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Shape-to-color associations in non-synesthetes: perceptual, emotional, and cognitive aspects

PhD student: Michela Malfatti

Advisor: Prof. Liliana Albertazzi

Doctoral School in Cognitive and Brain Sciences—Neuroscience
Center for Mind/Brain Sciences (CIMeC) & University of Trento

XXVII Cycle

Abstract

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by Michela Malfatti

Doctor of Philosophy in Neuroscience—Cognitive and Brain Sciences
Center for Mind/Brain Sciences (CIMeC) & University of Trento

The study of cross-modal and cross-dimensional associations in non-synesthetes has become an increasingly hot topic in recent times (see Spence, 2011, for a review). Despite the many examples of associations between shape/color-stimuli on one hand and stimuli of different sensory nature on the other hand, little is known about the way shape and color are interrelated with each other. The purpose of our research was to test whether non-synesthetes also exhibit systematic associations between these two different dimensions of the visual domain, that is, shape and color. Furthermore, our study also relates to art, and in particular to Kandinsky's theory on shape-color correspondences (1912/1994, 1926/1994), which could be tested indirectly. The project consisted of six experiments. Experiment 1 provided the first evidence that people tend to match certain hues to certain simple geometric shapes. The strongest relations were found between the triangle and yellows, and the circle and square with reds, confirming only in part Kandinsky's artistic findings. Experiment 2 replicated the results of Experiment 1 with a different group of participants and showed that the pattern of shape-color associations that previously emerged was independent of a shape's size, area/perimeter, and stability. Experiment 3 examined the relation between parts of shapes (angles) and hues, also in order to assess if the choice of a hue to be matched with a given shape could be partly driven by its angles. In the remaining experiments (4-5), we extended the previous studies to color dimensions other than the hue, and to an even wider variety of shapes and shape-features. The shape-features studied included pointedness, intersections, symmetry-axes, concavities, and the number of generating-points. We found that specific shape-features of line-shapes (Experiment 4) or closed geometric shapes (Experiment 5) influence specific color attributes (saturation, lightness, redness/greenness, and yellowness/blueness) of the associated colors. Our results also suggested that shape-color associations may be mediated, in part, by emotions; indeed people tend to match colors and shapes that have similar emotional associations (e.g., angry colors are matched to angry shapes). Finally, Experiment 6 assessed in an exploratory way the association between words related to abstract concepts and hues. Altogether, additional examples of associations in the non-synesthetic population were reported. We suggest that this new trend of research, at large, could improve the study of human perception and cognition, guide the search for neural correlates, as well as find possible applications in a variety of disciplines, including ergonomics, art, and design.

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Acknowledgments

First, I would like to thank my Advisor Prof. Liliana Albertazzi for initially starting such an exciting line of research. She supported me throughout the years of my PhD Project, always encouraging me to be open-minded, challenging me to look beyond the boundaries of every discipline, and pushing me to strive for novelty in research.

Many other people contributed to the development of the present Doctoral Project. In particular, I would like to thank Prof. David Melcher for his feedback and insight, Prof. Luisa Canal and Rocco Micciolo for their contribution to data analyses, and Prof. Osvaldo Da Pos for his expert and devoted consultancy on issues related to color. I am also thankful to all members and staff of the Center for Mind/Brain Sciences and University of Trento for providing a stimulating and outstanding environment for a young researcher, as well as prompt practical support for technical and bureaucratic issues.

I am also extremely grateful to Prof. Stephen Palmer. He was a great and truly inspirational teacher, who further contributed to my professional and personal growth. The time I spent at the Palmer Lab and UC Berkeley made my PhD experience even more unique. I thank everyone from the Lab: William Griscom, Kelly Whiteford, Thomas Langlois, Joshwa Peterson, and last but not least Karen Schloss, now Assistant Professor of Research at Brown University, for her hands-on teaching sessions and advice on everything, including programming, statistics, and data visualization.

Let me also thank all the experimental subjects who volunteered for the experiments, often showing interest and curiosity, reminding me of where I got started. Finally let me thank my family, my partner, my friends, and everyone else who supported me and helped me enjoy the time of my PhD.

CHAPTER 1

General introduction

1.1 Cross-modal and cross-dimensional associations

There is growing evidence that people from the general population, which is mainly non-synesthetic, have a propensity to make specific cross-modal and cross-dimensional associations. This is a very new research topic that has only recently caught the interest of the scientific community and is likely to become increasingly popular. I will borrow here the definition given by Spence (2011), according to which such cross-modal associations (or "correspondences") consist of "a tendency for a sensory feature, or attribute, in one modality—either physically present or merely imagined—to be matched with a sensory feature in another modality". Such a definition can be broadened to cross-dimensional associations: that is, to those cases where sensory features or attributes in the same modality are matched. Given the novelty of this trend, there is not yet a unique term for which there is common agreement and that can be consistently employed to refer to this phenomenon.

The variety of terms used over the years to refer to the phenomenon of such associations in non-synesthetes have included 'synesthetic associations', 'synesthetic correspondences', 'cross-modal correspondences', 'intermodal correspondences', 'correspondences', 'cross-modal equivalences', 'natural cross-modal mappings', 'metaphorical mappings', 'naturally-biased associations', and 'cross-modal associations'. Such labels provide some hints on the current state of research, its inconsistencies, its controversies, and the main issues of debate. In addition to uncovering the implicit position of different researchers about the issue at hand (i.e., the continuity between this phenomenon and synesthesia), some labels suggest the researchers' interpretation of why such associations would be occurring, that is, they seems to suggest different underlying processes. For example, the term 'naturally biased' used by Spector and Maurer (2008, 2011) suggests that there would be a class of associations that "cannot easily be explained by the learning of specific associations from the environment" (Spector & Maurer, 2011, p. 485).

1.2 Synesthetes vs non-synesthetes

It may be tempting to assimilate cross-modal and cross-dimensional associations to the by now well known phenomenon of synesthesia, as they both imply a "joining of the senses" (Melara & O'Brien, 1987; Wicker, 1968). The numerous examples of associations found both in synesthetes and non-synesthetes (e.g., Sagiv & Ward, 2006) strengthen the idea that the two phenomena could rely on some shared mechanisms and that they might therefore be seen as two sides of the same coin. But to what extent might this be true? There still seems to be a debate on whether and how the two phenomena might be related. While synesthesia has been reported to be a phenomenon that is experienced by up to 5% of the population (Simner et al., 2006), these other associations are believed to be very widespread, some of them perhaps even universal. According to the continuum view, first suggested by Martino and Marks (2001), these two phenomena would essentially be the same in nature and different only in terms of their consistency, automaticity, and reported phenomenology. This view has dominated the scene in the last decade although not all seem to agree with it (see Spence, 2011).

According to the separatist view (Deroy & Spence, 2013), such a conceptualization is not be well founded, and might even be counter-productive, because it would bias researchers to look for similarities with respect to synesthesia. The scientists who hold the strong position that the phenomenon of 'cross-modal correspondences' should be studied as a distinct one and that the term itself should reflect its distinctiveness. A critical evaluation of potential similarities and differences between 'cross-modal correspondences' and synesthesia can be found in Deroy and Spence (2013). For instance, the two phenomena appear to be be similar in that (i) seemingly unrelated features are being matched, (ii) precise dimensions of the stimulus are responsible for the mapping, (iii) mappings are rather consistent and affect behavior (such as in Stroop color-naming task), and (iv) both synesthetes and non-synesthetes prefer objects, events, or situations that reflect their own mappings. On the contrary, the two phenomena appear to be be different in that (i) synesthetic mappings are largely idiosyncratic whereas cross-modal correspondences are rather consistent across people, (ii) the perceptual experience of synesthetes is usually defined as 'anomalous' rather than 'natural', (iii) synesthetic associations are genuinely automatic while it is still unclear whether and to what extent cross-modal correspondences would be automatic, and (iv) synesthetic mappings produce conscious sensory experiences in an inappropriate modality or dimension, whereas non-synesthetic mappings do not.

At present, it seems difficult to definitively support or challenge either view. In any case, since there are many different nuances in these associations (Spence, 2011), as there are many different kinds of synesthesia (Simner, 2012), a final claim may be difficult to make until each case is considered separately.

1.3 Different types of associations

According to Spence (2011), there are at least three different kinds of cross-modal associations as defined by their causes: statistical, structural, and semantically mediated. The first class refers to those associations learned from the environment that are typically correlated in the world we experience, such as the correlation between the size or mass of an object and its resonant frequency (see Coward & Stevens, 2004; Grassi, 2005; McMahon & Bonner, 1983). The second class refers to those associations that seem to be due to the intrinsic structure of our brain and that could be already present at birth: for example, the tendency to match higher pitched sounds to smaller and lighter objects (see Mondloch & Maurer, 2004). The third class refers to those associations that appear to be mediated by the meaning of terms used to refer to related features or attributes. For instance, the words 'low' and 'high' are used to describe both the elevation of a visual stimulus and the pitch of a sound and could therefore explain the way these attributes relate to each other (see Gallace & Spence, 2006; Martino & Marks, 1999; Mudd, 1963). There is a fourth kind of mediation that might be present, however, based on affective associations: that is, associations between stimuli based on their shared emotional content, such as the association between happy music and happy colors (Palmer, Langlois, & Schloss, submitted; Palmer, Schloss, Xu, & Prado-Leon, 2013; Whiteford, Schloss, & Palmer, 2013).

The fact that there are different kinds of associations seems to justify the diversity of terminology to a certain extent. However, the need to unify terms still remains, as well as the proof for many documented associations of belonging to one class or the other. Indeed, the nature of many reported associations is not yet well defined. Therefore, some terms are being used in a speculative way while research is trying to answer the question on how and where (e.g. low/high-level) those very associations occur (see, for example, Albertazzi, 2013, and Jürgens and Nikolić, 2012). Further research (involving cross-cultural studies, animal studies, developmental studies, and the study of neural correlates) will hopefully help to clarify the most controversial issues and provide a better frame of reference for future studies as well as establish the basis for a proper taxonomy.

1.4 A renewed interest for a not so new topic

Despite the fact that this theme has only recently received renewed interest, this phenomenon had already been observed in the past. Historically, for example, Köhler (1929, 1947) reported that people tended to match consistently rounded shapes to the nonsense word 'Maluma' and angular shapes to the nonsense word 'Takete'. This constitutes early evidence of systematic associations between apparently unrelated stimuli. The recent renewal in interest (e.g., Ramachandran & Hubbard, 2001, who replicated the phenomenon using "bouba" and "kiki") is not surprising given the significance of this theme within the general frame of normal multisensory integration and perception research. Such studies could certainly contribute to informing us about the way the human brain combines features and provide new insights to other related research fields. It has been documented, for example, that these cross-modal and cross-dimensional associations have an influence on our behavior and performance. For instance, it has been reported that people tend to respond more rapidly to audio-visual stimuli that are perceived as congruent rather than incongruent (Miller, 1991) and tend to integrate such stimuli to a greater degree both spatially and temporally (Parise & Spence, 2008, 2009). Furthermore, this phenomenon could shed light into different processes of the human mind in an even broader sense, such as thought and language, as reported by Ramachandran and Hubbard (2001).

Overall, these few examples suggest that many areas of research could benefit from studying cross-modal associations in more depth. As stated previously, such associations can involve either stimuli of different sensory modalities (cross-modal) or different dimensions of the same sensory modality (cross-dimensional). Many associations of both kinds have been reported, especially in the last decade. As a result, it is likely that more and more pieces will be added to this mosaic of associations, with the consideration of newer stimulus pairings in different combinations of sensory modalities. Stimuli of different kinds and complexities could be employed and the relation of each pairing could be studied in both directions, suggesting that the research in this area could potentially become quite extensive.

1.5 Associations involving color and shape

As a vision scientist, what is most interesting to me is the way visual dimensions are interrelated with each other as well as to dimensions that differ in their sensory nature. I find particularly fascinating the studies involving color, as one of the most pregnant aspects of our visual experience. Its association with shape, within the visual domain, is particularly intriguing and is the central focus of the present research.

The association between shapes and colors and other features is well established. Color has indeed proven to be systematically matched by non-synesthetes to a variety of different stimuli including odors (Demattè, Sanabria, & Spence, 2006; Gilbert, Martin, & Kemp, 1996; Maric & Jacquot, 2013; Kemp & Gilbert, 1997; Schifferstein & Tanudjaja, 2004), tastes/flavors (see Spence et al., 2010, for a review), tactile sensations (Ludwig & Simner, 2013), and sounds (Melara, 1989; Sagiv & Ward, 2006; Ward, Huckstep, & Tsakanikos, 2006) as well as more complex auditory stimuli like music (Bresin, 2005; Palmer, Langlois, & Schloss, submitted; Palmer, Schloss, Xu, & Prado-Leon, 2013). Similarly, shape has been reported so far to be associated to stimuli like sounds (Nielsen & Rendall, 2011; Spence, 2012), tastes/flavors (Spence & Gallace 2011; Gallace, Boschin, & Spence, 2011; Spence & Kim Ngo, 2012) and odors (Caldwell and Flammia 1991; Hanson-Vaux et al., 2013; Maric & Jacquot, 2013; Seo et al., 2010; Deroy, Crisinel, & Spence, 2013).

Nevertheless, little research has been concerned with the interrelation between color on the one hand and shape on the other. Overall, it seems that most studies regarding associations between visual stimuli have concerned graphemes and colors (Jürgens & Nikolić, 2012; Lau, Schloss, Eagleman, & Palmer, 2011; Simner, Ward, Lanz, Jansari, Noonan et al., 2005; Spector & Maurer, 2008, 2011). The attention devoted to this topic is probably justified by the fact that such associations are among the most common and well documented in synesthetes. Preliminary results suggest that it would be the shape of the letters, such as the fact that they are round/angular or open/closed, that drive their association with specific colors (Brang, Rouw, Ramachandran, & Coulson, 2011). However, this evidence is specific to synesthetes at the moment. Some research conducted on infants suggests that they might experience certain shape-color associations during specific phases of their development (Wagner & Dobkins, 2009). Other research conducted on non-synesthetic adults showed that they tend to associate certain morphological patterns to certain hues (Dadam, Albertazzi, Da Pos, Canal, & Micciolo, 2012).

1.6 From Kandinshy’s art theory to empirical studies

Interestingly, despite the phenomenon of shape-color associations being extremely intuitive and noticeable, as well as the focus of interest and debate of many disciplines, such as art, design, and architecture, such reports lack adequate empirical evidence by current research standards. An exception to this has been recent studies that have intentionally taken inspiration from the claims made by artists over the years. For example Kandinsky (1912, 1926), the father of abstract art, claimed that specific colors were emphasized by certain forms, whereas others were diminished by them. This correspondence theory is well formulated in his writings, such as “Point and Line to Plane” and “Concerning the Spiritual in Art”.

The artist, conducting a survey at the Bauhaus at that time, found consistent shape-color associations between triangle and yellow, square and red, and blue and circle (Droste, 1990; Lupton & Miller, 1991). The study was replicated in more recent times with minor changes but producted conflicting results (Jacobsen, 2002; Kharkhurin, 2012; Makin & Wuerger, 2013). Even though the methods used in these latter studies was rigorous, the design of the experiments, which were intended to replicate Kandinsky's findings, was rather constrained. In the first study (i.e., Jacobsen, 2002), for example, only three shapes and three colors were considered and a one to one association had to be established, as in the original survey. The other studies, though relaxing the constraint of a one-to-one association, as well as adding implicit association tasks, still limited the research to the same few basic colors and shapes belonging to the artist's theory. No comprehensive and systematic study on the relationship between shape and color is yet available, at least to my knowledge.

Here we study shape-color associations while trying to overcome the major limitations of the previous studies. We employed a wider spectrum of both colors and shapes and expanded the set of potentially relevant perceptual features of the two domains, in agreement with evidence at the cutting edge of the field and with some of the most popular theories. As for color, we refer to the Natural Color System (based on Hering's opponent color theory), as one of the best currently available and widely acknowledged color models in describing the way that human beings perceive and experience colors. As for shape, we consider the perceived shape as well as some shape-primitives and shape-features that, in our opinion, are most likely to play a role in such associations. Finally, possible explanations for these phenomena are explored. In particular, we tested the Emotional Mediation Hypothesis (Palmer, Schloss, Xu, & Prado-Leon, 2013) for shape-color associations.

1.7 Project overview

The present project was conceived and conducted as part of a PhD program in 'Neuroscience—Cognitive and Brain Sciences' at the University of Trento, under the supervision of Prof. Liliana Albertazzi. The research consisted of six Experiments. Experiments 1, 2, 3, and 6 were run in the Experimental Psychology Labs (University of Trento, Center for Mind/Brain Sciences), whereas Experiments 4 and 5 were run in the Visual Perception and Aesthetics Lab (University of California Berkeley) under the supervision of Prof. Stephen Palmer. Both research experiences contributed importantly to the development of the topic at hand from slightly different and complementary perspectives and enriched the content of the present Doctoral Thesis. I will be presenting the experiments in groups, mainly based on the similarity of their aims or experimental methods. More precisely, Chapter 2 presents Experiments 1-3, which together provide the first striking evidence of associations between certain shapes (or parts thereof) and hues in the general population. Chapter 3 presents Experiments 4-5, which examine in more detail the associations between different color attributes and specific shape-features in non-synesthetes and explore the potential role played by emotions in mediating such associations. Finally, Chapter 4 presents Experiment 6, which extends the previous research to the study of associations between hues and terms related to abstract concepts.

Table 1.1 provides an overview of the six Experiments and gives the reader an intuition of how they relate to each other.

Table 1.1. Overview of Experiments 1-6. The table summarizes the main aim of each Experiment and how they relate to each other.

Experiment 1	• tests whether people from the general population systematically match **hues** to **shapes**, and • indirectly tests Kandinsky's art theory on shape-color correspondences (i.e., triangles are yellow, squares are red, and circles are blue).
Experiment 2	• replicates the results of Experiment 1 with a different sample of participants, and • tests whether the shape-color associations found previously were independent of a shape's size, area/perimeter and stability.
Experiment 3	• tests whether people from the general population systematically match **hues** to **angles**, and • indirectly tests the role of angles in determining shape-color associations (i.e., whether triangles "are" yellow because they are characterized by acute angles, which "are" yellow).
Experiment 4	• screens for synesthesia to restrict the analysis to non-synesthetes, • extends the study to a wider variety of color attributes and shapes, • studies how specific **shape features** (pointedness, symmetry-axes, intersections, and number of generating points) of **line-shapes** influence specific **color attributes** (saturation, lightness, redness/greenness, and yellowness/blueness) of the associated colors, and • tests the Emotion Mediation Hypothesis for shape-color associations.
Experiment 5	• extends the results of Experiment 4 to closed geometric shapes, • studies how specific **shape features** (pointedness, symmetry-axes, concavities, and number of generating points) of **closed geometric shapes** influence specific **color attributes** (saturation, lightness, redness/greenness, and yellowness/blueness) of the associated colors, and • tests the Emotion Mediation Hypothesis for shape-color associations
Experiment 6	• tests whether people from the general population systematically match **hues** to **words** pertaining to an abstract semantic field.

CHAPTER 2

Are there systematic shape-to-color associations in the general population?

2.1 Introduction to Experiments 1, 2, and 3

Our research started with an exploratory study on color and shape perception that intended to experimentally test the existence of systematic associations between particular geometric shapes and particular colors in the general population.

As mentioned in the introduction, recent evidence suggests that also non-synesthetes have a propensity to match stimuli of either different sensory modalities (cross-modal correspondences) or the same sensory modality (cross-dimensional correspondences). Only few examples of the latter kind can be found in the literature and relate directly to this dissertation, given the novelty of the theme as well as my specific interest in visual stimuli like shape and color. Some examples of such cross-dimensional associations are those between graphemes and colors (Jürgens & Nikolić, 2012; Lau et al. 2011; Simner et al., 2005; Spector & Maurer, 2008, 2011) or morphological patterns and colors (Dadam et al., 2012) in non-synesthetes. Preliminary results also suggest that the shape of letters or their elementary characteristics, such as the fact that they appear round/angular or open/closed, plays a role in determining their association with particular colors (Brang, Rouw, Ramachandran, & Coulson, 2011; Jürgens, Mausfeld, & Nikolić, 2010), but this evidence is currently limited to the synesthetic population. The association between particular shapes and colors has also been explored in the artistic domain. As is well known, Kandinsky (1926/1944), conducting a survey among the Bauhaus members, found a relation between yellow and triangle, red and square, and blue and circle (Droste, 1990; Lupton & Miller, 1991). He claimed that this correspondence was due to the relation between colors and angles. Others replicated Kandinsky's experiment with small changes (e.g. Jacobsen, 2002), obtaining different results. The purpose of our research was to test whether the general population, which is mostly non-synesthetic, exhibits associations between two different dimensions of the visual modality (shape and color). As a byproduct of the analyses, Kandinsky's hypothesis concerning the association between certain shapes and colors could be tested without the constraints of a one-to-one association. Also, the artist's hypothesis that this relation could be due to a shape's angles is evaluated.

As regards the aspect of color, we decided to start by analyzing surface color and, specifically, one of the most psychologically significant aspects of color's appearance: its hue. Given that we were interested in hues, we took the most chromatic color that could be produced on the monitor (or printed) appearing to be of a specific hue. Even though the colors did not differ systematically in lightness, each was characterized by its specific degree of natural lightness (i.e., the lightness of the most chromatic color among all those that appear of the same hue, which roughly corresponds to the brightness of the hues in the spectrum; see Spillmann, 1985a, 1985b). As regards the shapes with which colors are paired, we started with a selection of basic geometric shapes. Our hypothesis was that shapes with different perceptual characteristics would lead to consistent choices of colors (hues) or chromatic areas (groups of hues).

The research is divided into three parts. The first part, Experiment 1, verified the existence of systematic association between a shape and a specific hue, or groups thereof. The second part, Experiment 2, explored the relationship between colors and "spatial dimensions" of shapes (i.e., their size, area/perimeter, and stability), the purpose being to verify that the results obtained in the first part were independent of these spatial characteristics of shapes. The third part, Experiment 3, explored the associations between specific angles and hues, in order to evaluate if these could explain in part the associations between geometric shapes and hues previously found. We expected that these associations between shapes/angles and hues would be consistent across individuals, suggesting a predisposition to perceive specific relationships or "correspondences." The task given to the participants for these three experiments was exclusively visual in nature: the analysis focused on the choice of hue to be paired with a shape or angle on the basis of a subjective judgment. More precisely, in the first experiment, participants had to choose the color most appropriate to the shape while looking at the achromatic shape, whereas in the second and third experiments, they had to combine the shape (or angle) with a color so that the final result was the desired one.

2.2 Experiment 1

The purpose of the experiment was to examine whether shapes with varying perceptual characteristics led to consistent choices of colors (hues). The experiment also indirectly allowed us to test Kandinsky's hypothesis according to which the triangle is yellow, the square is red, and the circle is blue.

2.2.1 Methods

Participants

Sixty participants volunteered for Experiment 1 (mean age = 23.0, standard deviation = 4.6; range: 19-45 years). The experiment was repeated with the same group of participants between 4 and 6 weeks later. Participants were recruited from students at the Department of Psychology and Cognitive Science, University of Trento. The only exclusion criterion was self-reported defective color vision. Most of the participants were Italian and spoke Italian as their native language. The experiment was conducted after obtaining an informed consent.

Stimuli/Materials

Materials consisted of a series of 12 geometric shapes and the 40 colors of the NCS Hue Circle. Both shapes and colors were printed on paper.

As for shapes, twelve drawings of geometric shapes (Figure 2.1) were used. They consisted of two-dimensional shapes (circle, triangle, square, rhombus, hexagon, trapezoid, oval, parallelogram) and two-dimensional projections of three-dimensional shapes (cone, pyramid, truncated cone, truncated pyramid), whose hidden edges were made visible. They were printed and centered on white A4 cardboard pieces; only their outlines (0.26 mm, 0.021 deg, thick) were drawn in black ink. Shapes would fit into imaginary rectangles with the following dimensions: 11.5 x 11.5 cm (circle), 12.5 x 10.0 cm (triangle), 9.5 x 9.5 cm (square), 10.0 x 14.0 cm (rhombus), 12.0 x 10.4 cm (hexagon), 13.8 x 8.8 cm (trapezoid), 9.5 x 11.8 cm (oval), 14.5 x 7.6 cm (parallelogram), 14.0 x 11.7 cm (pyramid), 9.8 x 12.4 cm (cone), 11.4 x 10.2 cm (truncated cone), 15.3 x 9.6 cm (truncated pyramid). As for colors, we employed the Hue Circle, taken from the NCS (Natural Colour System) Atlas. The Hue Circle presents 40 hues, including the four unique hues—yellow, red, green, blue—and the intermediate ones (Figure 2.2). The Hue Circle (27.0 cm, 24.0 deg, diameter) was made up of 40 small circular patches (1.3 cm, 1.2 deg diameter) showing the full series of hues (reported in the Appendix 2.1). It was printed on a piece of cardboard and presented to each participant at four different orientations (i.e. 0°, 90°, 180°, 270°).

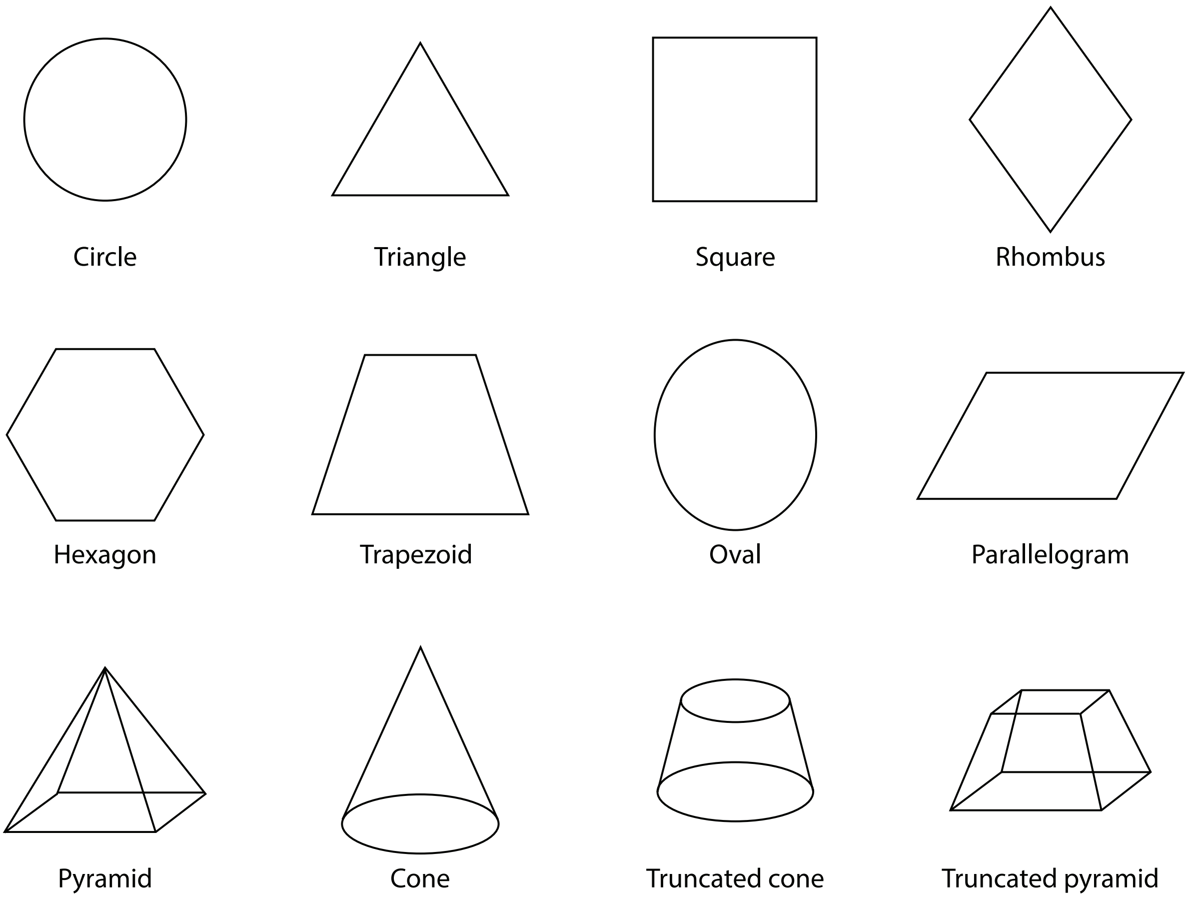


Figure 2.1. Shapes presented to participants in Experiment 1. The shapes consisted of two-dimensional shapes (circle, triangle, square, rhombus, hexagon, trapezoid, oval, parallelogram) and two-dimensional projections of three-dimensional shapes (cone, pyramid, truncated cone, truncated pyramid).

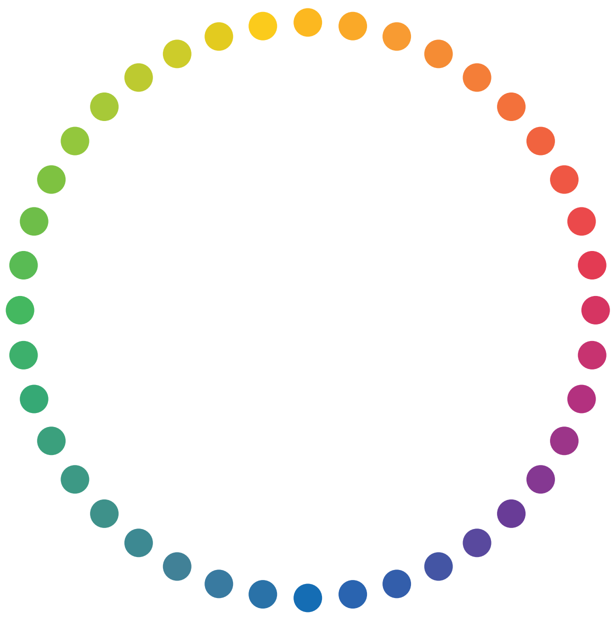


Figure 2.2. The 40 hues of the NCS Color Circle, as it appeared when presented to subjects at 0°.

Task and procedure

The experiment was conducted in a laboratory with constant lighting conditions (about 230-250 lux on the light grey working table, correlated color temperature 3400K, halogen lamp). The materials consisted of 12 geometric shapes presented one at a time in paper-based form directly to participants on the surface of the working table. The distance from the center of the shape to the eye was about 65 cm.

Each participant gave informed consent to take part in the study. Self-reported defective color vision was an exclusion criterion during the recruitment procedure. The actual experiment started immediately, giving participants the following written instructions for the task:

> *"You are about to take part in an experiment on the relationship between shape and color. You will be presented with a series of drawings, one at a time, representing a geometric shape. For each shape, you are asked to choose a color from the circle that you see as the one most naturally related to the shape, and to indicate your choice to the researcher, who will make a note of it and of the time it took to reach your decision. However, in your reply, please let accuracy take precedence over promptness."*

Before the experiment began, participants were also asked to avoid making associations between the shapes presented and any past experience of those shapes, or similar ones, in certain colors (e.g. colors used for triangles or circles in road signs). The experimenter carefully avoided mentioning color categories (e.g., 'red', 'green', 'blue', etc.) if additional explanations were required. The experiment consisted in just one task, organized in two experimental blocks, where the Hue Circle was presented at two different orientations (i.e. at 0° and 90°). The procedure is described below.

Participants were seated at the working table. In front of them was the Hue Circle and the stack of cardboard sheets on which the 12 shapes were printed was placed on one side, upside-down. The researcher sat next to the participant and presented the cardboard sheets one at a time, in random order, placing them right to the left of the Hue Circle. Participants chose the color that they most naturally matched to the shape and expressed their choice by placing their right index finger on it. The researcher made a note of the numeric codes identifying the shape and color, and then the next shape was presented. A chronometer was also used to check the task times (i.e. how long it took to point a color since the shape was presented). This procedure was repeated for the first six shapes, the Hue Circle was then set to a different orientation for the next six shapes. This concluded the first experimental session. About one month later (exactly between 4 and 6 weeks after the first experimental session), the same group of participants took part in the second experimental session. The procedure was identical to that of the previous session, with the only difference being that in Session 2 the Hue Circle was presented at the two orientations not presented during session 1 (i.e. at 180° and 270°), so that it appeared in total at each of the four orientations (0°, 90°, 180°, and 270°) to each participant. Also the order in which the shapes were presented changed randomly.

