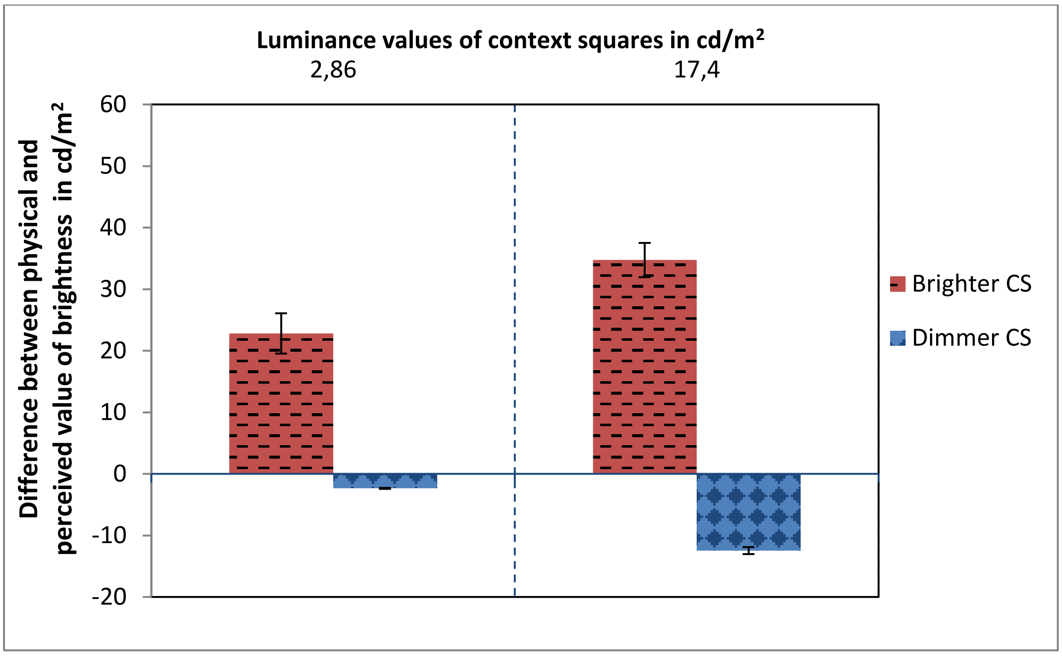


Figure 2.9. Mean divergence scores of brightness values of context squares obtained from 2AFC task with circular patch. Error bars show +/-1 SE.

Figure 2.9 displays the results obtained from 2AFC task with circular patch. The figure shows the mean perceived brightness value of context squares of 7 participants across 2 stimuli which have 2.86 and 17.4 candelas/m^2 luminance values. Analysis for the 2AFC data was implemented in OCTAVE; and t-test analysis was conducted in SPSS. The results of this task seemed to be similar with the method of adjustment task with circular patch except perceived values for brighter CSs are a bit higher than the MoA task. Results indicate that the difference between brightness values of two CSs for 2.86 cd/m^2 luminance level ($t(6)=7{,}57$, $p<0.001$), and the difference between brightness values of two CSs for 17.7 cd/m^2 luminance level ($t(6)=14.58$, $p<0.001$) were statistically significant. Further Student's t-test analysis was also implemented to see the effect of luminance on brightness illusion and it was shown that increasing the luminance increases the illusory effect (the perceived value of the stimulus diverges more its physical value) for both brighter CSs ($t(6)=-7{,}32$, $p<0.001$) and dimmer CSs ($t(6)=19{,}10$, $p<0.001$).

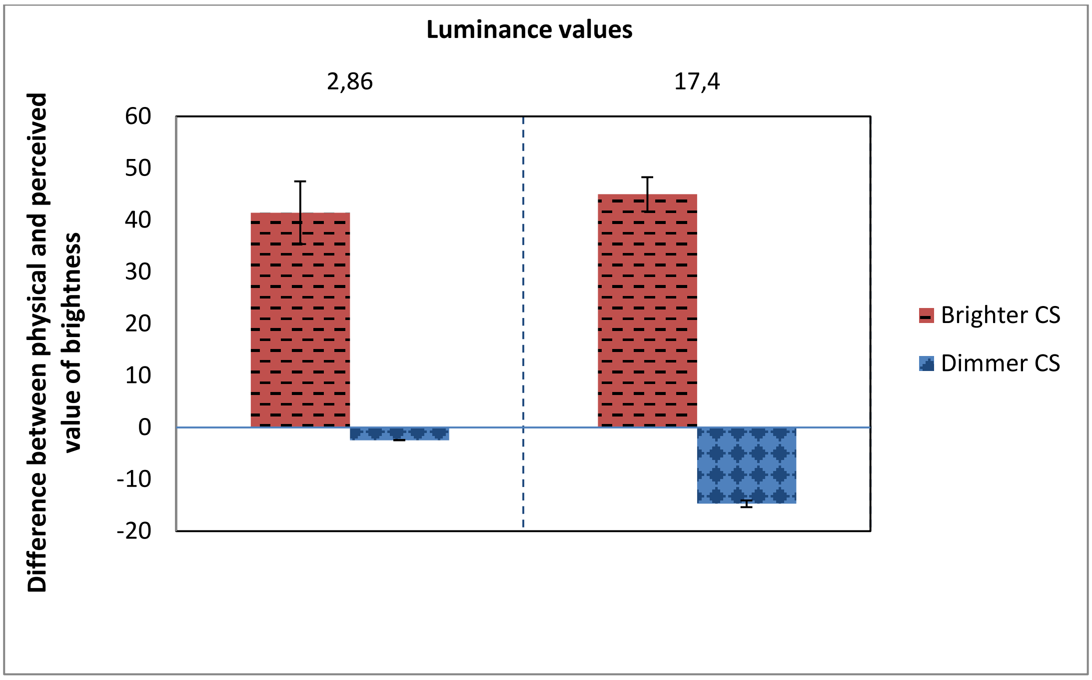


Figure 2.10. Mean divergence scores of brightness values of context squares obtained from 2AFC task with covering patch. Error bars show +/-1 SE.

Figure 2.10 demonstrates the results obtained from 2AFC task with covering patch. The figure shows the mean perceived brightness value of context squares of 7 participants across 2 stimuli which have 2.86 and 17.4 candelas/m^2 luminance values. The results of this task seemed to be similar with the method of adjustment task with covering patch except perceived values for brighter CSs are a bit higher than the MoA task. Results indicate that the difference between brightness values of two CSs for 2.86 cd/m^2 luminance level ($t(6)=7.23$, $p<0.001$), and the difference between brightness values of two CSs for 17.7 cd/m^2 luminance level ($t(6)=15.3$, $p<0.001$) were statistically significant. Further Student t-test analysis was also implemented to see the effect of luminance on brightness. It was shown that increasing the luminance increases the illusory effect (the perceived value of the stimulus diverges more from its physical value) for dimmer CSs ($t(6)=20.16$, $p<0.001$) but it does not have any effect on brighter CSs ($t(6)=-1.11$, $p>0.05$). It was shown that increasing luminance changes the effect of illusory context for brighter

CSs for the 2AFC task with circular patch, but it does not have any effect on brighter CSs for the 2AFC task with covering patch.

SUMMARY AND DISCUSSION

Results of experiment series 1 indicate that brightness judgement is affected by the experimental design. Although using the method of adjustment or 2AFC methods did not significantly influence the personal judgements, the location and the size of the adjustable patch directly affect the judgement. If adjustable patch is also located on the illusory stimulus, the illusory effect becomes greater. In addition, if adjustable patch covers the whole illusory region the effect becomes greater compared to a smaller covering.

In all of the conditions, and for all the luminance values the brightness of the context squares whose luminance values are the same were significantly different than each other. Besides, increase in luminance level make the difference between the brightness values of each context square greater. To sum up, the illusory effect in the present stimulus was so robust that it could be observed significantly in any condition used. Changes in method, luminance or design only affect the strength of the effect.

CHAPTER 3

EXPERIMENT SERIES II

MEASUREMENT OF PERCEIVED CONTRAST

In this experiment series, contrast perception across different luminance, brightness and spatial frequency conditions was examined. The gratings were located on the context squares and their perceived contrast was measured by using various methods. This gave the opportunity to compare the consistency among different methodologies used in the contrast perception literature.

METHOD

Participants

The data of contrast perception experiments was gathered from six participants who also participated in the first experiment series. Therefore, all information about participants mentioned above is valid.

Stimuli and Apparatus

The contrast perception experiments were conducted in the same laboratory and with the same circumstances as the first experiment series.

Procedure

A rectified square-wave grating was used to measure contrast perception (see Figure 3.1). Physical contrast of gratings was measured with Michelson Contrast which is formulated as $\mathbf{C=(L_{max}-L_{min})/(L_{max}+L_{min})}$ where L_{max} and L_{min} corresponds maximum and minimum luminance values respectively (Peli, 1990). The standard contrast of gratings is set at one of three levels; 10, 30, 60 per cent; and the standard frequency is set at 2.5, 5, 10, or 20 cycles/degree. Instead of adjustable patch, another grating (adjustable grating) whose contrast can be adjusted was presented on the screen.

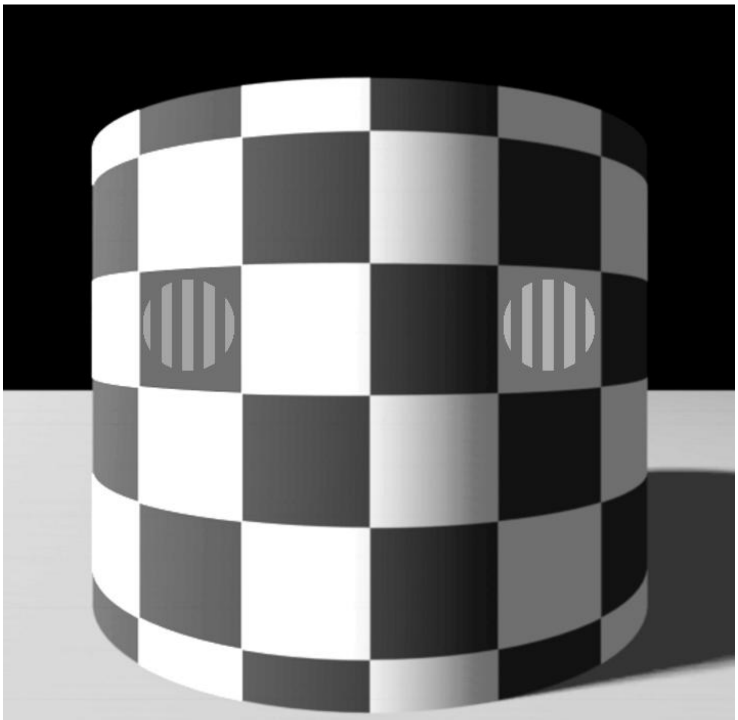


Figure 3.1. Presentation of the gratings.

The contrast of the adjustable grating was determined randomly. All physical properties except contrast of the actual grating (tested grating) and the adjustable grating were always same including the frequency. The frequency of gratings was determined before the session and one frequency level was used throughout the entire session. Therefore, experiments were repeated four times by using different frequency values to assess the effect of interaction between brightness and frequency on contrast perception. In these experiments, four illusory stimuli whose context squares had luminance values of 1.64, 2.86, 10.1, and 17.4 cd/m^2 were included. Besides, stimuli were presented randomly in all experiments on a dark grey background. No feedback was given during the experiments. In this experimental series, a bigger version of illusory stimulus (717 pixels; 17 degrees visual angle) was used to make the context squares bigger because it was needed to place gratings on them.

The details about the different experimental designs and procedures are explained below.

A. Method of adjustment of perceived contrast on distant background: The tested grating was located on one of the context squares randomly whereas adjustable grating was located on an isolated noisy background as in Experiment 1.1 (see Figure 3.2). Participants were asked to perceptually equalize the contrast of two gratings. Background luminance value of the adjustable grating was always the same as the actual grating. As indicated above, all the physical properties including frequency of gratings except contrast were identical. All conditions were repeated five times; as a result; because there were three levels of contrast (10, 30, and 60 per cent), four levels of CS luminance (1.64, 2.86, 10.1, and 17.4 cd/m^2) and two positions of context squares (left and right), a session consisted of 120 trials. Four sessions were applied by using different frequencies (2.5, 5, 10, 20 cycles per degree).

