Colorfulness Influences Perceptions of Valence and Arousal

Adam D. Pazda[1]

Christopher A. Thorstenson[2]

Adam K. Fetterman[3]

Word count: 8,979

[1] Department of Psychology, University of South Carolina Aiken
471 University Parkway, Aiken, SC 29801
adamp@usca.edu

[2] Munsell Color Science Laboratory, Rochester Institute of Technology, Rochester, NY

[3] Department of Psychology, University of Houston, Houston, TX

Author note: The method and results from Experiment 1 were presented at the Society for Personality and Social Psychology annual meeting in 2019. None of the ideas or data from Experiments 2, 3, or 4 have been presented, shared, or discussed outside of the research team.

Data, code, and stimulus materials are available on the Open Science Framework: osf.io/kbrmv

Adam Pazda served as lead for writing-original draft, formal analysis and contributed equally to conceptualization, investigation, methodology.

Christopher Thorstenson served as lead for resources, software, visualization, and contributed equally to conceptualization, investigation, methodology, validation, writing-review and editing.

Adam Fetterman served as lead for conceptualization, and contributed equally to investigation, methodology, validation, writing-review and editing.

Abstract

Research on color-emotion associations provides evidence that hue, chroma, and lightness relate to various emotional experiences. Most of this research has assessed these relationships via isolated color swatches while confounding color dimensions. We broadened the medium in which color-emotion associations were made by manipulating color in photographs varying in valence and/or arousal, and we solely focused on the chroma dimension. In Experiment 1, participants perceived neutral and positive valence photographs to be happier and more arousing when displayed chromatically, relative to achromatically. In Experiment 2, participants increased the chroma content of photographs to make them appear maximally happy, and they decreased the chroma content of photographs to make them appear maximally sad. In Experiment 3, participants altered the chroma content of photographs to their preferred levels, with positive valence photographs containing the most chroma, followed by neutral, then negative valence photographs. In Experiment 4, participants increased the chroma content of photographs to make them appear maximally positive or arousing, and they decreased chroma to make photographs appear maximally negative or calming. This pattern was similar regardless of the initial valence/arousal content of the images. These results indicate that chroma may convey emotion-relevant information independent of hue or lightness.

Keywords: color, emotion, arousal, valence, chroma

Public significance statement

This research highlights how color conveys emotional content in imagery. Images displayed with increased colorfulness (i.e., higher chromatic content) were associated with more positivity and arousal, and they were generally preferred to pictures that were relatively less colorful. This pattern emerged regardless of the emotional content of the images, indicating that color can convey emotion information through imagery broadly. Color appears to be intimately related to our emotional experience.

Colorfulness Influences Perceptions of Valence and Arousal

Researchers have given the relationship between color and emotions considerable empirical attention over several decades. This has led to a great deal of evidence for a variety of color-emotion associations. Even so, most of this evidence has focused solely on discrete colors viewed in isolation and in the absence of context (e.g., reporting the degree to which emotion categories are associated with various color squares; Hemphill, 1996; Kaya & Epps, 2004). Furthermore, much of the research in this domain has simultaneously investigated three color dimensions--hue, chroma, and lightness--in combination, making it difficult to draw conclusions regarding how each dimension is independently associated with emotion.

Hue, chroma, and lightness vary independently, which means each might contribute to emotion in different ways. Hue varies as a function of wavelength, and is the property of color typically used to categorize its appearance (i.e., red, blue, green, yellow). Lightness varies as a function of the relative amount of light coming from an object, and is related to brightness. Chroma corresponds to the perceived 'colorfulness' of an object, and is related to saturation or intensity[1]. If an investigation into color-emotion associations finds that yellow is associated with happiness, it might point to a hue effect (the category of yellow colors relates to happiness), a lightness effect (lighter colors are happy), or a chroma effect (the intensity of the yellow is happy) (D'Andrade & Egan, 1974; Schloss et al., 2020). Thus, it is difficult to discern the nature of each dimension's contribution to color-emotion associations when they are simultaneously investigated. We sought to provide some clarity in this domain by examining color-emotion

[1] Color terms, such as colorfulness, chroma, saturation, lightness, and brightness each have unique meanings when describing color perception. The discussion of color properties herein is simplified for ease of readability. We use "colorfulness", "intensity", and "chroma" interchangeably to help convey our conceptual background, as a detailed account of color models and terminology is beyond the scope of this paper. For a comprehensive overview of color models and systems, see Fairchild (2015).

associations solely along the chroma dimension. Specifically, we examine how image colorfulness across a wide array of hue and lightness values relates to emotions. Furthermore, instead of investigating isolated, context independent color swatches, we examine color-emotion associations in the context of photographs containing various degrees of emotional content.

Color and Emotion

Research on color-emotion associations has typically taken one of two forms. Most commonly, participants are shown an isolated color and then self-report what emotion they associate with the color, or what feelings the color evokes (Boyatzis & Varghese, 1994; Gao & Hin, 2006; Palmer et al., 2013b; Wilms & Oberfeld, 2018; Zenter, 2001). The color presentation typically takes the form of a rectangle via Munsell chips (Kaya & Epps, 2004; Valdez & Mehrabian, 1994), cardboard (Terwogt & Hoeksma, 2001; Zentner, 2001), or a computer monitor display (Wilms & Oberfeld, 2017). Sometimes color words, such as "red", are presented, rather than displaying actual colors (Adams & Osgood, 1973; Jonauskaite et al., 2020).

The other common methodology of investigating color-emotion associations entails showing participants an emotion category, then asking them to select a color that matches the emotion. These categories are often depicted with words (Burkitt et al., 2003; 2007; D'Andrade & Egan, 1974; Gilbert et al., 2016; Manav, 2007; Wexner, 1954), but are sometimes represented by facial expressions (Dael et al., 2016), drawings (Jue & Kwon, 2013), or music (Barbiere et al., 2007; Odbert et al., 1942; Palmer et al., 2013b). Color associations are typically assessed by having participants select an isolated color square that matches the emotion category.

There are two limitations with the methodological approaches outlined above. First, in most (but not all) cases, hue, chroma, and lightness are not controlled in color presentation. For example, some research has found that red (relative to green, blue, yellow, black, white, or gray) is associated with arousal (Adams & Osgood, 1973; Odbert et al., 1942; Wexner, 1954; Wilms & Oberfeld, 2017). This is typically interpreted as a hue effect (e.g., red is arousing). However, this interpretation is only warranted if each comparison hue controls for chroma and lightness (e.g., Wilms & Oberfeld, 2017). Otherwise, color-emotion associations may in fact be related to chroma (e.g., intense colors are arousing) or lightness (e.g., light colors are arousing; see D'Andrade & Egan, 1974). It may have been the case that the particular shades of red used in this research were particularly chromatic or light. In some instances, it is impossible to equate chroma and lightness when examining hue-emotion relations. Gray, for example, cannot be equated on chroma with red, blue, or green because gray is achromatic. Yellow and red are difficult to equate because yellow tends to be much lighter; thus, finding a suitable yellow comparison to red would significantly deviate from prototypical representations of the color. For colors that can be equated, matching chroma and lightness can be a laborious task that requires precise measurement with specialized equipment (see Elliot, 2019; Thorstenson, 2018).

It is reasonable to assume that hue, chroma, and lightness are often confounded in the majority of prior color-emotion investigations unless researchers explicitly stated whether color presentation was controlled. Even investigations using Munsell color chips as stimuli (which inherently control for hue, chroma, and lightness) can be problematic because various hues have different maximum levels of chroma. As such, selecting the highest chroma representations of different hue categories (e.g., yellow, blue) would inadvertently manipulate chroma in addition to hue (Kaya & Epps, 2004), as yellow has a higher level of maximum chroma than blue. These methodological issues render much of the extant research on color-emotion associations difficult to interpret. Stimulus sets that contain a large array of hues while controlling for chroma and lightness within hues (e.g., the Berkeley Color Project; Palmer & Schloss, 2010) can circumvent some of these pitfalls. However, allowing chroma to vary across hues can present additional problems, especially with regard to interpretation of potential interactive effects between hue and chroma.

The second methodological problem inherent with the research in this domain is that color-emotion associations are typically assessed in the absence of context via isolated color swatches. While useful, these types of associations may be limited, as it is evident that the context in which colors are perceived matters a great deal when studying psychological phenomena (Elliot & Maier, 2012). For example, red has been shown to elicit avoidance motivation in achievement contexts, but approach motivation in affiliation contexts (Meier et al., 2013). It is reasonable to assume that context might change the dynamic between color-emotion associations, e.g., red may be associated with anger under certain circumstances (Fetterman et al., 2011; 2012; Young et al., 2018), and happiness under others (Palmer et al., 2013b). Indeed, in contexts involving food judgments, red was positively associated with arousal (indicating approach motivation toward red food items), but no such association was present for natural non-food items or tools (Foroni et al., 2016). Furthermore, color-emotion associations that are documented with isolated swatches lack ecological validity. Real-world applications of color-emotion associations are less likely to feature isolated colors, but would almost certainly feature the content of multiple colors simultaneously throughout a scene (e.g., film, art, photographs, websites, advertisements, etc.), much like how emotional experiences are unlikely to be isolated categorical occurrences (Barrett, 2006).