2.2.2 Results and Discussion

Analyses were performed with R 2.13.0 software (R Development Core Team, 2011). Analysis of task duration did not reveal any significant result, so it will not be considered further.

The main aim of the experiment was to check whether there was any systematic association between specific shapes and colors (hues). A chi-square test was used to evaluate the departure from independence with respect to the association between the variables 'shape' and 'color'. The contingency table between shape (12 figures) and color (40 colors) had 420 out of 480 cells with an expected frequency of less than 5. The 40 colors were therefore grouped into 8 groups, corresponding to different chromatic areas, such that none of the cells of the contingency table between shape and grouped colors had an expected frequency of less than 5. Since there were 40 colors, 8 groups of 5 color patches each were made (Figure 2.3). We decided to group each unique hue (Yellow, Red, Green, Blue) together with the two colors which came before and the two colors which came after it. We thus identified four groups of colors, named after the unique hue that they were including: YY (mainly yellow), RR (mainly red), GG (mainly green), BB (mainly blue). In addition to these groups, we had four groups of five "transition" colors, labeled as follows: YR (yellow-red), RB (red-blue), BG (blue-green) and GY (green-yellow).

A significant association was found between the variables 'shape' and 'color' in both experimental sessions (Session 1: chi square =114; d.f.=77; $p<0.01$ – Session 2: chi square =134; d.f.=77; $p<0.01$), and the Fisher exact test (for a 12 x 8 contingency table) showed p-values of 0.002 and of 0.001 respectively. A log linear model was used to evaluate whether the pattern of association between the variables 'shape' and 'color' differed between the two sessions. Although no significant difference was found between sessions (chi square =69.4; d.f.=77; $p=0.49$), data were not collapsed over the two sessions in order to obtain adjusted estimates of the association between shape and color; the significance of this association was also confirmed after this adjusted analysis (chi square=192; d.f.=77; $p<0.001$).

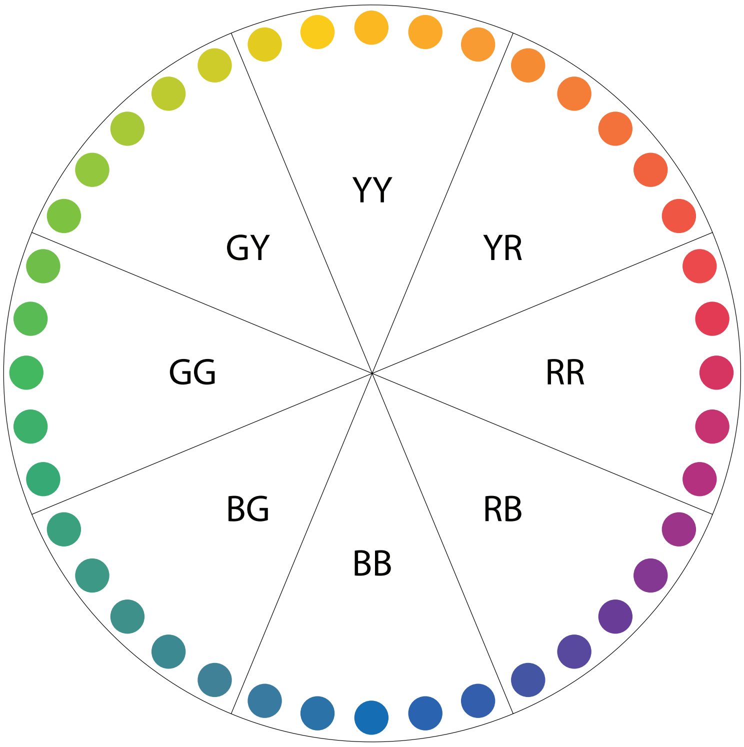


Figure 2.3. The Color Circle divided into eight chromatic areas. Each group consisted of 5 hues. Four groups included one of the 4 unique hues and the 2 hues right before/after: YY (mainly yellow), RR (mainly red), BB (mainly blue), GG (mainly green). The other 4 groups included transitional groups of hues in between: YR (yellow-red), RB (red-blue), BG (blue-green), GY (green-yellow).

Having rejected the hypothesis of independence, a residual analysis (Agresti, 2007) was performed on standardized residuals obtained after having aggregated the results of the two sessions. Table 2.1 lists the "row profiles" (i.e., the relative frequencies of color categories within each shape, together with the baseline percentage frequency of color categories). Comparison of each row profile with the baseline percentage shows that some colors are more frequently associated with certain shapes, whereas other colors are less frequently associated with other shapes. The corresponding cells of the contingency table for the former have positive residuals, while the corresponding cells of the contingency table for the latter have negative residuals. With 96 cells (12 shapes and 8 grouped colors) we expected about one standardized residual larger (in absolute value) than 2.50 and almost no residual larger than 3. Contrary to what we expected, five residuals were larger than 2.00, ten residuals were larger ten 2.50, and five residual were larger than 3. Both positive residuals, i.e., observed frequencies higher than those expected, and negative residuals, i.e., observed frequencies lower than those expected, were observed (see from Table 2.1). "Positive" associations (shown in Bold), were found, for instance, between the triangle and YY ($z = 3.69$), between the square and RR ($z=3.54$), between the circle and RR ($z=3.29$), between the square and BB ($z=2.73$), between the pyramid and YY ($z=2.66$), and between the hexagon and RB ($z=2.53$).

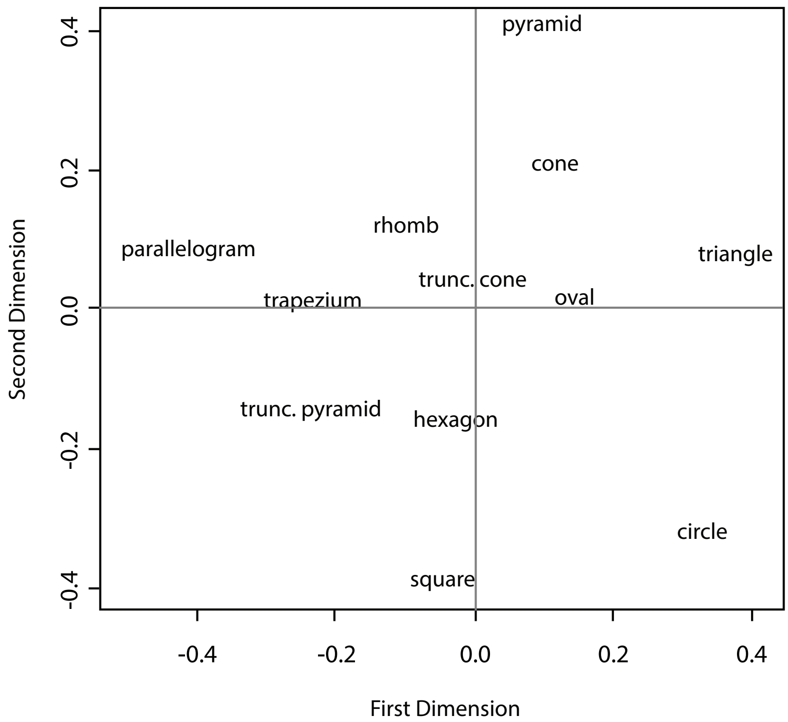
Conversely, "negative" associations (shown in Bold Italic), were found, for instance, between the pyramid and RR (z=-3.20), between the parallelogram and YY (z=-3.00), between the circle and BG (z=-2.59) and between the oval and GG (z=-2.56).

Table 2.1
Row profiles of the 12 shapes considered (two sessions together). Cells with standardized residuals higher than 2 are shown in Bold. Cells with standardized residuals lower than -2 are shown in Underline.

	YY	YR	RR	RB	BB	BG	GG	GY
Circle	**24.2**	5.8	**26.7**	12.5	15.0	1.7	9.2	5.0
Cone	18.3	13.3	15.8	6.7	8.3	7.5	15.8	14.2
Hexagon	15.8	8.3	15.8	**18.3**	16.7	5.8	11.7	7.5
Oval	22.5	10.8	16.7	15.0	10.0	9.2	5.0	10.8
Parallelogram	6.7	**16.7**	8.3	10.8	**21.7**	**12.5**	15.8	7.5
Pyramid	**25.0**	15.0	5.8	6.7	9.2	9.2	16.7	12.5
Square	8.3	10.0	**27.5**	10.0	**23.3**	2.5	10.8	7.5
Rhombus	12.5	14.2	14.2	9.2	13.3	9.2	15.8	11.7
Trapezoid	8.3	13.3	13.3	15.0	16.7	10.0	9.2	14.2
Triangle	**28.3**	8.3	18.3	5.8	10.0	3.3	14.2	11.7
Truncated cone	15.0	12.5	18.3	9.2	12.5	10.0	10.8	11.7
Truncated pyramid	11.7	5.0	12.5	16.7	**21.7**	11.7	13.3	7.5
Overall	16.4	11.1	16.1	11.3	14.9	7.7	12.4	10.1

Thereafter, a Correspondence Analysis was performed. Similar to Factor Analysis or Multidimensional Scaling, Correspondence Analysis (CA) helps to clarify the structural relations among variables and allows new latent variables to emerge. It is a suitable statistical technique for evaluating cross-tabular data in the form of numerical frequencies, which yields deeper understanding of the data by means of simple graphs (Greenacre, 2007). High-dimensional data are treated by representing the interrelationships among the variables on a reduced space, often two-dimensional or three-dimensional. In our case, CA of the contingency table obtained by cross-classifying participants' choices with respect to the shapes and the associated colors showed that about 75% of variance could be explained with two components. Figure 2.4 shows the projections of the 12 shapes on the plane formed by the two components (or factorial axes) for each experimental session. Note that the graphs of Session 1 and Session 2 were nearly identical. The first component (horizontal axis) accounted for 38.6% of the variance in the association in Session 1 and for 39.0% in Session 2. The second component (vertical axis) accounted for 35.8% of variance in Session 1 and for 34.4% in Session 2.

Correspondence Analysis (Session 1)



Correspondence Analysis (Session 2)

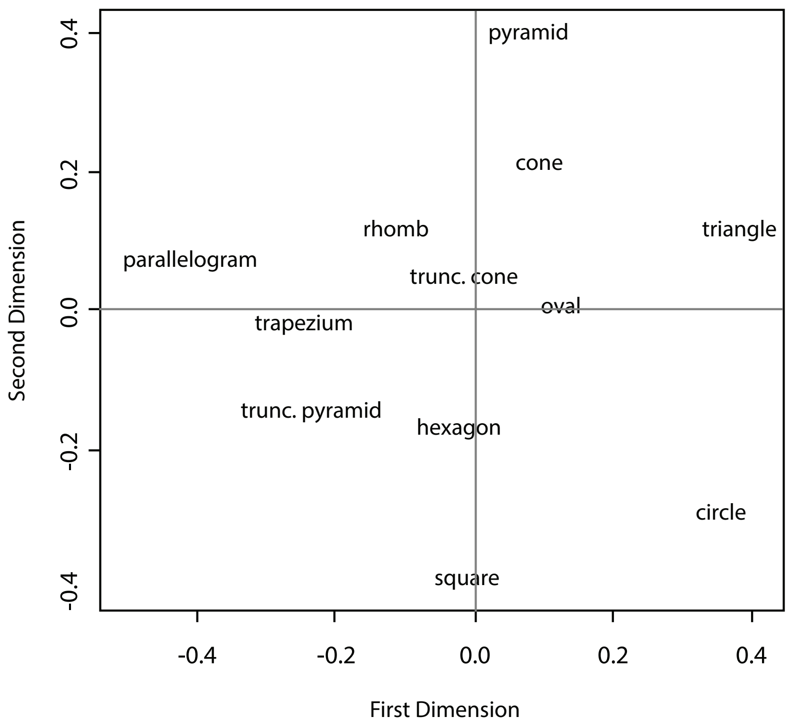


Figure 2.4. Projections of the 12 shapes considered onto the plane formed by the first two factorial axes. The horizontal axis can be interpreted as the "heat" of the colors (heat increases from left to right). The vertical axis can be interpreted as the level of "natural lightness" of the colors (lightness increases from bottom to top). Top panel: session 1. Bottom panel: session 2.

We interpreted the two components by looking at the percentage contribution of each group of colors to each axis (Figure 2.5). The first factorial axis is explained mainly by the color group YY (about 50%), while a further 43% is explained by the groups BG, RR, and BB together. In particular, YY, RR, GY have positive scores, while BG, BB, YR, RB, GG have negative scores on this axis. The shapes with higher values on the first axis (e.g. triangle), were mainly related to the groups YY and/or RR, while the shapes with lower values on the first axis (e.g. parallelogram), were mainly related to groups BG and/or BB.

We interpreted the first horizontal axis as the "warmth" of hues, since cool hues belonging to the BG/BB color groups were opposed to warm ones belonging to the YY/RR color groups on this axis. The second factorial axis is explained mainly by the groups RR, RB, and BB together (58%), and a further 42% is explained by the remaining groups BG, GG, GY, YY, YR together. On this second axis, RR, BB, and RB had positive scores, while YR, GY, BG, YY, GG had negative ones. The shapes with higher values on the second axis (e.g. pyramid), were mainly related to the groups RR, BB, and RB; conversely, the shapes that had lower values on the same axis (e.g. square) were mainly related to the remaining groups. We interpreted the second vertical axis as the "natural lightness" (see Spillman 1985a, 1985b) of colors. On the first horizontal axis, warmth increases from left to right; on the second vertical axis, lightness increases from bottom to top.

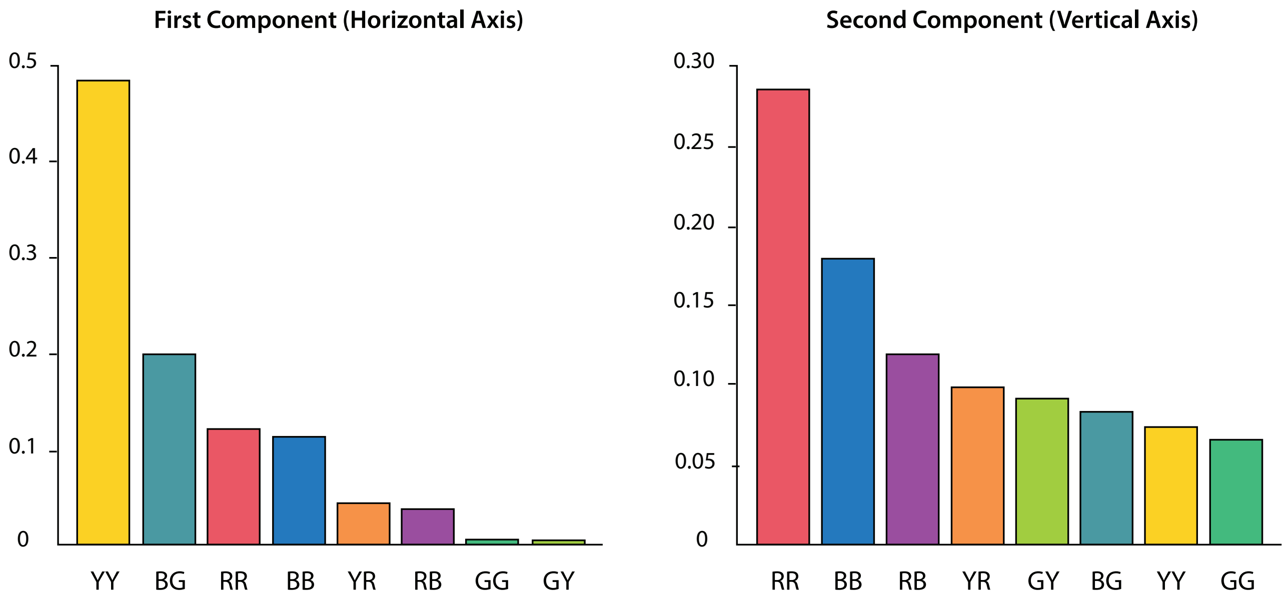


Figure 2.5. Percentage contribution of each group of colors to the first two factorial axes. (YY=Yellow, RR= Red, GG=Green, BB=Blue, YR=Yellow-Red, RB=Red-Blue, BG=Blue-Green, GY=Green-Yellow). On the first axis YY, RR, GY have positive scores, while BG, BB, YR, RB, GG have negative scores. On the second axis RR, BB, RB have positive scores, while YR, GY, BG, YY, GG have negative scores.

According to this interpretation, the circle and the triangle are the "warmest" shapes, while the parallelogram are the "coolest". Moreover, the square and the circle are the "darkest", while the pyramid and the cone are the "lightest". Two-dimensional shapes are spread along a "warmth continuum" (identified by the first dimension) ranging from the coolest (parallelogram) to the warmest (circle and triangle) going through "mild temperature" shapes (trapezoid, rhombus, square, hexagon, oval). On the other hand, two-dimensional shapes have a lesser extension on the second dimension (light/dark); some shapes are definitely dark (square and circle) while none of them is light. In particular, the circle has high values in both dimensions. The two-dimensional projections of three-dimensional shapes (pyramid, cone, truncated cone and pyramidal cone) essentially vary in the second dimension (light/dark) and are mainly neutral with respect to the first dimension (warm/cold). The pyramid, and to a lesser extent the cone, are the lightest shapes.

Our results suggest that non-random associations exist between shape and color. The pattern of these associations is consistent across time when evaluated on the same participants at the "group" level (i.e., across individuals). Since each participant was tested twice, consistency in individuals' choices across time could also be evaluated. Up to 25% of the color choices made in Session 1 were confirmed in Session 2, while the degree of concordance expected under the hypothesis of random choices is 13%. The observed consistency over time is therefore about double than that expected with a highly significant result ($p<0.001$). This result can be considered a "mean concordance". The observed concordance was particularly higher for certain shapes: 48% for the circle (48% of participants associated the same color to this shape in both sessions), 37% for the triangle, and 33% for the square. Moreover, the degree of concordance was higher for certain participants. In particular, two subjects (3.3%) choose the same color for the same shape 7 times or more in the two sessions. This percentage is quite similar to the estimates of the prevalence of synesthesia of 4.4% provided by Simner et al. (2006), so it is possible that our sample included some synesthetes, even if appropriate testing was not performed. Furthermore, twenty-one subjects (35%) choose the same color for the same shape 4 times or more in the two sessions. The corresponding percentage expected on the hypothesis of a random choice is about 6%, so that the observed odds of concordance (0.47) are seven times higher than those expected by chance alone (0.06) with a highly significant result ($p<0.001$).

These results together illustrate the relation which appears to be subjectively natural between the hues of highly chromatic colors and shapes in the general population. Analysis of the results showed that non-random relations exist between colors and shapes, and that these relations are remarkably systematic. In particular, the repeatability in time of the results at the group level, together with the fact that their factorial characteristics are maintained almost unchanged, is an important indication of the systematic patterns of shape-color associations, this being the focus of our study. Correspondence Analysis suggested relations between shapes and some color qualities, like cool/warm and light/dark. Nevertheless, it is difficult to interpret these results further at the present time and the data warrant deeper examination with further research.

2.3 Experiment 2

The results of Experiment 1 refer to shapes that differ in their geometric aspect, but whose spatial properties are not controlled for. A second experiment was therefore performed in which we evaluated variables like a shape's size, area/perimeter and stability, which could have been "confounders" or "effect modifiers". Since each shape had to be viewed multiple times, we decided to select only four shapes among the two-dimensional ones. Three shapes (circle, square and triangle) were those that yielded the most significant results with respect to the strength of the shape and color relationship and were the warmest and/or darkest shapes in Experiment 1. The rhombus was also included as a particular case of a parallelogram (the coolest shape in the previous experiment). This second experiment also aimed at ascertaining whether the pattern of results found in Experiment 1 was sufficiently robust to be repeated with a different group of participants and a different method of presentation (i.e. computer instead of cardboard pieces).

2.3.1 Methods

Participants

Seventy participants volunteered for Experiment 2 (mean age = 23.9, standard deviation = 6.6; range: 19-46 years). None of the participants who took part in Experiment 2 had participated in Experiment 1. Participants were recruited from students at the Department of Psychology and Cognitive Science, University of Trento. The only exclusion criterion was defective color vision. Defective color vision was self-reported, however, the verification procedure (identification of subjective unique hues by each participant) would have revealed visual defects like Daltonism or large deviations in unique hues perception that were not self-reported. Most of the participants were Italian and spoke Italian as their native language. The experiment was conducted after obtaining an informed consent.

Design

We firstly decided to generate two series of shapes, in which we equated either the shapes' area or perimeter. For each series we manipulated the shape's size at two levels (large/small). Four groups of shapes resulted from this procedure: large ones with the same area, and small ones with the same area; large ones with the same perimeter, and small ones with the same perimeter. Subsequently, each of these groups was made to include both a stable and an unstable version of each shape, which the exception of the circle (which was necessarily unaffected by orientation). The circle was therefore shown as "stimulus" 4 times, while each of the remaining three shapes (triangle, square, rhombus) was shown as "stimulus" 8 times: 2 series (same-area/perimeter) x 2 sizes (large/small) x 2 orientations (stable/unstable). It follows that each participant was displayed with a total of 28 stimuli.

Stimuli/Materials

Materials consisted of the series of 28 shape-stimuli and the 40 colors of the NCS Hue Circle. Both shapes and colors were presented on a computer monitor (a 19-inch CRT ViewSonic G90fB Graphics Series monitor, 1024 x 768 resolution) and were made to appear on a white background (92 cd/m^2, L* = 94.65, a* = -4.49, b* = 0.2, x = 0.3044, y = 0.3194).

Shapes were centered inside the 40-hue color wheel and only their black outline (0.25 mm, 0.024 deg, thick) was drawn. Four geometric shapes were adopted in Experiment 2: circle, rhombus, square and triangle. The circle was taken as a reference to generate shapes with the same area/perimeter in the small/large version. The series of 'small shapes' was generated starting from a circle with a circumference of 4.0 cm and therefore an area of about 1.3 cm^2; the series of 'large shapes' was generated starting from a circle with a circumference of 31.4 cm and therefore an area of about 78.2 cm^2. The other three shapes (triangle, square, and rhombus) belonging to the large/small series were generated with either the same area or the same perimeter of these circles. In this way, the four groups of shapes mentioned before were produced: large shapes with the same area, small shapes with the same area, large shapes with the same perimeter, and small shapes with the same perimeter. For each series, 'stable' shapes were constructed with orientation relative to the gravitational axis (e.g., the triangle with its vertex upwards); in addition the three stable shapes were also rotated to appear unstable: the rhombus by -18° (slanting-rhombus, which could appear as a slanted-parallelogram), the triangle by 15° (slanting-triangle), and the square by 45° (slanting-square). Two of the four groups of shapes presented to the participants (large shapes with the same perimeter, small shapes with the same area) are shown in Figure 2.6.

As for color, we used the NCS Color Circle as in Experiment 1. This time, the 40 colors of the Hue Circle were presented on a computer monitor, so the way they appeared was slightly different (see Appendix 2.2). The Hue Circle's orientation was randomized for each stimulus presentation: it could be displayed in up to 40 different orientations, i.e., the orientations that you obtain rotating the circle clockwise, and positioning each of the 40 hues at the North.

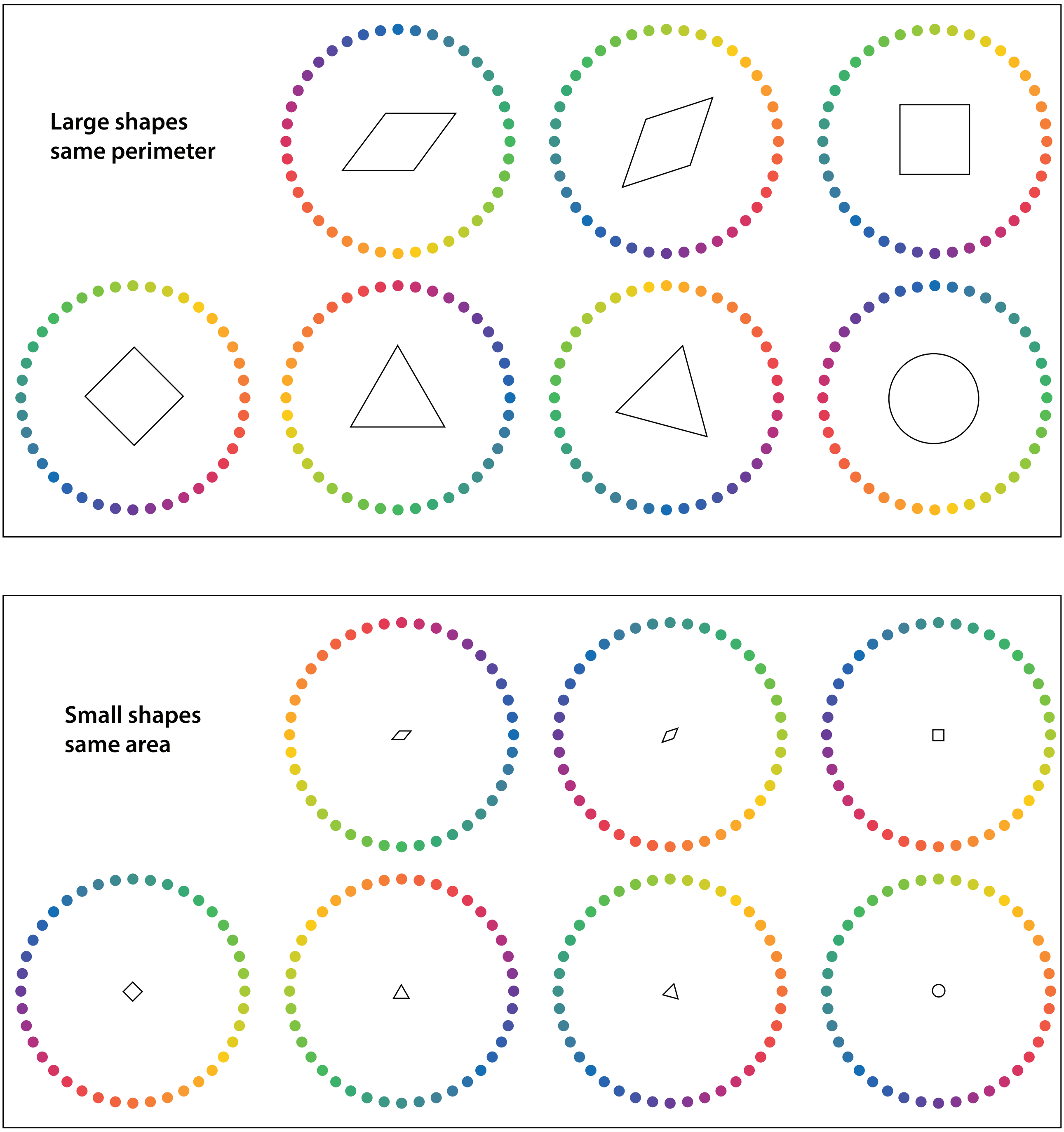


Figure 2.6. Shapes presented to participants in Experiment 2. The shapes were: Stable Rhombus, Unstable Rhombus, Stable Square, Unstable Square, Stable Triangle, Unstable Triangle, and Circle. Two of the four series are displayed in the figure: large shapes with the same perimeter (top panel), small shapes with the same area (bottom panel). Additional series displayed to participants were: large shapes with the same area, small shapes with the same perimeter.

Task and procedure

The experiment was conducted in a dimly lit laboratory (1 lux on the walls). Participants were seated at a working table at a distance of about 60 cm from the screen. They gave their informed consent to take part in the study and were then given the following written instructions for the task:

"You are about to take part in an experiment on the relationship between shape and color. You will be presented with a series of shapes, one at a time, representing a geometric figure. For each shape you are asked to choose a color from the circle that you see most naturally related to the shape, and double click to make your choice. You are allowed to change the color until you are satisfied with the result."

As in Experiment 1, participants were asked to avoid making shape-to-color associations based on their past experience of those shapes, or similar ones, in certain colors and the experimenter carefully avoided mentioning color categories (e.g., 'red', 'green', 'blue', etc.) while explaining the task or answering questions. The materials, were presented directly to participants on the monitor screen, and consisted of the Hue Circle and the series of 28 shapes representing 4 geometric figures with the characteristics described above. All shapes were made to appear at the center of the screen and were concentric with the circle. For each shape, participants had to choose the color from the 40-hue color wheel that they saw as most naturally related to it. When they pressed one color in the Hue Circle, it then filled the shape; the black outline of the shape was still visible, the purpose being to produce a greater differentiation of the color of the shape from the background. Participants could change the shape's color until they were satisfied, as displayed in Figure 2.7, and then click at the center of the screen to move on to the next stimulus. The procedure was repeated until all the 28 stimuli had been displayed, in random order. The orientation of the Hue Circle also changed randomly for each stimulus presentation.

In order to control for individual differences in hue perception, at the end of the experiment, participants were asked to identify, in a random sequence of four questions, their subjective unique hues: the green without shades of blue or yellow, the yellow without shades of green or red, the blue without shades of green and red, the red without shades of yellow or blue. When the Hue Circle appeared, participants chose their unique hues. After each choice, the circle was rotated at random for the following choices. Figure 2.8 displays as example the choice of unique red by a participant.

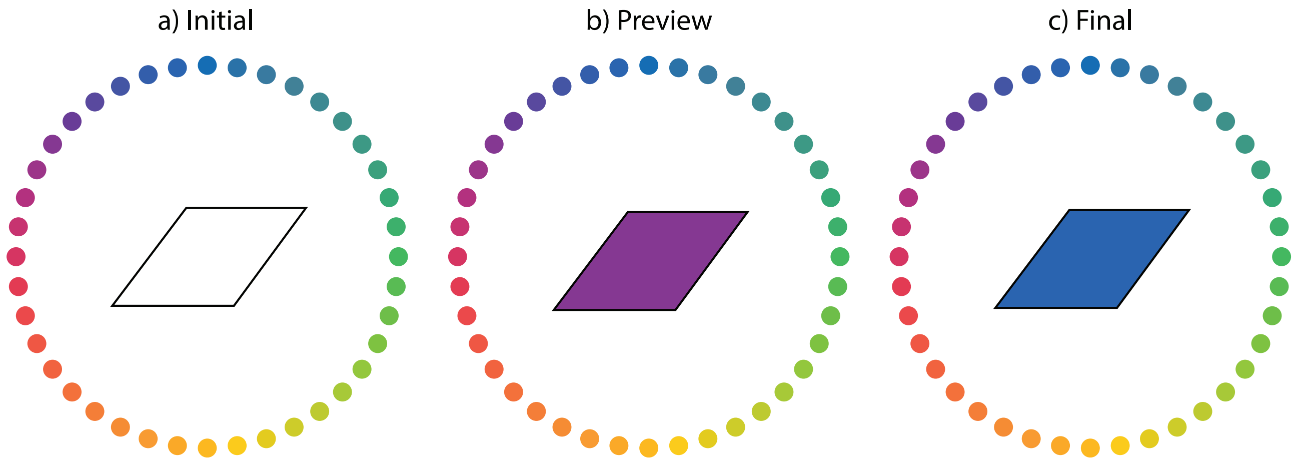


Figure 2.7. The image shows the shape-to-color association task: the subject initially saw the shape with only its outline in black (a), he could see the shape colored in one color by pressing the corresponding color patch (b), and confirm his choice when the color was the one perceived as most naturally related to the shape (c).

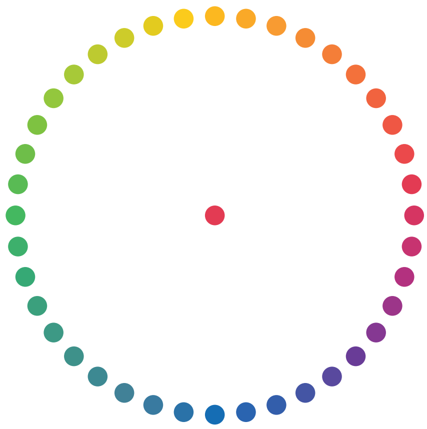


Figure 2.8. Example of choice of unique red ("the red without shades of yellow or blue").