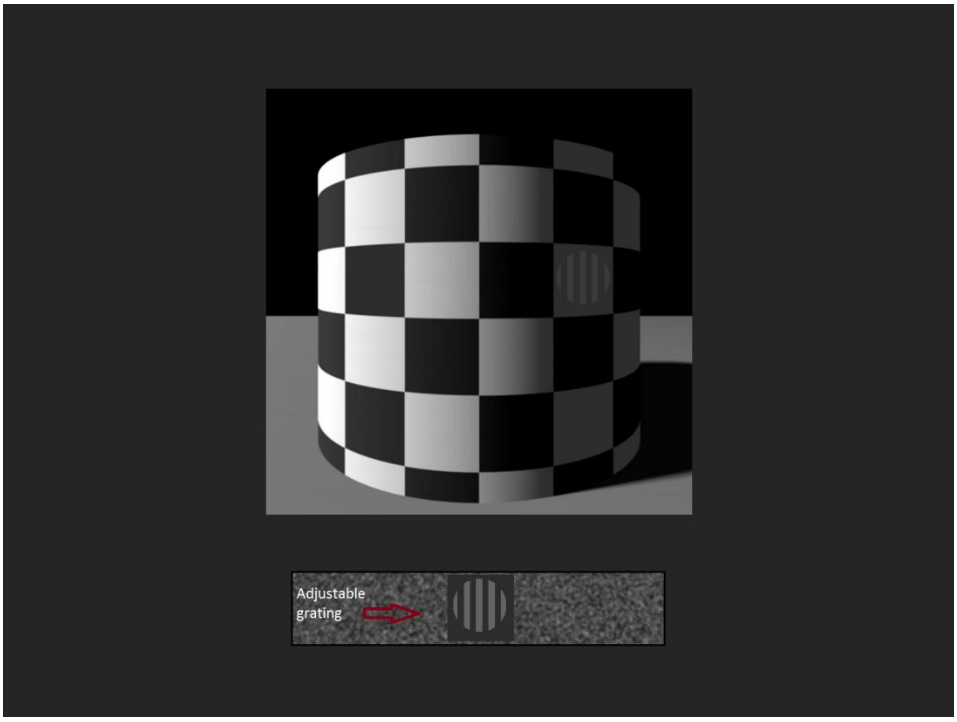


Figure 3.2. Experimental design used in the method of adjustment task of perceived contrast on distant background. The arrow; and the writing of adjustable grating were not shown on the screen during the experiment. Participants' task was perceptually equalizing the contrast of adjustable grating to the contrast of tested grating.

B. Method of Adjustment on Contextual Background: In this task, all the conditions and parameters were the same with the Experiment 2.1.A. However, in this design while tested grating was located on one of the context squares randomly, adjustable grating was located on the other context square. To demonstrate participant which one is the adjustable grating a small black dot was represented on the side of adjustable grating isolated from the stimulus (see Figure 3.3). The aim of this design was to compare perceived contrast of gratings while they were both in context. If context-dependent brightness has an effect on contrast perception, then in this experiment, the difference between perceived contrasts of tested and adjustable gratings should be greater compared to the experiment 2.1.A; because the adjustable grating is not affected from the context in experiment 2.1.A.

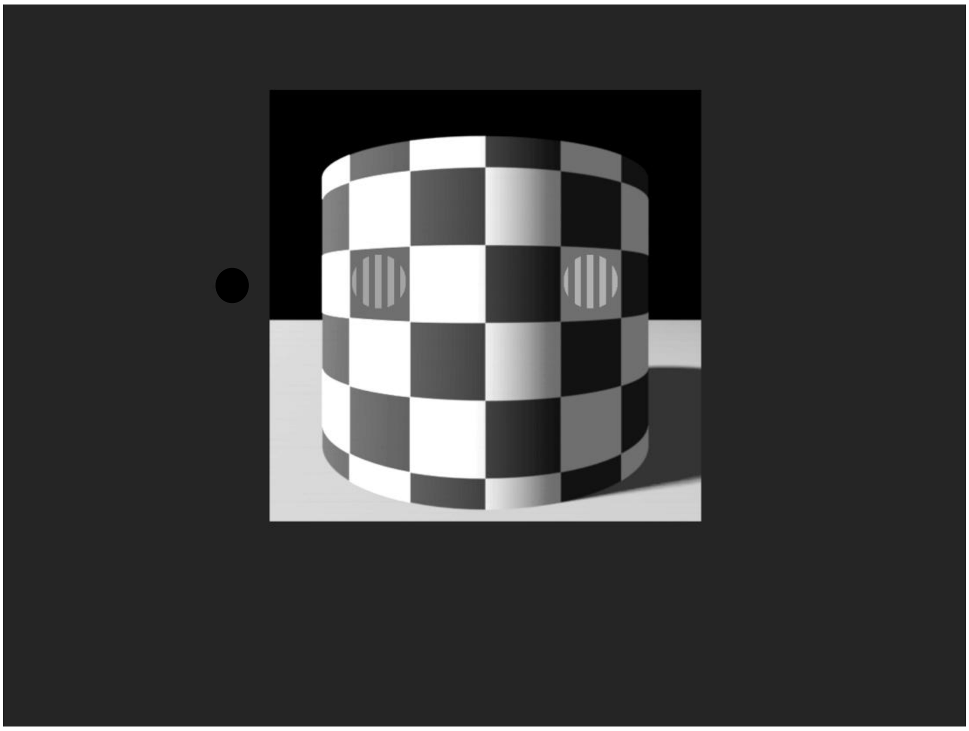


Figure 3.3. Experimental design used in method of adjustment task on contextual background for contrast perception experiment. The black dot is placed to show participants which of the gratings are adjustable. The task was to perceptually match the contrast of two gratings.

C. Measurement of perceived contrast on isolated backgrounds: In this part of the study, illusory stimulus was not used (see Figure 3.4). It was intended to see the effect of luminance value which corresponds to illusory brightness value used in the study on contrast perception. This measurement gives the opportunity to both compare the difference caused by perceptual and physical luminance difference and to replicate the Peli et al.'s study (1996). Depending on the perceived brightness values reported by each participant in the first experiment series, isolated backgrounds specific to each participant were created. Because context squares which have same luminance values were perceived differently in terms of brightness there were two isolated backgrounds for each luminance value (e.g. one of the participants result: setting for the "brighter" CS is 6.74 cd/m^2 and setting for the "dimmer" CS is 1.84 cd/m^2 for the square whose actual luminance is 1.64 cd/m^2).

Figure 3.4. Experimental design used in method of adjustment task on isolated background for contrast perception experiment. The black dot is placed to show participants which of the gratings are adjustable. The task was to perceptually match the contrast of two gratings.

Tested grating was presented on these backgrounds and adjustable grating was presented on the background with luminance values that are corresponding of brightness values decided by participants in the first experiment session. Four luminance values which are 1.64, 2.86, 10.1, and 17.4 cd/m^2 were chosen for this experiment. The contrast values of the tested grating were set at 10, 30 per cent while the contrast of the adjustable patch was determined randomly. Eight different sessions were implemented by using different frequencies (2.5, 5, 10, 20 cycles/degree) and two isolated backgrounds. Participants' task was to match the contrast of two gratings.

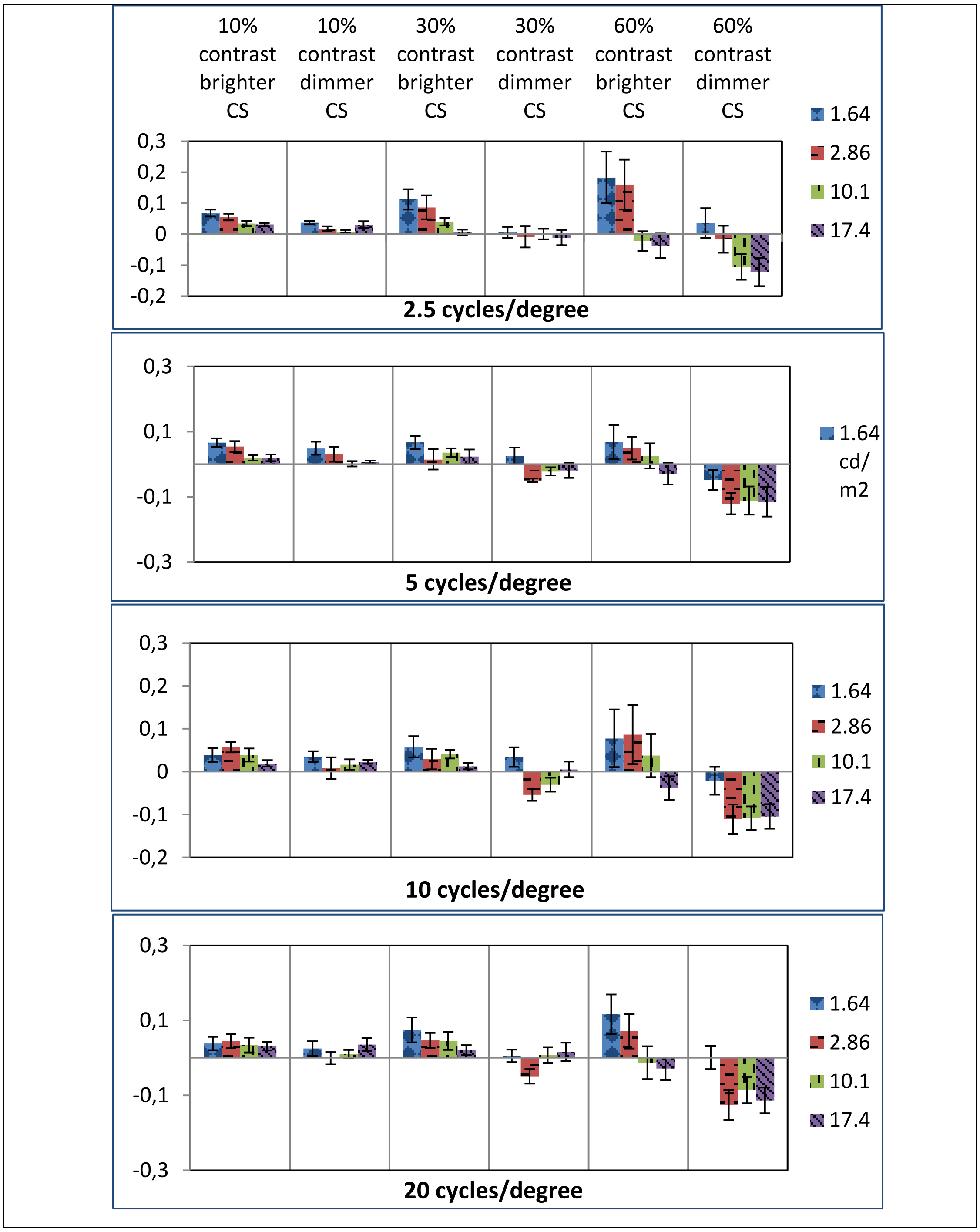
RESULTS

The analysis of the contrast perception experiments was performed on mean divergence scores based on subjective judgment across 6 participants. . Divergence score were preferred for the analysis since it is intended to compare the effect of each luminance and contrast value. For instance, if raw perceived values were used, then the main effect of contrast would always be arbitrarily significant (e.g., perceived contrast for 10% contrast is around 10 per cent whereas it is around 60 per cent for the stimulus with 60% contrast value. In this case, there seem to be 50 per cent difference between the conditions). Percentage changes were not also preferred because it was assumed that the perceptual difference between the 10 and 15 per cent contrast should be relatively equal to the difference between the 60 and 65 per cent contrast (Hamerly, Quick, & Reichert, 1977). If percentage changes would be considered there should be 50% and 8% discrepancy respectively between the physical and the perceived values. In this case, smaller contrast values would seem to be affected by the experimental conditions more. Therefore, instead of raw perceived values and percentage change values divergence scores were preferred for further analysis. Data gathered by various experimental designs (MoA on distant background, and MoA on contextual background) were compared by using repeated measures ANOVA with five factors (experimental design, luminance, frequency, contrast, and context square) in SPSS. Results show that the experimental design used to measure the contrast perception has an effect on perceived value of contrast (main effect of experimental design: $F(1,5)=7.21$, $p<0.043$). Because two different experimental designs were used for methodological concerns, and because it does not serve for the main purpose of the study, the further analysis was done separately for each method to see the effect of other factors on contrast perception more clearly.

D. Results of MoA on distant background task

Although literature demonstrates that frequency is one variable that affects contrast perception, in the present study, MoA on distant background task results indicate that different frequency levels do not have any effect on contrast perception (main effect of frequency: $F(3,15)=1.98$, $p>0.05$) (see Figure 3.4).

Figure 3.5. Mean perceived contrast values of gratings on four different luminance values (1.64, 2.86, 10.1, 17.4 cd/m²) of context squares. Each graph represents the data from different frequency levels. MoA on distant background task. Error Bars show +/-1 SE.



Because main effect of frequency and the interaction of frequency with any other independent variable were never significant, the data gathered from different frequency levels were combined in the following figures for simplification (see Figure 3.6) although in the analysis each level of frequency considered as separate.