Some research on color associations has examined pairs of colors presented simultaneously, in a side-by-side or foreground-background manner. Examinations of color associations with taste have found that combinations of colors sometimes evoke different associations than single colors (Woods et al., 2016; Woods & Spence, 2016). Studies on color preferences have revealed that liking a single color is only weakly related to liking color pairs (Palmer et al., 2013a; Schloss & Palmer, 2011). Though the focus of these investigations did not involve color-emotion associations specifically, they nonetheless indicate that color-emotion associations may also vary as a function of how colors are displayed in research designs.

The present research aims to address both of the methodological shortcomings outlined above. First, we isolate our focus to how the chroma dimension of color relates to emotions, specifically along the dimensions of valence and arousal. We chose chroma as our focal variable because it has been paid the least empirical attention in previous investigations, although there are reasons to posit why chroma and emotions may be linked (outlined below). Second, instead of examining color-emotion associations via isolated color swatches, we alter the chroma content of natural, emotion-laden images and assess how chroma information influences perceptions of those images. This allows us to address a more nuanced research question. Rather than inquiring whether single colors evoke feelings, we examine how color facilitates or dampens emotional experiences elicited by photographs. We hypothesized that higher chroma content would be positively associated with valence and arousal.

Chroma, Valence, and Arousal

Chroma is a dimension ranging from colorless (gray) to very colorful (e.g., fire engine red), with varying degrees of color intensity in between these anchors (e.g., Nantucket red, which appears more colorful than gray, but more faded than fire engine red). Retinal cones are responsible for chroma perception, and these require some amount of light to provide color information. In other words, chroma is not perceivable in the dark (Malacara, 2011; Stockman & Brainard, 2015).

Humans may have been conditioned to associate chroma with valence and arousal because of the nature of color vision in our diurnal behavioral patterns. Specifically, our species typically has higher physiological arousal during daylight hours and relatively lower arousal during the nighttime (Aschoff, 1960; Eysenck, 2017; Magoun, 1965). Due to the fact that some amount of light is required for chroma to be noticeable (i.e., between dawn and dusk), humans are most likely to perceive chroma precisely during the time in which our bodies are most aroused. Human diurnal activity is also characterized by approach behaviors (e.g., discovering food, exploring the environment, and seeking mates) during the day and avoidance behaviors (e.g., seeking shelter and protection) at night (Aschoff, 1960). These behavioral patterns are directly linked to our color vision system, with approach behaviors occurring when chroma is naturally perceivable (i.e., during the day) and avoidance behaviors occurring when it is not (i.e., during the night; Balaraman, 1962). Importantly, approach and avoidance motivation are associated with positive and negative emotion, respectively (Watson, 2000).

Taken together, there is a natural correlation between the times in which we experience positive and negative emotion, and the times in which we are able to perceive chroma. This repeated association between high arousal and positive outcomes when chroma is perceivable may have led humans to associate chroma with positive valence and high arousal states, and the lack of chroma (e.g., grayness or darkness) with negative valence and low arousal states. If so, then one might predict that people associate positive valence and high arousal with the presence of chroma and vice versa.

Evidence for these chroma-emotion associations can be found in language metaphors. According to Conceptual Metaphor Theory, the metaphors present in our language reflect the processing of abstract concepts through concrete referents (Lakoff & Johnson, 1980). As an example in the color domain, one might describe their anger in terms of perceptual redness (e.g., "I'm seeing red"). The person that describes their anger in terms of redness is not trying to be fanciful in their speech, but has come to associate anger and perceptual redness as a way to better process their anger (Gibbs, 1994; Kövecses, 2000). Social cognitive psychologists have found that these associations can be investigated through what has been termed the "metaphoric transfer effect" (Landau et al., 2010), whereby priming one concept of the metaphor (e.g., anger) leads to activation in the other domain (e.g., perceptual redness; Fetterman et al., 2012).

Most relevant to the current investigation is a class of metaphors that associate color with positive-valence and high-arousal states (e.g., "the world is filled with color and life") and lack of color with negative-valence and low-arousal states (e.g., "I'm in a dark place"). Gray, an achromatic color, is also a word used to describe gloomy and dismal affairs (Allan, 2009). Descriptors of high-chroma colors (e.g., lively, vibrant) clearly map onto concepts representing high-arousal, whereas descriptors of low-chroma colors (e.g., subtle, muted) clearly map onto low-arousal. Further, the word "faded" can refer to a relatively low-chroma color (e.g., Nantucket red), and it can also metaphorically refer to a reduction in human energy (i.e., low-arousal).

Many of the metaphors relating color to valence and arousal confound lightness with chroma. Black, for example, is an achromatic color that is also low on the lightness dimension. Numerous metaphors exist that use black to symbolize negativity (e.g., black sheep, black markets, Black Death). More generally, there is a class of metaphors that relate darkness with negativity ("dark days are ahead" indicates troubling prospects; questionable business dealings are shady; untrustworthy people have a dark side). Metaphor research has shown that perceptual lightness influences perceptions of valence (Meier et al., 2004), and that priming negative valence (e.g., via displaying frowning faces) influences perceptions of lightness (Meier et al., 2007; Hyunjin et al., 2012). Persich and colleagues (2019) found that preferences for darkness were associated with negative emotions, such as depression. Most relevant to the current research, Lakens et al. (2013) demonstrated that reducing the lightness of images elicited more negative evaluations of the images. It is possible that these relations between lightness and valence originate from the same sources from which we derived our hypotheses regarding chroma-emotion associations (i.e., human diurnal behavior patterns and metaphoric transfer effects). However, our goal is to examine whether chroma has unique associations with valence and arousal, independent of the documented associations between lightness and these dimensions.

Some of the extant research on color-emotion associations provides evidence for a relationship between chroma and valence/arousal, albeit indirectly due to the methodological issues previously discussed. For example, when matching color terms to music, participants were most likely to pick gray from a list of eleven color terms to match sad songs, and they were least likely to choose gray for happy songs (Barbiere et al., 2007). Gray is consistently associated with negativity or sadness (Hemphill, 1996; Kaya & Epps, 2004; Odbert et al., 1942). People with depression were more likely to select gray than those without depression to illustrate their mood (Carruthers et al., 2010). Children tended to choose achromatic colors to depict objects or persons described as nasty or sad, relative to nice or excited (Boyatzis & Varghese, 1994; Burkitt et al., 2003; 2007; Burkitt & Sheppard, 2014; Cimbalo et al., 1978; Terwogt & Hoeksma, 2001). High-chroma colors have been associated with higher arousal via musical tempo (Palmer et al., 2013b), word selections (Schifferstein & Tanudjaja, 2004), self-reported feelings (Valdez & Mehrabian, 1994), and electrodermal activity (Wilms & Oberfeld, 2017). Finally, participants were more likely to correctly identify whether artists were emotionally distressed when viewing their drawings in color, relative to black and white (Jue & Kwon, 2013), indicating that the chroma content used by artists may provide a window into their emotional state.

Most of the aforementioned investigations utilized methodology that prohibits drawing firm conclusions about chroma-emotion associations. This is due to lack of measurement of color properties, not controlling for lightness and hue when assessing chroma-emotion associations, or utilizing color words instead of presenting actual color stimuli. Some investigations have circumvented these problems (e.g., Jonauskaite et al., 2019; Palmer et al., 2013b; Schloss et al., 2020; Valdez & Mehrabian, 1994; Wilms & Oberfeld, 2017), which provide the most compelling evidence for relations between chroma and valence/arousal. However, they utilized methodology focusing on isolated color swatches, leaving the question of how chromatic content of objects or scenes (rather than color in isolation) relates to emotions.

Some research in the domain of consumer behavior has taken the approach of manipulating colors across objects (e.g., product packages, advertisements, and logos), and found conceptually similar patterns to those in the color-emotion literature. For example, chromatic packaging, relative to black and white packaging, increases product preferences and purchasing intentions (Rosa et al., 2018; Labrecque & Milne, 2012). Additionally, high-chroma advertisements increase excitement toward products (Gorn et al., 1997; Labrecque & Milne, 2012), and high-chroma logos increase excitement about brands (Labrecque & Milne, 2012).

While these patterns of results are consistent with general chroma-emotion associations, they do not directly address the emotional component (though some research has failed to show a relationship between chroma and emotions with regard to consumer perceptions, e.g., Lee et al., 2014). We sought to provide clarity in this domain by adopting the methodological approaches of consumer communication research (i.e., manipulating color across entire objects/scenes), while isolating chroma as our focal variable. This allowed us to determine how chroma relates to emotions across images with a wide array of hues and lightness values.

Overview of the present research

We conducted four experiments that directly tested the relationship between image colorfulness and image valence and/or arousal. In Experiment 1, we manipulated the chroma of neutral and positive valence images to be either grayscale or chromatic, and we assessed the influence of the images on participants' self-reported ratings of valence and arousal. In Experiment 2, we allowed participants to linearly change the chroma of neutral-valence images to make the images appear either maximally happy (positive valence) or sad (negative valence). In Experiment 3, we asked participants to linearly change the chroma of positive, neutral, and negative valence images to match their preferences for the images. In Experiment 4, we had participants linearly change the chroma of four different image categories (pairwise combinations of relatively high vs. low valence and arousal) to make the images appear maximally positive, negative, exciting, and calming. For each experiment, we expected that image valence, arousal, and preference would be positively associated with image chromaticity. We additionally investigated whether this valence-chroma association would vary as a function of initial image valence and/or arousal.