2.3.2 Results and Discussion

Analyses were performed with R 2.13.0 software (R Development Core Team). The chi-square test was used to evaluate the departure from independence with respect to the association between the variables shape and color. The 40 hues of the NCS Hue Circle were grouped into 8 chromatic areas, as in Experiment 1. When considering all participants' choices together (8 grouped colors with respect to 4 shapes), a significant connection was confirmed between shape and color (chi-square=114; d.f.=21; $p< 0.001$). Log linear models were used to evaluate whether the other experimental variables (size, area/perimeter, stability) could modify the interrelationship between shape and color. None of the variables considered significantly modified this interrelationship (*size*: chi-square=32.4; d.f.=21; *p*=0.054; *area/perimeter*: chi-square=15.4; d.f.=21; *p*=0.80; *stability* (circle excluded): chi-square =13.2; d.f.=14; *p*=0.51). In addition, after the effect of each of these three experimental variables was taken into account, a significant association was confirmed between the variables 'shape' and 'color', with *p-values* always well below 0.001. The "color profiles" of the four geometric shapes (circle, square, triangle, and rhombus, without considering the three spatial dimensions considered: size, area/perimeter and stability) were used to plot them on the plane of the first two factorial axes obtained from the Correspondence Analysis in Experiment 1. Figure 2.9 shows (lower-case letters) the positions of the four geometric shapes, which matched the pattern found in the previous experiment.

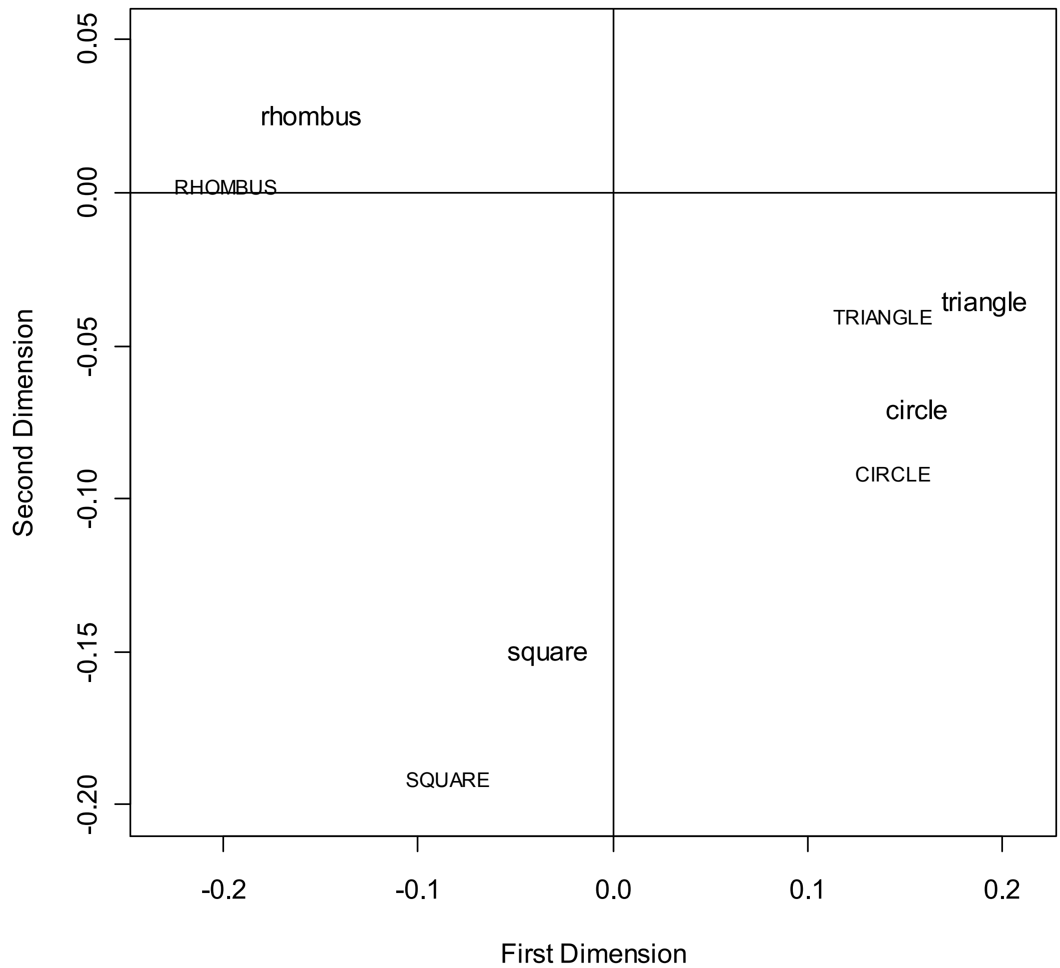


Figure 2.9. Projections of the 4 shapes considered in the second experiment onto the plane formed by the first two factorial axes (from Experiment 1). The horizontal axis can be interpreted as the "heat" of the colors (heat increases from left to right). The vertical axis can be interpreted as the level of "natural lightness" of the colors (lightness increases from bottom to top). Lower-case letters: original colors. Upper-case letters: colors after recalibration based on subjective unique hues.

In particular, the triangle and the circle were warm shapes, whereas the rhombus is “cool”. The rhombus was located on the left side of the horizontal axis in a position similar to that observed for the parallelogram in the first experiment; as mentioned above, because of the orientation, the rhombus can appear as a parallelogram, the “coolest” shape in the first experiment. The square, and to a lesser extent the circle, are “dark”.

According to Kuehni (2004), individual differences in the selection of unique hues can be very large and therefore they might consistently modify the results of our work by changing the subdivision of the hue circle in groups of hues. The procedure is analogous to the one followed when observing isoluminant colors, for which a subjective choice is preferable to the standard one. We wanted to check whether the subjective choice of unique hues, might bring on slightly different results to those obtained by using standard unique hues as presented by the Natural Colour System. Recoding the color grouping produced generally moderate shifts in classification. Table 2.2 show that 89% of the choices did not change grouping after the re-encoding procedure and confirms that observers show only a modest variability in the choice of unique hues. Using the color data modified as a function of the subjective unique hue selection, quite similar results were obtained with respect to both the significant association between the variables ‘shape’ and ‘color’ (chi-square=104; d.f.=21; p<0.001) and the non-significant interactions with size, area/perimeter, stability. The positions of the four geometric shapes considered on the plane of the first two factorial axes, as determined by the CA of Experiment 1, are very near to those obtained without considering the subjective selection of unique hues (Figure 2.9, upper-case letters).

Table 2.2.
Color choices before (columns) and after (rows) the recalibration based on individual unique hues. (Y=Yellow, R= Red, B=Blue, G=Green)

	YY	YR	RR	RB	BB	BG	GG	GY	Total
YY	288	3	0	0	0	0	0	1	292
YR	5	178	1	0	0	0	0	0	184
RR	0	37	347	3	0	0	0	0	387
RB	0	0	42	191	0	0	0	0	233
BB	0	0	0	24	276	3	0	0	303
BG	0	0	0	0	16	137	24	0	177
GG	0	0	0	0	0	0	184	53	237
GY	9	0	0	0	0	0	0	138	147
Total	302	218	390	218	292	140	208	192	1960

2.4 Experiment 3

The purpose of the experiment was to verify whether angles (two segments joined at their vertex) of different widths led to consistent choices of colors (hues). Also the present study has correlates in the analyses conducted by Kandinsky in the artistic field. The artist hypothesized a role of angles in determining the color matched to a shape. This analysis was part of his broader investigation into the elements of pictorial space in terms of points, lines, and surfaces and their cross-dimensional/cross-modal characteristics (Kandinsky, 1926/1944). Kandinsky considered an acute angle to be warm and tending to yellow, and an obtuse angle to be cool and tending to blue. In the research reported here, we wanted first to determine whether there is a natural association among angles formed by two lines, and hue and temperature of color. Our second objective was to conduct comparisons with results previously obtained (Albertazzi et al., 2012) in order to determine whether angles are decisive for the natural association between geometric figures and colors: for example, whether the presence of lines forming acute angles in a triangle or of lines forming right angles in a square influence the association of the overall figure with a particular hue/group of hues. With respect to the experimental design previously adopted, apart from the diversity of the stimuli, the intention was also to test for a possible influence of the background on the color in the associations.

2.4.1 Methods

Participants

Fifty-six participants volunteered for Experiment 3 (mean age = 22.03, SD = 3.72; range: 19–44 years). All participants were recruited from students at the Department of Psychology and Cognitive Science, University of Trento, Italy. The only exclusion criterion was self-reported defective color vision. A preliminary phase was performed, in which each subject was asked to identify unique hues, the purpose being to detect visual defects (such as Daltonism or large deviations in the choice of unique hue) that were not self-reported. Subjects were mainly Italian mother tongue. None declared a conscious synesthesia. The experiment was conducted after obtaining informed consent.

Design

Angles of 6 different widths were employed for the experiment: 22.5°, 45°, 90°, 135°, 157.5°, 180°. Each angle was displayed at each of 8 possible orientations (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). The experiment consisted of two experimental blocks where the same stimuli were presented first in the version with a white background and then in the version with a black background, or vice versa. In the course of the experiment, therefore, each subject saw a total of 96 stimuli: 6 angles x 8 orientations x 2 backgrounds.

Stimuli/Materials

Materials consisted of a series of 6 angles formed by two segments joined at their vertex and the 40 colors of the NCS Hue Circle (see Appendix 2). Both shapes and colors were presented on a 19-inch CRT ViewSonic G90fB Graphics Series monitor, 1024 x 768 resolution.

Lines forming angles of different widths (22.5°, 45°, 90°, 135°, 157.5°, 180°) were displayed with their vertex centered with respect to the Hue Circle (Figure 2.10). The angles were presented in achromatic grey on a white or a black background and reproducing only their sides (length = 97 mm; thickness = 3 mm). The Hue Circle had a diameter of 37.5 cm and was made up of 40 small circular patches of 1.8 cm. On every presentation the orientation of the Hue Circle varied at random as in Experiment 2 (i.e. the color to the north of the screen was not always the same).

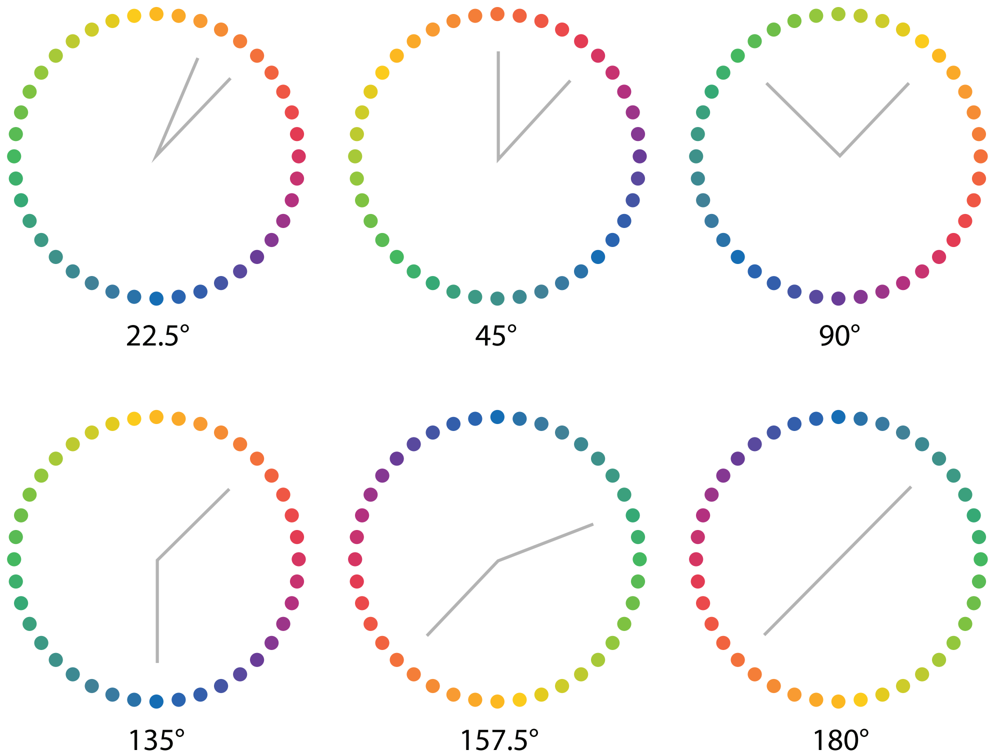


Figure 2.10. Shown above are the lines forming angles with the six widths studied (22.5°, 45°, 90°, 135°, 157.5°, 180°), in one of the eight orientations in which they could appear during the experiment with the white background. The Hue Circle rotated at random between one presentation and the next.

Task and Procedure

The experiment was conducted in a dimly lit laboratory (1 lux on the walls). The stimuli consisted of the series of angles and the Hue Circle described above. Participants were seated at a work desk at a distance of about 60 cm from the screen, in front of which was positioned a black cylinder which functioned as a reducer and isolator of light from the room. The cylinder had a diameter of 280 mm and was around 500 mm long (equal to the distance of the subject from the monitor). On looking through the cylinder, the subject saw the central part of the monitor in which the stimuli and the Hue Circle appeared. This procedure ensured that, during observation of the stimuli, the light originated from the monitor and not from reflections on the screen.

Firstly, participants were administered a questionnaire with questions relative to their experience of color, possible color blindness (including Daltonism), and synesthesia. Moreover, to check for the existence of color-related visual defects that were not self-reported, the participants performed a preliminary task which required them to identify their subjective unique hues on the NCS Hue Circle. The procedure for the identification of subjective unique hues was the same employed in Experiment 2. The interface asked each participant to select, upon the appearance in random orientation of the Hue Circle, the hue that she/he perceived as corresponding most closely to 'red without shades of blue or yellow'; to 'yellow without shades of red or green'; to 'green without shades of yellow or blue'; and to 'blue without shades of green and red'. Thereafter, participants were given the following written instructions for the angle/color matching task:

> *"At the center of the screen you will see, one at a time, a series of 'angles' (figures formed by two intersecting lines) with different orientations. On the basis SOLELY of the impression produced by the width of the angle, color the two lines that form the angle with the color that you perceive as most closely matched with it. Take care NOT TO FAVOUR the color or colors of the Hue Circle close to the edges of the figure in each presentation. You should not make associations between angle and color on the basis of past experience. To perform the task, click on the color that you associate with the angle. You can repeat your choice until you are satisfied with the result. When you are satisfied, click on the vertex of the colored angle to confirm your choice definitively and go on to the next test. N.B.: once you have confirmed your choice, you cannot go back on it. Press the SPACE BAR to proceed."*

The angle/color matching task consisted of two experimental blocks, carried out in sequence, in which the same stimulus figures were presented, first against a white background and then against a black background, or vice versa. Each stimulus was made to appear at the center of the screen and concentric with the circle. To perform the task, the subjects were required to use only the keyboard and the mouse. Proposed for each experimental block were 48 presentations of the circle of colors with different orientations. Shown internally to the circle were the lines forming angles of each width in their various orientations. The task of the participant was to color the lines, to see whether the given color was perceptually congruent with the angle width, choosing it from among the 40 hues of the Hue Circle. By clicking on a color, the subject could view the lines, which were originally grey, in the color selected. S/he could then confirm his/her choice by clicking on the colored lines and move to the next presentation; or s/he could make further attempts until s/he was satisfied with the lines/color association made (see Figure 2.11). There followed the second experimental block, in which the subject was asked to perform the same angle/color association task, the only variant being that the background was now black rather than white.

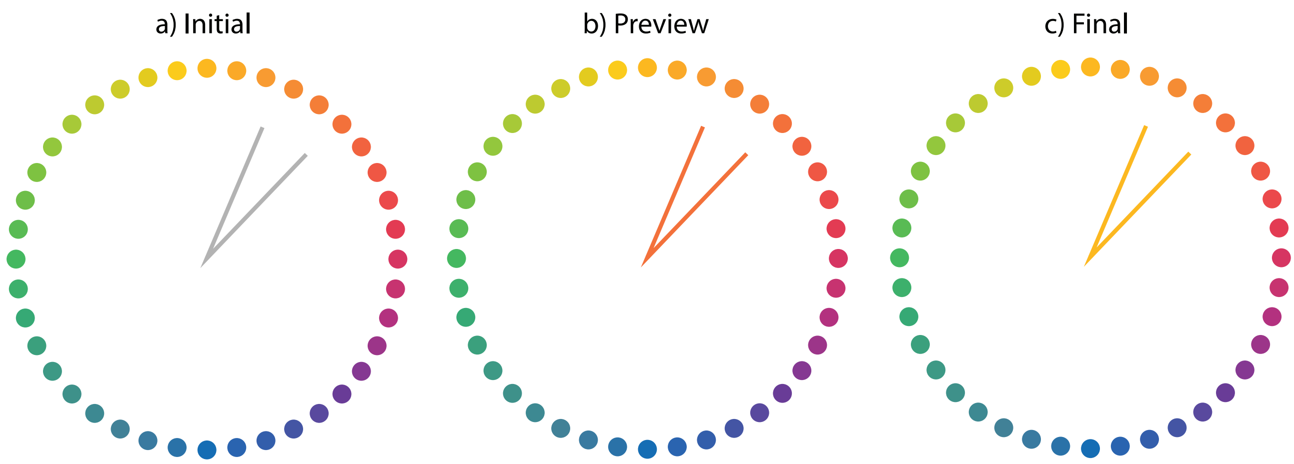


Figure 2.11. The figure shows an example stimulus as initially displayed to subjects in achromatic grey (a), thereafter the same stimulus colored in one color by the subject as a first attempt (b), and then the final choice (c).

2.4.2 Results and Discussion

The chi-square test for a contingency table was used to evaluate the departure from independence with respect to the association between the variables 'angle' and 'color' separately for the white and the black background. A significant association was found between these two variables both when the background was white (chi-square=317.5; DF=195; $p<0.001$) and when the background was black (chi-square=286.4; DF=195; $p<0.001$). A residual analysis was performed to identify those cells of the contingency table where the departure from the independence hypothesis was more evident. Analyses were performed with R 2.15.0 software (R Development Core Team, 2011). Results for stimuli presented on different backgrounds (white/black) are presented separately and then discussed together.

White background

When the background was white, there were 31 residuals greater than 1.96 in absolute value (12, i.e. 5% of the total, were expected if color was randomly selected). A positive residual means that the selected angle 'attracts' the corresponding color; a negative residual means that the selected angle 'repels' the corresponding color. As regards the acute angles, the highest positive residual (4.99) for 22.5° was associated with Y and the highest negative residual (-2.77) was associated with B70G; the highest positive residual (3.50) for 45° was associated with G40Y and the highest negative residual (-2.11) was associated with R90B. As regards the obtuse angles, the highest positive residual (2.26) for 135° was associated with G20Y and the highest negative residual (-2.05) was associated with R; the highest positive residual (2.06) for 157.5° was associated with R80B and the highest negative residual (-2.29) was associated with G40Y. Shown in Figure 2.12 are the residuals greater than 1.96 (in absolute value) for acute and obtuse angles.

Inspecting Figure 2.12, a pattern of residuals emerges. With respect to the two acute angles, positive associations were found mainly with red and yellow colors and negative associations with blue and green ones. The opposite was the case when the two obtuse angles were taken into account. These results are more evident if we consider the number of attractions and repulsions in Figure 2.12 after having divided the Hue Circle into two halves. The first half, starting with G50Y and ending with R40B, can be considered the 'warm' half of the Hue Circle. The second, starting with R50B and ending with G40Y, can be considered the 'cool' half of the Hue Circle (see Figure 2.13). The acute angles mainly attract a 'warm' color (5 out of 6), while they always repel a 'cool' color (3 out of 3). The reverse occurs when the obtuse angles are taken into account. They always attract a 'cool' color (6 out of 6) and mainly repel a 'warm' one (3 out of 4).

As far as the 90° angle is concerned, the two highest positive residuals were associated with G30Y (3.21) and with Y20R (2.58), while the highest negative residual (-1.98) was associated with B40G. The highest positive residual (3.68) for 180° was associated with G and the highest negative residual (-2.88) was associated with G30Y.

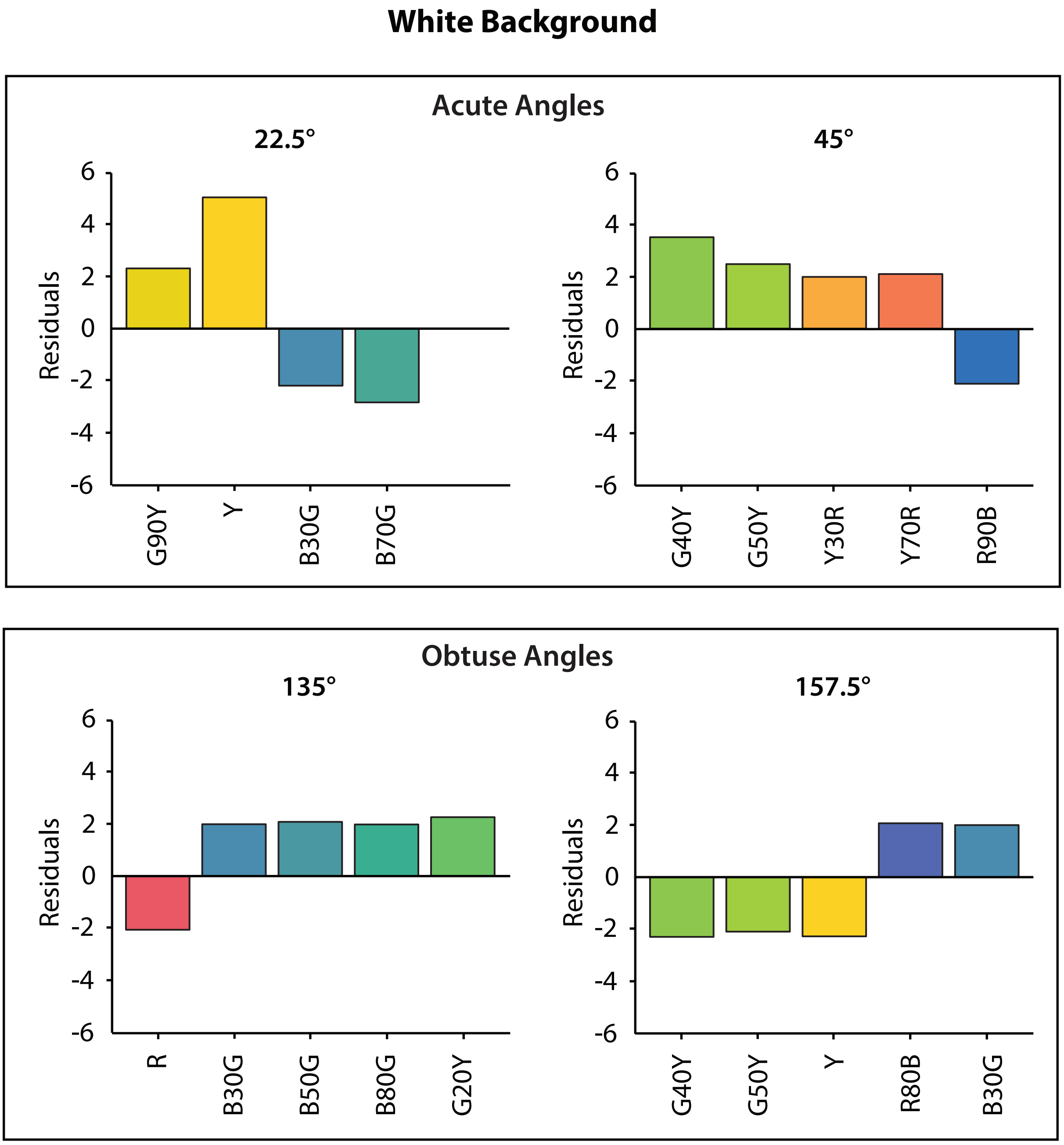


Figure 2.12. Bars represent the residuals greater than 1.96 (in absolute value) for acute angles (top) versus obtuse angles (bottom) when presented on a white background. In general the acute angles were mainly attracted to warm colors (red and yellow) and repulsed by cool colors (blue and green). The reverse is observed for obtuse angles. If you compare the most acute angle (22.5°) to the most obtuse one (157.5°) an opposite pattern emerges: the former is mainly attracted to yellow/green-yellow and repulsed by blue-greens, the latter is attracted to blue-green/red-blue and repulsed by yellow/green-yellows.

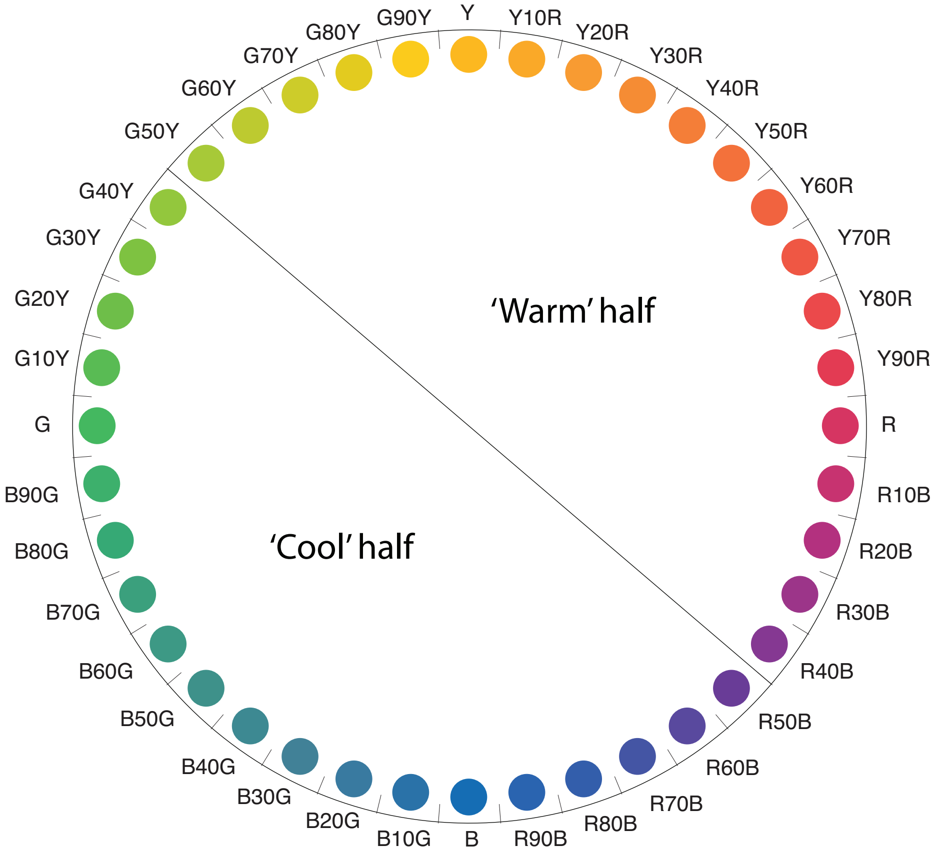


Figure 2.13. The image shows the 40 hues of the NCS Hue Circle and their labels. The thirty-six hues are identified by a letter–number combination indicating the chromatic attributes included and the relation between these (for example, Y90R is a yellow hue with 90% redness). The remaining 4 hues are identified by the letters Y (100% yellow), R (100% red), B (100% blue), and G (100% green). The circle is here divided into two halves ('cool half' and 'warm half') that represent an approximate subdivision between warm and cool colors. Individual hues have been categorized this way to analyze the attractions and repulsion between acute/obtuse angles and cool and warm colors.

Black background

When the background was black, there were 19 residuals greater than 1.96 in absolute value (12 were expected if color was randomly selected); on the other hand, there were 10 residuals greater than 2.57 in absolute value (2.4, i.e. 1% of the total, were expected if color was randomly selected). As regards the acute angles, the highest positive residual (3.46) for 22.5° was associated with G90Y and the highest negative residual (-2.60) was associated with G30Y; the highest positive residual for 45° was 1.95 and was associated with Y40R, while the highest negative residual (-2.41) was associated with G. As regards the obtuse angles, the highest positive residual (2.78) for 135° was associated with B30G and the highest negative residual (-3.78) was associated with G90Y; the highest positive residual (2.88) for 157.5° was associated with G while the highest negative residual (-1.81) was higher than -1.96. Shown in Figure 2.14 are the residuals greater than 1.96 (in absolute value) for acute and obtuse angles.

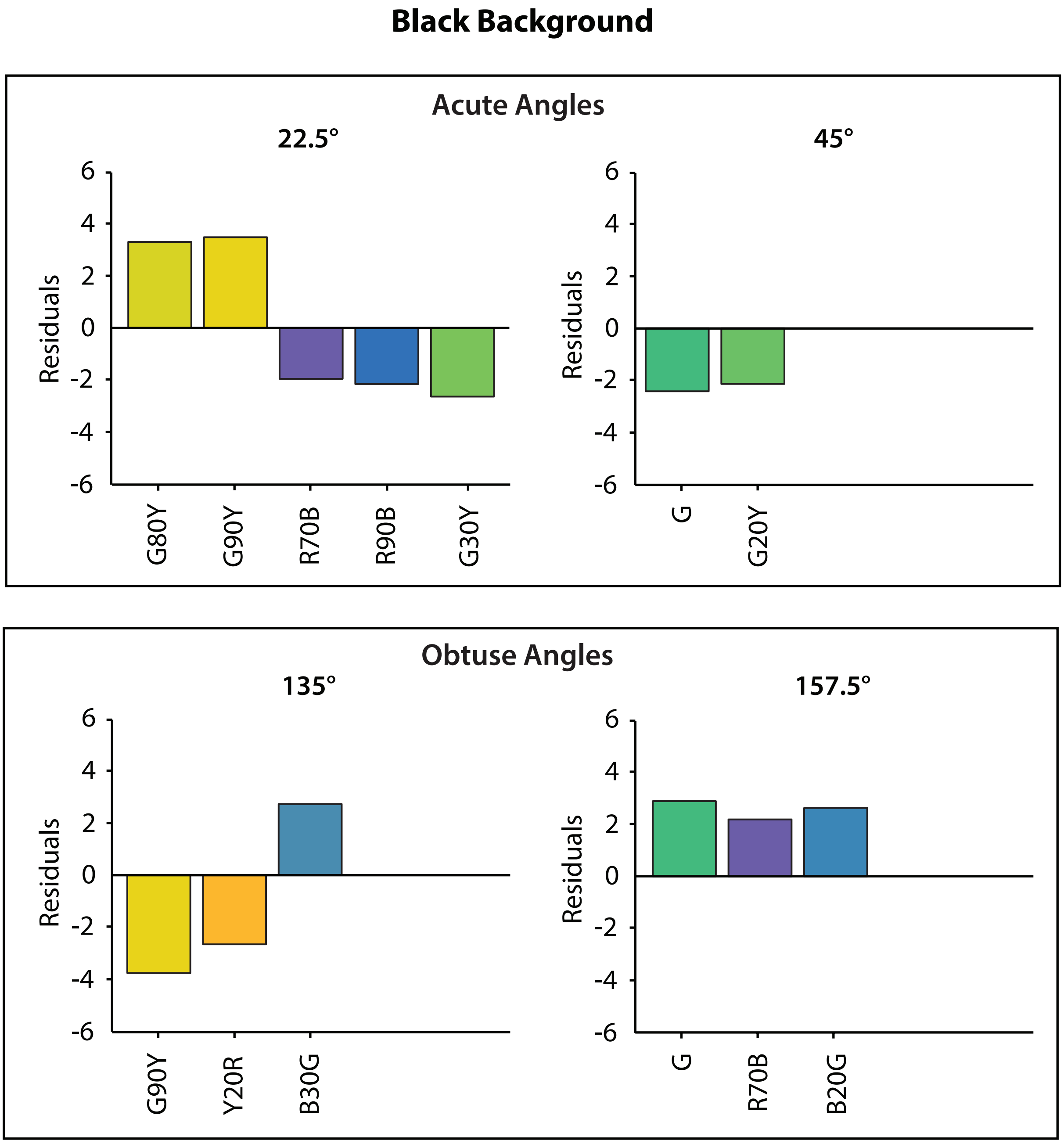


Figure 2.14. Bars represent the residuals greater than 1.96 (in absolute value) for acute angles (top) versus obtuse angles (bottom) when presented on black background. Overall, the acute angles were mainly attracted to warm colors (yellow) and repulsed by cool colors (blue and green), while the reverse is observed for obtuse angles.

