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Simultaneous contrast and gamut relativity in achromatic color perception

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ABSTRACT

Simultaneous contrast refers to the respective whitening or blackening of physically identical image regions surrounded by regions of low or high luminance, respectively. A common method of measuring the strength of this effect is achromatic color matching, in which subjects adjust the luminance of a target region to achieve an achromatic color match with another region. Here I present psychophysical data questioning the assumption—built into many models of achromatic color perception—that achromatic colors are represented as points in a one-dimensional (1D) perceptual space, or an *absolute* achromatic color gamut. I present an alternative model in which the achromatic color gamut corresponding to a target region is defined relatively, with respect to surround luminance. Different achromatic color gamuts in this model correspond to different 1D lines through a 2D perceptual space composed of blackness and whiteness dimensions. Each such line represents a unique gamut of achromatic colors ranging from black to white. I term this concept *gamut relativity*. Achromatic color matches made between targets surrounded by regions of different luminance are shown to reflect the relative perceptual distances between points lying on different gamut lines. The model suggests a novel geometrical approach to simultaneous contrast and achromatic color matching in terms of the vector summation of local luminance and contrast components, and sets the stage for a unified computational theory of achromatic color perception.

1. Introduction

One of the best known illusions in vision research is *simultaneous color contrast*. In the context of *achromatic color perception*—the perception of black, white and gray shades—simultaneous contrast manifests itself in the respective *whitening* and *blackening* of physically identical image regions, such as a series of disks of constant luminance, viewed against surrounding image regions of variable luminance, such as a series of rings varying in luminance from low to high (Fig. 1).

Simultaneous contrast and related effects in achromatic color perception are often modeled under the assumption that achromatic colors can be specified within a one-dimensional (1D) space, like numbers on a (real-valued) number line (Arrington, 1996; Blakeslee & McCourt, 1997, 1999, 2004; Cohen & Grossberg, 1984; Dakin & Bex, 2003; Grossberg & Todorović, 1988; Hamada, 1985; Heinemann & Chase, 1995; Land & McCann, 1971; Moulden & Kingdom, 1990; Pessoa, Mingolla, & Neumann, 1995; Rudd, 2010; Rudd & Arrington, 2001; Rudd & Zemach, 2004; Spehar, Debonet, & Zaidi, 1996; Vladusich, Lucassen, & Cornelissen, 2006b; Wallach, 1948, 1992, 1994a, 1994b). According to edge integration models, for instance, the achromatic colors of the disks shown in Fig. 1 are computed as the weighted sum of contrast values, defined in terms of *log luminance ratios*, determined at local (disk/ring) and remote (ring-background) edges (Land & McCann, 1971; Rudd, 2010; Rudd & Arrington, 2001; Rudd & Zemach, 2004; Vladusich, Lucassen, & Cornelissen, 2006b). In cases where local and remote edges have opposite contrast polarity, as in Fig. 1, these models posit that ‘whiteness’ and ‘blackness’ signals respectively induced at contrast *increments* and *decrements* cancel to produce net achromatic color values. Other models incorporate a local luminance component that sums with the positive and negative contrast components (Pessoa, Mingolla, & Neumann, 1995), or postulate that achromatic colors are computed with respect to the highest luminance values within prescribed regions of the image (Gilchrist, 2006; Gilchrist et al., 1999; Grossberg & Hong, 2006).

A standard computational convention associated with these models is that the computed achromatic color range corresponds to a fixed continuum of gray shades varying between black and white poles. I term such a fixed continuum an *absolute achromatic color gamut*: It corresponds to the range of achromatic colors perceivable in a target region as the luminance of that region is varied between some arbitrary lower and upper bounds. According to standard convention, progressively more-positive values on the achromatic number line correspond to progressively whiter gray shades, until the fixed white pole is reached. Similarly, progressively more-negative values correspond to progressively blacker gray shades, until the fixed black pole is reached. The existence of fixed black and white points is thus *independent of the luminance*

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Fig. 1. Simultaneous contrast. The disks all have the same luminance, yet one tends to perceive disks surrounded by rings with luminance higher and lower than the background as relatively blacker and whiter, respectively.

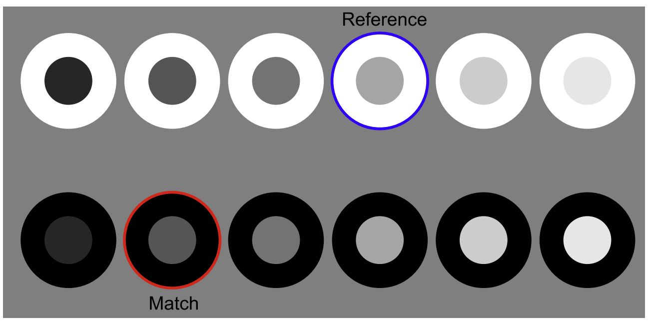

Fig. 2. Due to simultaneous contrast, disks surrounded by white rings all appear blacker than disks surrounded by black rings. The rings with the red and blue borders indicate the 'reference' and 'test' disks, respectively. The author has chosen as an *approximate* match, an achromatic color in the test series that corresponds to a disk of lower luminance than the luminance of the reference disk. The match appears unsatisfactory to the author, an observation consistent with a range of informal observations and psychophysical data (Ekroll et al., 2002; Ekroll, Faul, & Niederée, 2004; Logvinenko and Maloney, 2006; Niederée, 2010; Vladusich, Lucassen, & Cornelissen, 2006b, 2007; Whittle, 1994a, 1994b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