Experiment 1

In Experiment 1, we investigated whether changing the chroma of pictures would affect the emotional response to those pictures. As such, we had participants report their feelings toward chromatic (color) or achromatic (grayscale) images that were either neutral or positive in content. The chroma manipulation was administered between-subjects in order to disguise the study hypothesis, though all participants were shown neutral and positive images. We predicted a main effect of chroma, such that colored images would elicit higher responses on valence and arousal, compared to grayscale images. We did not make any specific predictions regarding how this pattern might depend on the valence of the images.

Method

One hundred twenty-eight undergraduate students (88 female, 28 male, 7 declined to indicate their sex; M_{age} = 19.54 years, SD_{age} = 2.27) from a U.S. University in the southeast participated in exchange for course credit. Sample size was determined a priori via power analysis (targeting .80 power to detect a *d* of .50 at p = .05). The images were 16 high-valence and 16 neutral-valence photographs selected from the IAPS image database (Lang et al., 2008) based on pre-validated valance ratings (positive valence M = 7.26; neutral valence M = 4.99). The positive valence photos were also pre-rated as eliciting higher arousal (M = 4.67) than the neutral valence images (M = 2.76). These images were additionally manipulated to be presented in either full color or in grayscale. See Figure 1 for an example of the stimuli used in this experiment. The dependent measure used was the SAM rating scale (Lang et al., 2008). For the SAM rating scale, participants were instructed to click on the pictures that were most similar to their feelings when viewing each image. Participants responded along a valence dimension (1 = sad, 5 = happy) and an arousal dimension (1 = calm, 5 = excited).

Participants completed the experiment on a computer with an EIZO Color Edge CX271 monitor, color-calibrated using an i1-pro spectrophotometer (achieved monitor specifications were D65, x = .31, y = .33, Y = 120 cd/m^2). A welcome screen indicated that the study would consist of viewing a slideshow of images, along with questions assessing how the images made them feel. Participants viewed the images one at a time, for 5 seconds each. Participants were randomly assigned to view the entire slideshow in either grayscale (*n* = 58) or in color (*n* = 65). Following each image, participants responded to the SAM rating scale. Participants viewed each of the images in random order, followed by the SAM rating scale for each image, for a total of 32 trials. Afterwards, participants completed a demographic questionnaire and were dismissed. Five participants indicated a color-vision deficiency and were thus excluded from analyses.

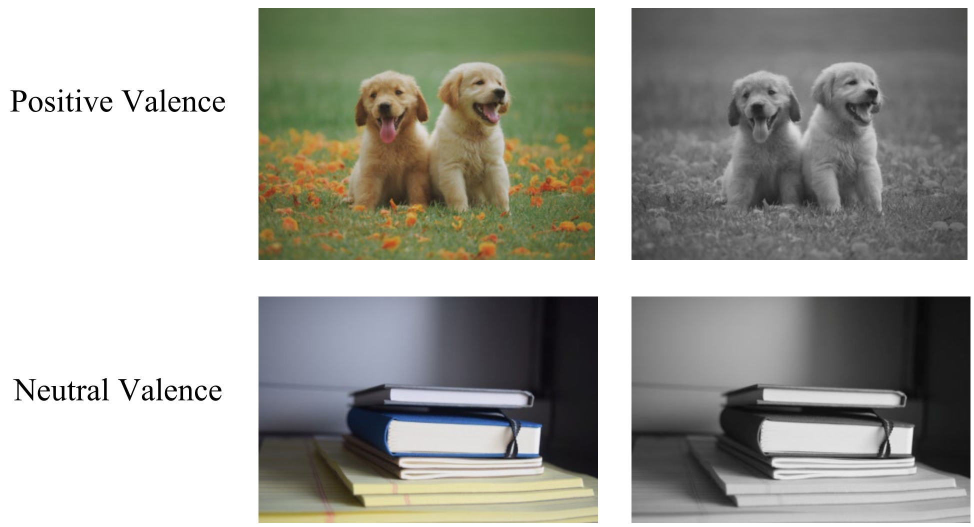

Figure 1. Example stimuli used in Experiment 1[2]

Transparency and openness

For each experiment, all data exclusions, manipulations, and variables analyzed are reported, and data collection was completed prior to any analysis. All participants were unique; each person only participated in one experiment. All analyses included only participants with color-normal vision, assessed by self-report at the end of each experiment; participants that reported a color vision deficiency were excluded from analyses *a priori*. Study procedures were approved by our institutional review boards, and we acquired informed consent from all participants in each experiment. All data, analysis codes, and descriptions of research materials

[2] Example stimuli presented in Figures 1, 3, and 5 are stock photos in the public domain obtained from Pexels.com. These photos were not used in any experiment, but they are included to provide a visual depiction of the color and valence manipulations.

are available at osf.io/kbrmv (we cannot directly share images obtained from the IAPS or NAPS databases, but we provide image category and numbers so that other researchers can request the same materials from the creators of these databases). Data were analyzed using SPSS version 28. None of the experimental designs or analyses were pre-registered.

Results and discussion

Two valence and arousal composite scores were created for each participant by averaging ratings across images (separately for positive-valence and neutral photographs). Higher numbers indicate more positive valence/higher arousal. We then conducted a 2 (chromatic vs. achromatic) x 2 (positive valence vs. neutral) mixed ANOVA for valence and arousal ratings.

Valence. As predicted, there was a main effect of chroma on valence, $F(1, 120) = 5.94$, $p = .016$, $d = .40$, indicating that chromatic images made people feel happier ($M = 3.54$, $SE = .03$) than achromatic images (3.42, $SE = .04$). There was also main effect of image type, $F(1, 120) = 599.23$, $p < .001$, $d = 2.19$, indicating that positive-valance images made people feel happier ($M = 3.99$, $SE = .03$) than neutral images ($M = 2.96$, $SE = .03$). The interaction between color and image type was not statistically significant, $F(1, 120) = .26$, $p = .61$, indicating that the effect of chroma on valence did not differ as a function of image type.

Arousal. As predicted there was a main effect of chroma, $F(1, 121) = 4.15$, $p = .044$, $d = .37$, such that chromatic images were perceived as more arousing ($M = 2.22$, $SE = .08$) than achromatic images ($M = 1.98$, $SE = .09$). There was also a main effect of image type, $F(1, 121) = 341.32$, $p < .001$, $d = 1.73$, such that positive-valence images were perceived as more arousing ($M = 2.67$, $SE = .08$) than neutral images ($M = 1.51$, $SE = .06$) (Figure 2). The interaction between color and image type was not significant, $F(1, 121) = 0.0$, $p = .99$, indicating that the effect of chroma on arousal did not differ as a function of image type.

These results were in accordance with our hypotheses. Chroma positively influenced valence and arousal, such that pictures with chromatic content led participants to experience more happiness and arousal than the same pictures without chroma. This did not depend on the initial valence of the images, meaning that chromatic pictures induced more favorable and higher arousal emotions regardless of whether the images depicted something neutral or positive.

We should note that comparing chromatic images to achromatic images introduces some potential alternative explanations for the observed results. First, the chromatic images contained various hues, meaning participants were exposed to hue information along with chromatic information for each image. Thus, it may be the case that perceiving certain hues led to the increase in perceived valence and arousal, rather than chroma content per se. Second, participants were exposed to chromatic and lightness contrasts in the full-color pictures, but only lightness contrasts in the black and white pictures. Therefore, it is possible that the conjunction of chroma and lightness contrasts elicited higher valence and arousal ratings when viewing the colorful pictures, rather than the presence of chroma by itself.

We treat chroma as a continuous (rather than dichotomous) variable in the subsequent experiments to rule out these possibilities. That is, hue information is perceivable (and equated) in all subsequent stimulus photograph sets, and the conjunction of chroma and lightness contrasts is also present in all subsequent photo sets. Finally, we hold the lightness values constant within each image sequence in all subsequent experiments. In other words, different images in our subsequent stimulus sets have different starting lightness values that naturally vary, but images within a sequence varying in chromatic content maintain identical lightness values. This enables us to draw conclusions about the unique relationship between chroma and valence/arousal, independent from the effects of hue and lightness.