Figure 2.14 resembles the pattern of residuals observed in Figure 2.12. The acute angles always attract a 'warm' color (2 out of 2), while they always repel a 'cool' color (5 out of 5). The reverse occurs when the obtuse angles are taken into account. They always attract a 'cool' color (4 out of 4) and repel a 'warm' color (2 out of 2). As far as the 90° angle is concerned, the two highest positive residual were associated with G30Y (3.37) and with R30B (2.50), while the highest negative residual (-2.42) was associated with B80G. The highest positive residual (2.86) for 180° was associated with B80G and the highest negative residual (-1.80) was higher than -1.96.

Our results confirm previous findings of the existence of natural associations in the general population—for example, those between different perceptual features in the same or different modalities—and they further extend the range of the associations of colors to angles of different amplitude. As regards the other specific aspects of colors examined here, the results suggest relations between angles and some color qualities, such as their temperature (warm/cool). Acute angles are mainly associated with warm colors, while obtuse angles are mainly associated with cool colors. This finding is particularly evident when considering the strongest attraction for acute (which is Y, i.e. a warm color, for the 22.5° angle) and obtuse angles (which is G, i.e. a cool color, for the 157.5° angle).

Kandinsky's (1926/1944) hypotheses on the color of angles—the right angle as cool/warm, the acute angle as warm and tending to yellow, the obtuse angle as cool and tending to blue—are partly supported by our results. Also in our study, acute angles appear to be warm, and obtuse angles appear to be cold. Specifically, on the white screen the 22.5° angle is Y, the 45° one is G40Y, the 135° one is G20Y, and the 157.5° one is R80B. On the black screen, the 22.5° angle is G90Y, the 45° one is Y40R, the 135° one is B30G, and the 157.5° one is G. The strongest attraction for the 90° angle was with G30Y both for black and for white background, but not with red-violet as hypothesized by Kandinsky. However, the second attraction for the angle of 90° with the black background is R30B, and therefore with Kandinsky's "violet". Not so with the white background, where the second attraction is with Y20R, and therefore not with violet. We may therefore say that with the black background Kandinsky's hypothesis is not confuted. Our results are overall consistent when considering both the background and the opposition between attractions and repulsions. A different consideration applies to the 180° angle, which is not seen as an angle but as a line.

2.5 Discussion of Experiments 1, 2, and 3

Our results provide, for the first time, evidence of shape-to-color associations in the general population, which is mainly non-synesthetic. These results are in line with recent evidence of systematic cross-modal or cross-dimensional associations in non-synesthetes.

In particular, Experiment 1 showed that people have a propensity to match certain hues (or group of hues) with certain geometric shapes. These results are very systematic, since the same pattern or results emerges from two independent experimental sessions, when data are analyzed at the group level. According to our interpretation, results suggest a relation between geometric shapes and properties of the hues, such as their temperature (Da Pos & Valenti, 2007) and their degree of natural lightness (Spillman, 1985a, 1985b). More precisely, the circle and the triangle were the 'warmest' shapes, whereas the parallelogram was the 'coolest' and the square and the circle were the 'darkest', as opposed to the pyramid and the cone, which were the 'lightest' shapes within the set of shapes studied. Experiment 2 confirmed results obtained in Experiment 1 with a different group of participants and a slightly different method in that (i) colors were presented on a monitor rather than printed on paper, and (ii) the interface allowed participants to see the shape actually colored in a given color when asking participants to judge the shape-color association that they perceived as the most natural. Experiment 3 showed the existence of systematic associations also between parts of shapes (angles) and hues. Also, these latter results suggest a relation between angles of different widths and color temperature: acute angles were mainly associated with warm hues while obtuse angles were mainly associated with cool hues. The results were consistent irrespective of the background's color (white/black). Some extracts of Experiments 1-2 (Albertazzi et al., 2012) and 3 (Albertazzi, Malfatti, et al., forthcoming) are now published or in press.

As a by-product of our analyses, we managed to test Kandinsky's hypothesis, which was only partially verified: a triangle "is" yellow and a square "is" red, while the circle—rather than being associated with blue—"is" red. However, we remark that in our experiments, as opposed to previous work (e.g. Jacobsen, 2002), Kandinsky's hypothesis was tested without the constraint of a one-to-one association. In our experiment participants were allowed to choose the same color for more than one shape, and this could explain the different results. Experiment 1 has been recently replicated in Japan using the same method that we explained here (Chen et al., accepted) and an association between triangle and yellow and circle and red has been reported for Japanese observers too. The results of Experiment 1-2 allowed some predictions to be made: for instance, we expected to find a correlation not only between color and type of shape but also between color and the parts of a shape like its angles, as suggested by Kandinsky's theory. Our analysis revealed an opposition between acute and obtuse angles and warm and cool colors. However, there does not seem to be a direct relationship between the color of a shape and the color of its angles. For instance, the triangle is made up of acute angles which "are" yellow and the resulting shape "is" indeed yellow. However, both the square and the circle, which are characterized by either the curve or the right angle, were associated with red by our participants. We recall that the right angle (which characterizes the square) was mainly associated to green-yellow, while the obtuse angle (which approximates the curve) was mainly associated to red-blue/blue-green. It seems clear that a shape's curvature does not explain in itself all shape-to-color associations. We hypothesize that other perceptual aspects of shapes, as well as non-perceptual ones, might play a role in determining the shape-to-color associations emerged.

The novelty of the study and the striking results warrant deeper examination. The current study could be extended in different ways. First, it could be extended with respect to the aspects of color and shape taken into consideration. With respect to color, the results could be extended to color attributes other than the hue, such as saturation and lightness. With respect to shape, it could be clarified which local/global perceptual aspects of the shape influence participants' color choices. Moreover, one could assess whether cognitive or emotional aspects might affect participants' color choices for a given shape too. Further research will try to explore additional explanations for this phenomenon, reported with great systematicity but not yet explained. Some of the issues just mentioned will be addressed in Experiments 4-5.

CHAPTER 3

Shape-to-Color Associations in Non-synesthetes: Emotional and Perceptual Mediation

3.1 Introduction to Experiments 4 and 5

Experiments 1-3 (Albertazzi et al., 2012; Albertazzi, Malfatti, et al., forthcoming) showed consistently that people tend to make systematic cross-dimensional associations between certain shapes and certain hues. In the following experiments we extend these previous results to a wider variety of shapes and shape features and to color-dimensions other than hue. We explore further explanations for this phenomenon, particularly the role of perceptual and emotional factors as possible mediators. Moreover, we screen the participants for synesthesia and restrict our analysis to non-synesthetes rather than referring to the general population in a broader sense. The current experiments were carried out as part of a research collaboration at the University of California, Berkeley. They were planned and run within the Visual Perception and Aesthetics Lab, under the supervision of Prof. Stephen Palmer. In particular, experiments 4-5 extended the previous studies on shape-to-color associations using the method developed by Palmer et al. (2013) to study music-to-color associations and emotional mediation in non-synesthetes.

So far we have mainly focused on the literature about cross-dimensional associations, i.e. associations between different dimensions of the same sensory modality: namely, vision. However, there is a large body of research concerning cross-modal associations, i.e., associations between stimuli of different sensory modalities. The literature in this field seems fruitful in providing possible insights and suggesting further questions. First, it seems promising to extend the study of shape-to-color associations to aspects of color other than the hue. Indeed, research concerning associations between auditory and visual stimuli suggests that the strongest effects may concern the saturation and lightness dimensions of color rather than the hue dimensions. It has been shown, for instance, that higher pitches match consistently to lighter colors for both synesthetes and non-synesthetes (Ward, Huckstep, Tsakanikos, 2006). Research involving higher level auditory stimuli, such as music, showed that different structural features of music map systematically on to different color-dimensions. For instance, there is evidence that music in the major mode matches to lighter colors than music in the minor mode (Bresin, 2005), and that faster music in the major mode matches to more saturated, lighter and yellower (warmer) colors than slower music in the minor mode (Palmer, Schloss, Xu, & Prado-Leon, 2013). These observations, together with the goal of studying shape-to-color associations in more depth, led to the change in the design of the current experiments.

Within the color domain, we used the 37 colors of the Berkeley Color Project (Palmer & Schloss, 2010; Schloss & Palmer, 2011; Schloss, Poggesi, & Palmer, 2011) rather than the 40 hues of the Natural Color System. The 37 colors of the BCP are sampled in an approximately uniform way from a Hering-like color space (whose axes correspond to red-green, blue-yellow, and black-white), within which they vary systematically in their hue (redness-greenness and yellowness-blueness), saturation, and lightness. In this sample, there are fewer hues (red, green, yellow, blue, orange, chartreuse, cyan, purple) but they each is represented at four different levels of saturation and lightness, in addition to a series of achromatic colors (black, white, and three different shades of grey).

As to shape, rather than considering different individual shapes, we generated a set of stimuli that changed systematically with respect to specific geometric/perceptual features. The aim was to study how each shape feature might affect different color appearance dimensions. The shape features were selected in part by looking at the literature on grapheme-color synesthesia. For instance, component features of graphemes—e.g., open/closed or round/angular—are believed to contribute to grapheme-to-color associations in synesthetes (Jürgens, Mausfeld, & Nikolić, 2010). Similarly, features such as curvature (i.e., amoeboid/jagged) are thought to play a role in grapheme-to-color associations in non-synesthetes (Spector & Maurer, 2011). These and other shape features were included in the design of the current experiments.

The current experiments were also designed to test the Emotional Mediation Hypothesis for shape-to-color associations. This hypothesis was originally proposed by Palmer et al. (2013) to explain music-to-color associations in non-synesthetes. They found that people tend to match colors to classical orchestral music on the basis of their shared emotional content (e.g., colors that participants rated as being "happy" were chosen as going best with music that the same participants rated as being "happy"). Whiteford et al. (2013) also found support for emotional mediation studying music-to-color associations with a broader sample of musical genres, including rock, jazz, salsa, country-western, and reggae. We therefore hypothesized that analogous mechanisms might be at work in the case of shape-to-color associations. While it is well established that both individual colors (see Da Pos & Green-Armytage, 2007) and shapes (see Collier, 1996; Hevner, 1935; Poffenberger & Barrows, 1924) are associated with specific emotions, it is not clear whether people associate colors and shapes on the basis of their emotional content or on other factors. The current experiments were designed to shed light on this issue. In particular, elements of Osgood's semantic differential were employed to obtain ratings of each color and each shape along a series of emotional and perceptual dimensions. These ratings were collected only after the shape-to-color matching task had been performed, however, so that the ratings could not contaminate the previously collected shape-to-color associations. These ratings allowed us to evaluate the extent to which the pattern of shape-to-color associations could be explained by the emotional or perceptual factors that were rated. The roles of preference and of possible object-mediated associations were also explored.

3.2 Experiments 4 and 5

The hypotheses that motivated Experiments 4 and 5 can be formulated as follows: (*i*) There may be systematic shape-to-color associations in non-synesthetes (i.e., there is an effect of shape features on the probability of associating it with colors that differ in saturation, lightness, redness-greenness, and yellowness-blueness; and (*ii*) shape-to-color associations may be mediated, at least in part, by emotions (i.e., participants choose the colors to go with a shape based in part on their shared emotional content). We chose to test both hypotheses in two separate experiments using different stimuli. Experiment 4 concerned shape-to-color associations for a set of open lines with two free ends. Experiment 5 concerned the same kind of associations for closed shapes with no free ends. The sets of lines [or shapes] varied in terms of several additional geometric features, such as their complexity (number of generating points), whether the connecting lines were straight or curved, and whether the stimuli were symmetric or asymmetric.

The hypothesis that there might be systematic shape-to-color associations was tested by analyzing the results of a task in which participants saw a single shape stimulus (either an open line in Experiment 4 or a closed shape in Experiment 5) together with a set of 37 diverse colors and were asked to choose the three colors that "were most consistent with the shape" and (later) to choose the three colors that "were most inconsistent with the shape." The chosen colors were coded in terms of their rated values on four standard color dimensions (saturation, lightness, redness-greenness, and yellowness-blueness) and the relation between these color attributes and the geometric features of the shape stimuli (e.g., complexity, symmetry, and side curvature) were assessed to determine whether such features produced systematic patterns among the colors people chose as going best (and worst) with the shaped stimuli: e.g., do people choose more saturated colors as going better with pointier shapes?

The hypothesis that such shape-to-color associations might be mediated by emotional and/or semantic factors was assessed though several additional tasks. One was having participants rate each shape stimulus on the same set of six emotional dimensions (happy/sad, agitated/calm, angry/not-angry, strong/weak, active/passive, and harmful/safe) and five additional semantic dimensions (warm/cool, complex/simple, familiar/unfamiliar, pleasant/unpleasant, and liked/disliked). Another was having participants make the same ratings for each color stimulus. We then examined the correlations between the average rated values of the shape stimuli with the average rated values of the color stimuli chosen as going best with them. High correlations between the emotional ratings of the shapes and colors are predicted if the shape-to-color associations are mediated by emotion. Various additional analyses were performed to further examine whether geometric or emotional features are better predictors of the colors people choose to go well with the shape stimuli.

3.2.1 General Methods

Participants

Forty-four participants volunteered for Experiment 4 (mean age = 21.43, SD = 3.46; range: 18–40 years), and forty-four participants volunteered for Experiment 5 (mean age = 21.02 SD = 4.19; range: 18–39 years). None of the participants who took part in Experiment 5 had participated in Experiment 4. Participants were recruited from students at the Psychology Department, University of California, Berkeley. The only exclusion criterion was defective color vision, as assessed using the Dvorine Pseudo-Isochromatic Plates. No participant was classified as a synesthete according to the online Synesthesia Battery (www.synaesthete.org) by Eagleman et al. (2007). Although this was not a cross-cultural experiment, participants were very diverse with respect to their ethnicity and native language[1].

Design

Forty-four drawings of line-shapes were used in Experiment 4 and forty-five drawings of closed geometric shapes were used in Experiment 5. Line-shapes could differ with respect to their number of generating-points (3/4/9), pointedness (curved/angular), symmetry-axes (0/1), and intersections (0/1/>1). Closed geometric shapes could differ with respect to their number of generating-points (3/4/9), pointedness (curved/angular/pointy), symmetry-axes (0/1/>1), and concavities (0/≥1). We will mark these factors with a 'G' in brackets after each term—i.e., 'generating-points[G]', 'pointedness[G]', 'symmetry-axes[G]', 'intersections[G]', and 'concavities[G]'—to stress the fact that they refer to 'geometric' features of the shape in the Results section. Similar features will be considered indeed from a subjective perceptual point of view later, and marked with a 'P', so that it is made clear when we refer to the ones or the others. The factors common to both sets were the number of generating points, pointedness, and symmetry-axes, even though Experiment 5 included more levels for symmetry-axes. Conversely, the 2 sets were different in that Experiment 4 included intersections, whereas Experiment 5 included shape-concavity as a factor.

Two different sets of stimuli for two separate experiments were generated in order to include some perceptual properties specific to the subgroups of lines versus closed shapes. For

[1] Participants from Experiment 4 were Asian (31), Caucasian (8), or Other (5), and their native languages included English (23), Chinese (9), Korean (5), Japanese (2), Indonesian (1), Danish (1), Spanish (1), Urdu (1), and a case of English/Tamil bilingualism (1). Participants from Experiment 5 were Asian (30), Caucasian (7), Black (2) or Other (5), and their native languages included English (19), Chinese (10), Korean (7), Indonesian (3), Arabic (2), Spanish (1), Portuguese (1), and Vietnamese (1).

example, overall shape-concavity can be geometrically defined only for closed shapes, because there must be a well-defined distinction between inside and outside. At least one stimulus for each combination of the factors mentioned above was included in each set. The number of combinations is not equal to the product of the number of levels of each factor (3x2x2x3 in Experiment 4; and 3x3x3x2 in Experiment 5) because (i) not all combinations were possible (e.g., the number of generating points limits the number of intersections and the concavities that can be present in principle for a given stimulus) and (ii) a broader distinction between asymmetric (0 symmetry-axes) and symmetric (≥1 symmetry-axes) was sometimes preferred to keep the overall number of stimuli smaller in Experiment 5. For instance there is no concave 9-sided shape and exactly 1 symmetry-axis, whereas there are concave 9-sided shapes with either 0/>1 symmetry-axes.

The orientation of the stimuli was balanced across participants so that half of them saw the stimuli as they appear in Figure 3.1, whereas the other half saw them rotated by 180°. Orientation was varied because most of the shapes that tended to remind observers of a particular object did not do so after the 180° rotation.

Materials

The drawings of both sets of stimuli were generated in Adobe Illustrator CS6. The angular version of each stimulus (i.e., the one in which the generating points were connected by straight lines) was generated first, including the factors to be manipulated other than pointedness. Variations of the stimulus edges were applied afterward, resulting in variations of its pointedness. The same general line/shape was therefore presented with either angular/curved edges in Experiment 4, and with angular/curved/pointy edges in Experiment 5. The curved equivalent of each angular line/shape was obtained by using the "Convert Anchor Point" tool in Illustrator, which uses Bézier curves to find the best path that goes through a given set of points (i.e., the vertices of the basic angular stimulus). Similarly, a pointy version for each angular shape of Experiment 5, was generated by consistently modulating the extent and direction of each pointy edge as a function of the length of the sides and the aperture of the starting angle. The concavity factor refers to the overall concavity of the polygon (angular shape) from which the equivalent curved or pointy version was generated, in which a polygon is concave if it has one or more interior angles greater than 180°. All drawings had a stoke width of 3 pt, appeared on a neutral gray background (CIE x=0.312, y=0.318, Y=19.26), and fit into an imaginary square whose sides were 9.52 cm long. The full set of Line-stimuli, Shape-stimuli is displayed in Figure 3.1. A further description of the stimuli and their labels is provided within the Method section of each Experiment.

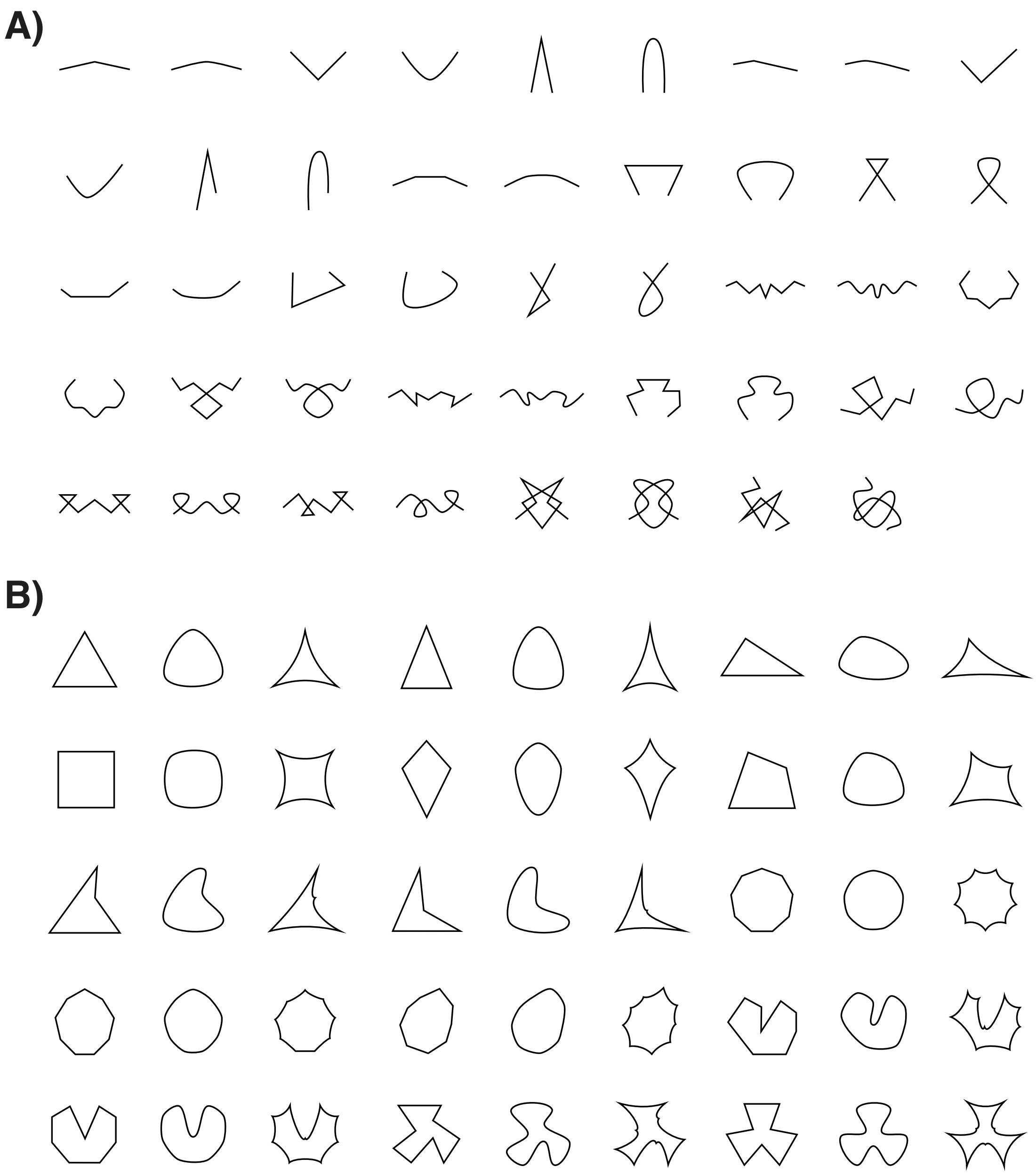


Figure 3.1. Overview of the 44 Line-stimuli of Experiment 4 (panel A) and the 45 Shape-stimuli of Experiment 5 (panel B). Line-stimuli changed with respect to their number of generating points (3/4/9), pointedness (curved/angular), symmetry-axes (0/1), and intersections (0/1/>1) whereas Shape-stimuli changed with respect to their number of generating points (3/4/9), pointedness (curved/angular/pointy), symmetry-axes (0/1/>1), and concavities (0/≥1). See the Method section of each Experiment for further details.

We used the 37 colors from the Berkeley Color Project (Palmer & Schloss, 2010; Schloss & Palmer 2011; Schloss, Poggesi, & Palmer, 2011) which are an approximately uniform sampling from a Hering-like color appearance space defined by prototypical red, green, blue, yellow, black, and white. The colors were chosen to vary systematically in their hue (redness-greenness and yellowness-blueness), saturation, and lightness (see Figure 3.2). The set included 32 chromatic colors and 5 achromatic colors. The eight hues consisted of the four unique hues—unique-red (R), unique-yellow (Y), unique-green (G), unique-blue (B)—plus four binary hues that had approximately the equal amounts of the adjacent unique hues—orange (O), chartreus (H), cyan (C), and purple (P). These eight hues were sampled for four "cuts" through color space defined by combinations of saturation and lightness: saturated (S), light (L), muted (M), and dark (D). S-colors were hues with the highest saturation that could be displayed on the computer monitor, L-colors were approximately half-way between S-colors and white, M-colors were approximately half-way between S-colors and neutral gray, and D-colors were approximately half-way between S-colors and black. The CIE 1931 values for the 32 chromatic colors are specified in Appendix 3.1. The set also included five achromatic colors: white (WH), black (BK), light (AL), medium (AM), and dark gray (AD). AL had the average lightness of L-colors, AM had the average lightness of M-colors and S-colors, and AD had the average lightness of D-colors.

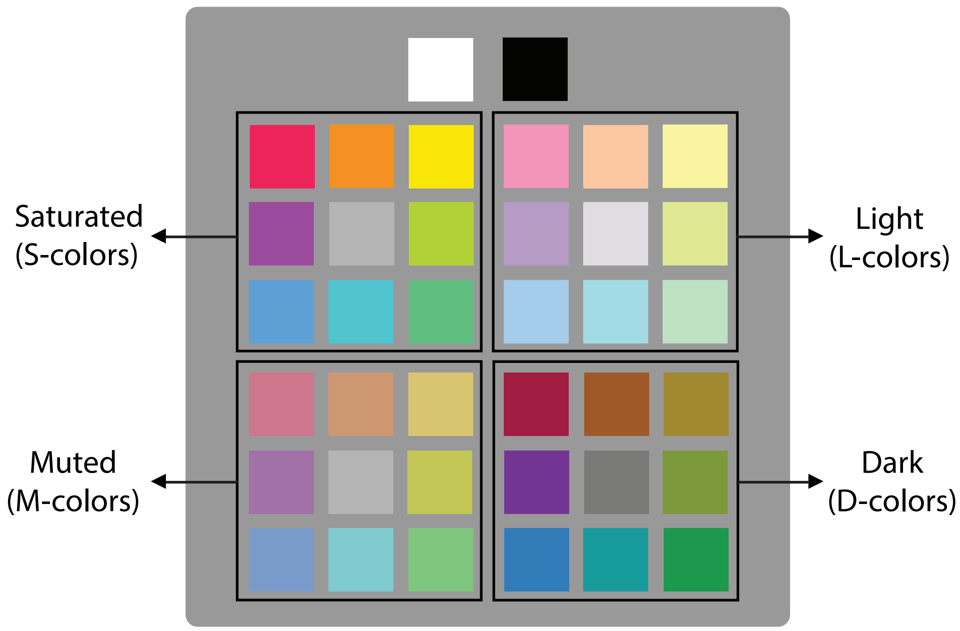


Figure 3.2. The 37 colors of the Berkeley Color Project. The set consisted of eight hues (red, orange, yellow, chartreuse, green, cyan, blue, and purple, as displayed clockwise from the top-left position within each outline square) sampled for four "cuts" through color space defined by combinations of saturation and lightness: saturated (S-Colors), light (L-Colors), muted (M-colors), and dark (D-colors), plus three grays, white, and black. (See text and Appendix 3.1 for details.) The gray corresponding to the saturated (top left) and muted (bottom left) cuts were the same because the saturated and muted cuts had similar mean lightnesses.

For the purposes of some analyses, each of the 37 BCP colors was represented by four values defined by the average ratings from 48 independent participants of its saturation, lightness, redness-greenness and yellowness-blueness (Palmer & Schloss, 2010). We will henceforth refer to these dimensions by their polar extremes, with the default name for the dimension followed by the contrasting name in italics—i.e., saturated/*unsaturated*, light/*dark*, red/*green*, yellow/*blue*—or just naming them after the first polar extreme—i.e., 'saturation', 'lightness', 'redness', and 'yellowness' respectively. The colors were presented in front of the same neutral gray background (CIE x=0.312, y=0.318, Y=19.26) as was used for the line/shape-stimuli. The monitor was calibrated using a Minolta CS100 Chroma Meter. Depending on the task, the colors were presented either all at once, arranged as in Figure 3.1, or one at a time, as small solid squares whose sides were 3.4 cm long.

Tasks and procedures

The experiment was conducted in a dark room. Participants were seated at a working table at a distance of about 60 cm from the calibrated monitor (a 21.5-inch iMac computer monitor, 1680 x 1050 pixel resolution). The materials, consisting of the line/shape-stimuli and the colors described above, were presented using Presentation software (www.neurobs.com).

Each participant gave his or her informed consent to take part in the study. Before the experiment started, participants' color vision was tested using the Dvorine Pseudo-Isochromatic Plates. The actual experiment, consisting of five computer-based tasks, a paper-based questionnaire, and an online battery started thereafter. Details of each computer-based task and the questionnaire are described below.

Shape-to-Color Matching Task

The first computer task was the Shape-to-Color Matching Task. Participants were given the following written instructions for this task for the line stimuli and shape, stimuli (in parentheses): *"During this experiment you will see a series of 44 lines (or 45 shapes), one at a time, with the set of colors below. For each line [or shape] you will be asked to choose the three colors from the set that are MOST consistent with the line [or shape]. Click on the most consistent color first, then the next most consistent, and so on. Then, you will be prompted to click on the three colors that are LEAST consistent with the line [or shape]. Again, click on the color that is least consistent first, then click on the next least consistent, and so on. Make your selection by clicking on the colored sample. Each time you make your selection, it will disappear. If you have any questions, please ask them now, otherwise, you may click to begin!"*

Before the task started, participants were shown a preview of all of the line/shape stimuli of the experiment on a single screen and were told *"Here is an overview of the lines [or shapes] you will be asked to judge. Please take a moment to look at all the* *lines [or shapes]. When you are ready, please click to begin the experiment"*. The preview continued until the participant pressed the key to go to the next screen. The Shape-to-Color Matching Task started right after their keypress. Participants were shown the same series of stimuli of the preview in random order, one at a time. Each stimulus appeared on the right side of the screen, together with the set of the 37 BCP colors one the left side (Figure 3.3).

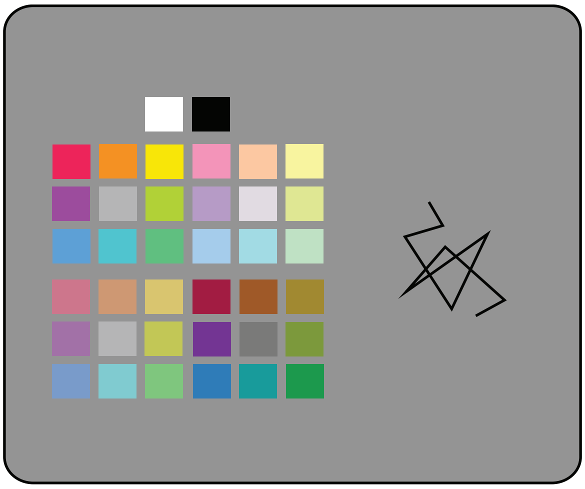


Figure 3.3. Shape-to-Color Matching Task. Participants were shown each of the line [or shape] stimuli to the right together with the 37 BCP colors to the left. For each line/shape-stimulus, they were instructed to pick the three colors in order that they felt were most consistent/inconsistent with the line or shape, choosing from the 37 BCP colors.

For each stimulus, participants were instructed to select the three colors, in order, that they felt were most consistent with it, choosing from the 37 BCP colors as explained in the instructions (see above). Once they had picked a color, that color disappeared from the screen, and they could choose the next-best color among the remaining colors. After they had picked three colors, they were shown the same stimulus and the full set of 37 colors again in the next screen. This time they were asked to pick the three colors, in order, that they felt were least consistent with it. A note at the bottom of the screen reported the written instructions for the ongoing display to avoid confusion during the execution of task, i.e. *"Please select the three colors that are MOST consistent with the line [or shape]. Please, select the one that is most consistent first, then select the one that is next most consistent and so on"* ('Most Consistent' condition/display), or *"Please select the three colors that are LEAST consistent with the line [or shape]. Please, select the one that is least consistent first, then select the one that is next least consistent and so on"* ('Least Consistent' condition/display). The procedure was repeated until all stimuli had been displayed and responses for the three most and the three least consistent colors for each stimulus had been recorded.

Shape-Emotional-Ratings and Color-Emotional-Ratings Tasks

The next two computer tasks were the Shape-Emotional-Ratings task and the Color-Emotional-Ratings task. The order of completion of these two tasks was balanced across participants. Participants rated each shape (Figure 3.4A) or color (Figure 3.4B) along a series of 10 bipolar dimensions, consisting of six emotional ones (happy/*sad*, agitated/*calm*, angry/*not-angry*, active/*passive*, strong/*weak*, harmful/*safe*) and four semantic dimensions (warm/*cool*, complex/*single*, familiar/*unfamiliar*, and pleasant/*unpleasant*). As for color appearance bipolar dimensions, we will name also these dimensions after the default name that comes first—i.e., 'happiness', 'agitation', 'angriness', 'activity', 'strength', 'harmfulness', 'warmth', 'complexity', 'familiarity' and 'pleasantness', respectively—in the coming sections (i.e., Results and Discussion).