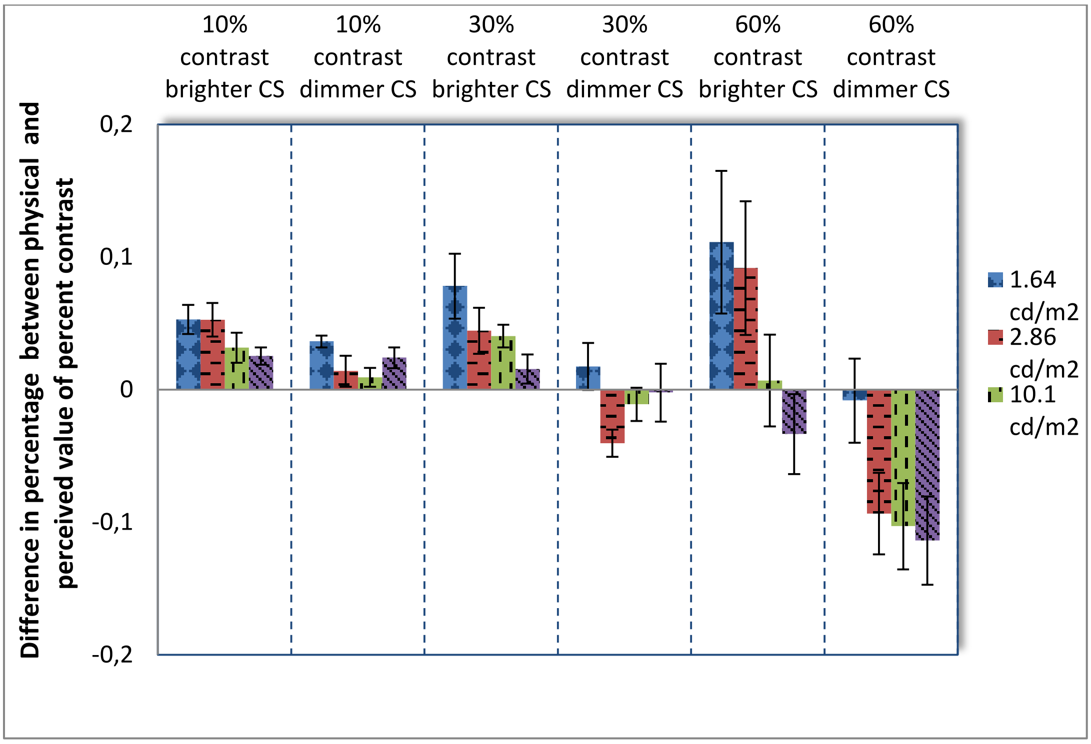


Figure 3.6. Mean perceived contrast values of gratings on four different CS luminance values (1.64, 2.86, 10.1, 17.4 cd/m^2) of context squares. The value "0" corresponds to the physical contrast value. MoA on distant background task. Error Bars show +/-1 SE.

Figure 3.6. demonstrates the results obtained from MoA on distant background task of contrast perception for three different contrast levels and two context squares across 4 illusory stimuli with different luminance values. The figure shows mean perceived contrast scores of gratings located on context squares of 6 participants. The value “0” corresponds to the physical contrast value of the grating. Therefore, negative values indicate that contrast is perceived lower than it is, and positive values indicate that perceived contrast is higher than its physical value. It can be seen in the

figure that for the 10 per cent contrast, perceived value is always higher than its physical value both for dimmer and brighter context squares. However, for the 30 and 60 per cent contrast value, contrast is higher when grating is on the brighter CS, but it is lower when grating is on the dimmer CS. Results indicate that there is a significant difference between contrast perception when the grating is put on dimmer CS and brighter CS (main effect of CS: $F(1,5)=15.85$, $p<0.01$). Also, different luminance levels seem to change the perceived value of contrast significantly (see Appendix 2 for detailed t-test results). However, although main effect of luminance is not significant, interaction between luminance and CS is statistically significant ($F(3,15)=14.83$, $p<0.01$).

To show the effect of different CSs on perceived contrast clearly, the difference between perceived contrast values of grating on brighter and dimmer CSs are demonstrated on another figure (see Figure 3.7.)

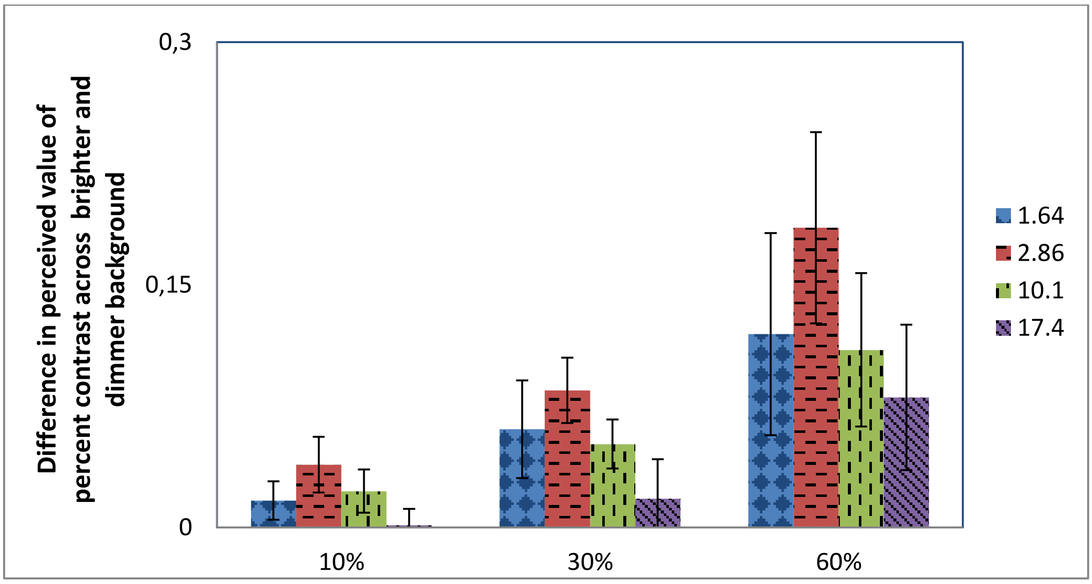


Figure 3.7. Difference between the perceived contrasts of gratings on brighter and dimmer context squares across four different luminance and three different contrast values. MoA on distant background task. Error Bars show +/-1 SE.

Results indicate that different contrast values does not have any effect on perception (main effect of contrast: ($F(2,10)=2.61$). However, the interaction between contrast and CS is statistically significant ($F(2,10)=11,73$, $p=0.017$). It can be seen in the figure that increase in the physical contrast value increases the difference between the perceived contrast values of gratings on brighter and dimmer CSs. As a result, it can be interpreted that in higher contrast values the effect of brightness on perceived contrast increases.

E. Results of MoA on contextual background task

As in the brightness experiments, although both MoA on distant background task and MoA on contextual background task have yielded similar results, illusory stimuli affect the MoA on contextual background task more compared to MoA on distant background task for contrast perception. Also, similar with the MoA on distant background task, results of MoA on contextual background task indicate that different frequency levels does not have any effect on contrast perception (main effect of frequency: $F(3,15)=2,45$, $p>0.05$) (see Figure 3.8).

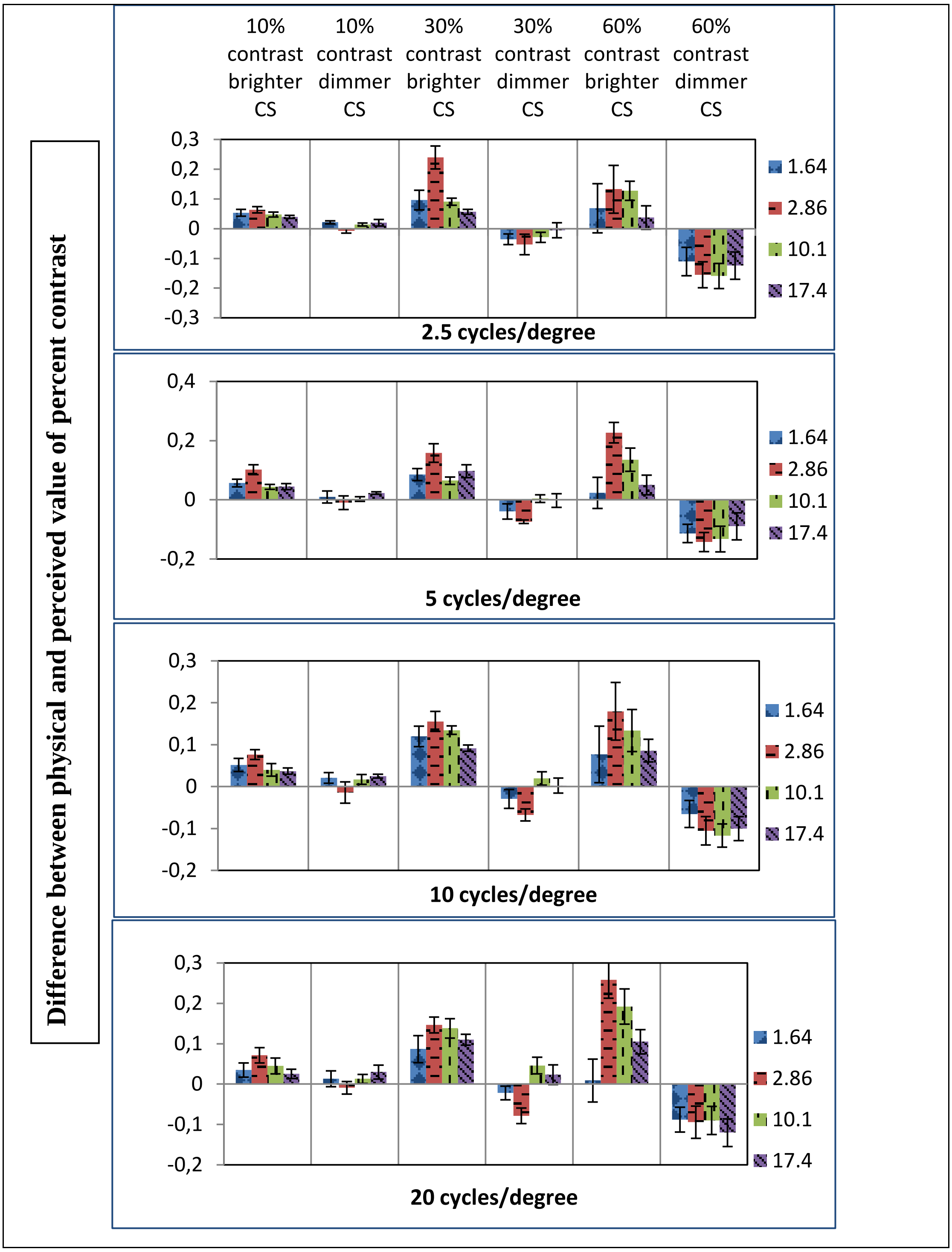


Figure 3.8. Mean perceived contrast values of gratings on different CSs across four different luminance values. Each graph represents the data from different frequency levels. MoA task. Error Bars show +/-1 SE**.**

Because main effect of frequency and the interaction of frequency with other independent variables were never significant, the data gathered from different frequency levels were combined in the following figures for simplification (see Figure 3.9) although in the analysis each level of frequency considered as separate.

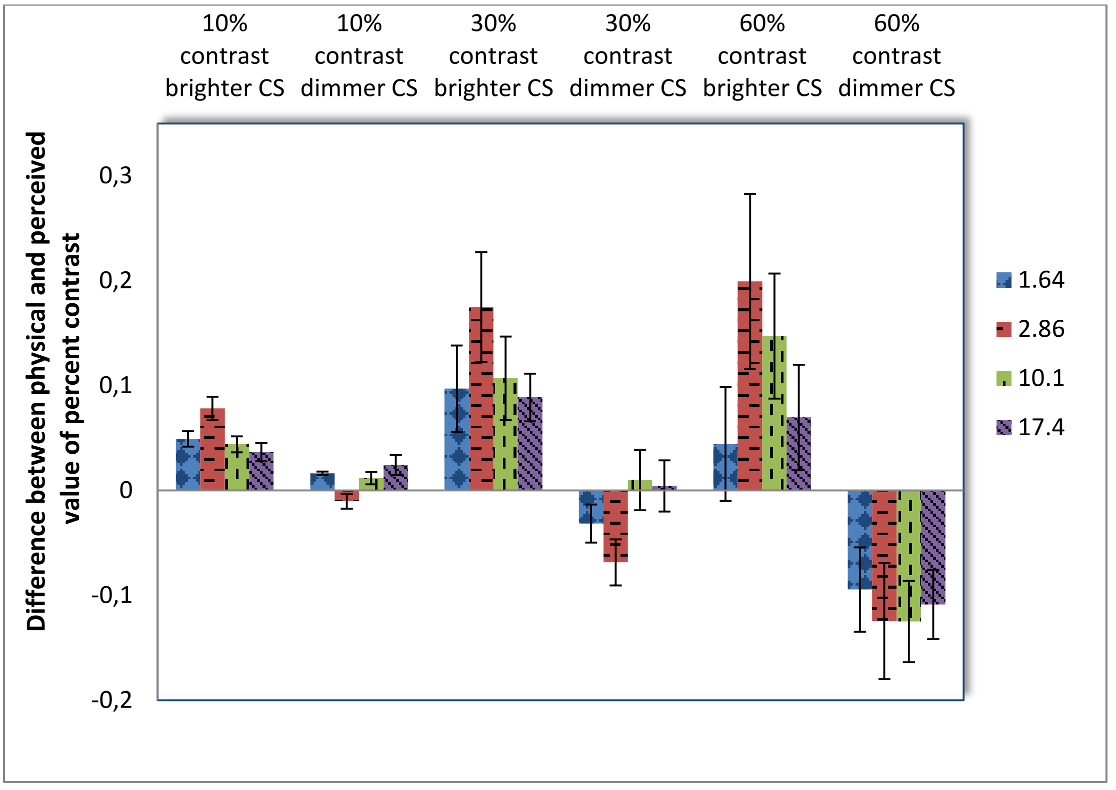


Figure 3.9. Mean perceived contrast values of gratings on different context squares across four different luminance values. The value "0" corresponds to the physical contrast value. MoA task on contextual background. Error Bars show +/-1 SE.