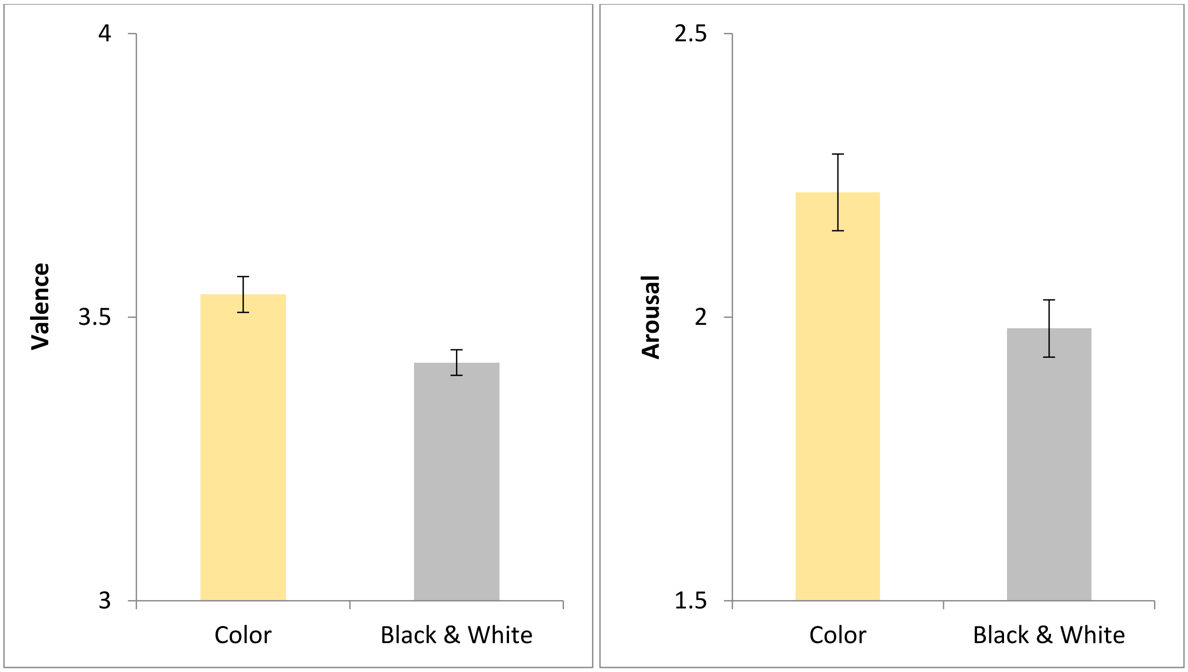

Figure 2. Mean valence and arousal ratings as a function of chroma condition (collapsed across positive and neutral valence photographs) in Experiment 1. Bars represent standard errors of the means.

Experiment 2

In Experiment 1, the results revealed that categorical image colorfulness was associated with more positive valence and higher arousal. Next, we wanted to further test our hypotheses by investigating whether continuous, linear differences in image chromaticity positively relate to the perceived valence of stimuli. Therefore, in Experiment 2 we allowed participants to change the chroma content of neutral valence images to make them look either maximally positive or maximally negative.

Method

Ninety-seven students (73 female, 22 male, 2 declined to indicate their sex; M_{age} = 19.96 years, SD_{age} = 1.53) from a U.S. university in the northeast with normal color vision participated in the experiment in exchange for course credit. Sample size (target n = 90) was determined a priori via power analysis (targeting .80 power to detect a d of .30 at $p = .05$), which we exceeded due to participant availability.

Eight neutral images were selected from the NAPS image database (Marchewka et al., 2014) based on pre-validated valence ratings ($M = 5.19$). The images were then manipulated using Matlab to either increase or decrease in colorfulness (by +/- 100 percent CIELAB Chroma in 11 steps) to form a continuous image sequence that ranged from grayscale to highly chromatic (image 1 = grayscale, image 2 = 20% chroma, image 6 = original image, image 11 = 200% chroma). See Figure 3 for an example of the stimuli used in this experiment. We verified that chroma was the only color dimension to vary across the photographs by converting sRGB images to CIELAB colorspace according to our display calibration, and calculating the average L*, C*, and h° values of pixels across each image sequence. Lightness and hue values were held constant within photographs; only chromatic content of the images varied across the 11 steps. Because part of the image sequence increased chroma beyond that of the original images, some image pixels were likely clipped to remain in gamut, particularly for images with higher initial chroma content, and for the highest extreme ends of the image sequence. Thus, while the chroma content of the images continued to increase throughout the sequence, it likely did so in a slightly non-linear way toward the high end of the sequence.

Participants completed the study on a computer with a CRT monitor that was color-calibrated using an i1-pro spectrophotometer (achieved monitor specifications were D65, x=.31, y=.33, Y=120 cd/m^2). An instructions screen informed the participants that they would view a series of images and would be asked to change the color of the images according to instructions at the beginning of each block (one for happy and one for sad). In addition, they were instructed to “change the color of the images to make the images look as happy [sad] as possible.”

Participants saw each of the 8 images once in each block, for a total of 16 trials. Block order and image order within blocks were randomized. When each image was presented, participants were able to change the chroma by moving the mouse horizontally over the image and selecting their choice by clicking. The starting chroma value of the image and the starting mouse position were randomized.

Figure 3. Example stimulus sequence used in Experiment 2.

Results and discussion

Chroma composite scores were created for each participant by averaging image selections across trials (separately for happy and sad instructions). Higher numbers indicate higher chroma image selections.

A paired-samples t-test revealed a main effect of instruction condition, $t(96) = 43.78$, $p < .001$, $d = 4.45$, indicating that participants made the images more chromatic to convey happiness ($M = 9.13$, $SE = .11$) than to convey sadness ($M = 2.30$, $SE = .09$). Further, one-sample t-tests (against a test-value of 6, representing the original image) revealed that participants significantly increased the image chroma to convey happiness, $t(96) = 29.37$, $p < .001$, $d = 2.98$, and significantly decreased the image chroma to convey sadness, $t(96) = -43.09$, $p < .001$, $d = -4.38$ (see Figure 4).

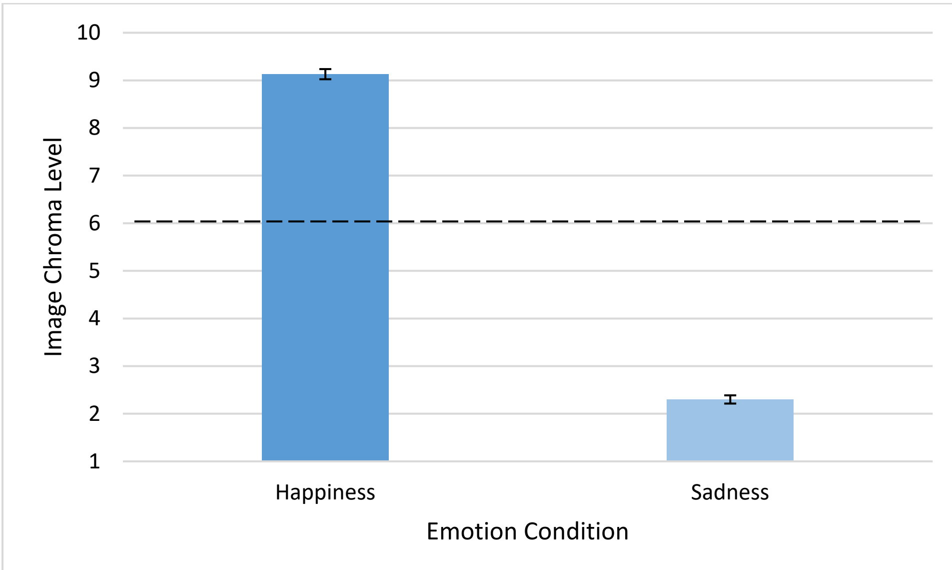

Figure 4. Means for participant chroma selections as a function of emotion instruction in Experiment 2. The dashed line indicates the baseline chroma level from the original images. Bars represent standard errors of the means.

Our hypotheses were supported by the data. The difference in chroma values across the instruction conditions (happy vs. sad) was large. Furthermore, the deviations in chroma values from the original images were significant and large in both conditions, whereby increases in chroma were applied to convey happiness, and decreases in chroma were applied to convey sadness. These results are complimentary to those of the previous experiment by showing a bidirectional relationship between chroma and valence; perceiving chroma led participants to rate images as happier (Exp. 1), and the task of making images appear happier led participants apply more chroma (Exp. 2).

Experiment 3

The results of Experiment 2 reveled that participants increased chroma to make neutral images appear maximally happy, and they decreased chroma to make images appear maximally sad. Next, we tested whether this relation extends to another measure of perceived image valence, specifically, image preference. Additionally, we tested whether the baseline, starting valence of the image further influenced this relation. Therefore, in Experiment 3, participants were asked to change the chroma of negative, neutral, and positive valence images to match their preference for the image (i.e., until they liked the image best).

Method

Ninety-three students (68 female, 22 male, 3 declined to indicate their sex; M_{age} = 20.17 years, SD_{age} = 1.45) from a U.S. university in the northeast with color-normal vision participated in the experiment in exchange for course credit. Sample size (target n = 90) was determined a priori via power analysis (targeting .80 power to detect a d of .30 at p = .05), which we exceeded due to participant availability.

Twenty-four images (eight each for negative, neutral, and positive valence) were selected from the NAPS image database (Marchewka et al., 2014) based on pre-validated valence ratings (negative valence M = 2.97; neutral valence M = 5.19; positive valence M = 8.21). The images were then manipulated in the same way as in Experiment 2. Matlab was used to either increase or decrease in colorfulness (by +/- 100 percent CIELAB Chroma in 11 steps) to form a continuous image sequence that ranged from grayscale to highly colorful (image 1 = grayscale, image 2 = 20% chroma, image 6 = original image, image 11 = 200% chroma). Lightness and hue values were held constant within photographs; only chromatic content of the images varied across the 11 steps. See Figure 5 for examples of stimuli used in this experiment.

Participants completed the study using the same computer and monitor (with the same color-calibration specifications) as in Experiment 2. A welcome screen informed participants that they would view a series of images and would be asked to change the color of the images according to instructions at the beginning of each block (one for each of negative, neutral, and positive valence images). They further read that they were to “Please change the color of the scene to match your preference. In other words, please adjust the scene until you like the image best.” Participants saw each of the 8 images once in each valence block, for a total of 24 trials. Block order and image order within blocks were randomized. When each image was presented, participants were able to change the chroma content by moving the mouse horizontally over the image, and selecting their choice by clicking the image. The starting chroma value of the image and the starting mouse position were randomized.