In the Shape-Emotional-Ratings task, participants were given the following written instructions: *"During this experiment you will be presented with each of the lines [or shapes] from the set below, one at a time. You will be asked to rate each line [or shape] along the following dimensions: happy vs. sad, agitated vs. calm, angry vs. not-angry, active vs. passive, strong vs. weak, harmful vs. safe, warm vs. cool, complex vs. simple, familiar vs. unfamiliar, pleasant vs. unpleasant. There will be ten sets of trials. In each set of trials you will be asked to rate the lines [or shapes] along the scale located at the bottom of the screen by sliding the slider along the scale and clicking to record your response. So you have an idea of what the endpoints of the scale mean for you, which line [or shape] is the most happy/sad? Also, to prepare you for the other sets of trials, which line [or shape] is the most agitated/calm? Angry/not-angry? Active/passive? Strong/weak? Harmful/safe? Warm/cool? Complex/simple? Familiar/unfamiliar? Unpleasant/pleasant? If you have any questions, please ask them now. Otherwise, you may click to begin!"*

As explained in the instructions, participants were first shown a preview of all the line [or shape] stimuli of the current experiment on one screen (i.e., the same set as in the Shape-to-Color Matching Task). While looking at the whole set, they were also shown the full list of terms on which they were about to be asked to make ratings and the slider-scale on which they were to make those ratings. For each pair of terms (e.g., sad/happy), they were asked to consider which stimulus from the set was most consistent with each of the poles (e.g., "Which shape is the most sad? And which shape is the most happy?"). The experimenter then showed how the slider could to be moved towards the negative/positive end of the scale accordingly. They were told that shape most consistent with the given term was to be rated at or near the corresponding endpoint, the saddest shape at or near the left endpoint and the happiest shape at or near the right endpoint). This anchoring procedure was performed for each pair of terms to allow the participant to become familiar with the use of the slider-scale.

The actual rating task included 10 blocks, each block corresponding to a bipolar dimension, which were completed in random order. In each block, participants were asked to rate each line [or shape] stimulus, presented one at a time and in random order, along the current bipolar dimension. Each stimulus was displayed at the center of the screen, with the continuous bipolar rating scale directly below it (see 3.4A). The scale appeared as a horizontal bar 13.6 cm long. The center of the scale was marked with a small vertical bar, and labels indicated the terms corresponding to the two endpoints (e.g., 'sad' was close to the left endpoint and 'happy' close to the right endpoint). The slider was repositioned in the middle of the scale, where the small vertical bar was, before every new rating. Ratings were recorded as values ranging from -200 to +200, given that the slider could actually be moved on the screen along the scale from -200 px to the left to +200 px to the right of the central marker. Ratings were rescaled to range from -100 to +100 thereafter.

In the Color-Emotional-Ratings task, participants were given the following written instructions: *"During this experiment you will be presented with each of the colors for the set below, one at a time. You will be asked to rate each color along the following dimensions: happy vs. sad, agitated vs. calm, angry vs. not-angry, active vs. passive, strong vs. weak, harmful vs. safe, warm vs. cool, complex vs. simple, familiar vs. unfamiliar, pleasant vs. unpleasant. There will be ten sets of trials. In each set of trials you will be asked to rate the colors along the scale located at the bottom of the screen by sliding the slider along the scale and clicking to record your response. So you have an idea of what the endpoints of the scale mean for you, which color is the most happy/sad? Also, to prepare you for the other sets of trials, which color is the most agitated/calm? Angry/not-angry? Active/passive? Strong/weak? Harmful/safe? Warm/cool? Complex/simple? Familiar/unfamiliar? Pleasant/unpleasant? If you have any questions, please ask them now, otherwise, you may click to begin!"*

Thereafter, the analogous procedure of the Shape-Emotional-Ratings task was repeated with the only difference being that color-stimuli were displayed in place of line [or shape] stimuli. That is, participants were initially shown the whole set of colors and asked to consider which color was most consistent with each of the terms of the bipolar scales. Later, they had to rate each color on the same 10 bipolar scales, organized in

10 experimental blocks, as explained in Figure 3.4B.

Figure 3.4. The Shape-Emotional-Rating task (A) and Color-Emotional-Rating task (B). Participants were instructed to rate each line [or shape] stimulus (A) or each of the 37 BCP colors along emotional dimensions (happy/sad, agitated/calm, angry/not-angry, active/passive, strong/weak, harmful/safe) and other dimensions (warm/cool, complex/simple, familiar/unfamiliar, pleasant/unpleasant). Ratings were made by moving the slider that initially appeared in the center, towards one or the other pole (as shown by the red arrow in the figures).

Shape-Preference-Ratings and Color-Preference-Ratings Tasks

The last two computer-based tasks were the Shape-Preference-Ratings and the Color-Preference-Ratings tasks. The order of completion of these two tasks was balanced across participants as well. The procedure was similar to the Shape-Emotional-Ratings and Color-Emotional-Ratings tasks, except that this time participants were asked to rate how much they liked each shape (Figure 3.5A) or color (Figure 3.5B) along a bipolar scale, whose poles were labeled "not-at-all" on the left end and "very-much" on the right end. We will refer to the ratings along this bipolar dimension (very-much/*not-at-all*) as 'Preference'.

In the Shape-Preference-Ratings task, participants were given the following written instructions: *"During this experiment you will see a series of displays with each display containing one of the lines [or shapes] from the set below. Your task will be to indicate how much you like each shape by clicking a point on a scale like the one below. Please choose which line [or shape] from the above set you like the MOST. When rating that line [or shape] you would click 'very much'. Now choose which line [or shape] you like the LEAST. When rating that line [or shape] you would click 'not at all'. If you have any questions, please ask them now. Otherwise, you may click to begin!"*

The Shape-Preference-Ratings task was similar to the Shape-Emotional-Ratings task. Participants were first shown a preview of all the line [or shape] stimuli of the current experiment (again, the same from the Shape-to-Color Matching Task) on a single screen. While viewing the whole set, they were asked to consider which stimulus they liked the least/most and were shown how to move the slider accordingly, so that the chosen stimulus was rated at or near the corresponding endpoints (e.g., the stimulus that they liked the least at or near the left endpoint; the stimulus that they liked the most at or near the right endpoint). The actual preference task was then completed in a single experimental block. All of the line [or shape] stimuli were displayed in random order, one at a time, and for each they had to make a rating along the slider-scale, which looked like the one in the previous task (see Figure 3.5A).

In the Color-Preference-Ratings task, participants were given the following written instructions: *"During this experiment you will see a series of displays with each display containing one of the colors from the set below. Your task will be to indicate how much you like each color by clicking a point on a scale like the one below. Please choose which color from the above set of colors you like the MOST. When rating that color you would click 'very much'. Now choose which color you like the LEAST. When rating that color you would click 'not at all'. If you have any questions, please ask them now, otherwise, you may click to begin!"*

Thereafter, the analogous procedure of the Shape-Preference-Ratings Task was repeated with the only difference being that color-stimuli were displayed in place of line/shape-stimuli. That is, participants were initially displayed the whole set of colors and asked to consider which one they liked the least/most. Next, they had to rate their preference for each color on the bipolar scale in a single experimental block (see Figure 3.5B).

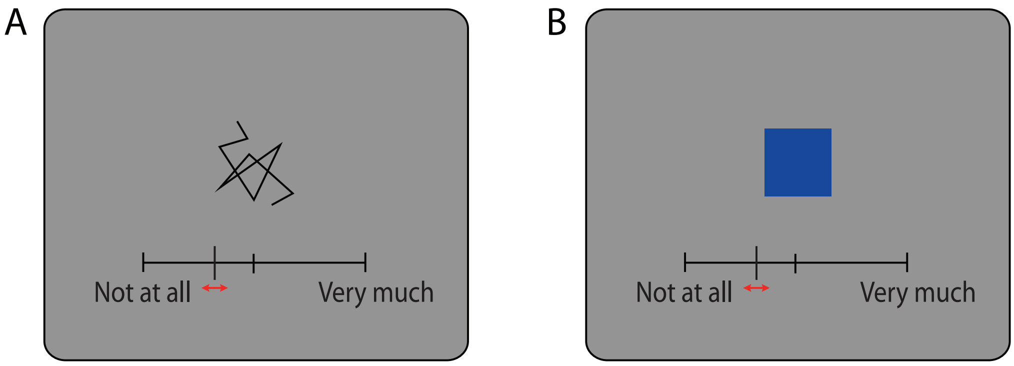


Figure 3.5. The Shape-Preference task (A) and Color-Preference task (B). Participants were instructed to rate how much they liked each line [or shape] stimulus (A) or each of the 37 BCP colors along one bipolar scale which poles were not-at-all/very-much. Ratings were made by moving the slider, that initially appeared in the center, towards the one or the other pole (as shown by the red arrow in figure).

Shape-Object Questionnaire

A paper-based Shape-Object Questionnaire was administered afterwards. Participants were initially asked to recall the shape-color matches that they made in the Shape-Color-Matching Task. For each line [or shape] stimulus, participants were asked first to indicate whether they thought they had chosen the color they choose to go with that stimulus on the basis of the color of an object it reminded them of. If so, they could list up to 3 objects per stimulus (column to the left), and subsequently the colors going with those objects (column to the right) in the corresponding lines, as shown in figure 3.6. No object had to be reported for those shapes for which they believed their choices were not, at least consciously, influenced by its resemblance to any object in the Shape-Color-Matching Task completed earlier. The questionnaire was completed at the end of the experiment to eliminate any bias it might otherwise have produced in participants completing the other tasks.

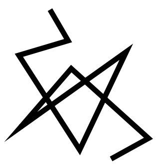
	Did this line remind you of any object that you consciously considered in choosing the colors that went best with the line? If so, please give a brief description of each object that you consciously considered in the color-choosing task for the line shown.	Please give a brief description of the color of each object you described in the first column.
	☐ No ☑ Yes 1. ______*lightning*_______ 2. ______________________ 3. ______________________	1. _________*red*_________ 2. ______________________ 3. ______________________

Figure 3.6. Example layout of the Shape-Object paper-based questionnaire. This figure shows only one row, corresponding to one example stimulus for one participant. For each of the line [or shape] stimuli, participants could list up to three objects (in the middle column) and their corresponding colors (in the right column). They were asked to list one or more objects only if they believed that their color choices in the Shape-to-Color Matching Task for that line [or shape] were influenced by its association to those specific objects.

Synesthesia Battery

Finally, after completing the computer-based tasks and the paper-based questionnaire, a Synesthesia Battery prescreening (see Appendix 3.2) was administered to identify possible synesthetes within our sample. Participants who received high scores in the

Synesthesia Battery prescreening were required to take the whole online Battery (Eagleman et al., 2007). No mentioning of synesthesia was made until all the computer-based tasks and the questionnaire had been completed. If a participant's score on any subtest of the Battery was below 1.00, his or her data were eliminated. This procedure identified 3 synesthetes (2 grapheme-color ones and one instrument-color one) within the total set of 91 participants (45 from Experiment 4, and 46 from Experiment 5). No synesthete was identified in the second group of 40 participants (20 from Experiment 4, and 20 from Experiment 5) who performed the Shape-Appearance-Ratings Task as a follow-up.

<u>Shape-Appearance-Ratings Task (Group 2 participants)</u>

The Shape-Appearance-Rating Task was completed by a second group of 20 participants for each experiment as a follow-up (Experiment 4, Group 2: mean age = 22.74, SD = 7.61; range: 18–49 years; Experiment 5, Group 2: mean age = 20.65, SD = 2.06; range: 18–28 years). The task consisted in rating each line/shape-stimulus on 5 bipolar perceptual dimensions (complex/*simple*, pointy/*smooth*, closed/*open*, symmetric/*asymmetric*, concave/*convex*), as shown in Figure 3.7. These additional data were collected to provide subjective ratings on a set of dimensions that roughly corresponded to the geometric features of the lines [or shapes] that were manipulated in the experimental designs of Experiments 4 and 5. As for other bipolar dimensions, we name also these additional dimensions after the default name which comes first, in this case followed by a 'P' in brackets—i.e., 'complexity[P]', 'pointedness[P]', 'closure[P]', 'symmetry[P]', and 'concavity[P]', respectively—to specify that we refer to shape features as perceptual rather than geometric. You will find these names being used in the Results section.

The procedure was exactly the same as the Shape-Emotional-Ratings Task. Participants in these two additional groups were also asked to rate each line [or shape] stimulus along the 10 bipolar emotional/semantic dimensions of the Shape-Emotional-Ratings task in order to get additional data for those features too.

In the Shape-Appearance-Ratings task, participants were given the following written instructions: *"During this experiment you will be presented with each of the lines [or shapes] for the set below, one at a time. You will be asked to rate each line [or shape] along the following dimensions: happy vs. sad, agitated vs. calm, angry vs. not-angry, active vs. passive, strong vs. weak, harmful vs. safe, warm vs. cool, complex vs. simple, familiar vs. unfamiliar, pleasant vs. unpleasant, pointy vs. smooth, closed vs.*

open, symmetric vs. asymmetric, concave vs. convex). There will be ten sets of trials. In each set of trials you will be asked to rate the lines [or shapes] along the scale located at the bottom of the screen by sliding the slider along the scale and clicking to record your response. So you have an idea of what the endpoints of the scale mean for you, which shape is the most happy/sad? Also, to prepare you for the other sets of trials, which shape is the most agitated/calm? Angry/not-angry? Active/passive? Strong/weak? Harmful/safe? Warm/cool? Complex/simple? Familiar/unfamiliar? Pleasant/unpleasant? Pointy/smooth? Closed/open? Symmetric/asymmetric? Concave/convex? If you have any questions, please ask them now, otherwise, you may click to begin!"

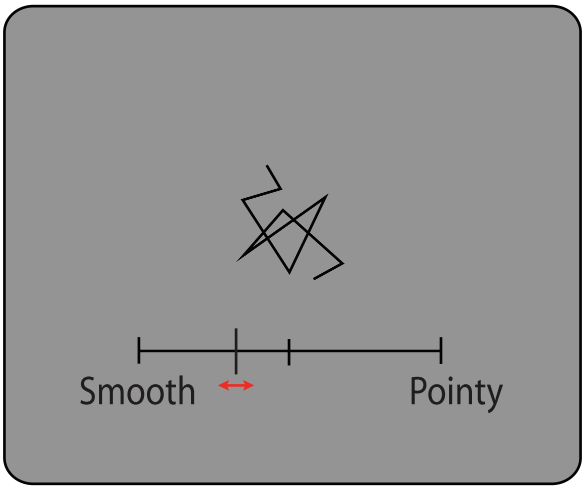


Figure 3.7. Participants were instructed to rate each line [or shape] stimulus along the following perceptual dimensions: pointy/smooth, closed/open, complex/simple, symmetric/asymmetric, and concave/convex. Ratings were made by moving the slider that initially appeared in the center, towards the one or the other pole (as shown by the red arrows in figure).

3.3 Experiment 4

We studied shape-to-color associations and emotional mediation in non-synesthetes for 44 line-stimuli using the 37 BCP colors.

3.3.1 Methods

Stimuli

The stimuli consisted of 44 Line-shapes, which could differ with respect to a number of geometric features (indicated by appending “[G]” after the variable name): the number of generating-points[G] (3/4/9), pointedness[G] (curved/angular), symmetry-axes[G] (0/1), and intersections[G] (0/1/>1). The full set of stimuli is displayed in Figure 3.8. Each stimulus is identified by ‘L’, which stands for Line, followed by the number of the Line (from 1 to 22) and its version (‘a’ for angular and ‘c’ for curved). (The same general line was presented with either angular/curved edges using exactly the same set of generating points.). The orientation of stimuli (0° vs. 180°) was balanced across participants. Details of stimulus preparation and presentation can be found in the General Methods section at the beginning of this chapter.

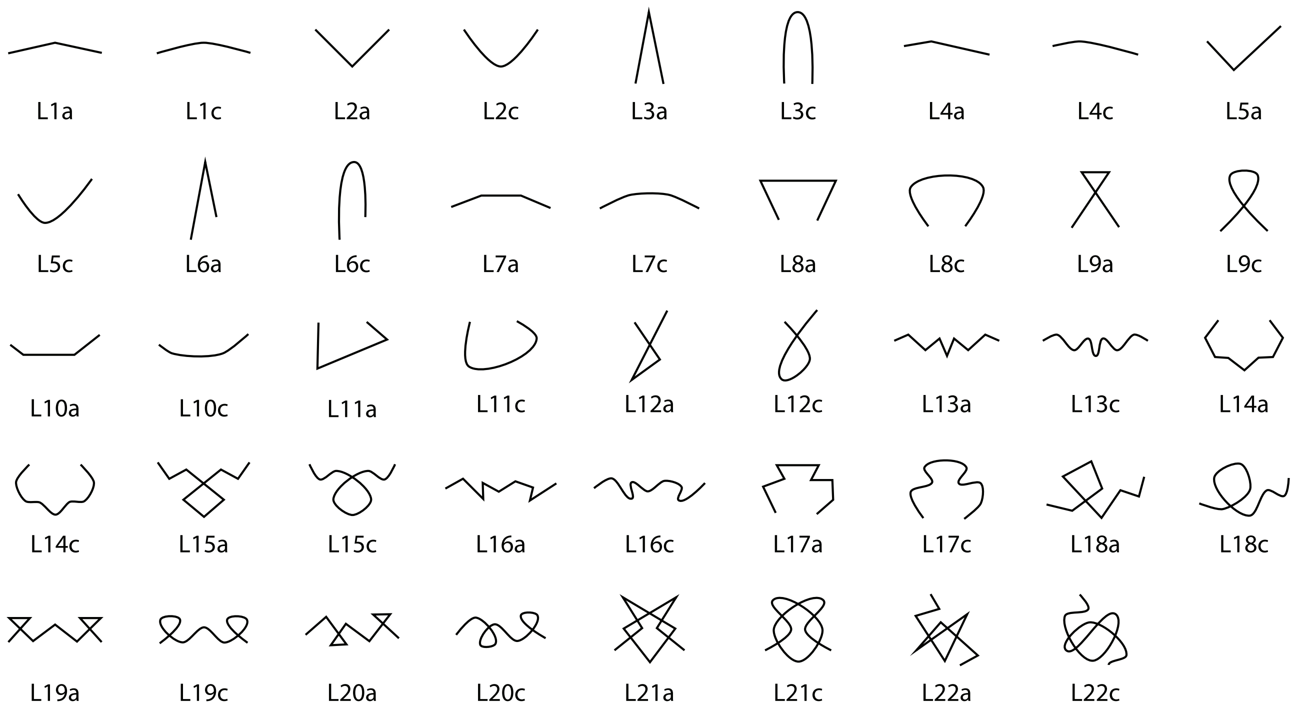


Figure 3.8. The forty-four line-stimuli from Experiment 4. Each line-stimulus is identified by ‘L’, which stands for line, followed by the number of the Line (from 1 to 22) and its version (‘a’ for angular and ‘c’ for curved). Line-shapes changed with respect to their pointedness[G] (curved/angular), but also with respect to their number of generating-points[G] (3/4/9), symmetry-axes[G] (0/1), and intersections[G] (0/1/>1).

3.3.2 Results and Discussion

The results of the experiment are presented here into two main sections, corresponding to the two different parts of our research question, that is (i) whether there are systematic shape-to-color associations in non-synesthetes and (ii) whether such shape-to-color associations are mediated, in part, by emotions.

The color of line-shapes

First, we were interested in determining whether the mapping from line shapes to colors was consistent and systematic, especially with respect to the geometric features that we manipulated in the experimental design (pointedness[G], symmetry-axes[G], intersections[G], and generating-points[G]). In particular, we explored whether each of these shape features influenced the colors participants judged as "going well" with the shape along four color appearance dimensions: saturation (saturated/*unsaturated*), lightness (light/*dark*), redness (redness/*greenness*), and yellowness (yellowness/*blueness*). We therefore initially computed a Shape-Color Association ($SCA_{s,d}$) score for each of the 44 line-shapes (*s*) along each color appearance dimension (*d*). Each BCP color can be described by four dimensional values, which corresponded to average participant ratings along those four color appearance dimensions in a previous experiment (Palmer and Schloss, 2010). The *SCA* formula was employed to weight the colors chosen for the different order in which they were picked in the Shape-to-Color Matching Task. The *SCA* score for the shape *s* along the color dimension *d* (say, saturation) is the linearly weighted average of the saturation values of the three colors chosen as most consistent with that shape ($C_{d,s}$) minus an analogous weighted average of the saturation values of the three colors chosen as most inconsistent with the same shape ($I_{d,s}$):

Equation 3.1. $SCA_{d,s} = C_{d,s} + I_{d,s}$

Equation 3.2. $C_{d,s} = (3c_{1,d,s} + 2c_{2,d,s} + 1c_{3,d,s})/6$

Equation 3.3. $I_{d,s} = (3i_{1,d,s} + 2i_{2,d,s} + 1i_{3,d,s})/6$

where $c_{j,d,s}$ is the value along the color dimension *d* of the j^{th} color picked as most consistent with the shape *s*, where *j* ranges from 1 to 3, and $i_{j,d,s}$ is the value along the color dimension *d* of the j^{th} color picked as most inconsistent with the same shape *s*.

After these *SCA* scores had been computed for each line-shape along each color appearance dimension *d*, we calculated the averages of the color appearance values for stimuli grouped into categories defined by the geometric features that were used to generate them in the experimental design. Since the orientation (0° vs 180°) of a line-shape did not have any significant effect on the colors matched to it along any color appearance dimension [$F(1,42)$ = 0.21, 0.19, 0.11, 0.90, p = 0.646, 0.891, 0.744, 0.347, for saturation, lightness, redness, and yellowness, respectively] the data were initially collapsed over the two orientations in which each line-shape could appear. Thereafter, we determined how the color appearance of the associated colors was influenced by the levels of the factors in the experimental design.

First, separate RM-ANOVAs were performed to test the effect of symmetry-axes[G], intersections[G], and pointedness[G] on each of the four color appearance dimensions, after having collapsed data over the different generating-points[G]. Table 3.1 reports F-ratios for main effects and interactions between factors (symmetry-axes[G], intersections[G], and pointedness[G]) for each of the four color appearance dimensions. color appearance dimensions as a function of a line-shape's pointedness[G] and intersections[G]. Conversely, they did not seem to change as a function of the shape's symmetry-axes[G].

Table 3.1. The table reports F-ratios for main effects and interactions between factors for each RM-ANOVA. Four RM-ANOVAs were run: one for each color appearance dimension, i.e., Saturation, Lightness, Redness, and Yellowness. ***p≤0.001, **p≤0.005, *p<0.05.

	Source of Variance	**F**	**df**	**p**
Saturation	Symmetry-axes[G]	3.25	1, 43	0.079
	Intersections[G]	26.11	2, 86	0.000***
	Pointedness[G]	8.79	1, 43	0.005**
	Symmetry-axes[G] x Intersections[G]	0.06	2, 86	0.939
	Symmetry-axes[G] x Pointedness[G]	0.41	1, 43	0.528
	Intersections[G] x Pointedness[G]	0.66	2, 86	0.520
	Symmetry-axes[G] x Intersections[G] x Pointedness[G]	0.00	2, 86	0.997
Lightness	Symmetry-axes[G]	1.18	1, 43	0.283
	Intersections[G]	0.65	2, 86	0.523
	Pointedness[G]	20.76	1, 43	0.000***
	Symmetry-axes[G] x Intersections[G]	0.26	2, 86	0.772
	Symmetry-axes[G] x Pointedness[G]	0.38	1, 43	0.543
	Intersections[G] x Pointedness[G]	3.37	2, 86	0.039*
	Symmetry-axes[G] x Intersections[G] x Pointedness[G]	1.19	2, 86	0.309
Redness	Symmetry-axes[G]	0.58	1, 43	0.450
	Intersections[G]	7.81	2, 86	0.001***
	Pointedness[G]	11.82	1, 43	0.001***
	Symmetry-axes[G] x Intersections[G]	0.45	2, 86	0.638
	Symmetry-axes[G] x Pointedness[G]	1.35	1, 43	0.250
	Intersections[G] x Pointedness[G]	0.45	2, 86	0.638
	Symmetry-axes[G] x Intersections[G] x Pointedness[G]	1.27	2, 86	0.287
Yellowness	Symmetry-axes[G]	3.59	1, 43	0.065
	Intersections[G]	1.64	2, 86	0.199
	Pointedness[G]	4.60	1, 43	0.038*
	Symmetry-axes[G] x Intersections[G]	1.45	2, 86	0.240
	Symmetry-axes[G] x Pointedness[G]	1.26	1, 43	0.268
	Intersections[G] x Pointedness[G]	0.98	2, 86	0.381
	Symmetry-axes[G] x Intersections[G] x Pointedness[G]	0.46	2, 86	0.955

A rather clear pattern emerged: the colors chosen changed systematically along at least some Separate RM-ANOVAs for each color appearance dimension showed that lines with more intersections were generally associated with more saturated, and redder colors [$F(2,86) = 26.11, 7.81$, $p<0.001, 0.001$, respectively] and that angular lines were generally associated with more saturated, darker, redder and yellower (warmer) colors than curved lines [$F(1,43) = 8.79, 20.76, 11.81, 4.60$, $p \leq 0.005, 0.001, 0.001, .05$, respectively]. There were no significant interactions between factors except for a weak interaction [$F(2,86) = 3.37$, $p<.05$] between intersections[G] and pointedness[G] only for the lightness color appearance dimension. Figure 3.9 shows the different color appearance dimensions of colors associated to shapes as a function of their pointedness[G] and intersections[G], averaged over symmetry-axes[G] and number of generating-points[G]. More precisely, the y-axis represents the color appearance along the dimension *d*, and the x-axis represents the number of intersections[G] (0/1/>1). Different lines within each graph stand for line-shapes with different pointedness[G] (curved/angular). Some representative line-shapes are displayed close to each dot, defined by different combinations of pointedness and intersections. Error bars represent standard errors of the mean (SEMs).

Secondly, separate RM-ANOVAs were performed to test the effect of the generating-points[G] on each of the four color appearance dimensions. The generating-points[G] factor could not be entered in the former RM-ANOVAs because the number of generating-points of a line constrains the number of intersections it can have, i.e., lines with three generating-points can only have 0 intersections, lines with four generating-points can have 0/1 intersections, whereas lines with nine generating-points can have 0/1/>1 intersections. RM-ANOVAs for each color appearance dimension showed that lines with more generating-points were generally associated with more saturated colors [$F(2,86) = 6.40$, $p<0.005$], whereas the generating-points[G] of a line did not have any significant effect on the colors associated to it along any other color appearance dimension [$F(2,86) = 0.59, 2.23, 0.24$, $p=0.556, 0.113, 0.784$, for lightness, redness, and yellowness, respectively].

Note that the geometric features of the line-shapes have been so far treated as if they were objective and could be defined as categorical variables. For instance, the actual number of intersection of a shape does not necessarily correspond to the subjects' perceptions of how much a shape is closed and/or intersecting. Because we had a second group of participants subjectively judging these perceptual features in the Shape-Appearance-Ratings task, we also analyzed the color choices with respect to those subjective perceptual ratings. Recall that ratings in the Shape-Appearance-Ratings task were given along bipolar continuous scales, so that subjects could tell to what extent a shape was 'smooth' vs. 'pointy', 'open' vs. 'closed', etc., along a continuum.

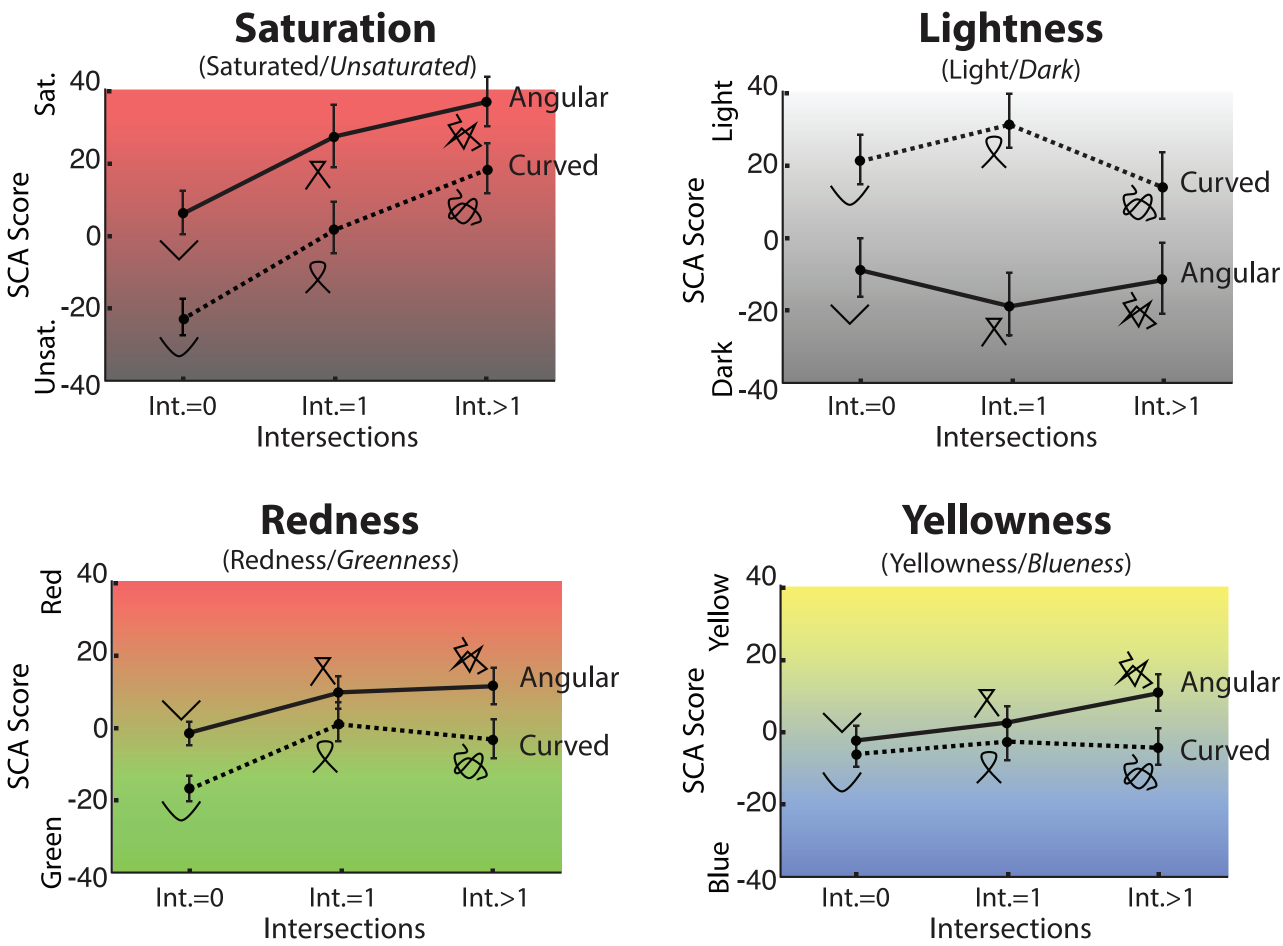


Figure 3.9. Color associations for line-shapes as a function of their pointedness[G] (angular, curved) and intersections[G] (int.=0, int.=1, int.>1) along each of the four color appearance dimensions considered: saturation, lightness, redness, and yellowness. A line-shape representative for each category has been placed close to each dot. Error bars represent standard errors of the mean (SEMs).