Figure 3.9 demonstrates the results obtained from MoA task of contrast perception for three different contrast levels and two context squares across 4 different CS luminance values. The data were gathered from 6 participants. The figure shows mean divergence scores of perceived contrast values through the gratings located on both context squares. The value "0" corresponds to the physical contrast value of the grating. Therefore, negative values indicate that contrast is perceived lower than its physical value, and positive values indicate that perceived contrast is higher than its physical value. It can be seen in the figure that the difference in perceived contrast between the gratings on brighter CS and dimmer CS is higher compared to MoA on distant background task. Results indicate that the effect of context square on contrast perception is statistically significant (main effect of CS: $F(1,5)=8.04$, $p<0.05$). Also, different luminance levels seem to change the perceived value of contrast significantly. The effect decreased due to the increase in physical luminance of CSs (see Appendix 3 for detailed t-test results). However, although main effect of CS luminance is not significant, interaction between CS luminance and position of CS is statistically significant ($F(3,15)=15.04$, $p<0.005$). To show the effect of different CSs on perceived contrast clearly, the difference between perceived contrast values of grating on brighter and dimmer CSs has demonstrated on another figure (see Figure 3.10.)

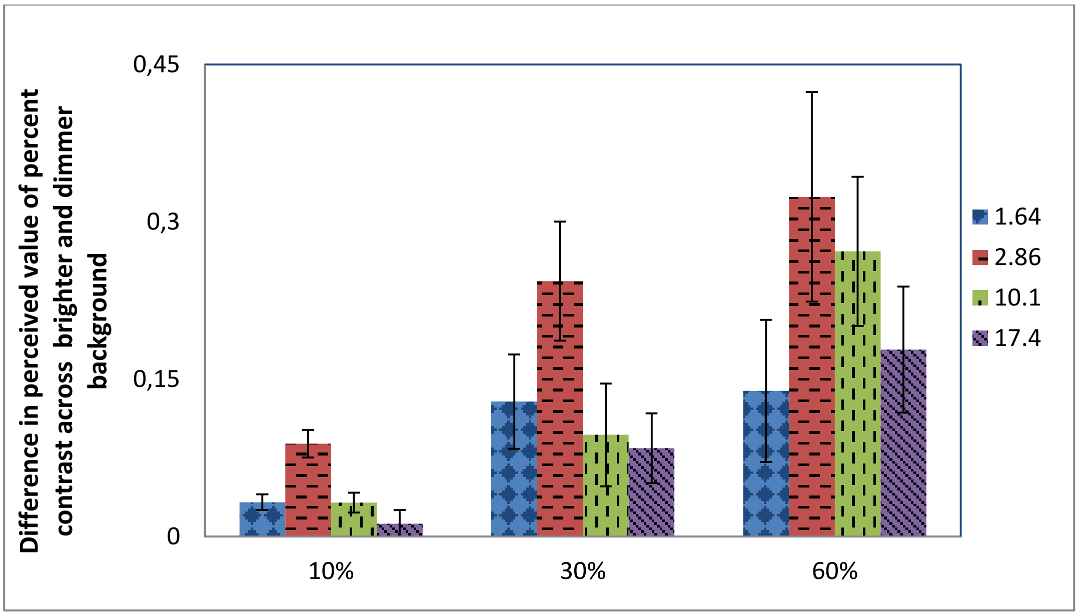


Figure 3.10. Difference between the perceived contrasts of gratings on brighter and dimmer context squares across four different luminance and three different contrast values. MoA task. Error Bars show +/-1 SE.

Figure 3.10 represents the difference between the perceived contrasts of gratings on brighter and dimmer context squares across four different luminance and three different contrast values gathered via MoA task. Results indicate that different contrast values do not have any effect on perception (main effect of contrast: ($F(2,10)=2.27$, $p>0.05$). However, the interaction between contrast and position of CS is statistically significant ($F(2,10)=6.43$, $p<0.05$). It can be seen in the figure that increase in the physical contrast value increases the difference between the perceived contrast values of gratings on brighter and dimmer CSs.

F. Results of measurement of perceived contrast on isolated backgrounds

Depending on the perceived brightness values reported by each participant in the first experiment series, isolated backgrounds (IB) specific to each participant were created. Because context squares which have the same luminance values were perceived differently there were two isolated backgrounds (brighter IB, dimmer IB) for each luminance value. The data were obtained from three participants. Results indicate that main effect of IB is statistically significant ($F(1,2)=24.68$, $p<0.05$). However, similar with the previous results, the main effect of frequency ($F(3,6)=0.192$, $p>0.05$), and the main effect of IB luminance ($F(3,6)=13.76$, $p>0.05$) were not statistically significant. Also, different contrast values do not have a statistically significant effect on perceived value of contrast (main effect of contrast: $F(1,2)=1.53$, $p>0.05$). Any interactions between the factors were also not significant ($p>0.05$) in this measurement. Considering the insignificant interaction results, the data was averaged in frequency results to simplify the representation (See Figure 3.11).

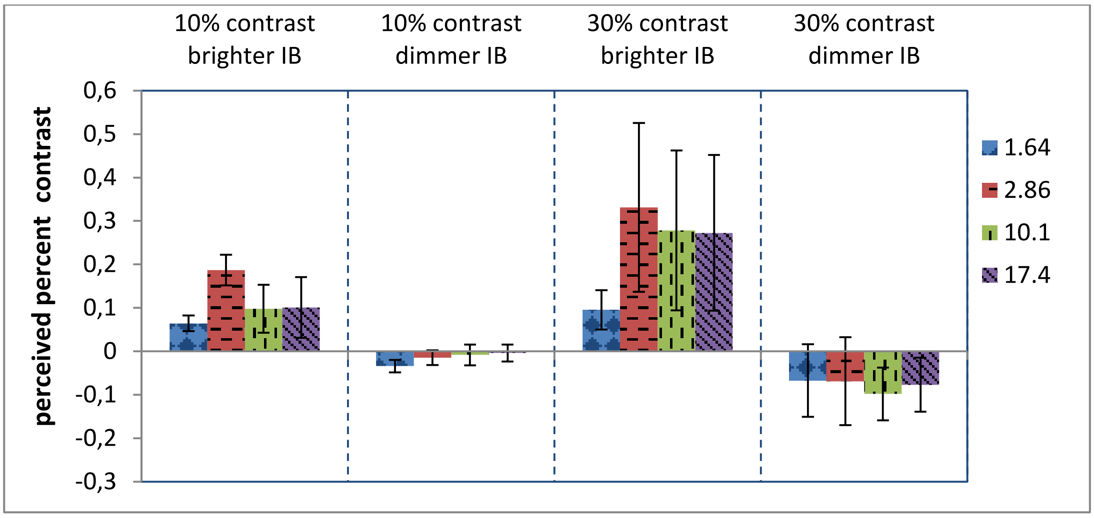


Figure 3.11. Mean divergence scores of perceived contrast values of gratings on isolated backgrounds of different luminance values. Error bars show +/-1 SE.

Figure 3.11 demonstrates the mean divergence scores of perceived contrast values of gabor gratings located on isolated backgrounds across two contrast values and four luminance values. Because different frequency levels did not have any effect, the frequency data was avaraged across other conditions. Luminance value of isolated backgrounds was defined based on the subjective brightness judgments for the squares whose luminance values were 1.64, 2.86, 10.1, and 17.4 cd/m^2 in the illusory stimuli. It can be seen in the figure that for the corresponding values of 1.64 cd/m^2, contrast of gratings on dimmer IB were perceived as lower than the physical contrast value. Oppositely, gratings on brighter IB were perceived as higher than its phyical value.

Considering the corresponding luminance values for 2.86 cd/m^2 luminance square in the illusory stimuli, it can be seen in the figure that discrepancy between the physical and perceived contrast is higher than the 1.64 cd/m^2 luminance value. Except this, the pattern seems to be similar that contrast of gabor gratings on dimmer IB were perceived lower than the physical contrast value, and contrast of gratings on brighter IB were perceived higher than the its phyical value.

For the luminance value of isolated backgrounds that was defined based on the subjective brightness judgments for 10.1 cd/m^2 luminance square in the illusory stimuli, it can be seen in the figure that the data is similar to 2.86 luminance value. However, difference between the physical and perceived contrast is lower compared to the 2.86 cd/m^2 luminance value. Also, pairwise comparison results indicate there is no difference between the 10.1 and 1.64 or 10.1 and 2.86 cd/m^2 luminance value. The pattern seems to be similar with two previous luminance values that contrast of gratings on dimmer IB were perceived as lower than the physical contrast value, and contrast of gratings on brighter IB were perceived as higher than the its phyical value. Different fequency levels and different contrast values do not have any effect on contrast perception.

For the luminance value of isolated backgrounds defined based on the subjective brightness judgments for 17.4 cd/m^2 luminance square in the illusory stimuli, it can be seen in the figure that the data is similar to 10.1 cd/m^2 luminance value. Pairwise comparison results indicate there is no difference of 17.4 cd/m^2 luminance value from any of the other luminance values. The pattern seems to be similar with three previous luminance values that contrast of gratings on dimmer IB were perceived as lower than the physical contrast value or very near to the physical level, and contrast of gratings on brighter IB were perceived as higher than the its phyical value. Different fequency levels and different contrast values does not have any effect on contrast perception.

ADDITIONAL EXPERIMENTS

There are potential confoundings of contrast perception studies. One of them is that participants might misunderstand the concept of contrast and they may try to adjust the luminance of the bars of gratings. Another potential confounding might be the choice of contrast type. Therefore, two additional experiments were conducted. First, to ensure that participants understood the concept and they adjusted the contrasts of gratings we implemented an additional experiment to two randomly selected participants. We asked participants to adjust the luminance of the bar of the grating to match an adjustable luminance patch. We repeated the experiment with MoA on distant background. Because we wanted to keep the contrast values the same with the previous experiments, we do not have the corresponding personal judgment data to the luminance values of gabor bars. However, some of the values are rather similar with the ones we used in luminance adjustment experiments. Therefore, we can compare the luminance adjustment values of gabor bars with the previous experiments. For instance, the luminance of gabor bar was 1.92 cd/m^2 for 1.64 background and 10% contrast. We have the personal judgment results from luminance adjustment experiment for the luminance value of 1.64 cd/m^2. The average judgment across eight participants was 1.91 cd/m^2 for dimmer CS and 7.30 cd/m^2 for brighter CS whereas it is 4.22 cd/m^2 and 10.6 cd/m^2 respectively for the adjustment of bar's luminance. Similarly, luminance value of the bar was 2.31 cd/m^2 for the 30% contrast of the same background. If we compare the results with our previous value 2.86 cd/m^2, the personal judgment average was 1.32 cd/m^2 for dimmer CS, and 10.39 cd/m^2 brighter CS in the previous experiments while it is 5.74 cd/m^2 for dimmer CS and 12.7 cd/m^2 for brighter background in the adjustment of luminance of bar experiments. Although the results are not the same, they are very similar (See Figure 3.12).

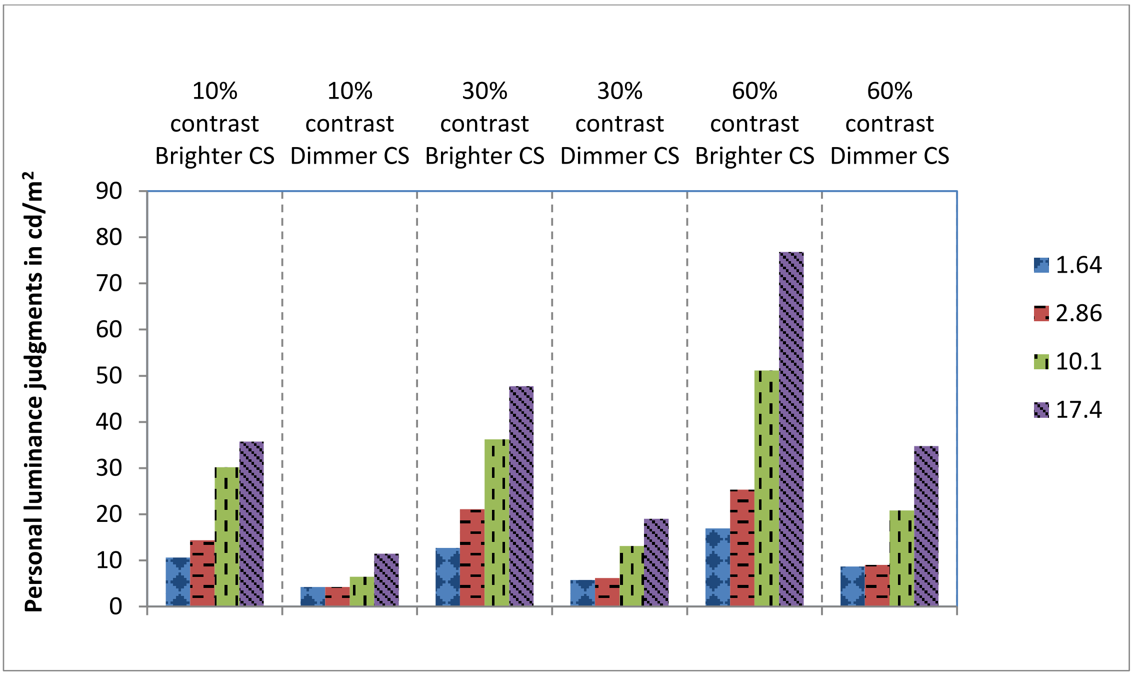


Figure 3.12. Mean brightness values of bars' luminance values across different backgrounds and overall image contrast values.