Negative

Neutral

Positive

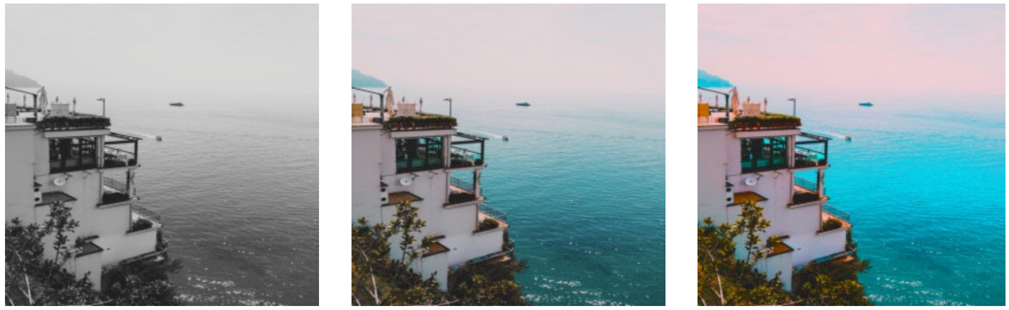

Figure 5. Example stimuli used in Experiment 3. Images reflect the following steps in the chroma manipulation sequence: 1 (achromatic), 6 (original image), and 11 (200% chroma).

Results and discussion

Chroma composite scores were created for each participant by averaging image selections across trials (separately for negative, neutral, and positive valence images). Higher numbers indicate higher chroma image selections.

Across all images, participants increased chroma to match their preference (*M* = 7.02, *SE* = .114), *t*(92) = 8.92, *p* < .001, *d* = .92, indicating a general trend of preferring images with relatively higher chroma content. However, a repeated measures ANOVA revealed a main effect of valence condition on image chroma selections, *F* (2,184) = 40.69, *p* < .001, η_p^2 = .31. Pairwise comparisons indicated that participants increased chroma more for positive valence (*M* = 7.93, *SE* = 0.13) images, relative to neutral valence images (*M* = 6.97, *SE* = 0.13), *t*(92) = 6.48, *p* < .001, *d* = .67 and negative valence images (*M* = 6.15, *SE* = 0.21), *t*(92) = 7.61, *p* < .001, *d* = .79. Likewise, participants increased chroma more for neutral valence images, relative to negative valence images, *t*(92) = 4.09, *p* < .001, *d* = .42. One-sample t-tests (against a test-value of 6, representing the original images) indicated that participants significantly increased image chroma for positive valence images, *t*(92) = 15.22, *p* < .001, *d* = 1.58, and neutral valence images, *t*(92) = 7.25, *p* < .001, *d* = .75, but did not significantly change image chroma for negative-valence images, *t*(92) = .722, *p* = .47, *d* = .08 (Figure 6).

In general, participants tended to prefer images with higher chroma content, relative to the original images' chromaticity. This was especially the case for images with positive valence. However, participant preferences for chroma were roughly the same as the original images' chromaticity for negative valence images. In other words, participants neither increased nor decreased chroma to match their preference for negative images, which provides some insight into the relative amount of influence of chroma vs. content on image preferences. On the one hand, adding color to an unpleasant image is unlikely to change the valence of that image if the content is sufficiently negative. This would explain why chroma did not increase in this image condition. On the other hand, reducing chroma may make an already negative image appear even more negative. This would explain why chroma did not decrease in this image condition. These possibilities are merely speculative, but they point to a preference for images that are matched in context (valence) and content (chroma). In other words, people may prefer images that elicit happiness most when the properties of that image (i.e., high-chroma) convey happiness. Conversely, people may prefer images that elicit sadness most when the properties of that image (i.e., low-chroma) convey sadness. Further, this finding supports the notion that context plays an important role in color preferences more broadly. In line with Ecological Valence Theory (Palmer & Schloss, 2010), which has demonstrated that color preferences can be modified by the valence of objects that correspond to different colors (Strauss et al., 2013), preference for colored images depends on the emotional context of the images.

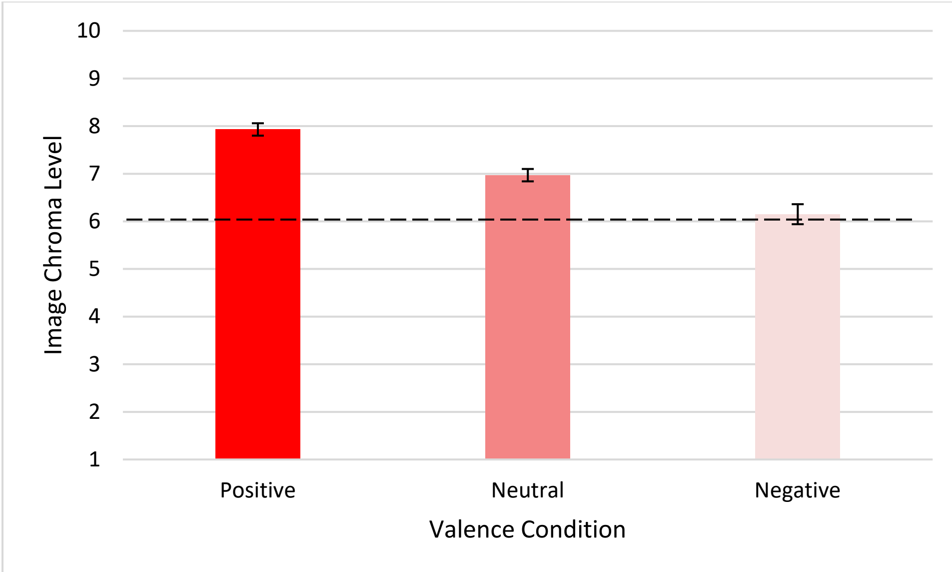

Figure 6. Means for participant chroma selections as a function of image valence in Experiment 3. The dashed line indicates the baseline chroma level from the original images. Bars represent standard errors of the means.

Experiment 4

Our first experiment investigated how valence and arousal were related to the chromatic content of photographs, although the subsequent two experiments focused solely on the relation between valence and chroma. We return our focus to both valence and arousal in Experiment 4 to rule out some alternative explanations for the results of the previous two experiments. Specifically, the comparison between happiness and sadness in Experiment 2 could have confounded valence and arousal, as sadness is typically characterized as having negative valence and low arousal, whereas happiness has positive valence but may be high or low arousal, depending on the circumstances. Furthermore, in Experiment 3, the stimulus photographs representing high, neutral, and low valence did not hold arousal constant. Therefore, the differences in chromatic content applied to photographs may have been due to valence differences, arousal differences, or a combination of the two dimensions. We sought to reduce this ambiguity by separating the valence and arousal dimensions in Experiment 4.

Method

Seventy-three students from a southern U.S. university with color-normal vision participated in the experiment in exchange for course credit. Sample size (n = 73) was determined by recruiting as many participants as possible during two academic semesters.

Twenty images (five each from the following categories: positive valence and high arousal, positive valence and low arousal, negative valence and high arousal, negative valence and low arousal) were selected from the NAPS image database (Marchewka et al., 2014) based on pre-validated valence and arousal ratings. The positive images were rated as higher in valence (M = 7.55) than the negative images (M = 3.65), and the high arousal images were rated as more arousing (M = 6.44) than the low arousal images (M = 3.93). Valence ratings were similar across arousal categories ($M_{valence}$ for high-arousal images = 5.34; $M_{valence}$ for low-arousal images = 5.77). However, it was not possible to equate image arousal across valence categories ($M_{arousal}$ for positive valence images = 4.16; $M_{arousal}$ for negative valence images = 6.20), although arousal ratings were greater for the high (vs. low) arousal images within each valence category. Thus, these image categories representing the intersection of valence and arousal are best conceptualized as relative rather than absolute.

The images were then manipulated in the same way as in Experiment 3. Matlab was used to either increase or decrease in colorfulness (by +/- 100 percent CIELAB Chroma in 11 steps) to form a continuous image sequence that ranged from grayscale to highly colorful (image 1 = grayscale, image 2 = 20% chroma, image 6 = original image, image 11 = 200% chroma).

Lightness and hue values were held constant within photographs; only chromatic content of the images varied across the 11 steps.

Participants completed the study using the same computer and monitor (with the same color-calibration specifications) as in Experiment 1. A welcome screen informed participants that they would view a series of images and would be asked to change the color of the images according to instructions at the beginning of each block. There were four blocks in total, with instructions stating "Please change the color of the scene to make the photographs appear maximally positive [negative, calm, exciting]." Participants saw each of the 20 images once in each block for a total of 80 trials. Block order and image order within blocks were randomized. When each image was presented, participants were able to change the chroma content by moving the mouse horizontally over the image and selecting their choice by clicking the image. The starting chroma value of the image and the starting mouse position were randomized. To summarize, there were 4 different picture types (positive valence and high arousal, positive valence and low arousal, negative valence and high arousal, negative valence and low arousal). All of these pictures were included in 4 different block types (instructions to make photographs appear maximally positive, negative, calm, exciting), where participants changed the chroma content of the pictures accordingly.

Results and discussion

Chroma composite scores were created for each participant by averaging image selections across trials (separately for positive valence and high arousal, positive valence and low arousal, negative valence and high arousal, negative valence and low arousal images). Higher numbers indicate higher chroma image selections.