To determine whether how well these perceptual factors and the corresponding geometrical factors could predict the values of the colors that were chosen, two series of Stepwise Multiple Linear Regression analyses were performed. For each color appearance dimension *d*, the analysis attempts to predict the values of the colors chosen to go well with each line-shape from either the objective geometric features of that line-shape (Figure 3.10A) or the subjective perceptual ratings of that line-shape (Figure 3.10B). We will refer to the first class of models, which uses objective geometric features as predictors, as Geometric Models and to the second class of models, which uses subjective perceptual ratings as predictors, as Perceptual Models. As mentioned above, we will use the bracketed letter '[G]' for 'geometric' factors and will henceforth use the bracketed letter '[P]' for 'perceptual' factors to clarify its referent. The predictors for the Geometric Models were closure[G] (open = 0, closed =1), pointedness[G] (curved = 0, angular = 1), symmetry-axes[G] (0, 1), generating-points[G] (3, 4, 9), and intersections[G] (0, 1, 2, 4). The closure factor differentiated between open lines (e.g. L8c) and any intersecting line, irrespective of the actual number of intersections (e.g. L12c, L22c). The predictors for the Perceptual Models were the average ratings on the bipolar scales referring to a shape's closure[P] (closed+/*open*-), pointedness[P] (pointy+/*smooth*-), symmetry[P] (symmetric+/*asymmetric*-), complexity[P] (complex+/*simple*-), and concavity[P] (concave+/*convex*-). The criterion variables that were predicted separately by each series of predictors were saturation (saturated+/*unsaturated*-), lightness (light+/*dark*-), redness (redness+/*greenness*-), and yellowness (yellowness+/*blueness*-).

Four separate Stepwise Multiple Linear Regressions (Geometric Models) were used to determine the degree to which the objective geometric features of line-shapes could account for color choices (see Figure 3.10A). For saturation, 73% of the variance could be explained by two geometric factors: 37% from a line-shape's closure[G], and additional 36% from its pointedness[G], with more saturated colors being chosen for angular closed line-shapes. For lightness, 66% of the variance could be explained by pointedness[G] alone, with lighter colors being chosen for curved lines. For redness, 50% of the variance could be explained from pointedness[G] (30%) and closure[G] (20%), with redder colors being chosen for angular closed lines. For yellowness, only 10% of the variance could be explained by pointedness[G], with yellower colors being chosen for angular lines.

A second series of four Stepwise Multiple Linear Regressions (Perceptual Models) was employed to determine the degree to which the subjective perceptual ratings of line-shapes could account for color choices. The pattern of shape-color associations was almost the same, even though the amount of variance explained when considering subjective ratings in place of objective features as predictors increased slightly: 74% of the variance in saturation could be explained by pointedness[P] (47%), closure[P] (25%), and concavity[P] (2%); 70% of the variance in lightness could be explained by pointedness[P] alone; 55% of the variance in redness could be explained by pointedness[P] (36%) and closure[P] (19%); and 14% of the variance in yellowness could be explained by pointedness[P] alone.

Overall, Perceptual Models, which employ the subjective perceptual ratings as predictors, performed only slightly better than Geometric Models, the former explaining an average of 53% of the variance across color appearance dimensions in comparison with 49% for the latter. The color appearance dimensions that was best predicted was saturation, with lightness, redness and yellowness following in that order. Pointedness and closure were the best predictors. To sum up, participants apparently mainly differentiated between curved and angular line-shapes and between open and closed ones, and these features seemed mainly to impact the associated colors along the saturation and lightness color appearance dimensions, with closed, angular line-shapes being associated with darker, more saturated colors.

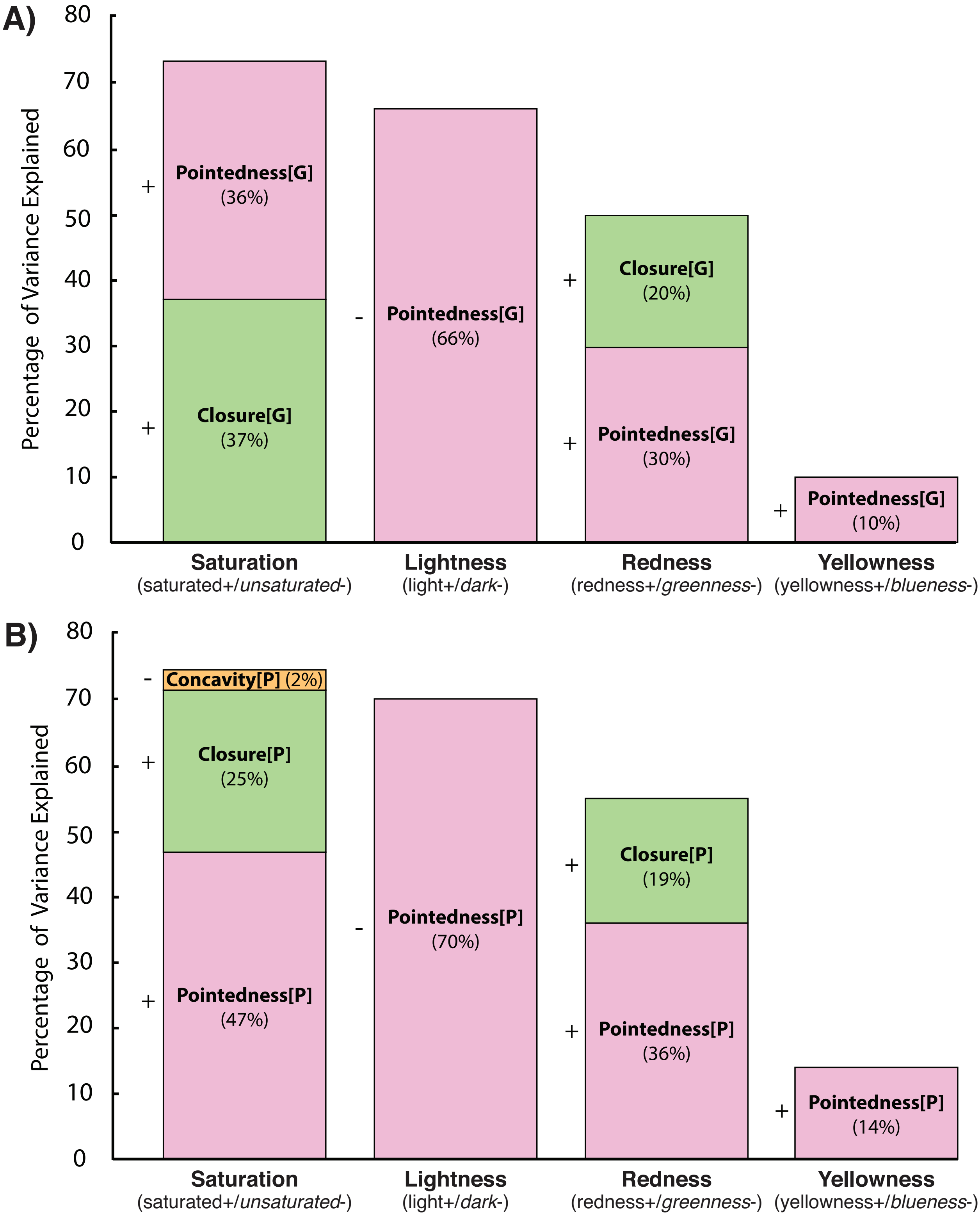


Figure 3.10. The results of Stepwise Multiple Linear Regression Analyses in which each color appearance dimension is predicted by either objective geometric features (Geometric Models, panel A) or subjective perceptual ratings (Perceptual Models, panel B). Bars show the overall percentage of variance explained by the best-fitting model for each color appearance dimensions. Stripes within each bar show the percentages of variance explained by each factor in the order with which they were entered in the regression model (bottom to top). The percentages of variance explained by each factor are shown in parenthesis. The plus- or minus-sign to the left of each stripe indicates whether there was a positive or negative relation between that color appearance dimension and that factor (e.g., '+' to the left of 'Pointedness[G]' or 'Pointedness[P]' for Saturation means that more saturated colors were picked for line-shapes geometrically or perceptually *more* pointy, whereas '-' to the left of 'pointedness[G]' or 'pointedness[P]' for lightness means that lighter colors were picked for line-shapes geometrically or perceptually *less* pointy).

The results of the regressions presented in Figure 3.10 are consistent with those displayed in Figure 3.9, in which more angular line-shapes were matched with more saturated, darker, and redder colors, and more intersecting line-shapes matched with more saturated and redder colors. Such shape-to-color relationships may even be better established if one takes into account the way participants respond to the shapes emotionally.

Despite this clear pattern of results, it is likely that some noise in the data might be caused by object-mediated associations. That is, the color chosen as going with a shape could be partly due to objects it reminded participants of and not to its abstract geometric/perceptual properties. On average, about 31% of color choices were self-reported to be influenced by object-associations in the Shape-Object Questionnaire. Some examples are 'L9c', reminding some participants of an awareness ribbon (mainly pink/red), 'L14c' reminding some participants of a nose (light-pinkish/brown), and 'L1c' reminding some participants of a hill (mainly green). It is difficult to assess to what extent participants' choices were actually influenced by these object associations in the Shape-to-Color Matching Task. It is possible that some object-mediated associations of this kind might have weakened certain effects, whereas it is unlikely that they would have actually produced the systematic trends observed, especially after averaging across multiple shapes and across the two orientations in which each shape could appear. It should also be kept in mind that the questionnaire only allowed us to assess conscious associations, which may be indicative of a much wider realm of such associations that might occur unconsciously.

Emotional mediation in shape-to-color associations

The Emotional Mediation Hypothesis (EMH) suggests that cross-modal matches might be made on the basis of shared emotional associations for the two relevant domains (Palmer et al., 2013). The EMH in the present case implies that, for example, angry-looking shapes would be matched to angry-looking colors and calm-looking shapes to calm-looking colors. To examine whether this might be true in the present associations, we calculated the correlations between the emotional associations of each line-shape and the emotional associations of the colors chosen as most consistent/inconsistent with that line-shape. The emotional associations of the line-shapes were estimated by the average ratings of each shape on all six emotional dimensions (happy/*sad*, agitated/*calm*, angry/*not-angry*, strong/*weak*, active/*passive*, and harmful/*safe*). The emotional associations of the colors chosen as going well/poorly with each shape were estimated by computing the $CEA_{d,s}$ (Color-Emotion Association) for each emotional dimension (d) and each shape (s), according to a formula analogous to the $SCA_{d,s}$ (Shape-Color Association), except for replacing the 4 color dimensions with the 6 emotional dimensions:

Equation 3.4. $CEA_{d,s} = C_{d,s} + I_{d,s}$

Equation 3.5. $C_{d,s} = (3c_{1,d,s} + 2c_{2,d,s} + 1c_{3,d,s})/6$

Equation 3.6. $I_{d,s} = (3i_{1,d,s} + 2i_{2,d,s} + 1i_{3,d,s})/6$

where $c_{j,d,s}$ is the value along the emotional dimension *d* of the j^{th} color picked as most consistent with the shape *s*, where *j* ranges from 1 to 3, and $i_{j,d,s}$ is the value along the emotional dimension *d* of the j^{th} color picked as most inconsistent with the same shape *s*.

The correlations between the emotional associations of the line-shapes and those of the colors chosen as going best with the line-shapes were very high with p-values lower than 0.001 for all the emotional dimensions except happiness, which had a near-zero correlation (see Figure 3.11). The highest correlations were for harmfulness and strength (r = 0.84) followed by angriness (r = 0.82), agitation (r = 0.81), and activity (r = 0.72). A Principal Components Analysis (PCA) of the emotional dimensions showed that 83% of variance could be explained by one component that corresponded most closely to angriness (PC loadings: angriness = 0.99; harmfulness = 0.99; agitation = 0.99; activity = 0.93; strength = 0.91; happiness = -0.62). These results are consistent with the EMH, but the evidence is purely correlational, so it does not allow one to infer a causal role of emotion in producing this pattern of results. Interestingly, the one dimension that failed to produce a significant correlation between the emotional ratings of the line shapes and those of the colors chosen as going best with the shapes was happy/*sad*, which was the dimension that produced one of the highest correlations (.97) when cross-modal matches were made between music and best/worst associates among the same set of 37 colors. Given that the previously reported high correlation implies that happy/sad is a robust emotional dimension of these colors, it seems likely that happy/sad is not a robust emotional dimension of line-shapes and that this is the reason for the present low correlation. It is also consistent with the recent finding that when music is cross-modally matched to line-based textures, the correlation between the happy/*sad* ratings of the music and those of the textures chosen as going best with the music is near-zero (Langlois, Peterson, & Palmer, 2014; Peterson, Langlois, & Palmer, 2014). Happy/*sad* thus appears not to be a salient emotional dimension of line-based spatial patterns.

Further results suggest that other factors, such as preference, may also be at work. Analogously, we calculated the correlation between preferences for each shape and the preferences for the colors most consistent with that shape, as measured by the *CEA* for preference ratings (i.e., using the preference dimension for *d*), and we found that participants also tended to pick colors they liked to go with shapes they liked (r = 0.58, $p < 0.001$), although this relation was not as strong as the emotional dimensions represented in Figure 3.11. Moreover, it is possible that the correlation with liking is actually driven by the emotional associations, given that people tend to like things that are closely related to the emotions that load heavily on the first principal component: calm, not-angry, and safe (rather than agitated, angry, and harmful).

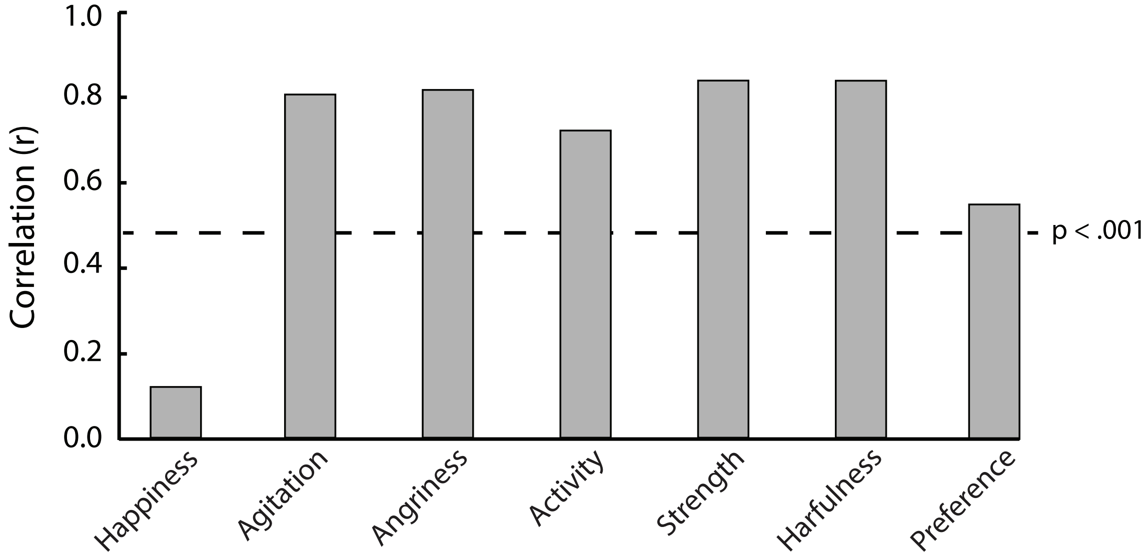


Figure 3.11. Correlations between the emotional ratings of each of the 44 line-shapes and the emotional ratings of the colors that were chosen to be most consistent/inconsistent with that shape, as measured by the CEA (Color-Emotion Association) scores for each of six emotional dimensions: happiness (happy/*sad*), agitation (agitated/*calm*), angriness (angry/*not-angry*), activity (active/*passive*), strength (strong/*weak)*, harmfulness (safe/*harmful*). The image also include the correlation between preference ratings of each of the 44 line-shapes and the preference ratings of the colors that were chosen to be most consistent/inconsistent with that shape, measured analogously.

Further analyses were performed averaging over the emotional ratings given by Group 1 and Group 2 participants. To deepen our understanding of the structure of the emotional space of line-shapes, we performed an emotion-based Multidimensional Scaling (MDS) of line-shapes based on their ratings on the six emotional dimensions (happiness, agitation, angriness, activity, strength, harmfulness). The best two-dimensional solution for the emotional structure of line-shapes (Figure 3.12) gave a good fit (stress = 0.07). We interpreted the dimensions by rotating the MDS point configuration in one degree increments 360 times to find the angles at which each dimension was most highly correlated with the emotional ratings. Angry/*not-angry* had the highest correlation at 10° degrees of rotation for Dimension 1 (r = 0.93), while happy/*sad* had the highest correlation at -30° degrees of rotation for Dimension 2 (r = 0.68), as indicated by the dashed lines in Figure 3.12. The two dimensions were therefore interpreted as angriness and happiness, although they are not entirely orthogonal, presumably because sad and angry are both negative emotions, whereas not-angry and happy are more positive.

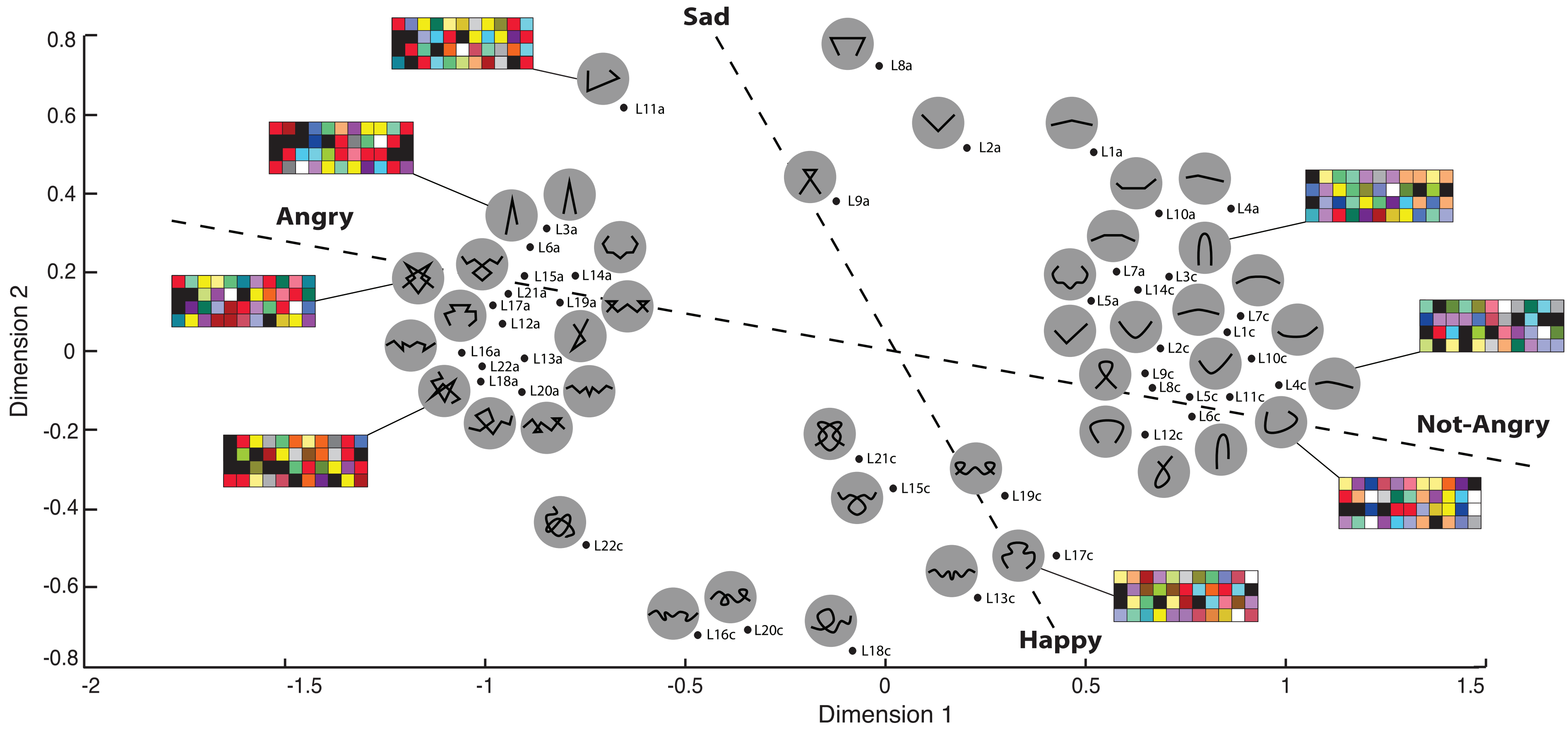


Figure 3.12. Multidimensional Scaling of line-shapes based on emotional similarity on six emotional dimensions: Happy/*sad*, agitated/*calm*, angry/*not-angry*, active/*passive*, strong/*weak*, harmful/*safe*.

Line-shapes seem to mainly differ along the angriness dimension, which is not surprising, given that this dimension is nearly the same as the axis of the first principal component. Two main clusters appear clearly from the graph: angry shapes that tend to be pointy and/or complex and intersecting are grouped to the left, as opposed to not-angry shapes that tend to be smoothly curved and/or simple and non-intersecting are grouped to the right. The figure also shows some samples of the actual colors picked by participants as the single most consistent color for a representative sample of the shapes of each group. These color matrices give a sense of the kind of colors associated with the two clusters of shapes (angry vs not-angry ones). Despite the wide variety of colors picked by different participants for the same shape, colors associated with angry shapes were overall more saturated, darker, and redder relative to those associated with non-angry shapes.

We performed a further Stepwise Multiple Linear Regression to see how well we could predict the color appearance dimensions of the colors associated with the line-shapes on the basis of their subjective emotional ratings (Figure 3.13). We will refer to this class of models, which uses subjective emotional ratings as predictors, as Emotional Models. Each of the four color appearance dimension was predicted separately on the basis of the ratings given by participants on six emotional scales. The predictors for Emotional Models were happiness (happy+/*sad*-), agitation (agitated+/*calm*-), angriness (angry+/*not-angry*-), activity (active+/*passive*-), strength (strong+/*weak*-), and harmfulness (harmful+/*safe*-). The criterion variables were saturation (saturated+/*unsaturated*-), lightness (light+/*dark*-), redness (redness+/*greenness*-), and yellowness (yellowness+/*blueness*-). For saturation, 72% of the variance could be explained by a shape's strength, with stronger shapes producing more saturated color choices. For lightness, 67% of the variance could be explained by angriness (47%) and activity (20%), with less angry and more active shapes producing lighter color choices. For redness, 49% of the variance could be explained by a shape's strength, with stronger shapes producing redder color choices. For yellowness, only 16% of the variance could be explained by a shape's strength, with stronger shapes producing yellower color choices.

Overall, the Emotional Models that use emotional ratings as predictors performed about as well (explaining an average of 51% of the variance) as Perceptual Models that use subjective perceptual ratings as predictors (explaining an average of 53% of the variance) and Geometric Models that use objective geometric features as predictors (explaining an average of 48% of the variance). However, does the emotional content of a shape add any variance to that explained by the perceptual features alone? After performing the regression with the subjective perceptual ratings as predictors (Perceptual Models), we performed a regression on the residuals using the emotional ratings as predictors to see whether there was any additional variance explained after removing that explained by perceptual ratings. The procedure was repeated for each color appearance dimension *d* separately. Little additional variance could be explained by emotional ratings after we accounted for all the variance explained by perceptual ratings only for one color appearance dimension, namely saturation. More precisely, 22% additional variance in saturation was explained by a line-shape's happiness (12%) and strength (10%) after we accounted for all the variance in saturation explained by perceptual ratings. No additional variance was explained for any other color appearance dimension after we accounted for all the variance explained by perceptual ratings. This could mean that the happiness (and also, in part, strength) value of a line-shape was conveyed by properties that were not captured entirely by the perceptual features we entered in the regression, i.e., closure[P], pointedness[P], symmetry[P], complexity[P], and concavity[P].

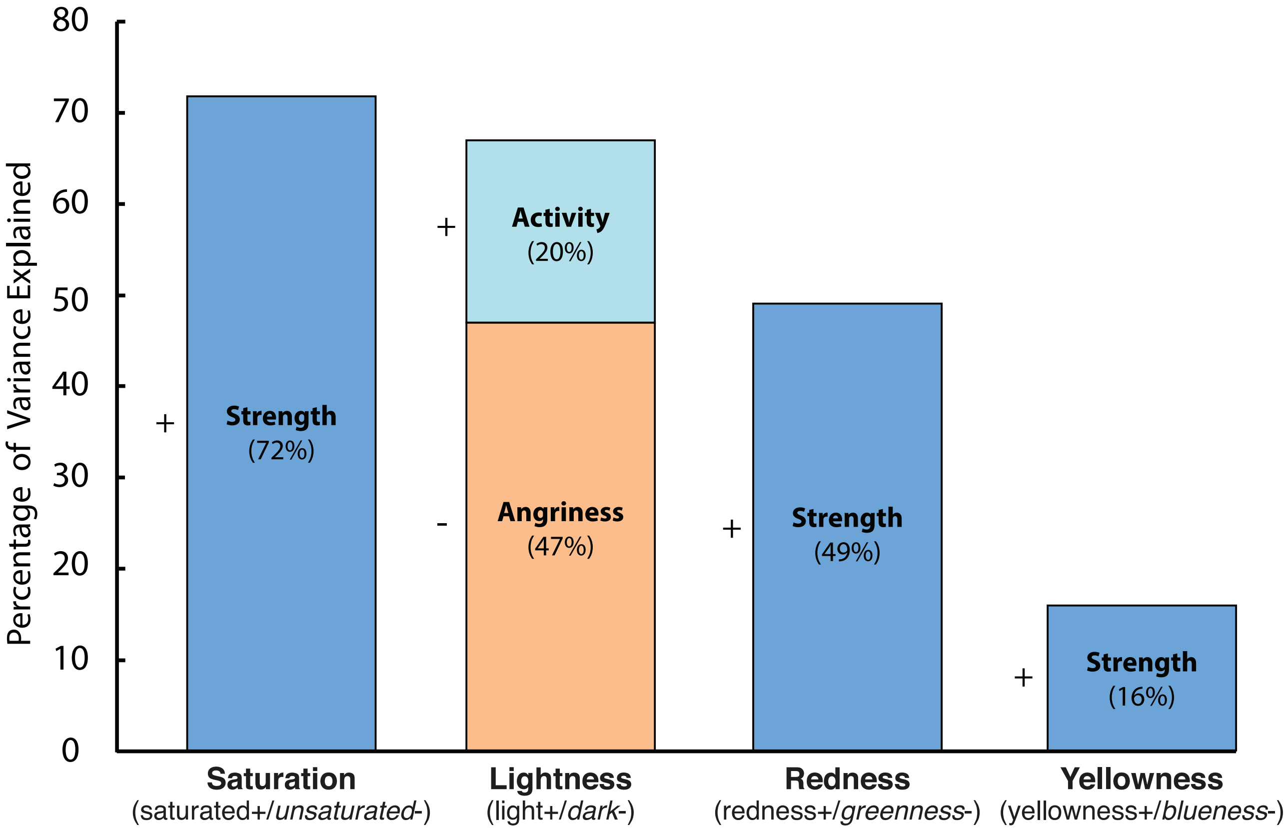


Figure 3.13. Stepwise Multiple Linear Regression Analyses in which each color appearance dimension is predicted by subjective emotional ratings (Emotional Models). Bars show the overall percentage of variance explained by the best-fitting model for each color appearance dimension. Stripes within each bar show the percentages of variance explained by each factor in the order in which they were entered into the regression models (bottom to top). The exact percentage explained by each factor is shown in parenthesis. The sign to the left of each stripe indicates whether there was a positive or negative relation between the color appearance dimension and that emotional factor (e.g. '+' close to 'Strength' for saturation means that more saturated colors were picked for shapes rated as *more* strong, whereas '-' close to 'Angriness' for lightness means that lighter colors were picked for shapes rated as *less* angry).

These data suggest that the geometric features, perceptual features and the emotional associations of a shape could be seen just as different ways to describe the same shape, ones that correlate with each other to different extents. Some of the perceptual and emotional ratings considered in our experiment were indeed strongly correlated with p-values well below 0.005. For instance, pointier shapes were also rated as stronger (r = 0.67), angrier (r = 0.61), more harmful (r = 0.60), and more agitated (r = 0.55). Additionally, closed/intersecting shapes tended to be rated as more active (r = 0.62), more agitated (r =0.49), more harmful (r = 0.49), stronger (r = 0.45), and angrier (r = 0.44). Additional research is needed to clarify the interplay between emotional, perceptual, and geometric factors and their causal role in producing the observed shape-to-color associations.

3.4 Experiment 5

In the second experiment, we performed a similar study of shape-to-color associations and emotional mediation in non-synesthetes, but this time for 45 closed geometric shapes.

3.4.1 Methods

Stimuli

The stimuli consisted of 45 closed geometric shapes, which could differ with respect to a number of geometric features (indicated by appending "[G]" after the variable name): the number of generating-points[G] (3/4/9), pointedness[G] (curved/angular/pointy), symmetry-axes[G] (0/1/>1), and concavities[G] (0/≥1). The full set of stimuli is displayed in Figure 3.14. Each stimulus is identified by 'S', which stands for Shape, followed by the number of the Shape (from 1 to 15) and its version ('a' for angular, 'c' for curved, and 'p' for pointy). (The same general shape was presented with either angular/curved/pointy edges using exactly the same set of generating points). The orientation of stimuli (0° vs. 180°) was balanced across participants. Details of stimulus preparation and presentation can be found in the General Methods section at the beginning of this chapter.

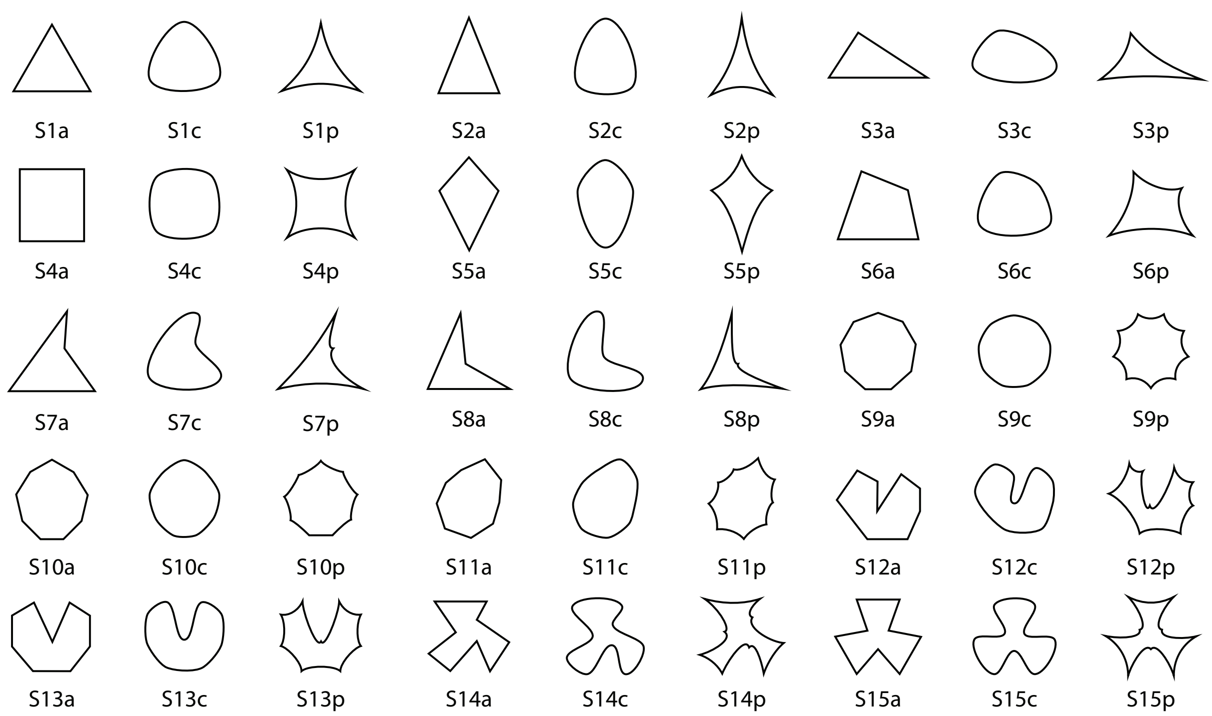


Figure 3.14. The forty-five Shape-stimuli from Experiment 5. Each Shape-stimulus is identified by 'S', which stands for Shape, followed by the number of the Shape (from 1 to 15) and its version ('a' for angular, 'c' for curved, and 'p' for pointy). Closed geometric shapes changed with respect to their pointedness[G] (curved/angular/pointy), but also with respect to their number of generating-points[G] (3/4/9), symmetry-axes[G] (0/1/>1), and concavities[G] (0/≥1).