However, when we consider the corresponding contrast values of gratings whose luminance values of gabor bars was measured via participants' personal judgments, we can see that results are not similar with any personal judgment data gathered from any of our previous contrast experiments. Therefore, we can safely conclude that participants were able to differentiate the concepts luminance and contrast (See Figure 3.13).

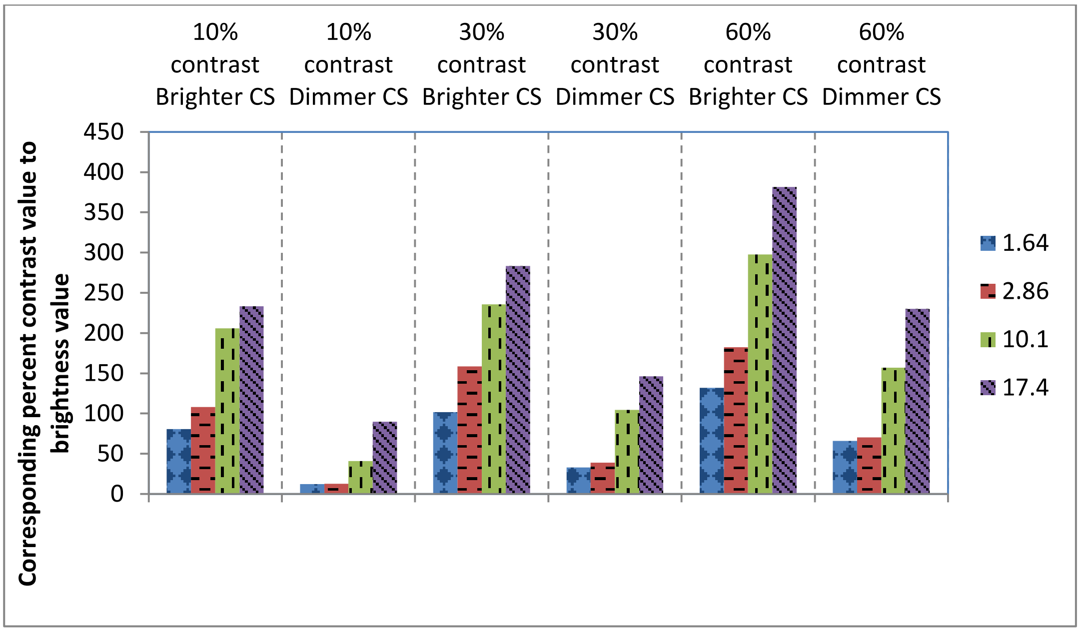


Figure 3.13. Mean corresponding contrast values of gratings whose brightness of bars was measured across different backgrounds and overall image contrast values.

Another potential confounding might be the choice of contrast type. Literature suggests that ON and OFF retinal ganglion cells behave differently across decremental and incremental contrast (Zaghloul, Boahen, & Demb, 2003). Incremental contrast means that a stimulus is brighter than the background mean luminance; and it is opposite for the decremental contrast (see Figure 3.14). In primate, although an ON cell responds to both increment and decrement of low contrast, OFF cells responds only to a decrement of relatively high contrast (Chichilnisky and Kalmar, 2002). In our original experiments we always used the incremental contrast. Therefore, it is important to know how the effect changes due to the contrast type. Beyond this, one might claim that because the luminance of bars is also affected by the illusory context, therefore, increase in perceived contrast is observed. In other words, the context which causes to perceive a region brighter than as it is, also causes to evaluate the contrast higher than actually as it is because in this condition higher contrast mean brighter bars. However, if we use decremental contrast we can eliminate such an effect. Because in that case, higher contrast would mean dimmer gabor bars.

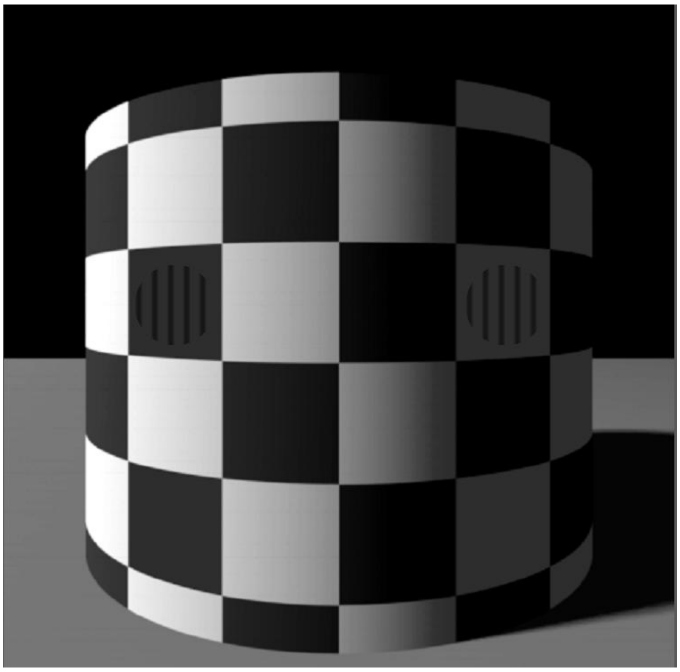


Figure 3.14. An example of grating with decremental contrast

To test this possibility we conducted an additional contrast perception experiment with the MoA on contextual background by using decremental contrast across four participants. Although there was a statistically significant difference in the effect of different CS on contrast perception (main effect of CS: $F(1,3)=20.08$, $p=0.021$) it was observed that the effect of brightness on decremental contrast perception is not as strong as incremental contrast perception. Compared to incremental data, results should be interpreted more cautiously because the direction of the effect is more dependent to other variables, namely luminance (main effect of luminance: $F(3,9)=16.77$, $p=0.011$), and contrast (main effect of interaction between luminance and contrast: $F(6,18)=32.24$, $p=0.001$) (see Figure 3.14).

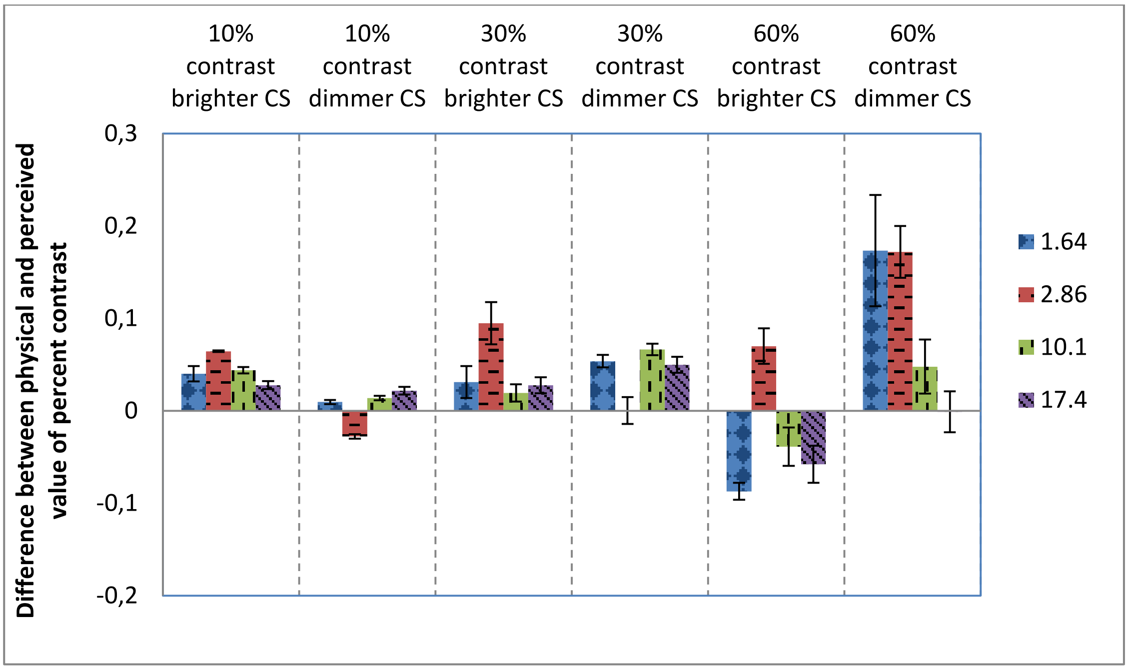


Figure 3.15. Mean percentage perceived contrast values of decremental gratings on different context squares across four different luminance values. The value "0" corresponds to the physical contrast value. Error Bars show +/-1 SE.

It can be seen in the figure that when contrast increases the direction of the effect changes. Perceived contrast is greater when grating is located on brighter CS for low contrast value whereas it is smaller for higher contrast value. Therefore, we cannot claim that brighter background cause to perceive contrast higher than it is. Instead, we can safely indicate that brightness has an effect on contrast perception both in decremental and incremental contrast values. However, perceptually brighter background always correlates with greater perceived contrast only for incremental contrast.

SUMMARY AND DISCUSSION

The results of experiment series 2 demonstrate that different brightness values influence the perceived value of the contrast both in decremental and incremental contrast values although luminance value is the same. In other words, despite the physical value of luminance was kept constant, the perceived changes in luminance affect the contrast perception. This finding indicates that the effect of luminance on contrast perception in literature may not be the consequence of the physical changes but the perceptual changes. Furthermore, findings indicate that luminance and contrast networks should interact in higher level visual areas instead of retina or LGN because perceived value of luminance drives the effect on contrast perception.

As in the luminance adjustment experiments results, the experimental design influences the perceived contrast. When adjustable grating is located on the illusory stimulus the discrepancy between the perceived values was greater. Although evidence by many studies (e.g. Peli et al., 1996) shows that the spatial frequency is an important variable which have impact on contrast perception, in our data spatial frequency did not influence the contrast perception in any condition. This discrepancy might be caused by the difference in methodologies which will be explained in general discussion part in detail. Isolated background experiments demonstrate that change in luminance correspondences of illusory brightness values influenced contrast perception as contextual background. The difference in perceived contrast between dimmer and brighter luminance correspondence backgrounds was statistically significant ($F(1,2)=24.68$, $p<0.05$). However, the difference between isolated background scores and contextual background scores was also statistically significant ($F(1,2)=19.31$, $p<0.05$). Therefore, results might be concluded that although both the isolated backgrounds with physically different luminance levels and the contextual background with perceptually different luminance (brightness) levels affect the perceived contrast of a grating, their effects are significantly different than each other.

CHAPTER 4

EXPERIMENT SERIES III

FMRI OF CONTRAST PERCEPTION IN CONTEXT

An fMRI study was conducted to see whether the difference in brightness and perceived contrast correlate with any changes in brain activity in a particular brain region. The experiment was completed in two separate sessions, one for experimental session and the other for the retinotopic mapping. As spatial attention has been shown to alter visual perception (Posner, 1980; Yeshurun and Carrasco, 1998; Herrman et al., 2010), and physiological evidence indicates it changes neural activities at various levels of cortical visual pathways (Ito, & Gilbert, 1999) attention on stimuli was controlled in the study in separate runs.

METHOD

Participants

Nine participants participated in the experimental session, and three of them participated in the retinotopy session. Three participants of fMRI study also participated in the pscyhophysical experiment series. The age range was from 21 to 36. Each participant provided informed consent and they were paid for their participation.

Stimuli and Design

In the first session of the fMRI study, the main fMRI experiment that will be explained below was conducted. In the second session, standard retinotopic mapping procedures were performed to define retinotopic areas (Sereno et al. 1995, Engel et al. 1997). The main fMRI experiment of the study included an anatomical scan, a functional localization scan, and four experimental scans for two attention conditions. fMRI stimuli was similar with the psychophysical experiments. Illusory stimulus was presented on the screen and gratings which are exactly the same in terms of all physical properties are located on both context squares. Gratings were flickering at 4 Hz to avoid adaptation of neurons. In the first 24 s and last 12 s, subjects viewed only the illusory stimulus without gratings. In a block design, subjects viewed five 12 seconds alternating blocks of two conditions. In the first condition (experimental block), gratings were present, and in the second conditions they were absent (control block). In both blocks, subjects viewed the fixation mark. With the help of the fixation mark, attention on stimuli was controlled. Increasing the attentional load at fixation allows controlling top-down attentional mechanisms and evaluating the automatic sensory-driven responses of early visual cortical areas for a given peripheral stimulus (Kastner et al., 1998; Pessoa et al., 2003). Therefore, in the study, it was also attempted to examine how manipulating attention modulates the effects of different brightness values caused by the same luminance value on contrast perception, using a demanding fixation task. For this purpose, two attentional conditions were designed. In the fixation condition, participants performed a demanding fixation task which required to detect the color changes of the fixation mark by pressing a response button. In the passive view condition participants were asked to fixate the dynamic fixation mark; however, they were not required to respond across changes in color of the fixation mark. Four fMRI scans were applied; two for fixation conditions and two for passive view condition. Also, an additional functional region of interest (ROI) localization scan was applied in the main fMRI experiment.