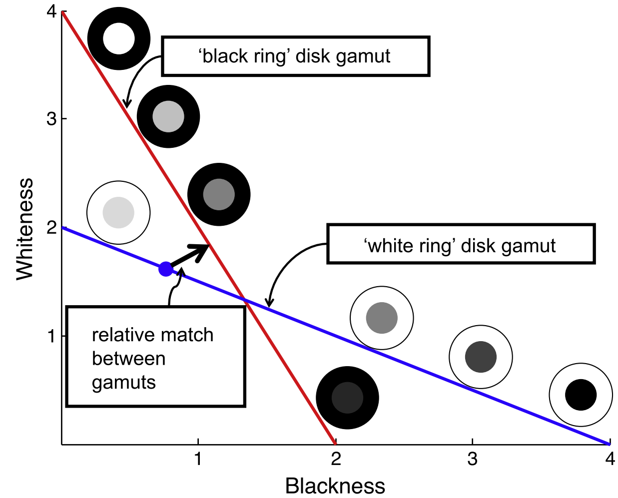

Fig. 3. Gamut relativity and relative achromatic color matching in blackness–whiteness space. According to the model, a fixed range of disk luminance values is mapped to different gamut lines in blackness–whiteness space, each depending on ring luminance. The term *gamut relativity* describes the family of lines that slice up blackness–whiteness space in different ways depending on the polarity of disk/ring contrast. The red and blue lines denote the achromatic color gamuts of a target disk viewed against regions of low and high luminance, respectively. A gamut is thus defined relatively as the range of achromatic colors that can be perceived in a target disk as the luminance of that disk is varied from a lower bound to an upper bound, for any given ring luminance. The points at which each line intersects the blackness and whiteness axes represent the *unique shades of black and white* associated with that gamut. All intermediate points along each line represent various shades of gray characterized by different mixtures of blackness and whiteness. Relative achromatic color matches made between disks viewed against rings of different luminance are conjectured to represent minimal perceptual distances between points constrained to lie on different gamut lines. In this case, the blue dot represents the achromatic color of the reference disk (belonging to the 'white ring' gamut). The vector joined to this point represents the minimal perceptual distance between the reference achromatic color and all points belonging to the 'black ring' gamut. Detailed explanations of the relationship between local simultaneous contrast and gamut lines is provided in the computational results section of this article. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of surrounding regions: It should always be possible, within the limits imposed by the displayable range of luminance values, to adjust the luminance of a target region to make it appear a fixed shade of white or black. Due to this independence with respect to surround luminance, furthermore, standard models predict that it should always be possible to establish *perfect* achromatic color matches between pairs of disks viewed against rings of different luminance, modulo the effects of internal noise (Vladusich, Lucassen, & Cornelissen, 2007). I term such putative matches *absolute* achromatic color matches, as their existence follows as a direct corollary of the notion of an absolute achromatic color gamut that is independent of surround luminance.

Many vision researchers have, however, noted that subjects are often unable to make absolute color matches between pairs of targets viewed against backgrounds that differ in luminance or hue (Ekroll et al., 2002; Ekroll, Faul, & Niederée, 2004; Heggelund, 1974a, 1974b, 1992; Logvinenko & Maloney, 2006; Logvinenko & Tokunaga, 2011; Niederée, 2010; Vladusich, Lucassen, & Cornelissen, 2006b, 2007; Whittle, 1992, 1994b, 1994a). The difficulty in setting achromatic color matches is illustrated in Fig. 2, where two physically identical rows of disks, varying within a row from low to high luminance, are embedded in black and white rings. The disks viewed against the black rings are contrast increments, whereas the disks viewed against the white rings are contrast decrements. The task, then, is to choose an increment in the 'black ring' series that best corresponds to a specific decrement in the 'white ring' series. In this example, the author has chosen, as an approximate match, an increment in the 'black ring' series that corresponds to a disk of slightly lower luminance than the target decrement in the 'white ring' series. The match does not, however, appear to be satisfactory, and so does not satisfy the condition of an absolute match, in the sense defined above.

In this article, I psychophysically and computationally characterize the difficulty in making achromatic color matches between pairs of disks viewed against rings of different luminance. I conjecture that the difficulty in establishing absolute matches arises because the achromatic color gamut is *relative*, meaning that it depends on the luminance of the region directly surrounding the target. I develop this conjecture in terms of a recently introduced model postulating that *blackness* and *whiteness* constitute the *perceptual dimensions* of a 2D achromatic color space (Vladusich, Lucassen, & Cornelissen, 2007).[1]

Unlike conventional 1D models of achromatic color perception—in which the absolute achromatic color gamut is itself 'aligned' with the perceptual dimension that represents achromatic colors—values represented along the perceptual dimensions of whiteness and blackness do not themselves correspond to achromatic color gamuts. Rather, points represented directly on the

[1] Vladusich, Lucassen, and Cornelissen (2007) originally termed these dimensions *brightness* and *darkness*. The term brightness has, however, been used in a number of different ways in the literature, and the term darkness, when used at all, is generally taken to mean the negative of brightness. Not wishing to cause further confusion, I here adopt the terms *blackness* and *whiteness*. The claim that these terms constitute labels for *perceptual dimensions* is an empirically testable postulate that forms the subject of this article (see Section 4).