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# Context-dependent lightness affects perceived contrast

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ABSTRACT

Perceived contrast of a grating varies with its background (or mean) luminance: of the two gratings with the same photometric contrast the one on higher luminance background appears to have higher contrast. Does perceived contrast also vary with context-dependent background lightness even when the luminance remains constant? We investigated this question using a stimulus in which two equiluminant patches ("context squares", CSs) appear different in lightness. First we measured the lightness effect in a behavioral experiment. After ensuring that it was present for all participants, we conducted perceived contrast experiments, where participants judged the contrast of rectified incremental and decremental square-wave gratings superimposed on the CSs. For the incremental gratings participants' settings were significantly different for the two CSs. Specifically, perceived contrast was higher when the gratings were placed on the context square that was perceived lighter. In a follow-up experiment we measured perceived contrast of rectified gratings on isolated patches that differed in luminance. The pattern of results of the two experiments was consistent, demonstrating that possibly shared mechanisms underpin the effects of background luminance and context-dependent lightness on perceived contrast.



## 1. Introduction

By now it is well established that the human visual system is not primarily concerned with estimating the physical and optical properties of images formed on the retina. Instead it seems to be more interested in estimating object and scene properties that are critical for the fitness of the organism (see e.g., Koenderink, 2012; Purves, Morgenstern, & Wojtach, 2015). While how the visual system accomplishes this remarkable feat given a pair of inherently ambiguous retinal images is far from being completely understood, it is certain that it uses myriad of contextual cues that are present in a typical everyday scene. For example, even though two surfaces marked as A and B in Fig. 1 are equiluminant, the visual system estimates (correctly) that their lightnesses are different (also see Adelson, 2000; Blakeslee & McCourt, 2004; Goldstein, 2009; Purves & Lotto, 2011; Purves et al., 2008).

Now let us suppose that we superimpose grating patterns on these patches (see Fig. 4). What happens to the perceived contrast of those gratings? Vision scientists calculate the local contrast in an image using various formulas. (e.g., Michelson or Weber contrast). But these metrics do not always capture the relevant perceived qualities in the image (Haun & Peli, 2013). It is well known that perceived contrast of a simple isolated stimulus, such as a grating, is affected by its spatial frequency and background (or mean) luminance even when its calculated photometric contrast remains the same (e.g., Kane & Bertalmiío, 2016; Kilpeläinen, Nurminen, & Donner, 2011; Kilpeläinen, Nurminen, & Donner, 2012; Peli, Yang, Goldstein, & Reeves, 1991; Peli, Arend, & Labianca, 1996; Van & Bouman, 1967). In such simple configurations luminance and lightness covary. However as Fig. 1 convincingly demonstrates lightness and luminance do not always covary. Then the question arises: does the perceived contrast of a grating vary with the luminance or lightness of its background? Finding an answer to this question is critical to fully understand the underlying mechanisms of contrast perception, because it could indicate at which level contrast, luminance and lightness operate and interact in the visual system.

Even though context-dependent lightness has been studied extensively (e.g., Boyaci, Doerschner, Snyder, & Maloney, 2006; Gilchrist, 2015; Kingdom, 2011), its effects on perceived contrast were not studied directly and systematically previously. In a number of studies, related problems, particularly the effects of context-dependent lightness (and brightness) on luminance discrimination and detection thresholds were addressed (e.g., Hillis & Brainard, 2007; Maertens & Wichmann, 2013; Rieger & Gegenfurtner,

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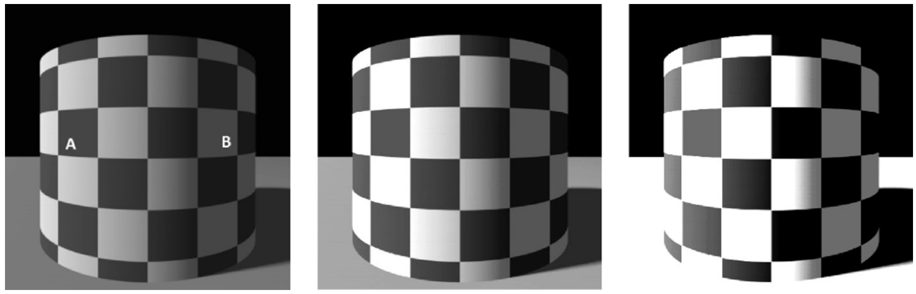


**Fig. 1.** Examples of the stimulus after image manipulations. "Context squares" (CSs), A and B in the first image and in the same position in all images, have identical luminance but different lightness.

1999, also see Kingdom, 2011; Singh & Anderson, 2002, for a general discussion of two-way interactions between contrast, and brightness and lightness). However to the best of our knowledge, there is no study directly investigating the effect of context-dependent lightness on perceived contrast and the interaction between contrast and luminance sub-systems.