3.4.2 Results and Discussion

The results of Experiment 5 are presented into two sections, corresponding to the two different parts of our research question: (i) are there systematic shape-to-color associations in non-synesthetes and (ii) are such shape-to-color associations mediated, in part, by emotions.

The color of closed geometric shapes

As we did for line-shapes, we started by exploring whether each of the shape features (generating-points[G], pointedness[G], symmetry-axes[G], and concavities[G]) influenced the colors participants judged as "going well" with the shape along four color appearance dimensions: saturation (saturated/*unsaturated*), lightness (light/*dark*), redness (redness/*greenness*), and yellowness (yellowness/*blueness*). We first computed a Shape-Color Association ($SCA_{s,d}$) score for each of the 45 closed geometric shapes (*s*) along each color appearance dimension (*d*) (see Equations 3.1-3.3). Since the orientation of a shape (0° vs 180°) did not have any effect on the associated colors along any color appearance dimension [$F(1,42) = 0.11, 0.76, 1.44, 0.02$, $p = 0.746, 0.387, 0.237, 0.897$, for saturation, lightness, redness, and yellowness, respectively], the data were initially averaged over the two orientations in which each shape could appear. Thereafter, we compared shapes according to the different levels of each variable that we manipulated in our design and examined how the associated colors changed with respect to those variables.

First, separate RM-ANOVAs were performed to test the effects of pointedness[G], symmetry-axes[G], and concavities[G] on the chosen colors for each color appearance dimension, after having averaged the data over the different generating-points[G]. The generating-points[G] factor could not be entered in the same RM-ANOVAs because the number of generating-points of a shape constrains the number of concavities it can have (i.e., shapes with three generating-points are necessarily convex). However, a further RM-ANOVA showed that the generating-points[G] of a shape did not have any effect on the associated colors along any color appearance dimension [$F(2,86) = 0.75, 2.53, 1.83, 1.06$, $p = 0.477, 0.086, 0.167, 0.353$, for saturation, lightness, redness, and yellowness, respectively]. Figure 3.15 shows graphs of the average SCA values (y-axis) for the colors associated with the shapes separately for each color dimension and shape-concavity condition, averaged over the number of generating points. The symmetry-axis conditions are plotted on the x-axis and the shape-concavity conditions as line types. Error bars represent standard errors of the means (SEMs). The colors chosen changed systematically along at least some color appearance dimensions as a function of the shape features considered. Table 3.2 reports F-ratios for main effects and interactions between symmetry-axes[G], concavities[G], and pointedness[G] for each of the four color appearance dimensions.

Table 3.2. The table reports F-ratios for main effects and interactions between factors for each RM-ANOVA. Four RM-ANOVAs were run: one for each color appearance dimension, i.e., Saturation, Lightness, Redness, and Yellowness. ****p<0.001, ***p<0.005, **p<0.01, *p<0.05.

	Source of Variance	F	df	p
Saturation	Symmetry-axes[G]	6.83	2, 86	0.002***
	Concavities[G]	0.62	1, 43	0.436
	Pointedness[G]	14.44	2, 86	0.000****
	Symmetry-axes[G] x Concavities[G]	0.44	2, 86	0.648
	Symmetry-axes[G] x Pointedness[G]	0.35	4, 172	0.844
	Concavities[G] x Pointedness[G]	20.07	2, 86	0.000****
	Symmetry-axes[G] x Concavities[G] x Pointedness[G]	1.27	4, 172	0.284
Lightness	Symmetry-axes[G]	2.37	2, 86	0.100
	Concavities[G]	17.48	1, 43	0.000****
	Pointedness[G]	4.96	2, 86	0.009**
	Symmetry-axes[G] x Concavities[G]	2.23	2, 86	0.114
	Symmetry-axes[G] x Pointedness[G]	4.90	4, 172	0.001***
	Concavities[G] x Pointedness[G]	11.21	2, 86	0.000****
	Symmetry-axes[G] x Concavities[G] x Pointedness[G]	3.85	4, 172	0.005**
Redness	Symmetry-axes[G]	8.03	2, 86	0.001***
	Concavities[G]	0.16	1, 43	0.692
	Pointedness[G]	2.76	2, 86	0.069
	Symmetry-axes[G] x Concavities[G]	3.62	2, 86	0.031*
	Symmetry-axes[G] x Pointedness[G]	0.98	4, 172	0.420
	Concavities[G] x Pointedness[G]	0.29	2, 86	0.751
	Symmetry-axes[G] x Concavities[G] x Pointedness[G]	1.15	4, 172	0.961
Yellowness	Symmetry-axes[G]	1.97	2, 86	0.146
	Concavities[G]	1.14	1, 43	0.293
	Pointedness[G]	2.47	2, 86	0.091
	Symmetry-axes[G] x Concavities[G]	0.31	2, 86	0.732
	Symmetry-axes[G] x Pointedness[G]	0.70	4, 172	0.592
	Concavities[G] x Pointedness[G]	6.40	2, 86	0.003***
	Symmetry-axes[G] x Concavities[G] x Pointedness[G]	1.41	4, 172	0.232

For saturation, there was a main effect of symmetry-axes[G] [$F(2,86) = 6.83$, $p<0.005$], in which more symmetric shapes were matched with more saturated colors. There was also a main effect of pointedness[G] [$F(2,86) = 14.44$, $p < 0.001$], which interacted with concavities[G] [$F(2,86) = 20.07$, $p<0.001$], resulting primarily from the facts that the saturation effects due to pointedness[G] were much larger for the convex shapes (concavities=0) than for the concave shapes (concavities>1) and that the colors chosen as going best with pointy shapes were the most saturated when the overall shape was convex, but the most unsaturated when the overall shape was concave. Conversely, the colors chosen as going best with curved shapes were very unsaturated when the overall shape was convex, but their saturation increased when the overall shape was concave.

For lightness, there was a main effect of concavities[G] [$F(1,43) = 17.48$, $p<0.001$], in which shapes that were overall convex were associated with lighter colors. There were also several significant interactions: a two-way interaction between concavities[G] and pointedness[G] [$F(2,86) = 11.21$, $p<0.001$], a two-way interaction between symmetry-axes[G] and pointedness[G] [$F(4,172) = 4.90$, $p<0.005$], and a three-way interaction among concavities[G], pointedness[G], and symmetry-axes[G] [$F(4,172) = 3.85$, $p<0.01$]. Pointy shapes were associated with lighter colors if the overall shape was convex, but with darker colors if the overall shape was concave. Lightness also increased for the colors associated with more symmetry-axes depending on a shape's pointedness: for instance, lightness increased with number of symmetry-axes consistently for pointy shapes, but it did not for curved shapes. The relation between pointedness and symmetry-axes also changed depending on a shape's shape-concavity.

For redness, we found a main effect of symmetry-axes[G] [$F(2,86) = 8.03$, $p<0.005$], with more symmetric shapes being associated with redder colors. There was also a weak interaction between symmetry-axes[G] and concavities[G] [$F(2,86) = 3.62$, $p<0.05$], given that the redness of the colors chosen as a function of the symmetry-axes changed depending on whether the overall shape was concave or convex. Indeed, the difference is mainly due to the marked increase in greenness for the curved concave shapes having more than one symmetry axis (i.e., S15c in Figure 3.14), which looks distinctly like a clover leaf. For yellowness, no main effect was found, but there was a reliable interaction between concavities[G] and pointedness[G] [$F(2,86) = 6.40$, $p<0.005$]. This interaction appears to reflect the fact that the colors chosen as going best with convex shapes were yellower when they were pointy than then they were angular or curved, whereas no similar effect was present for the concave shapes. This difference may be due to object-mediated associations, as we now discuss.

We considered the possibility that at least some of the reported effects may be due to object-mediated associations by examining the results reported by our subjects in the Shape-Object Questionnaire. For instance, pointy shapes with an overall convex shape (e.g. 'S5p', 'S9p') reminded participants of objects like the sun, stars, diamonds or sparkles, whereas pointy shapes with an overall concave shape (e.g. 'S12p', 'S13p') reminded them of dark objects such as bats. This could explain, in part, why the colors (especially the lightnesses, but possible also in yellowness) going with pointy shapes changed dramatically depending on whether the overall shape was convex or concave (compare the left versus right graphs in Figure 3.15 for lightness and yellowness). Other effects were more evident along other color appearance dimensions. For instance, the resemblance of shape 'S15c' to a clover increased the greenness of the associated colors, whereas other shapes belonging to the same category (e.g., curved shapes with more than one symmetry-axes) were associated with more reddish colors (compare the left versus right graphs in Figure 3.15, for redness).

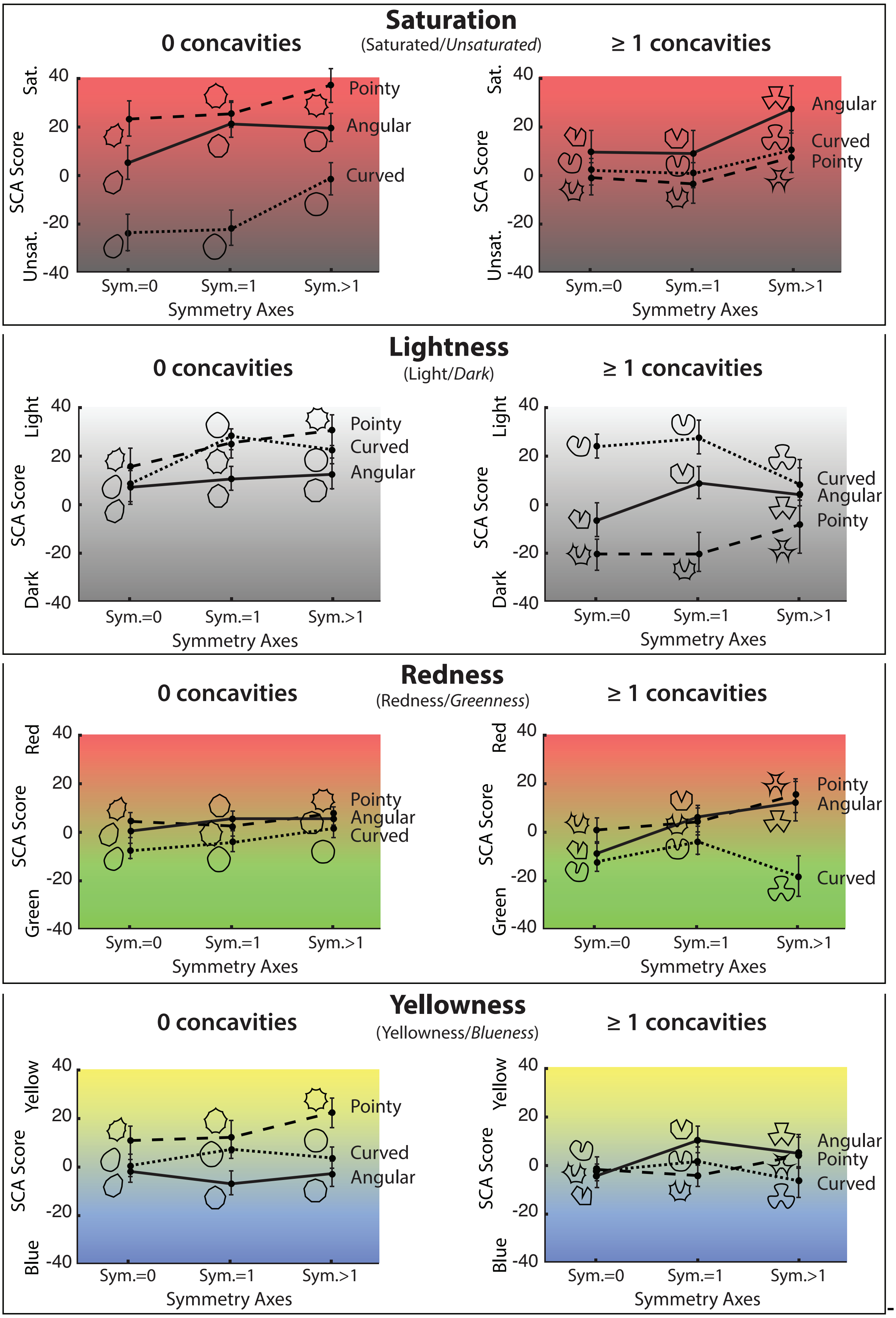


Figure 3.15. Color associations for shapes as a function of their pointedness[G] (curved, angular, pointy) and symmetry-axes[G] (sym.=0, sym.=1, sym.>1) for convex shapes (0 concavities) to the left and concave shapes (≥1 concavities) to the right. Color associations are displayed separately for each of the four color appearance dimensions: saturation, lightness, redness, and yellowness. Example shapes for each category are displayed close to each dot. Error bars represent standard errors of the means (SEMs).

We also analyzed these color choices with respect to the subjective perceptual ratings given by participants in the Shape-Appearance-Ratings task, where observers were judging subjectively almost the same geometric features that were manipulated in our experimental design. Two series of Stepwise Multiple Linear Regressions were performed, in which we were predicting each color appearance dimension (*d*) of the colors associated with a shape on the basis of either the shape's objective geometric features (Figure 16A) or its subjective perceptual ratings (Figure 16B). We will refer to the first class of models, which uses objective geometric features as predictors, as Geometric Models and to the second class of models, which uses subjective perceptual ratings as predictors, as Perceptual Models. As mentioned before, we will use the bracketed letter '[G]' for 'geometric' factors and will henceforth use the bracketed letter '[P]' for 'perceptual' factors to clarify its referent.

The predictors for Geometric Models were pointedness[G] (curved = 0, angular =1, pointy = 2), symmetry-axes[G] (0, log(1) +1, log(3) +1, log(4) +1, log(9) +1), concavities[G] (convex = 0, one-concavity = 1, three-concavities = 3), and generating-points[G] (3, 4, 9). The predictor values for pointedness increase with the sharpness of the vertices. For symmetry-axes[G], we used 0 if there were zero symmetry axes, and a log function (base 10) of the number of symmetry-axes plus 1, if the number of symmetry-axes was greater than or equal to 1. The predictors for Perceptual Models were the average ratings on the bipolar scales referring to a shape's closure[P] (closed+/*open*-), pointedness[P] (pointy+/*smooth*-), symmetry[P] (symmetric+/*asymmetric*-), complexity[P] (complex+/*simple*-), and concavity[P] (concave+/*convex*-). The criterion variables that were predicted separately by each series of predictors were saturation (saturated+/*unsaturated*-), lightness (light+/*dark*-), redness (redness+/*greenness*-), and yellowness (yellowness+/*blueness*-).

First, a series of Stepwise Multiple Linear Regressions (Geometric Models) was used to determine the degree to which the objective geometric features of shapes could account for color choices (see Figure 3.16A). For saturation, 38% of the variance could be explained by two geometric factors: 30% by a shape's pointedness[G] and 8% from its symmetry-axes[G], with more saturated colors being associated with pointier and more symmetric shapes. For lightness, 31% of the variance could be explained by concavities[G] (12%), pointedness[G] (11%), and symmetry-axes[G] (8%), with lighter colors being associated with convex, curved, and more symmetric shapes. For redness, 39% of the variance could be explained by pointedness[G] (23%), and symmetry-axes[G] (16%), with redder colors being associated with pointier and more symmetric shapes. No variance could be explained for yellowness (i.e., no variables were entered into the regression equation).

Second, we performed a series of Stepwise Multiple Linear Regressions (Perceptual Models) to determine the degree to which the subjective perceptual ratings of shapes could account for color choices (see Figure 3.16B). For saturation, 37% of the variance could be explained by two factors: 31% by pointedness[P], and an additional 6% by symmetry[P], with more saturated colors being associated with pointier and more symmetric shapes. For lightness, 23% of the variance could be explained by complexity[P] alone, with lighter colors being associated with simpler shapes. For redness, 43% of the variance could be explained by pointedness[P] (24%) and symmetry[P] (19%), with redder colors being associated with pointier and more symmetric shapes. No variance could be explained for yellowness.

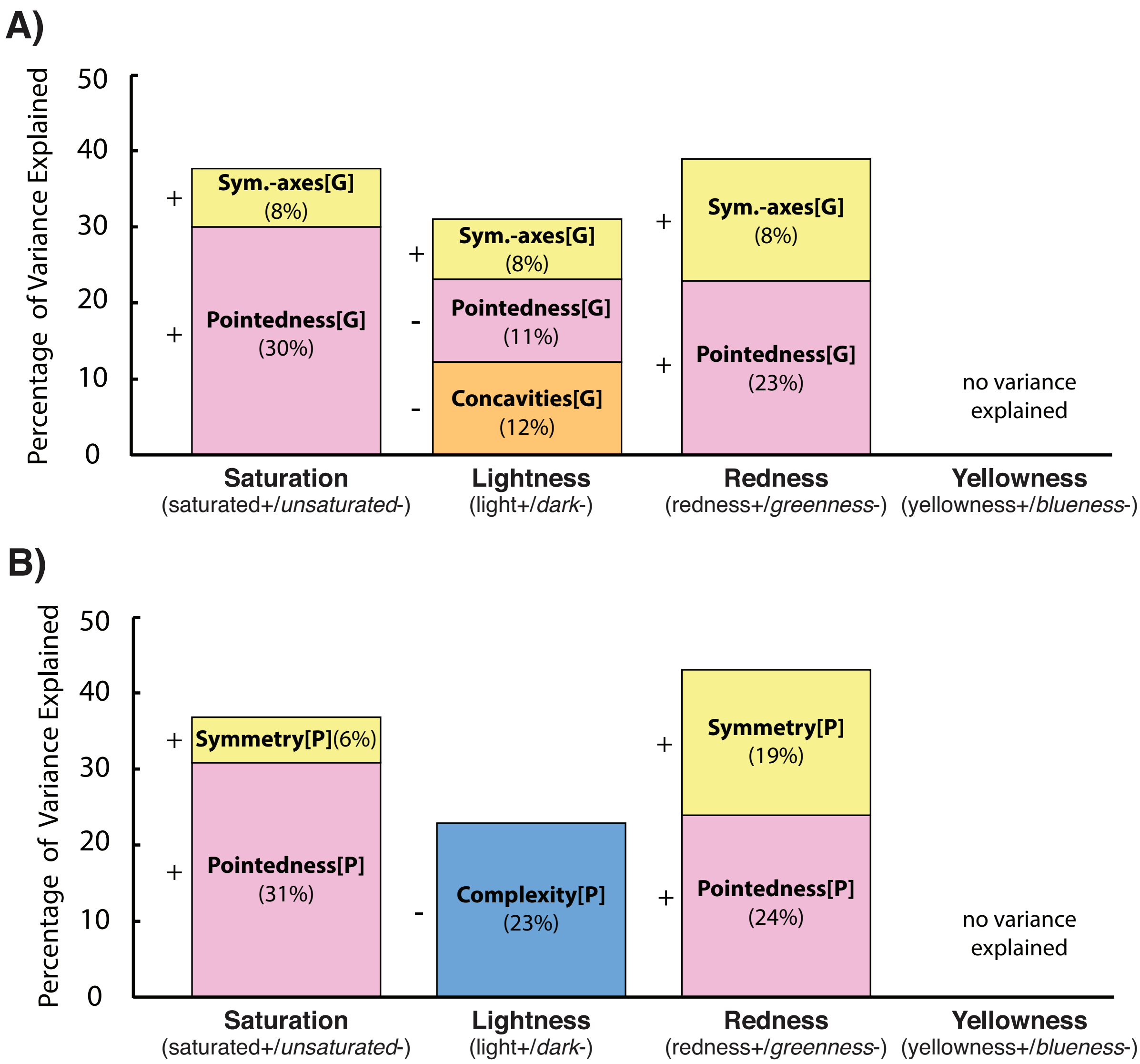


Figure 3.16. The results of Stepwise Multiple Linear Regression Analyses in which each color appearance dimension is predicted by either objective geometric features (Geometric Models, panel A) or subjective perceptual ratings (Perceptual Models, panel B). Bars show the overall percentage of variance explained by the best-fitting model for each color appearance dimensions. Stripes within each bar show the percentages of variance explained by each factor in the order with which they were entered into the regression model (bottom to top). The exact percentage explained by each factor is shown in parenthesis. The sign to the left of each stripe indicates whether there was a positive or negative relation between that color appearance dimension and that factor. For instance, '+' to the left of 'Pointedness[G]' for Saturation means that more saturated colors were picked for shapes that were geometrically *more* pointy, whereas '-' to the left of 'Pointedness[G]' for Lightness means that lighter colors were picked for shapes that were geometrically *less* pointy. Similarly, '+' to the left of 'Pointedness[P]' for Saturation means that more saturated colors were picked for shapes that were perceptually *more* pointy, whereas '-' to the left of 'Complexity[P]' for Lightness means that lighter colors were picked for shapes that were perceptually *less* complex).

Overall, Perceptual Models, which employ the subjective perceptual ratings as predictors, did not perform better than Geometric Models, the former explaining an average of 26% of the variance across color appearance dimensions in comparison with 27% for the latter. The color appearance dimension that was best predicted was redness, with saturation and lightness following in that order. The best predictors were those related to a shape's pointedness and symmetry for both series of Models. Some minor differences can be observed if we look at the variance explained for each color appearance dimension separately. For instance, subjective ratings (symmetry[P] and pointedness[P]) predicted redness slightly better than geometric features (symmetry-axes[G] and pointedness[G]) (43% vs. 39%, respectively). Conversely, subjective ratings predicted lightness slightly worse than geometric features (23% vs. 31%). It is worth noting that the concavity factor, which explained the highest amount of variance for lightness in Geometric Models (Concavities[G]), explained no variance for lightness in Perceptual Models (Concavity[P]). This can possibly be explained by the ambiguity of the terms 'convex' and 'concave' in the Shape Appearance Ratings task, given that the same term could be applied both globally and locally (e.g. shape 'S11p' has a convex-configuration but locally concave-sides, while 'S15c' has a concave-configuration but locally convex-sides), making the ratings noisy and inconsistent. On the other hand, complexity[P] alone explained a good amount of variance for lightness in Perceptual Models.

To sum up, participants mainly differentiated between curved and pointy shapes and between symmetric and asymmetric ones in choosing the most consistent colors, and these features seemed to mainly impact the associated colors along the redness and saturation color appearance dimensions, with pointy, symmetric shapes being associated with redder, more saturated colors.

<u>Emotional mediation in shape-to-color associations</u>

To test the Emotional Mediation Hypothesis, we calculated the correlations between the emotional ratings of each shape and the emotional ratings of the colors most consistent/inconsistent with that shape, as measured by the *CEA* (Color-Emotion Association) values for each emotional dimension *d* (see Equations 3.4-3.6). As displayed in Figure 3.17, these correlations were very high with p-values lower than 0.001 for all the emotional dimensions considered. The highest correlation was that for harmfulness (r = 0.68), followed by agitation (r = 0.63), angriness (r = 0.62), happiness (r = 0.59), strength (r = 0.48), and activity (r = 0.46). A Principal Components Analysis (PCA) of the emotional dimensions showed that 97% of variance could be explained by two components: 79% by the first component and 18% by the second component. The first component corresponded most closely to harmfulness (PC loadings: harmfulness = 0.99; activity = 0.99; agitation = 0.98;

angriness = 0.98; strength = 0.94), whereas the second component roughly corresponded to happiness (PC loading: happiness = 0.99; strength = 0.17; harmfulness = -0.11; agitation = -0.14; angriness = -0.17). The results are consistent with the Emotional Mediation Hypothesis in that strong correlations were obtained between the emotional content of a shape and the emotional content of colors most consistent/inconsistent with that shape, suggesting that emotions play a role in mediating shape-to-color associations. Nevertheless, other factors may play a role in mediating such associations as well. Moreover, a causal relationship cannot be established with any of these factors given the correlational nature of the results.

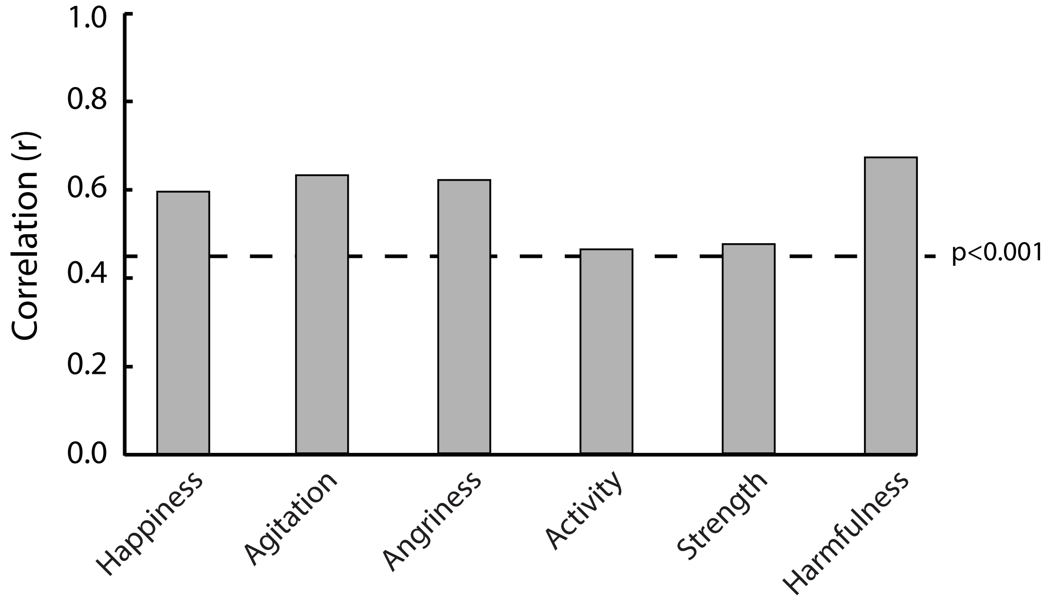


Figure 3.17. Correlations between the emotional ratings of each of the 45 closed geometric shapes and emotional ratings of the colors that were chosen to be most consistent/inconsistent with that shape, as measured by the SCA (Shape-Color Association) scores for each of six emotional dimensions: happiness (happy/*sad*), agitation (agitated/*calm*), angriness (angry/*not-angry*), activity (active/*passive*), strength (strong/*weak)*, harmfulness (safe/*harmful*).

We calculated analogously the correlation between ratings for each shape and the ratings for the colors most consistent with that shape, as measured by the *CEA* for the other (non-geometric, non-perceptual, non-emotional) dimensions from the Shape Ratings task (i.e., using other dimensions for *d* in the Equations 3.4-3-6). As displayed in Figure 3.18, we found strong correlations with p-values below 0.001 between the ratings of each shape and the ratings of colors most consistent/inconsistent with that shape for these additional dimensions: preference (like/*dislike*), pleasantness (pleasant/*unpleasant*), familiarity (familiar/*unfamiliar*), and warmth (warm/*cool*). Such correlations, suggest that participants tended to match shapes they "liked" with colors they "liked" (r = 0.57), more "pleasant" shapes with more "pleasant" colors (r = 0.57), more "familiar" colors with more "familiar" shapes (r = 0.62), and "warmer" colors with "warmer" shapes (r = 0.46). A Principal Components Analysis (PCA) of these dimensions (i.e. preference, pleasantness, familiarity, and warmth) showed that 84% of variance could be explained by two components: 59% by the first component that corresponded most closely to pleasantness (PC loadings: preference = 0.92; pleasantness = 0.92; familiarity = -0.82), and an additional 25% by the second component, that roughly corresponded to warmth (PC loading: warmth = 0.99).

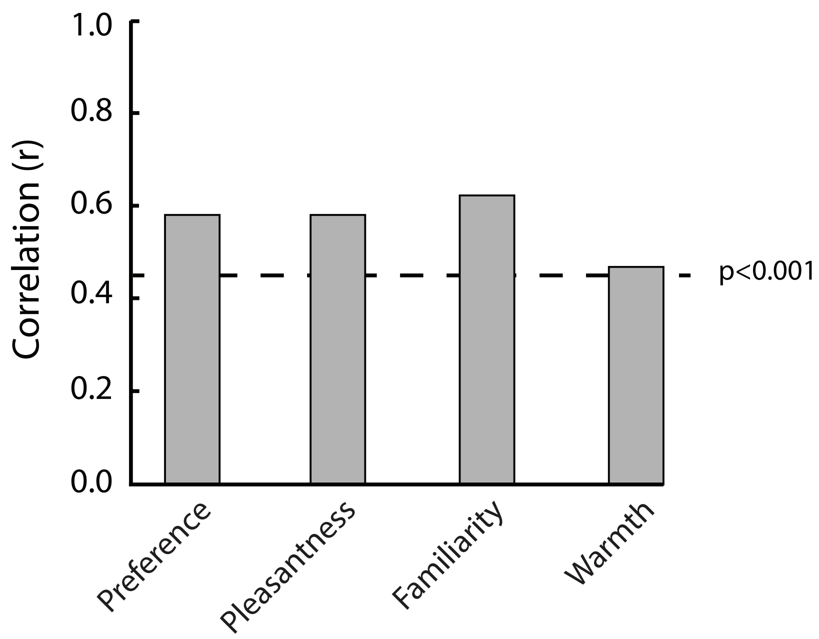


Figure 3.18. Correlations between ratings of each of the 45 closed geometric shapes and ratings of the colors that were chosen to be most consistent/inconsistent with that shape, as measured by the SCA (Shape-Color Association) scores for each of four semantic dimensions: preference (like/dislike), pleasantness (pleasant/unpleasant), familiarity (familiar/unfamiliar), and warmth (warm/cool).

Further analyses were performed averaging over the emotional ratings given by Group 1 and Group 2 participants. To deepen our understanding of the structure of the emotional space of closed geometric shapes, we performed an emotion-based Multidimensional Scaling (MDS) of shapes based on their ratings on the six emotional dimensions (happiness, agitation, angriness, activity, strength, harmfulness). The best two-dimensional solution for the emotional structure of closed geometric shapes (Figure 3.19) gave a good fit (stress = 0.06). We interpreted the dimensions by rotating the MDS point configuration in one degree increments 360 times to find the angles at which each dimension was most highly correlated with the emotional ratings. Harmful/*safe* had the highest correlation at 10° degrees of rotation for Dimension 1 (r = 0.93), while happy/*sad* had the highest correlation at 20°

degrees of rotation for Dimension 2 (r = 0.28), as indicated by the dashed lines in Figure 3.19. These two dimensions are almost orthogonal (80° apart) and were interpreted as harmfulness and happiness, respectively. Shapes seem to mainly differ along the harmfulness dimension, which is not surprising, given that this dimension is nearly the same as the axis of the first principal component of the PCA for emotional dimensions. Two main clusters appear clearly from the graph: harmful-looking shapes that tend to be pointy and/or complex and concave are grouped to the left, as opposed to safe-looking shapes that tend to be smoothly curved and/or simple and convex are grouped to the right. The figure also shows some samples of the actual colors picked by participants as the single most consistent color for a representative sample of the shapes of each group. These color matrices give a sense of the kind of colors associated with the two clusters of shapes (harmful vs. safe ones). Despite the wide variety of colors picked by different participants for the same shape, colors associated with harmful shapes were overall more saturated and darker than those associated to safe shapes.

We performed a further Stepwise Multiple Linear Regression to see how well we could predict the color appearance dimensions of the colors associated with the shapes on the basis of their subjective emotional ratings (Figure 3.20). We will refer to this class of models, which uses subjective emotional ratings as predictors, as Emotional Models. Each of the four color appearance dimension was predicted separately on the basis of the ratings given by participants on six emotional scales. The predictors for Emotional Models were happiness (happy+/*sad*-), agitation (agitated+/*calm*-), angriness (angry+/*not-angry*-), activity (active+/*passive*-), strength (strong+/*weak*-), and harmfulness (harmful+/*safe*-). The criterion variables were saturation (saturated+/*unsaturated*-), lightness (light+/*dark*-), redness (redness+/*greenness*-), and yellowness (yellowness+/*blueness*-).