We conducted a 4 (picture category) by 4 (instruction category) repeated-measures ANOVA to examine the degree to which chroma content varied as a function of the valence/arousal of the images, the instructions (e.g., making the pictures appear maximally positive, negative, exciting, calm), and the interaction between these variables. Main effects emerged for picture category, $F(3, 216) = 11.26$, $p < .001$, $\eta_p^2 = .14$, and instruction category, $F(3, 216) = 356.29$, $p < .001$, $\eta_p^2 = .83$. However, these effects were qualified by a significant two-way interaction, $F(9, 648) = 14.05$, $p < .001$, $\eta_p^2 = .16$. To further probe this interactive effect, we examined the simple effects for each picture category separately across instruction categories. See Figure 7 for a summary of the results from Experiment 4.

Positive instructions. When participants were instructed to make the images appear as positive as possible, a main effect of picture category emerged, $F(3, 216) = 16.06$, $p < .001$, $\eta_p^2 = .18$. Pairwise comparisons revealed that participants added a greater amount of chroma to pictures representing positive valence and high arousal than to the rest of the picture categories. The lowest amount of chroma was applied to pictures representing low valence and high arousal, and this category significantly differed from all others. The two picture categories representing low arousal (but differing in valence) were not significantly different from each other. One-sample t-tests (against a test-value of 6, representing the original images) for each picture category indicated that participants significantly increased image chroma for all picture types (*t*s > 9.85, *p*s < .001, Cohen's *d* range = 1.15 - 3.08). Thus, chroma was added to all picture types when attempting to make the images appear maximally positive. This was especially the case for images that contained positive valence and high arousal (e.g., fun, delight).

Negative instructions. When participants were instructed to make the images appear as negative as possible, a main effect of picture category emerged, $F(3, 216) = 16.80$, $p < .001$, $\eta_p^2 =$

.19. Pairwise comparisons revealed that all picture categories were significantly different from each other, with positive valence and low arousal having the least amount of chroma, and negative valence and high arousal having the most amount of chroma. However, it is important to note that in all picture categories, chroma values were significantly lower than the original images (one-sample *t*s > 10.52, *p*s < .001, Cohen's *d* range = 1.23 – 4.04). Thus, participants greatly reduced chroma to convey image negativity in general. This was especially the case for positive valence and low arousal (e.g., calm, content) imagery, and was less so for negative valence and high arousal (e.g., fear, distress) imagery.

Exciting instructions. When instructed to make the images appear as exciting as possible, a main effect of picture category emerged, $F(3, 216) = 2.69$, $p = .047$, $\eta_p^2 = .04$. Pairwise comparisons revealed that positive valence and high arousal pictures elicited higher chroma selections than pictures representing positive valence and low arousal ($p < .001$). No other differences were observed. One-sample t-tests revealed that participants increased chroma (relative to the original images) for all picture categories (*t*s > 16.85, *p*s < .001, Cohen's *d* range = 1.97 – 2.66).

Calm instructions. When instructed to make the images appear as calm as possible, a main effect of picture category emerged, $F(3, 216) = 13.02$, $p < .001$, $\eta_p^2 = .15$. Pairwise comparisons indicated that low valence and high arousal pictures elicited significantly lower chroma values than all other picture categories (*p*s < .001). No other differences were observed. One-sample t-tests revealed that participants decreased chroma (relative to the original images) for all picture categories (*t*s > 4.55, *p*s < .001, Cohen's *d* range = .53 – 1.03). In sum, participants greatly reduced chroma to convey calmness in the images, and this was especially the case for low valence and high arousal (e.g., fear, distress) photographs.

These results shine further light on the relation between chroma and valence/arousal. With regard to valence, chroma values for images intended to convey something positive far exceeded the original images' chromaticity, and this was the case for all picture types. In contrast, chroma was virtually nonexistent for images intended to convey something negative. With regard to arousal, a similar pattern emerged such that chroma was strongly and positively associated with excitement (high arousal) but negatively associated with calmness (low arousal), relative to the original images' chromaticity. Interestingly, the magnitude of reduction in image chromaticity was much stronger for the negative valence condition than the calm condition, indicating that a lack of chroma corresponds more strongly to negative valence than it does for low arousal. Although the initial valence and arousal content of the images created some variability in the chromaticity applied, these tended to be relatively small and they all followed the same general pattern.

Figure 7. Means for participant chroma selections as a function of image category and instruction category in Experiment 4. The dashed line indicates the baseline chroma level from the original images. Bars represent standard errors of the means.

General Discussion

We found support for our hypotheses across all four experiments. In Experiment 1, manipulating the chromatic content of pictures influenced participants' self-reported happiness and arousal when viewing the pictures. In Experiment 2, participants added chroma content to photographs to make them appear maximally happy, and they decreased chroma content to make them appear maximally sad. In Experiment 3, participants increased the chromatic content of pictures in a linear fashion (corresponding to negative, neutral, and positive valence) to make those pictures appear in accordance with their preferences. Finally, in Experiment 4, participants increased the chromatic content of images to make them appear positive or exciting, but decreased chroma to make images appear negative or calm. This was the case regardless of the images' initial valence and arousal content.

We propose that the association between chroma, valence, and arousal likely stems from repeated pairings between chromaticity and emotional experiences. First, the diurnal nature of human activity tends to afford our species with more positive experiences (e.g., exploration, food foraging) during the day, when we are able to perceive the chromatic dimension of color (versus the night when we are unable to naturally perceive chroma). Second, Conceptual Metaphor Theory (Lakeoff & Johnson, 1980) suggests that people use metaphors to convey concepts that are conceptually associated with one another, and that they reflect a conceptual pairing of otherwise disparate constructs. The fact that chroma and valence are intertwined in our lexicon (e.g., one definition of 'gray' is 'lacking cheer or brightness in mood') supports the notion that there is a strong experiential pairing between chroma and valence/arousal. Third, seasonal changes in weather patterns sometimes correspond to changes in mood, with grayer skies during fall and winter (and consequently lower environmental chromaticity) generally corresponding to negative affect, relative to sunny spring and summer (Klimstra et al., 2011). Although we did not explicitly test the degree to which these potential mechanisms are responsible for the chroma-emotion relationships documented herein, future research examining this would be welcomed.

The present research has several strengths that advance our understanding of the relationship between color and emotions. Specifically focusing on the chroma dimension provides insight regarding how color intensity relates to valence and arousal independent of hue and lightness content. These studies also expanded the context in which color-emotion associations were assessed by utilizing photographs varying in emotional content, rather than isolated color swatches. Our results provide compelling research opportunities in several applied settings, such as art, photography, home and office decor, social media, web design, and advertising. For instance, when artists, advertisers, or software engineers intend to convey certain emotional content through images, manipulating chroma may provide a simple avenue to change the emotional tone (Schwarz et al., 2017). Indeed, this is already a common practice in cinema and television (Bellantoni, 2012; Zettl, 2014). Achromatic imagery may be especially relevant when conveying the emotion of nostalgia, as black and white visual media tends to be perceived as more strongly related to the past than colorful stimuli (Grainge, 2002; Greenleaf, 2010; cf. Lee et al., 2014). Expanding the scope of chroma investigations to include numerous discrete emotions would help elucidate this possibility.

Limitations and future directions

Although our series of experiments provides compelling evidence for the relation between chroma and emotions, there are several caveats that warrant discussion. First, the domain of human emotions is large and complex. Our treatment of emotions in the present research largely focused on dimensions of emotions (e.g., valence, arousal) instead of discrete emotions, excepting Experiment 2 where our target emotions were happy and sad. Although combinations of emotional dimensions can map onto discrete emotions in some ways (e.g., the emotion of feeling calm entails positive valence and low arousal), we cannot draw firm conclusions about how chroma relates to categorical emotions that have similar valence and arousal patterns (e.g., anger and anxiety are both highly arousing and unpleasant, yet qualitatively distinct). It may not be the case that all negative valence emotions are equally associated with low chroma. Anger, for example, might deviate from this pattern due to its prevalent association with red (Fetterman et al., 2011; 2012), a color that is typically highly chromatic. Similarly, black, an achromatic color, may relate to high arousal emotions (e.g., fear; Hupka et al., 1997) and low arousal emotions (e.g., sadness; Burkitt & Sheppard, 2017) in different contexts. Additional research focusing on discrete emotions might identify some notable exceptions to the patterns observed here.

Second, although the relations between chroma and valence/arousal in the present research appear to follow a linear trend, we are hesitant to make generalizations about how these patterns would emerge in different contexts. From a methodological standpoint, the chroma content in our stimulus images maxed out at 200% of the original values. We find it reasonable to think that increasing chroma beyond this level may yield diminishing (or possibly reversed) effects. Research by Kuijsters et al. (2009) has shown that perceived image quality tends to follow an inverted U shape with higher amounts of chroma, such that low chroma and excessive chroma tend to reduce quality perceptions. This may be applicable to our experiment examining image preferences (Exp. 3), and it could possibly extend to emotion associations. From a conceptual standpoint, Color-in-context theory (Elliot & Maier, 2014) emphasizes the notion that color meanings vary across contexts, and we acknowledge that our inquiry into the association between chroma and emotions omitted some contexts that might yield different results. Highly chromatic stimuli may be incongruent with some settings due to social norms. For example, achromatic attire is widely expected at funerals. Therefore, in contexts related to bereavement, chroma may carry negative connotations. Furthermore, there are some contexts in which achromatic colors have positive connotations (e.g., formal events), and Color-in-context theory would predict that reduced chroma in these situations would be viewed favorably. Exploring boundary conditions of chroma-emotion associations in contexts like these would provide a fuller understanding of these relationships.