Region of Interest (ROI) localization

Functional ROI were identified in a different scan within the main experimental session. Cortical areas corresponding to the location of gratings on context squares were functionally localized by conventional methods in which subjects viewed flickering black-and-white checkerboard. Their size and location was exactly the same as gratings. After a blank period of 24 s, flickering checkerboard was represented for 12 s. This cycle was repeated for five times in each scan, separated by 12 s control blocks. In control blocks there was only fixation mark on the screen. In this scan, participants were required to respond to changes in color of fixation mark.

Retinotopic visual areas were defined based on responses to rotating wedge and expanding rings of flickering black and white checks, using phase-encoded standard retinotopic methods (Sereno et al. 1995, Engel et al. 1997).

MRI data acquisition

Scanning was performed on a 3 Tesla scanner (Siemens Trio) using a thirty two-channel phase-array head coil at the National Magnetic Resonance Research Center (UMRAM), Bilkent University. Functional data were acquired with an echo-planar imaging (EPI) sequence (TE: 35ms, TR: 2000 ms, FOV: 192x192 mm^2, matrix: 64x64, flip angle: 75, slice thickness: 3 mm, number of slices: 30, slice orientation: parallel to calcarine sulcus). Each session began with an anatomical scan using a high resolution T1-weighted 3D MPRAGE sequence (1x1x1 mm^3 resolution, TE: 3.02 ms, TR: 2600 ms, FOV read: 256, FOV phase: 87.5, flip angle: 8, slice thickness: 1mm).

Visual stimuli were presented on a MR-compatible LCD monitor that was viewed by participants through a mirror located above their eyes inside the scanner. The viewing distance was 125 cm. The monitor was calibrated using a Cambridge Research Systems Ltd. SpectroCAL colorimeter.

Data processing and analyses

MRI data were pre-processed using BrainVoyager QX (Brain Innovation, Maastricht, The Netherlands). Firstly, functional images were preprocessed to correct for 3D head motion, to filter out low temporal variations (below 0.015 Hz) and to remove linear trend (Smith et al., 1999). The anatomical T1-weighted images were inflated for visualization. The functional images were transformed into AC-PC space and aligned with the anatomical images.

Regions of interest (ROIs) were selected by a General Linear Model procedure using Brain Voyager QX. The borders of different visual areas, V1, V2, and V3, were drawn manually with BrainVoyager QX using cross-correlation maps of the BOLD response to rotating wedge and expanding ring stimuli.

For each experimental scan, the time course and event related average of fMRI signals from defined ROIs was extracted. For each fMRI scan, the time course of BOLD responses was extracted by averaging the data across all the voxels within the pre-defined ROI, and then normalized by the mean BOLD signal across the scan. Event related averaging were then performed for each trial type (experimental, control) by averaging time points from third to sixth (between 6 and 12s) starting at the onset of the stimulus and the average response to the control trials was subtracted from the averages of the experimental condition. The data gathered from different hemispheres was compared. Paired sample t-tests were applied in SPSS to determine the statistical significance of differences between conditions averaged across participants.

RESULTS

Nine participants were scanned for the experimental session. However, retinotopy session could be performed with only three of them. Because V1 could be identified anatomically, activation in V1 was identified across 9 participants. However, V2 results show the data from three participants. Mean BOLD signal change in the experimental conditions and control conditions were calculated across participants. Signal change between the time courses 6-12 sn. (3.-4.-5. TR) was averaged for each condition. Pairwise comparison t-test was applied to acquired scores. The data gathered from fixation condition and passive-view condition was analysed separately. Results demonstrate that the only significant difference caused by the perceived differences (brightness, and contrast) was observed in V1 in fixation condition ($t(8)= 5.53$, $p=0.001$) (See Figure 4.1).

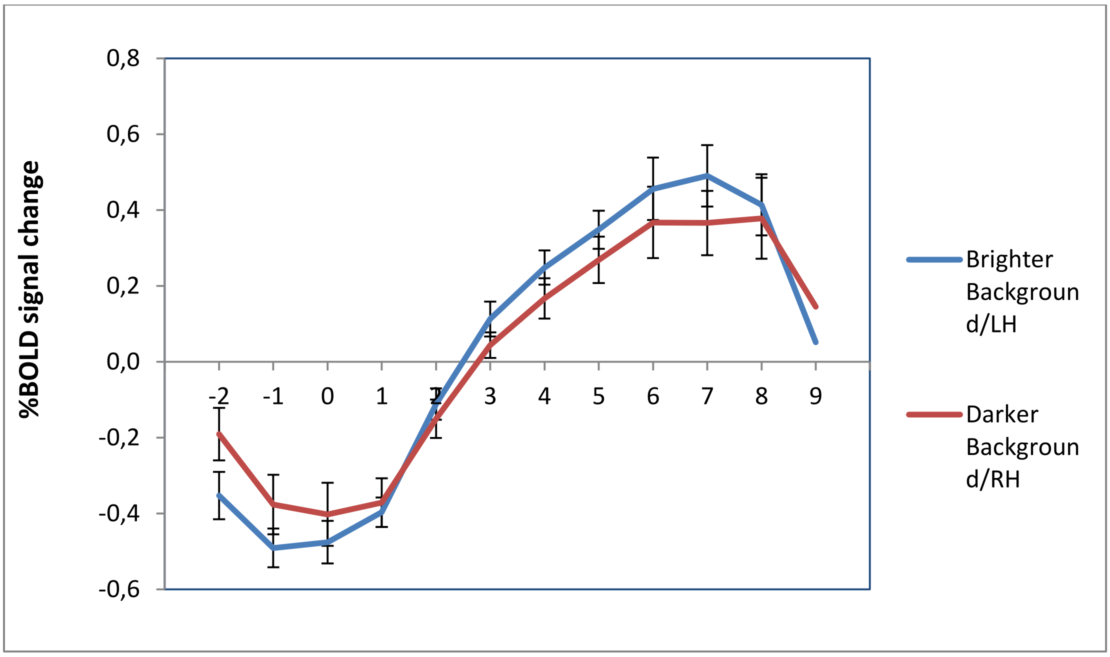


Figure 4.1. Event related averaged time course representation of V1 activity for fixation condition.

Figure 4.1 shows the event related time course representation of % BOLD signal change gathered from V1 in fixation task condition. It can be seen in the figure that in fixation task condition when the patch is located on brighter context square activation gathered from V1 (M=0.236, SD= 0.12) is greater compared to on dimmer context square (M=0.159, SD= 0.12). As it was shown in the third chapter additional experiments part, perceived luminance of gratings on perceptually brighter context squares is higher compared to the gratings on perceptually dimmer context squares. This might be the reason of greater activation in V1 for brighter context square and grating on it. However, in passive-view condition there is no difference caused by the gratings located on different context squares (see Figure 4.2).

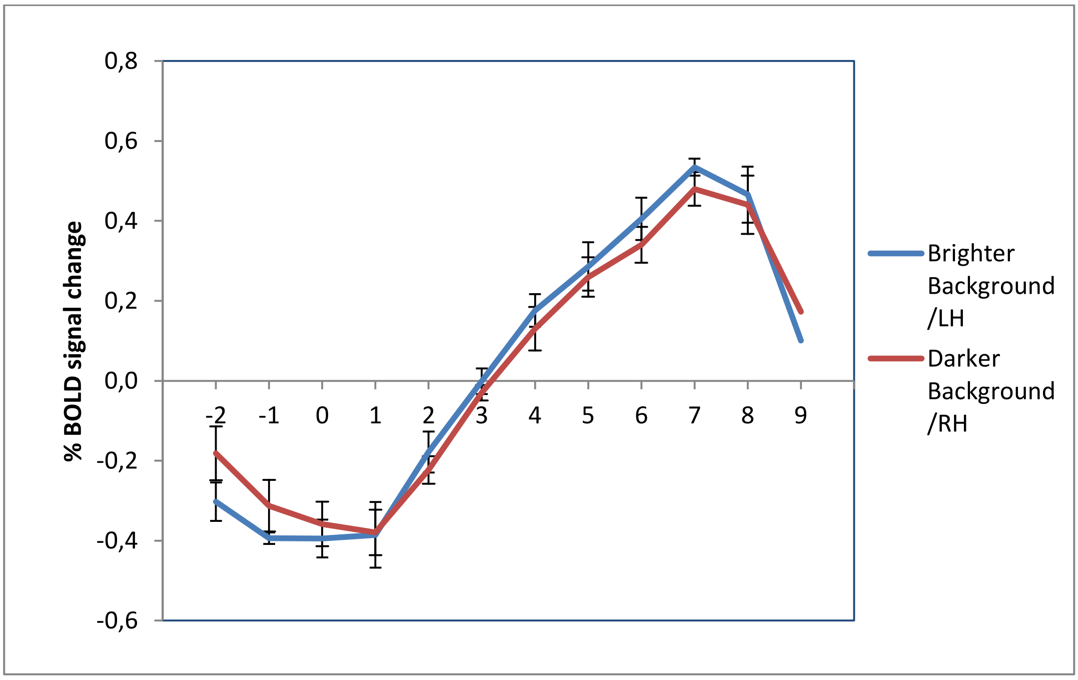


Figure 4.2. Event related averaged time course representation of V1 activity for passive-view condition.

Figure 4.2 shows the event related time course representation of % BOLD signal change gathered from V1 across nine participants in passive-view condition. It can be seen in the figure that in passive-view condition there is no difference between the conditions whether the grating is located on brighter context square (M=0.144, SD= 0.06) or on dimmer context square (M=0.114, SD= 0.06).

Considering the activation in V2 it was seen that the perceived differences in contrast and brightness did not cause any differences in the BOLD signal change in V2 both for fixation condition and passive-view condition. In other words, the activation in V2 correlates with the physical properties of the stimulus. Because the stimulus is physically identical there is no difference in the BOLD signal change caused by gratings located on brighter or dimmer context squares (See Figure 4.3, and Figure 4.4).

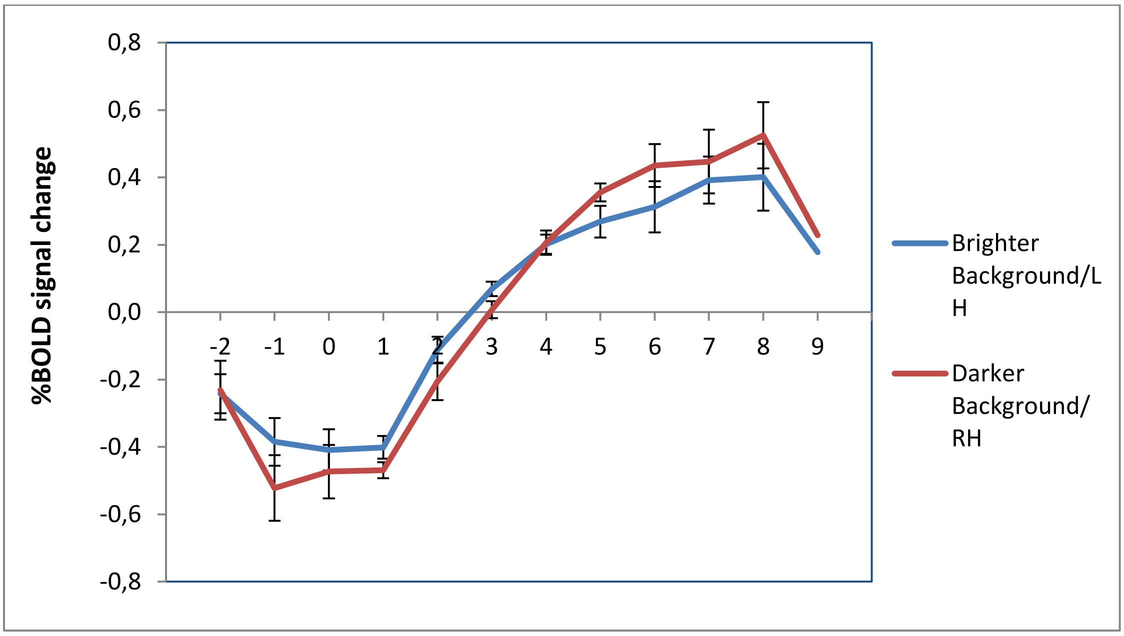


Figure 4.3. Event related averaged time course representation of V2 activity for fixation condition.

Figure 4.3 indicates the event related time course representation of % BOLD signal change gathered from V2 across three participants in fixation condition. Although the BOLD signal change caused by the grating located on dimmer context square is greater as opposed to the activation in V1, results show that there is no statistically significant difference between the conditions whether the grating is located on brighter context square (M=0.179, SD= 0.05) or on dimmer context square (M=0.189, SD= 0.07).