Maertens, Wichmann, and Shapley (2015) investigated the effect of surrounding context on the lightness of elliptical regions using Adelson's cylinder-and-checkerboard stimulus (Adelson, 1995), and Shapley and Reid's stimulus (Shapley & Reid, 1985). In both types of context they placed elliptical targets on perceived-dark and perceived-light squares which were in fact equiluminant. They found that lightness of ellipses were assimilated, for example the ellipse placed on perceived-lighter square was also perceived lighter. However Maertens et al. (2015) did not asses perceived contrast between those ellipses and their background explicitly, in fact they offered models to explain their lightness results based on the photometric contrast values.

To directly examine the effect of context-dependent lightness on perceived contrast we conducted behavioral experiments using a stimulus inspired by Adelson's checkerboard stimulus (Adelson, 1995). There were two equiluminant context squares (CSs) on the stimulus, lightnesses of which appeared considerably different (Fig. 1). This stimulus allowed us to keep the luminance constant and test only the effect of context-dependent lightness. We had two main reasons for using this stimulus: firstly it leads to a very strong lightness effect, which increases our chances to find an empirical evidence for the effect of context-dependent lightness on perceived contrast. Secondly, in this configuration the target squares A and B are symmetrically positioned (they are not in Adelson's original stimulus), which makes better experimental conditions for future behavioral and neuroimaging studies that we are planning.

Firstly we assessed the lightness effect in the stimulus after applying several image manipulations. Results confirmed that the CSs differed statistically significantly in lightness for all observers. Another purpose of this experiment was to identify the image-manipulated stimuli that yield large lightness effects to use in the subsequent contrast experiments. In the second experiment we measured the perceived contrast of rectified square-wave gratings superimposed on the CSs (see Fig. 4). Using rectified gratings allowed us to study positive and negative contrast patterns independently, which was critical because both behavioral and neural evidence in previous studies suggest fundamental differences between processing of incremental and decremental luminance patterns (e.g., Blackwell, 1946; Chubb & Nam, 2000; Economou, Zdravkovic, & Gilchrist, 2007; Kremkow, Jin, Wang, & Alonso, 2016; Patel & Jones, 1968; Rekauzke et al., 2016; Rudd & Zemach, 2004, 2005; Sato, Motoyoshi, & Sato, 2016; Whittle, 1986; Zaghloul, Boahen, & Demb, 2003). Previous studies in literature have found interactions between spatial frequency and mean luminance in contrast perception using simple gratings (Chubb, Sperling, & Solomon, 1989; Georgeson & Sullivan, 1975; Peli et al., 1996; Robilotto & Zaidi, 2004; Van & Bouman, 1967). More specifically, perceived contrast of high-frequency gratings were more strongly affected by the mean luminance (Peli et al., 1996). Therefore, in our experiments we included spatial frequency as a further condition. Two more experiments were conducted to address possible confounds and the effect of luminance alone.

## 2. Experiment 1: measurement of the lightness effect

In the first experiment we quantified the lightness effect in the contextual stimulus after several image manipulations (Fig. 1). One of the main purposes of this experiment was to find the impact of image manipulations on the strength of the lightness effect. This allowed us to identify the stimuli with strong lightness effects to use in subsequent contrast experiments.

### *2.1. Methods*

#### *2.1.1. Participants*

Eight participants including the author ZP participated in the experiment (three male). The mean age was approximately 23.4 ranging from 21 to 26. All participants reported normal or corrected-to-normal vision, and had no history of neurological or visual disorders. Participants gave their written informed consent and the experimental protocols were approved by the Human Ethics Committee of Bilkent University.

#### *2.1.2. Stimuli, experimental procedure and analyses*

The experimental software was prepared by us using the Java programming platform. The stimuli were presented on a CRT monitor (HP P1230, 22 inch, 1600 $\times$ 1200 resolution). Presentation of correct luminance values was ensured by using a gray scale look-up table prepared after direct measurements with a colorimeter (SpectroCAL, Cambridge Research Systems Ltd., UK). Participants were seated 75 cm from the monitor, and their heads were stabilized using a head-and-chin rest. Participants' responses were collected via a standard computer keyboard.

A variant of Adelson's checkerboard stimulus ("contextual stimulus" or "stimulus" from here on, Fig. 1) was generated using the open source rendering package Radiance (Larson & Shakespeare, 1998). The lightness effect is defined and quantified as the difference between the lightnesses of the context squares (CSs) marked "A" and "B" in Fig. 1. The stimulus subtended 9.5 by 9.5 degrees of visual angle. Approximate size of the CSs was 0.85 by 0.85 degrees of visual angle. We prepared eleven different versions of the stimulus by manipulating the overall image contrast and luminance using the open-source software GIMP (http://www.gimp.org/). After these image manipulations, luminance of the context squares