Third, there may be differences in the perceived naturalness of images varying in chroma, which could have implications for our findings. For example, extremely low chromaticity (i.e., black and white) images might be perceived as relatively unnatural because most people are accustomed to encountering chroma information in natural scenes. Thus, chromatic imagery may lead to favorable evaluations via familiarity processes (e.g., Zajonc, 1968). Alternatively, images with exaggerated chroma content (e.g., the 200% chroma images in our research) may be perceived as unnatural because people do not typically encounter scenes appearing so highly chromatic in the real world. This might lead to more positive emotional responses and preferences via novelty (Berlyne, 1970). Research on image preferences supports this possibility, as incrementally higher chromatic content increases perceptions of quality despite a corresponding reduction in perceived naturalness (de Ridder et al., 1995). Future investigations that include an assessment of perceived naturalness could help identify the degree to which this plays a role in emotions and/or preferences.

Fourth, some research indicates that chromatic images may be processed differently than achromatic images due to perceptual features varying among the image types (Gilchrist, 2006;

Meyers-Levy & Peracchio, 1995; Nothdurft, 2000). For example, details in black and white photographs are more difficult to discern because hue contrast information is not available. This leads people to process achromatic photographs in a relatively holistic fashion, whereas chromatic pictures are processed by attending to more specific features (Lee et al., 2014). It is conceivable that this difference in processing may have accounted for the results obtained in Experiment 1, such that more attention to the chromatic images may have increased perceived valence and arousal, rather than the chroma content per se. Our focus on linear differences along the chroma dimension in Experiments 2, 3 and 4 casts doubt on this possibility. Nonetheless, future research examining whether differences in processing speed or cognitive effort play a role in color-emotion associations would be worthwhile.

Fifth, it is worth noting that our methodological approach differed between Experiment 1 (whereby participants viewed chromatic vs. achromatic images and evaluated their emotional content) and Experiments 2-4 (whereby participants adjusted the chromatic content of images to match an emotional prompt). These approaches likely offer conceptually distinct insights into the influence of chroma on emotion: Do people have different emotional responses to variable image chroma, or do people utilize variable chroma to supplement or clarify an image’s emotional meaning? While the current results provide affirmative support for both types of questions, we expect that these represent conceptually distinct processes. Future work would do well to clarify color’s role in emotion as it relates to these distinguishable processes.

Finally, although our research design allowed us to assess how chroma relates to emotions, it did not provide opportunities to address how hue or lightness may potentially moderate these relationships. Previous research indicates that the lightness dimension is related to positive emotions (Dael et al., 2015; Lakens et al., 2013; Meier et al., 2004; Valdez &

Mehrabian, 1994), which raises the question of whether the chroma effects observed herein would vary as a function of lightness (e.g., perhaps high chromaticity more strongly relates to positive valence and arousal at high, relative to low, levels of lightness). Future research examining the degree to which color dimensions interact with each other when testing color-emotion associations would be particularly informative.

In sum, the current work advances our understanding of the relationship between color and emotions by demonstrating a positive influence of chroma, independent of other color properties such as hue or lightness, on the perceived valence, arousal, and preference of colored images. The current work highlights the utility of chroma to convey emotional meaning in applied domains, and the role of chroma in emotion communication more broadly.

Constraints on generality

Our findings provide evidence that people associate image colorfulness with positive valence and high arousal. Although our samples were comprised of undergraduate students, we anticipate that our findings will generalize to broader populations, with some potential exceptions. For example, we exclusively sampled English speaking participants in our research. Because our hypotheses were partially derived from color-emotion metaphors in the English language, it is unknown whether our results might replicate in a non-English speaking population. Further, dispositional variables, such as extraversion or sensory-processing sensitivity, may moderate the relation between chroma and emotion (see Pazda & Thorstenson, 2018). Finally, our experiments were conducted in a laboratory setting where stimuli were displayed on color-calibrated computer monitors. We do not have direct evidence that our results will generalize to other displays, including printed media. Identifying boundary conditions of our findings would be a worthwhile endeavor.

References

Adams, F. M., & Osgood, C. E. (1973). A cross-cultural study of the affective meanings of color. *Journal of Cross-Cultural Psychology, 4,* 135-156.

Allan, K. (2009). The connotations of English colour terms: Colour-based X-phemisms. *Journal of Pragmatics, 41,* 626-637.Aschoff, J. (1960). *Exogenous and endogenous components in circadian rhythms.* In Cold Spring Harbor symposia on quantitative biology (Vol. 25, pp. 11-28). Cold Spring Harbor.

Balaraman, S. (1962). Color vision research and trichromatic theory: A historical review. *Psychological Bulletin, 59*, 434-448.

Barbiere, J. M., Vidal, A., & Zellner, D. A. (2007). The color of music: Correspondence through emotion. *Empirical Studies of the Arts, 25*, 193-208.

Barrett, L. F. (2006). Are emotions natural kinds? *Perspectives on Psychological Science, 1*, 28-58.

Bellantoni, P. (2012). *If it's purple, someone's gonna die: The power of color in visual storytelling.* Burlington, MA: Focal Press.

Berlyne, D. E. (1970). Novelty, complexity, and hedonic value. *Perception & Psychophysics*, *8*, 279-286.

Boyatzis, C. J., & Varghese, R. (1994). Children's emotional associations with colors. *The Journal of Genetic Psychology, 155*, 77-85.

Burkitt, E., Barrett, M., & Davis, A. (2003). Children's colour choices for completing drawings of affectively characterised topics. *Journal of Child Psychology and Psychiatry, 44*, 445-455.

Burkitt, E., & Sheppard, L. (2014). Children's colour use to portray themselves and others with happy, sad and mixed emotion. *Educational Psychology, 34*, 231-251.

Burkitt, E., Tala, K., & Low, J. (2007). Finnish and English children's color use to depict affectively characterized figures. *International Journal of Behavioral Development, 31*, 59-64.

Carruthers, H. R., Morris, J., Tarrier, N., & Whorwell, P. J. (2010). The Manchester Color Wheel: Development of a novel way of identifying color choice and its validation in healthy, anxious and depressed individuals. *BMC Medical Research Methodology, 10:12*.

Cimbalo, R. S., Beck, K. L., & Sendziak, D. S. (1978). Emotionally toned pictures and color selection for children and college students. *The Journal of Genetic Psychology, 133*, 303-304.

Dael, N., Perseguers, M., Marchand, C., Antonietti, J., & Mohr, C. (2016). Put on that colour, it fits your emotion: Colour appropriateness as a function of expressed emotion. *The Quarterly Journal of Experimental Psychology, 69,* 1619-1630.

D'Andrade, R., & Egan, M. (1974). The colors of emotion. *American Ethnologist, 1*, 49-63.

de Ridder, H., Blommaert, F. J., & Fedorovskaya, E. A. (1995). Naturalness and image quality: Chroma and hue variation in color images of natural scenes. In *Human Vision, Visual Processing, and Digital Display VI* (Vol. 2411, pp. 51-61). SPIE.

Elliot, A. J. (2019). A historically-based review of empirical work on color and psychological functioning: Content, methods, and recommendations for future research. *Review of General Psychology, 23,* 177-200.

Elliot, A. J., & Maier, M. A. (2012). Color-in-context theory. *Advances in Experimental Social Psychology, 45,* 61-126.

Eysenck, H. (2017). *The biological basis of personality.* New York: Routledge.

Fairchild, M. D. (2015). Color models and systems. In A. Elliot, M. Fairchild, & A. Franklin (Eds.) *Handbook of color psychology*. Cambridge University Press.

Fetterman, A. K., Robinson, M. D., Gordon, R. D., & Elliot, A. J. (2011). Anger as seeing red: Perceptual sources of evidence. *Social Psychological and Personality Science, 2*, 311-316.

Fetterman, A. K., Robinson, M. D., & Meier, B. P. (2012). Anger as “seeing red”: Reaction time evidence for an implicit association. *Cognition and Emotion, 26*, 1445-1458.

Foroni, F., Pergola, G., & Rumiati, R. I. (2016). Food color is in the eye of the beholder: the role of human trichromatic vision in food evaluation. *Scientific Reports, 6*: 37034.

Gao, X., & Hin, J. H. (2006). Investigation of human's emotional responses on colors. *Color Research and Application, 31*, 411-417.Gibbs, R. W. (1994). *The poetics of mind: Figurative thought, language, and understanding*. Cambridge: Cambridge University Press.

Gilbert, A. N., Fridlund, A. J., & Lucchina, L. A. (2016). The color of emotion: A metric for implicit color associations. *Food Quality and Preference, 52,* 203-210.

Gilchrist, A. (2006). *Seeing black and white*. New York: Oxford University Press.

Gorn, G., Chattopadhyay, A., Yi, T., & Dahl, D. (1997). Effects of color as an executional cue in advertising: They're in the shade. *Management Science, 43*, 1387-1400.

Grainge, P. (2002). *Monochrome memories: Nostalgia and style in 1990s America*. Westport, CT: Praeger.