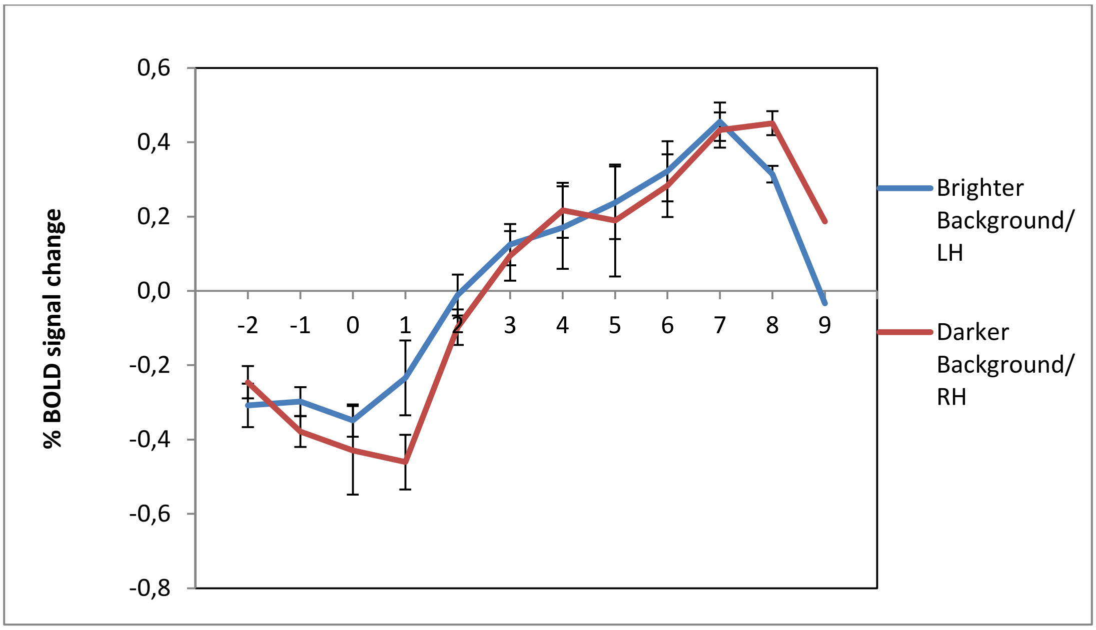


Figure 4.4. Event related averaged time course representation of V2 activity for passive-view condition.

Figure 4.4 demonstrates the event related time course representation of % BOLD signal change gathered from V2 across three participants in passive-view condition. It can be seen in the figure that there is no statistically significant difference between the conditions whether the grating is located on brighter context square (M=0.177, SD= 0.07) or on dimmer context square (M=0.167, SD= 0.06). To sum up, the activation was significantly changed based on the fixation condition. When there is a demanding fixation task, activation in V1 was correlated with the perceptual properties of the stimulus. However, when thee is not any other demanding task V1 activation was correlated with the phyical properties of the stimulus. Activation in V2 was correlated with the phyical properties of the stimulus both in the presence and the absence of the demanding fixation task.

SUMMARY AND DISCUSSION

With the help of the illusory effect, it was demonstrated the impact of brightness on contrast perception. Results indicated that not only the luminance itself but also the brightness drives the contrast perception. Effect of brightness on contrast perception demonstrates that networks processing contrast information and luminance information interact in higher-level visual areas.

To understand the process, an fMRI study was conducted. The activation in primary visual cortex, V1, and V2 was analysed. A demanding fixation condition was used in half of the experiments to control attention. Results showed that activation in V1 correlated with perceptual properties of the stimulus if there is also a demanding fixation task. However, except this; activity in all other regions of interest for all conditions was correlated with physical properties of the stimulus. Although results are informative, they should be considered cautiously because we could not counterbalance the side of context squares due to the time limitation. Therefore, perceptually "brighter" context square was always processed by left hemisphere and the "dimmer" context square was processed by right hemisphere. Therefore, before being confident about the results, we should eliminate the possibility if there is an effect of any particular hemisphere on the illusory stimulus by counterbalancing the right and left side of the image (by changing the side where light comes to the stimulus).

CHAPTER 5

GENERAL DISCUSSION

The present study investigated the difference between human sensation and perception by focusing on the visual contrast perception. Our aim was to demonstrate whether contextual (top-down processing) or stimuli-based changes (bottom-up processing) affect contrast perception. One of the ways of conducting a study which demonstrate the differences between sensation and perception is using visual illusions. With the help of context in illusions, perception can be changed by keeping the physical stimulus constant. Based on this idea, we chose luminance as the variable because luminance is a physical property and its perception, brightness, is easy to manipulate in illusions with the help of context. Therefore, by using a different version of Adelson Checkerboard Illusion (Adelson, 1995), brightness was manipulated by keeping the luminance value constant. There were two context squares on the present illusory stimulus whose brightness values seem considerably different although their luminance values are exactly the same. Contrast perception was measured putting Gabor gratings on these context squares. The main reason we especially focussed on the contrast perception is that we know from the previous studies (e.g. Peli et al., 1991) that physical luminance affects contrast perception. However, we do not know the effect of brightness on contrast perception because in previous studies only the physical value of the luminance has been manipulated and brightness value has changed dependently. Therefore, by showing the effect of brightness on contrast perception we have the opportunity to make interpretation about the difference between sensation and perception in terms of visual contrast perception.

We first intended to demonstrate that context squares in the illusory stimulus have significantly different brightness values. To prove this, we measured the brightness value of each context square by asking personal judgments of participants with various experimental designs including method of adjustment and 2-alternative forced choice method. Although measuring the brightness with different methods was not critical for the purpose of the present study, we intended to see if there is an effect of experimental design on brightness judgment in visual illusions. Results demonstrated that for all the experimental designs two context squares have significantly different brightness values. In addition, the experimental design used to measure brightness also affects the personal judgements. If the adjustable patch is also on the context the perceived value is diverged from its physical value more compared to adjustable patch on an isolated background. Furthermore, the size of the adjustable patch on the context also matters. If adjustable patch covers the whole illusory region (context square) divergence increases compared to a smaller patch on illusory region. This indicates that because illusion has also an effect on the perception of adjustable patch which is on the illusory stimulus, putting the relatively small adjustable patch away from the context may lead the closest judgement to the physical value. Results of these experiment series can be summarized as that method of adjustment or 2AFC does not differ, instead the place where adjustable patch is located on and its size matters for the judgment of brightness perception.

Our brightness perception findings have yielded contrary evidence to the center-surround antagonism. When we consider center-surround antagonism, it has been claimed that a stimulus surrounded by relatively dark region is less inhibited because darker light causes less neuronal firing compared to brighter light, therefore it cannot dramatically change the excitatory response of the center of receptive field (Goldstein, 2010). In this case, brightness of the context square surrounded by the dimmer squares (brighter CS in our illusory stimulus) should be closer to its luminance value compared to dimmer CS. However, our results contradict with this claim because there was much more discrepancy between the physical and the perceived value of the brighter CS compared to dimmer CS.

After we have ensured that brightness values of context squares are significantly different, we conducted experiments to see the effect of brightness on contrast perception. As in the brightness experiments, we used different experimental designs, both MoA on distant background task and MoA on contextual background, to see the effect of experimental design on contrast perception in context. We predicted that if context-dependent brightness has an effect on contrast perception, then the difference between perceived contrasts of tested and adjustable gratings should be greater in MoA on contextual background task compared to the MoA on distant background task; because the adjustable grating is also affected by the context when it is located on contextual background. Contrast perception experiments have supported our predictions and they have yielded similar results with brightness experiments that illusory stimuli affect the MoA on contextual background task more compared to MoA on distant background. In other words, difference in perceived contrast of gratings on CSs has increased when the MoA on contextual background task was applied. Although there is a difference caused by experimental design, results gathered from both of the experimental designs indicate the same conclusion that perceived contrast of gratings has changed depending on the CS that they are located on. Targeting the main concern of the study, this finding indicates that difference in brightness changes the perceived contrast value even if the luminance value is the same. Therefore, we claim that when we need to decide the contrast of an object we reference the brightness, perceptual value of the luminance, not the physical luminance itself. Therefore, our findings support to the phylogenetic and the ontogenetic explanation of visual perception which indicate that the behavioural significance of a stimulus matters more than its physical properties. In our case, brightness dictates the behavioural significance and instead of luminance, brightness plays the key role for the higher-level complex visual functions. Furthermore, the findings indicate that the interaction between contrast and luminance networks occurs in higher level cognitive regions because instead of physical properties, perceptual appearance of luminance, namely brightness, dictates contrast perception.

Although our results gave important clues that perceptual properties dominate the interaction between two fundamental physical qualities in context, we should also consider the involvement of other mechanisms to understand human cognition better because not only two physical feature within a system interacts but also different systems interacts. For instance, there is evidence in the literature that language interacts with and influences our ability to represent and retain information from vision (Dessalegn, & Landau, 2013). It is claimed that spatial structure (with the help of vision) and conceptual structure (with the help of language) are combined to understand the character of perceived world (Jackendoff, 2012). For example, when speakers of different languages engaged in a language task and a visual task simultaneously, their pattern of eye movement changes depending on their language. As a result, it is claimed that language allows a perceiver to move beyond visual representations and store information that would otherwise be degraded (Dessalegn, & Landau, 2013). Therefore, focusing on the interaction between specific systems as a next step can offer us deeper understanding of human cognition.

Peli et al. suggested that high frequency gratings are strongly affected by mean luminance, whereas low-frequency gratings are much less affected. Therefore, in our study, we repeated all contrast perception experiments by changing frequency levels in four different sessions. However, in any of them we could not see any significant differences caused by spatial frequency. Therefore, our results contradict with the literature at this point. The reason may be the methodological differences. For instance, Peli et al. (1996) used a standard patch whose spatial frequency is always the same but the spatial frequency of their test patch (refers to adjustable patch in our study) was changed. However, we changed the spatial frequency of both the standard and the test patch simultaneously because we intended to keep the all physical properties the same at a time. This difference between the two studies may result from the difference caused by spatial frequency.

fMRI findings have yielded considerable results. Although our stimulus was physically identical we observed difference in BOLD signal in primary visual cortex

(V1) due to the perceptual differences. This difference was present only when attention was controlled via a demanding fixation task. It is important to note that although there is a hemispheric lateralization for different attention types, namely focal attention and global attention, in temporal and parietal cortex, fMRI studies show that attention is not lateralized in the occipital cortex (Sasaki et al., 2001). Therefore, although additional fMRI runs are still needed to counter-balance the conditions processed by each hemisphere in the future studies, any differences between the hemispheres we have seen cannot be attributed to the lateralization of attentional mechanisms. Furthermore, it is well known that neural activity in V1 is affected by attentional modulation (e.g. Ito, & Gilbert, 1999). Therefore, a difference between attentional conditions in V1 was expected. However, the direction of the attentional effect in the present study was surprising. Difference in V1 activity through visual illusion caused by attentional conditions was shown by Fang et al. in 2008. They used the size illusion to see the representation in V1. Similar with our findings, they showed that activation in V1 is consistent with the perceptual appearances instead of the physical properties. In some sessions, they controlled attention by adding a demanding central fixation task and they showed that when participants attend to the fixation task, the difference in V1 caused by perceptual difference disappears. Therefore, they concluded that the difference in V1 activation through illusory stimulus is the consequence of the cortical feedback. When there is a demanding attention task, the cortical feedback is interrupted and V1 only responds to the physical properties of the stimulus. Their explanation is consistent with assumptions in the literature about the role of V1 that because visual information is initially processed in V1 in the occipital cortex, V1 is mostly responsible for processing the physical properties of the visual stimulus (Lamme, Supér, & Spekreijse, 1998). On the contrary, when we controlled the attention with the same method, we have observed the reverse effect of attention that when there is a demanding task the activation in V1 differs due to the illusory stimulus. However, when there is not any demanding task, V1 responds to the physical properties of the visual stimulus.

Considering the results we observed, we claim the effect we saw might still be the consequence of the feedback mechanisms as previous assumptions claim. When there is not any demanding attention task, the higher cortical areas have enough resources to process the information more accurately. Therefore, feedback is consistent with the actual properties of the stimulus. However, when there is a demanding attentional task, higher level cortical areas do not have enough resources to evaluate the stimulus in detail. Therefore, the feedback only carries the information about the perceptual properties of the stimulus. However, this explanation still cannot answer the question why the size illusion and the brightness illusion lead to opposite patterns when they interact with attention.

Based on the previous findings in literature, we might speculate two possible explanations why the effect of attention on brightness and size illusion differs. First, some studies provided evidence that although attention does not have any significant effect on the response to an isolated stimulus, it facilitates the response when there are additional contextual properties (e.g. Ito, & Gilbert, 1999). It was claimed that the effect might be the consequence of not only feedback mechanisms from higher level cortical areas but also horizontal connections within V1. According to this, attention influences the interaction between cells that have separate receptive fields, receptive field sizes, and surround interactions. Therefore, attention produces a specific effect on different contextual influences such as contrast, foreground/background relationships, and texture boundaries. Considering the time course of events, it was claimed that the facilitation through attention from contextual effects of brightness arises at the same time as the response itself supports that feedforward mechanisms dominate the process. However, facilitation from texture boundaries arises late in response, therefore, contextual effect of texture boundaries might be mediated by feedback connections. If we consider the texture boundary as a sign of size determination, this finding might explain the different effect of attention on size and brightness illusions. According to this, attentional load occurs in V1 for brightness illusion whereas it occurs in higher level cortical areas for size illusion. This difference might cause differences in V1 activity through attention.

Another possible reason of the difference between size and brightness illusions might be the different characteristics of brightness and size. Visual system has two visual pathways, dorsal and ventral pathways (Goodale, & Milner, 1992). Dorsal pathway, also known as “where” pathway, travels to the parietal cortex and is involved in the motion perception, localization and spatial orientation. Ventral pathway, also known as “what pathway”, travels to the temporal cortex and is involved in the object recognition. Considering size and brightness, because of its spatial properties, size might be processed mostly by the dorsal pathway(Milner, & Goodale, 2008), whereas brightness should be processed by the ventral pathway. Furthermore, it is clear in literature that the visual information does not travel only through V1 to parietal cortex, there are direct connections from LGN to parietal cortex (Lamme, & Roelfsema, 2000). Feedback to V1 from parietal cortex reaches approximately at the same time with the information from LGN to V1. However, there is no direct connection from LGN to temporal visual regions (Lamme, & Roelfsema, 2000). In addition, it is known that attention is mostly processed in frontal and parietal cortices (Buschman, & Miller, 2007). Therefore, compared to features processed by the ventral pathway, any feature mostly processed in the dorsal pathway could yield different results when interacting with attention because of the conflict and processing load increase in parietal cortex. To test this claim, two different experiments might be conducted. First, instead of visuo-spatial attention task, any other type of attention such as auditory attention might be manipulated to see what the consequence of decreasing the process load in parietal cortex is. Second, the effect of attention on other visual illusions could be studied by grouping them according to the pathway they are processed to see the effect of interaction between attention and visual pathways. Additional experiments are needed to understand the mechanism.

CHAPTER 6

LIMITATIONS AND FUTURE DIRECTIONS

The results of psychophysical experiments helped us to see the effect of brightness on contrast perception, and also optimize the experimental conditions. Therefore, we believe that this study both with behavioural and fMRI results will be an important base to our future brain imaging studies on contextual effects of brightness on contrast perception.

Although small number of participants seem to be a limitation of the study, both the effects in luminance adjustment and contrast perception was consistently observed in all participants. Therefore, we can interpret that results are valid despite the relatively small number of participants (Boyaci, Doerschner, & Maloney, 2006). However, if we could not see such a strong validity especially in fMRI experiments, we could need more participants. Besides, considering the vision research, small number of participants is very common. For instance, the study of Peli et al. which we referenced has four participants (Peli et al., 1996). Therefore, our number of participants seems sufficient for the psychophysical experiments. However, we still need to gather more data from our participant because we need to counterbalance some conditions such as the side which light comes from in the stimulus.

As a limitation, because retinotopy session could be applied to only three participants we are not confident about the V2 results. Therefore, firstly retinotopy session of all participants will be completed to see the pattern in V2 activation in a bigger population.

The biggest question raised by the present study why attention has such an effect on V1 activation through illusory brightness and contrast perception and why the effect of attention on these features and size is different. Therefore, future research will be directed to this question. Furthermore, in the fMRI study, because our stimulus consisted of both illusory background and gratings for contrast perception we do not know whether the activation we observed caused by illusory contrast or illusory brightness. Therefore, we need to implement additional studies to discriminate the separate effects of these variables.

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APPENDICES

APPENDIX 1

Table 1. t-test results of brigtness value of CSs							
Adjustable patch on	**Lum cd/m^2**	**Mean**	**SD**	**SEM**	**t**	**df**	**P**
distant background	1,64	-5,39	1,58	0,56	-9,629	7	0,000
distant background	2.74	-9,16	1,95	0,69	-13,303	7	0,000
distant background	2.86	-9,06	2,47	0,87	-10,374	7	0,000
distant background	4.34	-12,20	4,51	1,59	-7,651	7	0,000
distant background	6.58	-12,61	3,33	1,18	-10,701	7	0,000
distant background	10.1	-18,29	4,95	1,75	-10,451	7	0,000
distant background	12.65	-13,07	5,55	1,96	-6,657	7	0,000
distant background	16.11	-16,04	6,75	2,39	-6,724	7	0,000
distant background	17.4	-19,35	5,59	1,98	-9,788	7	0,000
distant background	20.41	-11,69	5,19	1,83	-6,375	7	0,000
distant background	26.15	-16,67	6,11	2,16	-7,721	7	0,000
contexual background_circular	1,64	-6,83	3,36	1,19	-5,753	7	0,001
contexual background_circular	2.74	-17,42	6,81	2,41	-7,238	7	0,000
contexual background_circular	2.86	-18,26	5,96	2,11	-8,670	7	0,000
contexual background_circular	4.34	-21,28	7,31	2,58	-8,236	7	0,000
contexual background_circular	6.58	-23,74	8,47	3,00	-7,925	7	0,000
contexual background_circular	10.1	-32,59	11,29	3,99	-8,161	7	0,000
contexual background_circular	12.65	-24,39	6,15	2,17	-11,223	7	0,000
contexual background_circular	16.11	-34,53	14,04	4,96	-6,959	7	0,000
contexual background_circular	17.4	-37,49	11,68	4,13	-9,083	7	0,000
contexual background_circular	20.41	-23,92	7,40	2,62	-9,136	7	0,000
contexual background_circular	26.15	-36,06	10,37	3,66	-9,840	7	0,000

contexual background_covering	1,64	-7,39	1,90	0,67	-11,002	7	0,000
contexual background_covering	2.74	-26,79	7,05	2,49	-10,757	7	0,000
contexual background_covering	2.86	-37,16	12,16	4,30	-8,643	7	0,000
contexual background_covering	4.34	-40,22	9,64	3,41	-11,800	7	0,000
contexual background_covering	6.58	-35,09	6,80	2,40	-14,592	7	0,000
contexual background_covering	10.1	-52,09	7,87	2,78	-18,722	7	0,000
contexual background_covering	12.65	-35,79	7,89	2,79	-12,828	7	0,000
contexual background_covering	16.11	-50,37	12,02	4,25	-11,858	7	0,000
contexual background_covering	17.4	-53,50	12,59	4,45	-12,022	7	0,000
contexual background_covering	20.41	-39,49	8,39	2,97	-13,308	7	0,000
contexual background_covering	26.15	-52,42	9,04	3,19	-16,410	7	0,000

APPENDIX 2

Table 2. t-test result of perceived contrast values of gratings located on brighter CS and dimmer CS (Adjustable patch on context square)

Luminance values cd/m^2	Spatial Frequency	Contrast %	Mean	SD	SEM	t	df	P
1.64	2.5	10	0,03	0,02	0,01	4,009	5	0,010
1.64	2.5	30	0,11	0,04	0,02	6,619	5	0,001
1.64	2.5	60	0,15	0,11	0,05	3,158	5	0,025
2.86	2.5	10	0,04	0,03	0,01	3,053	5	0,028
2.86	2.5	30	0,10	0,06	0,03	3,683	5	0,014
2.86	2.5	60	0,18	0,19	0,08	2,272	5	0,072
10.1	2.5	10	0,03	0,02	0,01	3,582	5	0,016
10.1	2.5	30	0,04	0,06	0,02	1,660	5	0,158
10.1	2.5	60	0,08	0,10	0,04	1,977	5	0,105
17.4	2.5	10	0,00	0,03	0,01	0,026	5	0,980
17.4	2.5	30	0,02	0,05	0,02	0,861	5	0,429
17.4	2.5	60	0,08	0,11	0,04	1,980	5	0,105
1.64	5	10	0,02	0,04	0,02	1,183	5	0,290
1.64	5	30	0,04	0,06	0,02	1,866	5	0,121
1.64	5	60	0,12	0,09	0,04	3,267	5	0,022
2.86	5	10	0,02	0,06	0,02	0,981	5	0,372
2.86	5	30	0,06	0,08	0,03	2,045	5	0,096
2.86	5	60	0,17	0,08	0,03	5,348	5	0,003
10.1	5	10	0,02	0,01	0,00	7,995	5	0,000
10.1	5	30	0,06	0,02	0,01	6,920	5	0,001
10.1	5	60	0,14	0,09	0,04	3,545	5	0,016
17.4	5	10	0,01	0,03	0,01	1,008	5	0,360
17.4	5	30	0,04	0,04	0,02	2,468	5	0,057
17.4	5	60	0,09	0,11	0,05	1,840	5	0,125
1.64	10	10	0,00	0,02	0,01	0,432	5	0,684

1.64	10	30	0,02	0,01	0,01	4,658	5	0,006
1.64	10	60	0,10	0,10	0,04	2,473	5	0,056
2.86	10	10	0,05	0,05	0,02	2,595	5	0,049
2.86	10	30	0,08	0,06	0,02	3,683	5	0,014
2.86	10	60	0,20	0,17	0,07	2,828	5	0,037
10.1	10	10	0,02	0,03	0,01	1,810	5	0,130
10.1	10	30	0,07	0,06	0,02	3,047	5	0,029
10.1	10	60	0,15	0,09	0,04	3,771	5	0,013
17.4	10	10	0,00	0,02	0,01	-0,539	5	0,613
17.4	10	30	0,01	0,03	0,01	0,568	5	0,594
17.4	10	60	0,07	0,06	0,02	2,792	5	0,038
1.64	20	10	0,01	0,02	0,01	1,397	5	0,221
1.64	20	30	0,07	0,05	0,02	3,151	5	0,025
1.64	20	60	0,12	0,11	0,04	2,617	5	0,047
2.86	20	10	0,05	0,03	0,01	3,414	5	0,019
2.86	20	30	0,10	0,04	0,02	5,717	5	0,002
2.86	20	60	0,20	0,17	0,07	2,763	5	0,040
10.1	20	10	0,02	0,04	0,02	1,421	5	0,215
10.1	20	30	0,04	0,10	0,04	0,913	5	0,403
10.1	20	60	0,07	0,11	0,05	1,559	5	0,180
17.4	20	10	0,00	0,05	0,02	-0,214	5	0,839
17.4	20	30	0,00	0,07	0,03	0,141	5	0,893
17.4	20	60	0,08	0,11	0,04	1,956	5	0,108

APPENDIX 3

Table 3. t-test result of perceived contrast values of gratings located on brighter CS and dimmer CS (Adjustable patch on context square)								
Luminance cd/m²	**Spatial Frequency**	**Contrast %**	**Mean**	**SD**	**SEM**	**t**	**df**	**P**
1.64	2.5	10	0,03	0,03	0,01	2,26	5	0,073
1.64	2.5	30	0,13	0,14	0,06	2,30	5	0,070
1.64	2.5	60	0,18	0,23	0,09	1,90	5	0,116
2.86	2.5	10	0,07	0,02	0,01	8,10	5	0,000
2.86	2.5	30	0,29	0,28	0,11	2,57	5	0,050
2.86	2.5	60	0,29	0,24	0,10	2,90	5	0,034
10.1	2.5	10	0,03	0,04	0,01	2,28	5	0,072
10.1	2.5	30	0,12	0,15	0,06	1,91	5	0,114
10.1	2.5	60	0,29	0,22	0,09	3,13	5	0,026
17.4	2.5	10	0,02	0,04	0,02	1,16	5	0,299
17.4	2.5	30	0,06	0,13	0,05	1,17	5	0,294
17.4	2.5	60	0,16	0,21	0,09	1,87	5	0,120
1.64	5	10	0,05	0,04	0,02	2,63	5	0,047
1.64	5	30	0,12	0,14	0,06	2,11	5	0,089
1.64	5	60	0,14	0,12	0,05	2,78	5	0,039
2.86	5	10	0,11	0,07	0,03	3,99	5	0,010
2.86	5	30	0,23	0,17	0,07	3,45	5	0,018
2.86	5	60	0,37	0,27	0,11	3,36	5	0,020
10.1	5	10	0,04	0,02	0,01	5,30	5	0,003
10.1	5	30	0,06	0,12	0,05	1,21	5	0,280
10.1	5	60	0,27	0,30	0,12	2,17	5	0,082
17.4	5	10	0,02	0,04	0,02	1,22	5	0,276
17.4	5	30	0,10	0,12	0,05	2,07	5	0,093
17.4	5	60	0,14	0,21	0,09	1,61	5	0,169
1.64	10	10	0,03	0,01	0,00	6,36	5	0,001

1.64	10	30	0,15	0,10	0,04	3,66	5	0,015
1.64	10	60	0,14	0,17	0,07	2,10	5	0,090
2.86	10	10	0,09	0,05	0,02	4,74	5	0,005
2.86	10	30	0,22	0,09	0,04	5,91	5	0,002
2.86	10	60	0,29	0,28	0,11	2,49	5	0,055
10.1	10	10	0,02	0,03	0,01	1,67	5	0,156
10.1	10	30	0,12	0,22	0,09	1,25	5	0,265
10.1	10	60	0,25	0,21	0,09	2,91	5	0,033
17.4	10	10	0,01	0,04	0,02	0,75	5	0,486
17.4	10	30	0,09	0,09	0,04	2,32	5	0,068
17.4	10	60	0,19	0,20	0,08	2,28	5	0,071
1.64	20	10	0,02	0,03	0,01	1,59	5	0,172
1.64	20	30	0,11	0,16	0,06	1,68	5	0,154
1.64	20	60	0,10	0,16	0,07	1,45	5	0,206
2.86	20	10	0,08	0,06	0,02	3,46	5	0,018
2.86	20	30	0,23	0,12	0,05	4,43	5	0,007
2.86	20	60	0,35	0,33	0,14	2,59	5	0,049
10.1	20	10	0,03	0,04	0,02	2,12	5	0,087
10.1	20	30	0,09	0,19	0,08	1,20	5	0,286
10.1	20	60	0,28	0,20	0,08	3,43	5	0,019
17.4	20	10	0,00	0,03	0,01	-0,40	5	0,703
17.4	20	30	0,09	0,15	0,06	1,46	5	0,205
17.4	20	60	0,23	0,17	0,07	3,35	5	0,020