Greenleaf, E. (2010). Does everything look worse in black and white? The role of monochrome images in consumer behavior. In A. Krishna (Ed.), *Sensory marketing: Research on the sensuality of products* (pp. 241-258). New York: Routledge.

Hemphill, M. (1996). A note on adults' color-emotion associations. *The Journal of Genetic Psychology, 157*, 275-280.

Hupka, R. B., Zaleski, Z., Otto, J., Reidl, L., & Tarabrina, N. V. (1997). The colors of anger, envy, fear, and jealousy: A cross-cultural study. *Journal of cross-cultural psychology*, *28*, 156-171.

Hyunjin, S., Vonasch, A., Meier, B. P., & Bargh, J. A. (2012). Brighten up: Smiles facilitate perceptual judgments of facial lightness. *Journal of Experimental Social Psychology*, *48*, 450-452.

Jonauskaite, D., Althaus, B., Dael, N., Dan-Glauser, E., & Mohr, C. (2019). What color do you feel? Color choices are driven by mood. *Color Research and Application, 44*, 272–284.

Jonauskaite, D., Parraga, C. A., Quiblier, M., & Mohr, C. (2020). Feeling blue or seeing red? Similar patterns of emotion associations with colour patches and colour terms. *I-Perception, 11*.

Jue, J., & Kwon, S. (2013). Does colour say something about emotions?: Laypersons' assessments of colour drawings. *The Arts in Psychotherapy, 40*, 115-119.

Kaya, N., & Epps, H. H. (2004). Relationship between color and emotion: A study of college students. *College Student Journal, 38*, 396-405.

Klimstra, T. A., Frijns, T., Keijsers, L., Denissen, J., Raaijmakers, Q., van Aken, M., Koot, H., van Lier, & Meeus, W. (2011). Come rain or come shine: Individual differences in how weather affects mood. *Emotion, 6*, 1495-1499.Kövecses, Z. (2005). *Metaphor in culture: Universality and variation.* New York, NY: Cambridge University Press.

Kuijsters, A., Ijsselsteijn, W. A., Lambooij, M. T., & Heynderickx, I. E. (2009). Influence of chroma variations on naturalness and image quality of stereoscopic images. In *Human Vision and Electronic Imaging XIV* (Vol. 7240, pp. 461-469). SPIE.

Labrecque, L., & Milne, G. (2012). Exciting red and competent blue: the importance of color in marketing. *Journal of the Academy of Marketing Science, 40*, 711-727.

Lakens, D., Fockenberg, D., Lemmens, K., Ham, J., & Midden, C. (2013). Brightness differences influence the evaluation of affective pictures. *Cognition and Emotion, 27*, 1225-1246.

Lakoff, G., & Johnson, M. (1980). *Metaphors we live by.* Chicago, IL: The University of Chicago Press.

Landau, M. J., Meier, B. P., & Keefer, L. A. (2010). A metaphor-enriched social cognition. *Psychological Bulletin, 136,* 1045-1067.

Lang, P. J., Bradley, M. M., & Cuthbert, B. N. (2008). International affective picture system (IAPS): Affective ratings of pictures and instruction manual. Technical Report A-8. University of Florida, Gainesville, FL.

Lee, H., Deng, X., Unnava, H. R., & Fujita, K. (2014). Monochrome forests and colorful trees: The effect of black-and-white versus color imagery on construal level. *Journal of Consumer Research, 41,* 1015-1032.

Magoun, H. W. (1965). *The waking brain* (2nd ed.). Springfield, IL: Charles C Thomas.

Malacara, D. (2011). *Color vision and colorimetry: theory and applications*. Bellingham, WA: SPIE Press.

Manav, B. (2007). Color-emotion associations and color preferences: A case study for residences. *Color Research and Application, 32*, 144-150.

Marchewka, A., Żurawski, Ł., Jednoróg, K., & Grabowska, A. (2014). The Nencki Affective Picture System (NAPS): Introduction to a novel, standardized, wide-range, high-quality, realistic picture database. *Behavior Research Methods, 46*, 596-610.

Meier, B. P., D'Agostino, P. R., Elliot, A. J., Maier, M. A., & Wilkowski, B. M. (2013). Color in context: Psychological context moderates the influence of red on approach and avoidance motivated behavior. *PLoS ONE, 7*, e4033.

Meier, B., Robinson, M., & Clore, G. (2004). Why good guys wear white: Automatic inferences about stimulus valence based on brightness. *Psychological Science, 15*, 82-87.

Meier, B. P., Robinson, M. D., Crawford, L. E., & Ahlvers, W. J. (2007). When 'light' and 'dark' thoughts become light and dark responses: Affect biases brightness judgments. *Emotion, 7,* 366-376.

Meyers-Levy, J., & Peracchio, L. (1995). Understanding the effects of color: How the correspondence between avaliable and required resources affects attitudes. *Journal of Consumer Research, 22,* 121-138.

Nothdurft, H. (2000). Salience from feature contrast: additivity across dimensions. *Vision Research, 40*, 1183-1201.

Odbert, H. S., Karwoski, T. F., & Eckerson, A. B. (1942). Studies in synesthetic thinking: Musical and verbal associations of color and mood. *The Journal of General Psychology, 26*, 153-173.

Palmer, S. E., & Schloss, K. B. (2010). An ecological valence theory of human color preference. *Proceedings of the National Academy of Sciences of the United States of America*, *107*, 8877–8882.

Palmer, S. E., Schloss, K. B., & Sammartino, J. (2013a). Visual aesthetics and human preference. *Annual Review of Psychology, 64*, 77-107.

Palmer, S. E., Schloss, K. B., Xu, Z., & Prado-Leon, L. R. (2013b). Music-color associations are mediated by emotion. *Proceedings of the National Academy of Sciences, 110*, 8836-8841.

Pazda, A. D., & Thorstenson, C. A. (2018). Extraversion predicts a preference for high-chroma colors. *Personality and Individual Differences, 127*, 133-138.

Pazda, A. D., Thorstenson, C. A., & Fetterman, A. K. (2022). Open Science Framework. osf.io/kbrmv

Persich, M. R., Bair, J.L., Steinemann, B., Nelson, S., Fetterman, A. K., & Robinson, M. D. (2019). Hello darkness my old friend: preferences for darkness vary by neuroticism and co-occur with negative affect. *Cognition and Emotion, 33,* 885-900.

Rosa, V., Spence, C., & Tonetto, L. (2019). Influences of visual attributes of food packaging on consumer preference and associations with taste and healthiness. *International Journal of Consumer Studies,* 43, 210-217.

Schifferstein, H. N., & Tanudjaja, I. (2004). Visualising fragrances through colours: The mediating role of emotions. *Perception, 33*, 1249-1266.

Schloss, K. B., & Palmer, S. E. (2011). Aesthetic response to color combinations: preference, harmony, and similarity. *Attention Perception & Psychophysics, 73*, 551-571.

Schloss, K. B., Witzel, C., & Lai, L. Y. (2020). Blue hues don't bring the blues: questioning conventional notions of color–emotion associations. *Journal of the Optical Society of America A, 37*, 813.

Schwarz, K., Fuchs, C., Finckh, M., & Lensch, H. (2017). Emotune – changing emotional response to images. In *Color and Imaging Conference* (Vol. 2017, No. 25, pp. 317-323). Society for Imaging Science and Technology.

Strauss, E. D., Schloss, K. B., & Palmer, S. E. (2013). Color preferences change after experience with liked/disliked colored objects. *Psychonomic Bulletin and Review, 5*, 935-943.

Stockman, A., & Brainard, D. H. (2015). Fundamentals of color vision I: color processing in the eye. In A. Elliot, M. Fairchild, & A. Franklin (Eds.) *Handbook of color psychology*, 27-69.

Terwogt, M. M., & Hoeksma, J. B. (2001). Colors and emotions: Preferences and combinations. *The Journal of General Psychology, 122*, 5-17.

Thorstenson, C. A. (2018). The social psychophysics of human face color: Review and recommendations. *Social Cognition, 36*, 247-273.

Valdez, P., & Mehrabian, A. (1994). Effects of color on emotions. *Journal of Experimental Psychology: General, 123*, 394-409.

Watson, D. (2000). *Mood and temperament*. New York: Guilford Press.

Wexner, L. B. (1954). The degree to which colors (hues) are associated with mood-tones. *The Journal of Applied Psychology, 38*, 432-435.

Wilms, L., & Oberfeld, D. (2018). Color and emotion: Effects of hue, saturation, and brightness. *Psychological Research, 82*, 896-914.

Woods, A. T., Marmolejo-Ramos, F., Velasco, C., & Spence, C. (2016). Using single colors and color pairs to communicate basic tastes II: Foreground-background color combinations. *i-Perception, 7*, 5.

Woods, A. T., & Spence, C. (2016). Using single colors and color pairs to communicate basic tastes. *i-Perception, 7,* 4.

Young, S., Thorstenson, C.A., & Pazda, A.D. (2018). Facial redness, expression, and masculinity influence perceptions of anger and health. *Cognition and Emotion, 32,* 49-60.

Zajonc, R. B. (1968). Attitudinal effects of mere exposure. *Journal of Personality and Social Psychology*, *9*, 1.

Zentner, M. R. (2001). Preferences for colours and colour-emotion combinations in early childhood. *Developmental Science, 4*, 389-398.

Zettl, H. (2014). *Sight, sound, motion: Applied media aesthetics*. Belmont, CA: Wadsworth.