The emotional associations of the shapes predicted substantial amounts of the variance for saturation (59%), lightness (53%) and redness (39%) of the colors associated to shapes, whereas no variance could be predicted for yellowness by these emotional factors. For saturation, 59% of the variance could be explained from activity (38%) and happiness (21%), with more saturated colors being associated with more active, happier shapes. For lightness, 53% of the variance could be explained from happiness (37%) and strength (16%), with lighter colors being associated with happier, weaker shapes. For redness, 39% of the variance could be explained from strength (26%) and activity (13%), with redder colors being associated with stronger, more passive shapes. The perceived happiness of a shape seemed to impact mainly the saturation and lightness of the colors associated to it. The other emotional dimensions, like activity and strength, that loaded heavily on Principal Component 1 in the previous PCA, explained almost equally the remaining variance for saturation, lightness, and redness.

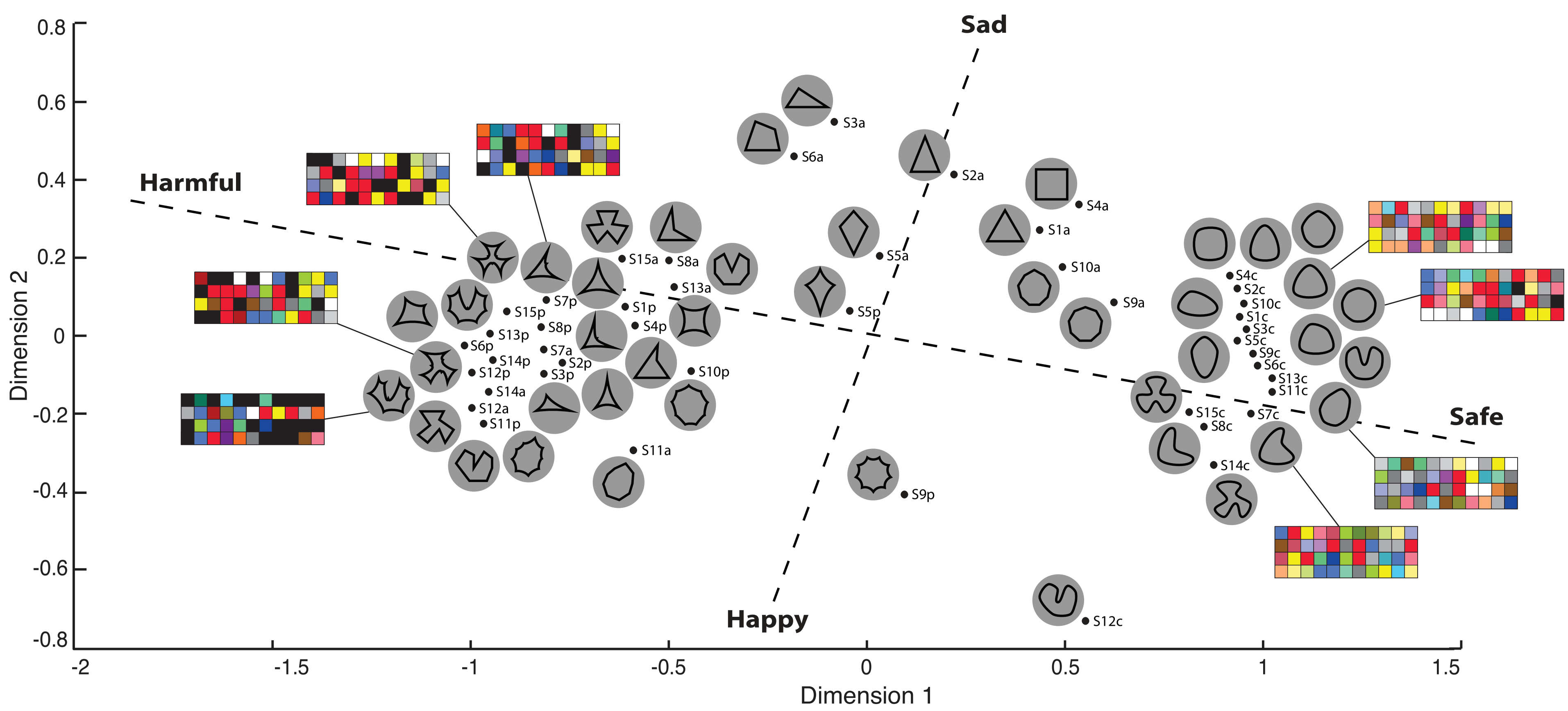


Figure 3.19. Multidimensional Scaling of shapes based on emotional similarity on six emotional dimensions: Happy/*sad*, agitated/*calm*, angry/*not-angry*, active/*passive*, strong/*weak*, harmful/*safe*.

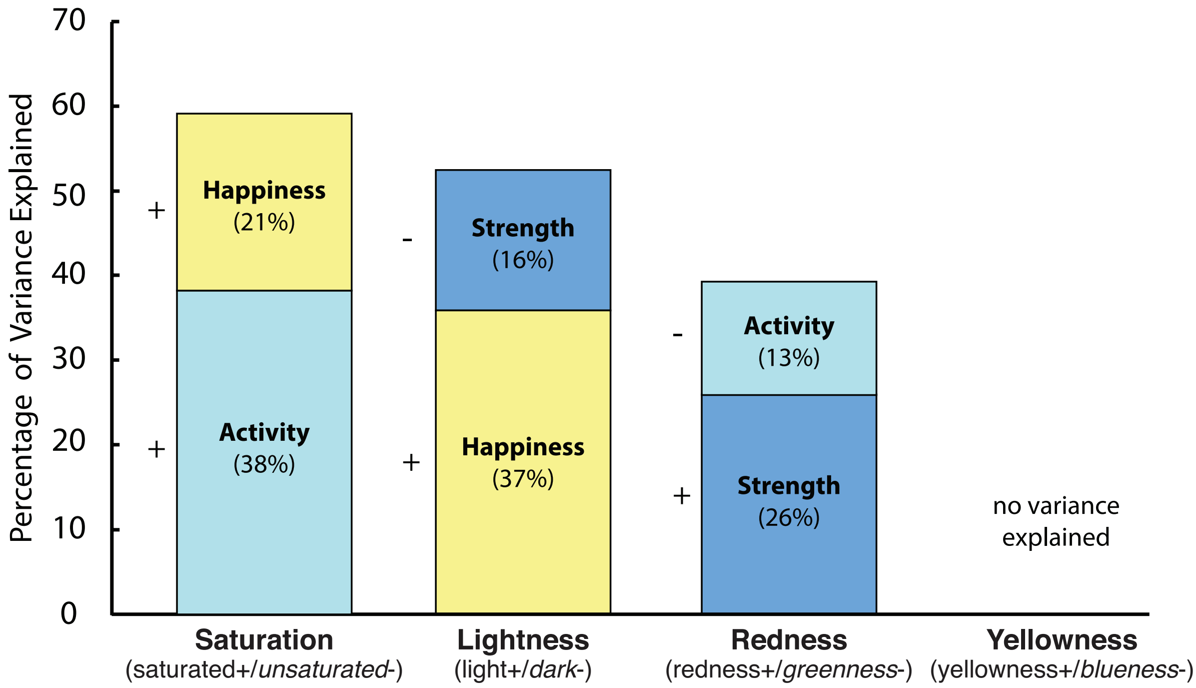


Figure 3.20. Stepwise Multiple Linear Regression Analysis in which each color appearance dimension is predicted by subjective emotional ratings (Emotional Models). Bars show the overall percentages of variance explained by the best-fitting model for each color appearance dimension. Stripes within each bar show the percentages of variance explained by each factor in the order with which they were entered into the regression models (bottom to top). The exact percentage explained by each factor is shown in parentheses. The sign to the left of each stripe indicates whether there was a positive or negative relation between the color appearance dimension and that emotional factor (e.g. '+' to the left of 'Happiness' for saturation means that more saturated colors were picked for the shapes rated as *more* happy, whereas '-' to the ledt of 'Strength' for lightness means that lighter colors were picked for the shapes rated as *less* strong).

The Emotional Models were notably better than the Perceptual and Geometric dimensions at predicting the non-chromatic dimensions (saturation and lightness) of the colors chosen, but no better than Perceptual Models or Geometric Models at predicting the chromatic dimensions (redness and yellowness). A further series of regressions was performed to see whether the emotional ratings of a shape explained any additional variance after the variance explained by subjective perceptual ratings was removed. After performing the regression with the subjective perceptual ratings as predictors (Perceptual Models), we performed a regression on the residuals using the emotional ratings as predictors to see whether there was any additional variance explained after removing that explained by perceptual ratings. The procedure was repeated for each color appearance dimension *d* separately. Some additional variance could be explained by emotional ratings after we accounted for all the variance explained by perceptual ratings for the saturation and lightness dimensions. More precisely, 20% additional variance in saturation and 20% additional variance in lightness was explained by the rated happiness of the shapes. No additional variance was explained for either of the chromatic color appearance dimensions after we accounted for all the variance explained by perceptual ratings.

To conclude, the color of a closed geometric shape could be predicted rather well from its perceptual features and from its emotional content. Moreover, some of the perceptual and emotional factors involved seem to be interrelated since their ratings strongly correlate with p-values well below 0.001: more complex shapes were also judged as more agitated (r = 0.46) and harmful (r = 0.55), while pointier shapes were also judged as more agitated (r = 0.61), angry (r = 0.60), strong (r = 0.81), and harmful (r = 0.63). In addition, more symmetric shapes were judged as happier (r = 0.40, $p < 0.005$). The fact that an additional 20% of the variance could be explained by happiness ratings after all the variance explained by the perceptual factors was removed implies that shapes differed with respect to their happiness associations in a way that is not totally captured by the perceptual features that we examined here. Again, further evidence could help in clarifying the interrelationships between emotional and perceptual factors as well as the causal role of the former and the latter in producing the observed pattern of shape-to-color associations.

3.5 Discussion of Experiments 4 and 5

Experiments 4 and 5 (Malfatti et al., 2014a, 2014b) consistently showed the existence of systematic associations between colors and shapes in a different population (US participants). The main contributions of the present experiments, beyond the results described in Chapter 2, are that they extend the study of shape-to-color associations to color attributes other than the hue, to a wider variety of shapes and shape features, and to people's emotional associations to the shapes. More precisely, the experiments were designed to assess how non-synesthetes associate specific shape features of line shapes (Experiment 4) and closed geometric shapes (Experiment 5) to specific attributes of color: their saturation, lightness, redness/*greenness*, and yellowness/*blueness*). The present experiments further contribute in providing possible explanations for these shape-to-color associations, exploring in particular the role of perceptual and emotional factors as mediators.

The first aim of Experiments 4 and 5 was to study in more depth the relationship between shape and color, extending both the attributes of colors and the features of shapes considered, and studying how these specific color attributes and shape features are associated with each other. With respect to color, we expected that a given shape-stimulus would influence the colors chosen to go best (and worst) with it, not only with respect to their hue, but also with respect to their saturation and lightness. For instance, given a certain shape, people could choose colors that were strikingly different in hue, but quite similar in being highly saturated (or unsaturated) or very light (or dark). Effects of this kind have been reported consistently for other cross-modal associations involving, for instance, auditory stimuli and their associations to colors (see Ward, Huckstep, Tsakanikos, 2006; Palmer, Schloss, Xu, & Prado-Leon, 2013). With respect to shape, we expected that specific features of the shape stimuli would be correlated with their associations to colors (or attributes thereof). This expectation was supported by the literature on grapheme-to-color associations, suggesting that the color picked to go with graphemes are influenced by perceptual features such as their curvature and/or closure (see Jürgens, Mausfeld, & Nikolić, 2010; Spector & Maurer, 2011).

Two set of stimuli were generated for the present experiments: 44 line-stimuli for Experiment 4 and 45 closed geometric shapes Experiment 5. These shapes were manipulated systematically with respect to a number of features: pointedness, symmetry, generating-points, intersections, and concavities. The set of open line stimuli varied systematically on all of these features except concavities, whereas the set of closed geometric shapes varied on all of these features except intersections. For each shape, participants were asked to pick the three colors that, in their opinion, "went best" (or "went worst") with it by choosing among the thirty-seven colors of the Berkeley Color Project (Palmer & Schloss, 2010; Schloss & Palmer 2011; Schloss, Poggesi, & Palmer, 2011), which differ systematically with respect to their hue (redness/*greenness* and yellowness/*blueness*), saturation (saturated/*unsaturated*) and lightness (light/*dark*). Separate RM-ANOVAs for each color appearance dimension, showed that the color going best with a shape varied systematically as a function of at least some of its geometric and perceptual features for at least some color appearance dimensions.

We also performed a series of Stepwise Multiple Linear Regression analyses of the data to see which factors predicted the variance in the color appearance dimensions of the colors chosen as going best (and worst) with the shape stimuli. In general, the results showed that geometric and perceptual features predicted more variance in the color appearance dimensions of the colors chosen as going best with the line-stimuli (average = 50%) than in the color-appearance dimensions of the colors chosen as going best with the closed shapes (average = 26.5%). For the line-shape stimuli, the geometric and perceptual features predicted the saturation and lightness of the chosen colors best (average = 72%, 67.5%, for saturation and lightness respectively), the redness of those colors less well (average = 50.5%), and the yellowness least well of all (average = 10%) (see Figure 3.10). For the closed shapes, the geometric and perceptual features predicted the variance in the saturation, lightness, and redness dimensions of colors about equally (average = 37.5%%, 27%, 41%, respectively) and essentially none of the variance in their yellowness (see Figure 3.16).

Specific mappings between shape features and color attributes were found in both experiments. For both sets of shapes, pointedness was one of the features producing the strongest effect, meaning that the vertices of a shape are important features in determining the colors people most naturally match to it. For instance, more angular line-shapes were matched with more saturated, darker, and redder colors in Experiment 4. Similarly, pointier closed geometric shapes were associated with more saturated, redder colors in Experiment 5. Other geometric effects were observed for these same dimensions: e.g., the number of intersections for line-shapes, and the number of symmetry-axes for closed geometric shapes, both of which increased the saturation and redness of the associated colors.

Further aims of the present experiments were to evaluate the role of emotional factors as possible mediators and to compare those emotional factors with geometric and perceptual ones. The Emotional Mediation Hypothesis was initially proposed to explain music-to-color associations in non-synesthetes. Palmer et al. (2013) found that non-synesthetes tend to match colors to music on the basis of their shared emotional content (e.g., colors rated as looking "happy" were chosen as going best with music that was rated as sounding "happy" by the same participants). Here we used a similar method to study emotional mediation in shape-to-color associations. Elements of Osgood's semantic differential were used to obtain ratings of each color and each shape along a series of emotional dimensions (happiness, strength, activity, angriness, harmfulness, and agitation) and non-emotional conceptual dimensions (preference, pleasantness, familiarity, and warmth). The results showed that there were high correlations between the emotional associations of each shape and the emotional associations of the colors chosen as most consistent/inconsistent with that shape. In particular harmfulness produced the strongest shape-to-color correlations in both experiments (i.e., colors rated as being "harmful" were chosen as going best with line-shapes or closed geometric shapes that were rated as being "harmful"). The happiness dimension seemed to play a role for closed geometric shapes (i.e., colors rated as being "happy" were chosen as going best with closed geometric shapes that were rated as being "happy"), but this relation was not evident for line-shapes. Because this evidence is purely correlational, however, it does not allow us to assess whether there is a causal role of such emotions in producing the observed pattern of results.

Principal Component Analysis (PCA) showed that the emotional dimensions of the shapes studied (i.e., happiness, strength, activity, angriness, harmfulness, and agitation) could be reduced to just one component, reflecting a shape's angriness, in Experiment 4, and to two components, reflecting respectively a shape's harmfulness and happiness, in Experiment 5. These results are consistent with previous suggestions by other researchers on color-emotion associations (Wright & Rainwater, 1962; D'Andrade, Egan, 1974), who found that the emotional content of stimuli appear to be characterized by two main dimensions, roughly reflecting their potency (high/low) and valence (positive/negative). The fact that the happiness emotional dimension, which is related to valence, did not show up for line-shapes, is consistent with what has been recently found for line-based textures, where angriness was the main emotional dimension (Langlois, Peterson, & Palmer, 2014; Peterson, Langlois, & Palmer, 2014). However, it is possible that this is due in part to the type of line-stimuli (or line-based textures) employed in these particular experiments and their characteristic features. Other features of line-shapes, not studied here, might be relevant to the presence/absence of valence as a second relevant dimension of the emotional space for line-stimuli, such as being opened upwards/downwards (see Jürgens & Nikolić, 2012), like a smile or a frown, or having ascending/descending elements (see Collier, 1996; Poffenberger & Barrows, 1929), metaphorically related to an "up" or "down" mood.

To compare the role of emotional and perceptual factors as mediators, elements of Osgood's semantic differential were used also to obtain ratings of each shape along a series of perceptual dimensions related to its pointedness, symmetry, complexity, closure, and concavity. Thereafter, a series of Stepwise Multiple Linear Regressions was performed to see how well we could predict the color appearance dimensions of the colors associated with the shapes based on their subjective perceptual versus emotional ratings. Empirically, the results showed that the color appearance dimensions of the colors associated with the line-shapes could be predicted almost equally well from its objective geometric features, its subjective perceptual features, or its subjective emotional content (see Figures 3.10 and 3.13); conversely, the color appearance dimensions of the colors associated with the closed geometric shapes could be predicted slightly better from its subjective emotional content than from its objective geometric or subjective perceptual features (see Figures 3.16 and 3.20). Here some interesting conceptual issues arise.

One obviously and important question is whether the geometric and/or perceptual features of the shapes and their emotional associations could be seen as just different ways to describe the same shape, ones that correlate with each other to different extents. For instance, the results suggest that the strength/activity/angriness emotional associations of a line-shape are closely related to its pointedness and intersections, because these emotional and perceptual factors alone predicted the color appearance of colors picked to go with shapes to comparable degrees. However, it is more difficult to establish similar direct connections between the geometric and/or perceptual features of a closed geometric shape and its emotional associations, also given that the former were worst predictors in predicting the associated colors. It is possible, at least in principle, that the emotional associations of the shapes were driven in part by some geometric and/or perceptual features not captured by our experimental design (and therefore not entered in the geometric/perceptual regressions). Nevertheless, an explanation based on such geometric and/or perceptual features of the shapes does not have necessarily to be preferred to an explanation based on their emotional associations.

Lower-level explanations are often preferred in science because it is claimed that they are simpler, more objective, and more straightforward. But is that true in the present case of the colors cross-dimensionally associated with shapes? It makes perfect sense to talk about the "pointiness" or "closure" of shapes as being objective, low-level and simple. The corresponding features of colors may have to be interpreted much more metaphorically, however. What makes a color more or less "pointy", or "closed", for example? Is saturated red a "pointy" color—as if pointedness were actually an alternative mediator—or is pointedness related to redness because of more complex associations, such as the fact that pointy objects can puncture flesh and draw red blood? And is the associative chain among objects and physical features actually any simpler and more straightforward than a chain that is mediated by a common emotional association, such as both pointiness and redness being associated with anger or harm? Indeed, don't these different associative possibilities have a great deal in common, given how closely associated anger and harm are to blood? So little is yet known about how such complex associative processes operate that it is impossible to answer such basic and obvious questions definitively, based on consensually agreed-upon, empirical facts.

CHAPTER 4

New frontiers: associations between hues and concepts

4.1 Introduction to Experiment 6

The study reports research conducted to test the existence of systematic associations between percepts and concepts. Associations of this kind have already been tested in both synesthetic and general populations in different perceptual domains. Experiments 1-5 are good examples of associations between shapes and colors, for instance.

The consistency of the reported associations between shapes and color suggests a similarity, more than a difference, between natural perception and synesthetic perception. If, besides the field of perception, the existence of systematic associations was confirmed between the field of abstract concepts and some perceptual characteristics, such as color, this would be relevant for better understanding of the nature of cognitive processes, and of the concepts themselves. For example, it would contribute to the debate on whether the abstract meanings of the terms of natural language are rooted in perceiving, and whether there exists a relation of dependence between concrete and abstract concepts (Arnheim, 1969; Lakoff 1990; Lakoff & Johnson. 1999; Pinna & Albertazzi, 2010).

In the research reported here, and on the basis of previous results obtained in the perceptual domains, we were also interested in testing the natural association with color characteristics for concepts whose meanings are related to abstract semantic fields. As well known, a semantic field is a conceptual space of limited dimensions which refers to the organization of a set of concepts. The semantic fields theory studies the semantic relations which 'hold together' and 'distinguish' the elements of a field (Cruse, 1986; Geeraerts & Grondelaers, 1994; Kittay & Lehrer, 1992; Lyons, 1977; Trier, 1934; Vassilyev, 1974; Wierzbicka, 1980, 1985); and it is developed mainly in reference to analysis of lexical fields (i.e. to the organization of a set of lexemes) obtained by filtering a semantic field. Cruse (1992), however, and the main exponents of the cognitive linguistic approach to the analysis of natural language (Lakoff, 1990; Langacker, 1991, 2000; Talmy, 2000), recognized that a lexical semantics is not autonomous and needs to be related to an underlying independent conceptual structure, and that it is not sufficient to treat meaning exclusively in terms of relations between lexical items.

In our research the choice of concepts to consider was a small set of concepts related to the 'frame' (Kittay & Lehrer, 1992) of ethics in social behavior: which in principle should not be assumed to be immediately associated with color, because of their intrinsic abstractness. The concepts chosen for consideration were the following: 'accuracy', 'impartiality', 'independence', 'legality', and 'responsibility'. We then added, for each word, three synonyms and three antonyms, expecting that if the subjects associated a word with a color, they would also associate its synonyms in the same way. Vice versa, the antonyms of the same word would be negatively associated with that color. The leading idea was that, in the general population, not only the meanings of empirical concepts, such as the visual shapes of an item, but also the meanings of abstract concepts, expressed by linguistic terms, might show natural associations with color. To sum up, we hypothesized that a few words related to a specific semantic field (in this case, ethics in social behavior) and their synonyms would be associated with certain colors, while their antonyms would not be associated with those colors. The purpose of the experiment was to test whether the meanings of abstract terms lead to consistent choices of color (hue). The task of the experimental subjects was to color with one of the 40 colors of the hue circle a series of words representing abstract concepts (35 in total and in Italian). Because of the novelty of the study, we chose to test a large number of participants and to conduct the experiment online.

4.2 Experiment 6

The purpose of the experiment was to check whether terms pertaining to an abstract semantic field (related to the frame of ethics in social behavior) led to consistent choices of colors (hues).

4.2.1 Methods

Participants

Two hundred and eighty-one subjects participated in the experiment on a voluntary basis: one hundred and eighty-nine females and ninety-two males (mean age = 31.29; standard deviation = 11.51; range: 18–86 years). The participants were invited to take part in the experiment online through the main social networking websites. The participants were all mother-tongue speakers of Italian. The only exclusion criterion was self-reported defective color vision. No subject declared a conscious synesthesia. The experiment was carried out in accordance with the relevant institutional and national regulations and legislation, and with the World Medical Association Helsinki Declaration as revised in October 2008. The experiment was conducted after obtaining an informed consent.

Stimuli/Materials

The test was conducted online using PHP and HTML software. The materials consisted of a hue circle and a series of words presented by video. There were no time limitations. The Hue Circle, taken from the Natural Color System (NCS) Atlas, had 40 hues, including the four unique hues—yellow, red, green, and blue—and the intermediate ones. There were 35 words representing abstract concepts, and they consisted of the following five terms: accuracy (acting with care), impartiality (acting or judging objectively), independence (not being subject to constraints of some kind), legality (compliance with the law), and responsibility (awareness of being accountable for one's actions or those of others), as well as three synonyms and antonyms for each of them.

The terms stated in Table 4.1 are in English, the original set of Italian stimuli is shown below, in Table 4.2. For each key term there were three synonyms and three antonyms. Synonyms and antonyms were chosen from an Italian dictionary, and relatively to the semantic field considered. The words were presented in Trebuchet MS font, with a font size of 36 pixels, in achromatic grey (RGB = 153, 153, 153) and centered within the hue circle (see Figure 4.1a). The hue circle was made up of 40 small circular patches showing the full series of hues and had a diameter of 225 pixels. Both the hue circle and the words were presented against a white background.

Table 4.1. Stimuli words presented to the participants (English translations of Italian stimuli). The five initial words are in the first column, followed by the respective synonyms and antonyms tested for each of them.

Key words (English)	**Synonyms**	**Antonyms**
Accuracy	Diligence conscientiousness precision	Negligence carelessness imprecision
Impartiality	Fairness neutrality objectivity	Unfairness bias partisanship
Independence	Autonomy freedom emancipation	Dependence subjection subordination
Legality	Legitimacy lawfulness regularity	Illegitimacy unlawfulness arbitrariness
Responsibility	Awareness judiciousness sagaciousness	Irresponsibility recklessness foolishness

The task consisted of coloring a word belonging to a series of 35 with a color taken from the hue circle. The experiment involved the presentation in random order of all 35 words. Also, the orientation of the hue circle varied randomly between one word and the next. The independent variable was the word presented, a 35-level qualitative variable; the dependent variable was the color selected to render the word, a 40-level qualitative variable: the 40 hues of the NCS Hue Circle. The hue circle was taken from the NCS Atlas; it presented 40 hues, including the four unique hues—yellow, red, green, blue—and intermediate ones as the one used in Experiments 1-3 (see Figure 2.2, Chapter 2).

Table 4.2. Actual stimuli words presented to the participants in Italian. Again, the five initial words are in the first column, followed by the respective synonyms and antonyms tested for each of them.

Key words (Italian)	**Synonyms**	**Antonyms**
Accuratezza	Diligenza coscienziosità precisione	Negligenza trascuratezza imprecisione
Imparzialità	Equità neutralità obiettività	Iniquità parzialità partigianeria
Indipendenza	Autonomia libertà emancipazione	Dipendenza soggezione subordinazione
Legalità	Legittimità liceità regolarità	Illegittimità illecito arbitrio
Responsabilità	Consapevolezza assennatezza avvedutezza	Incoscienza insensatezza dissennatezza

Task and procedure

The participants were invited to take part in the experiment online, and they logged on via the relevant link. Before the experiment began, participants were expressly told to avoid making associations between the words presented and any past experience they might have had of the color in the lettering of advertisements, newspapers, etc. Moreover, in the instructions given, care was taken to avoid mentioning the use of color categories (e.g. 'red', 'green', 'blue'). Each subject who agreed to participate accessed a registration form including an informed consent declaration. This was followed by a data entry form to be completed with: age, gender, mother tongue, manual preference, conditions of eyesight, and possible difficulties in the perception of colors. Then, the following written instructions were given for the task:

> *"You will be shown a series of screens with words representing abstract concepts. For each word, choose the color that you most closely associate with it from among the 40 colors of the Hue Circle arranged around the word."*

The experiment then began. Projected on the subject's monitor was the hue circle, at the center of which the 35 words were presented one at a time in grey. For each of these words, the subject chose the color among the 40 hues of the circle which, in his or her opinion, best characterized that word. As the word was rendered with the color chosen, the subject viewed the effect of the choice and, when satisfied, confirmed his or her choice (Figure 4.1). The next word then appeared, again in grey, within the hue circle, and so on until all the words had been presented. The experiment concluded with thanks to the volunteers for their participation.

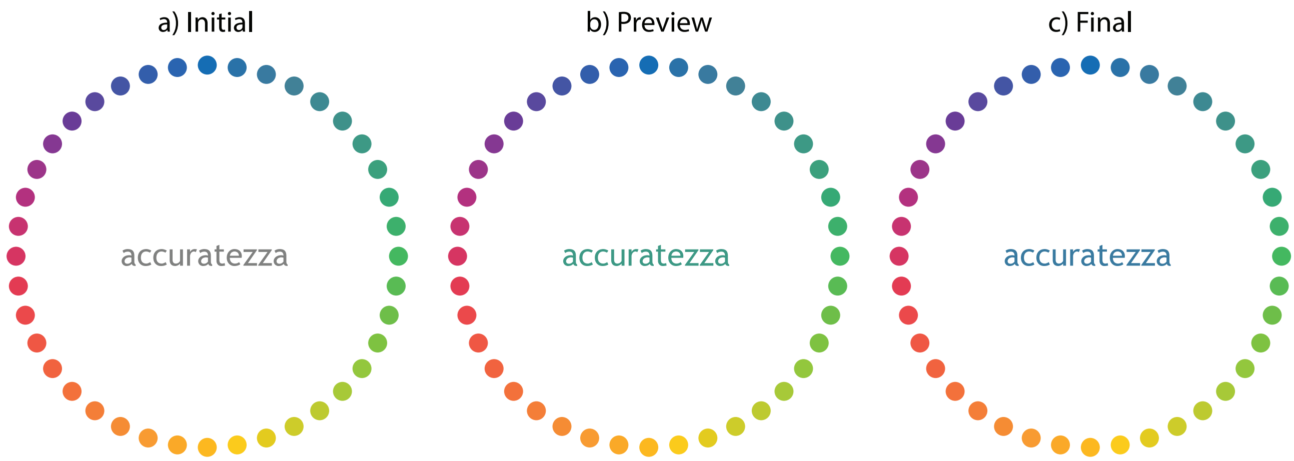


Figure 4.1. Word–color association task, as presented to the participants: an example with the key word 'accuratezza' (accuracy). The participants saw the word in grey at the center of the Hue Circle (a); they could view the effect of the filling by clicking on more than one color in the hue circle (b), and could confirm their choice when satisfied (c).

4.2.2 Results

The chi-squared test for a contingency table was employed to evaluate the association between words and colors. A residual analysis was performed to identify which color–word combinations were significant (Canal & Micciolo, 2013). Analyses were performed with R 2.15.0 software (R Development Core Team, 2011).

The chi-squared test was used to evaluate the departure from independence with respect to the association between the variables 'concept' and 'color'. A significant association was found between these two variables (chi-square = 3603; d.f. = 1326; $p < 0.001$).

The contingency table between color (40 colors) and concept (35 words) had 420 out of 1400 cells (30%) with an expected frequency less than 5. We therefore grouped together the three synonyms and the three antonyms of each of the five original words ('accuracy', 'impartiality', 'independence', 'legality', 'responsibility'), thus obtaining a new variable with 15 levels. The contingency table between the 40 colors and this new variable had 60 out of 600 cells (10%) with an expected frequency less than 5 (the minimum expected frequency was 3.63). Again, a significant association was found between color and concept (chi-square = 2280; d.f. = 546; $p < 0.001$) after aggregation.

There were 202 residuals greater than 1.96 in absolute value (30 were expected if color was randomly selected). Table 4.3 shows the cells where these residuals were located; '+' indicates a residual greater than 1.96, while '−' indicates a residual lower than −1.96. A positive residual means that the selected group of words 'attracts' the corresponding color; a negative residual means that the selected group of words 'repels' the corresponding color.

A pattern of residuals is well evident in Table 4.3. In particular, the sign of the residuals of the original words and the sign of the corresponding (aggregated) synonyms are always the same (when both are shown in Table 4.3) and opposite to the sign of the residuals of the corresponding (aggregated) antonyms. Therefore, the sign of the synonyms and the corresponding antonyms are opposite each other. In fact, the correlation coefficient between the residuals of synonyms and antonyms (considering all the residuals and not only those greater than 1.96 in absolute value) was −0.708 (d.f. = 279; $p < 0.001$).

As regards the original words, the highest positive residual (3.18) for accuracy was associated with B10G, and the highest negative residual (−2.26) was associated with R40B; the highest positive residual (2.84) for impartiality was associated with B40G, and the highest negative residual (−2.97) was associated with R; the highest positive residual (3.28) for independence was associated with G30Y, and the highest negative residual (−2.39) was associated with R70B; the highest positive residual (4.04) for legality was associated with G40Y, and the highest negative residual (−2.63) was associated with R20B; the highest positive residual (4.16) for responsibility was associated with B, and the highest negative residual (−2.50) was associated with Y. The most evident pattern in the residuals was observed for impartiality, whose synonyms were generally positively associated with colors containing green and negatively associated with colors containing red, and whose antonyms were generally positively associated with colors containing red and negatively associated with colors containing green.

Table 4.3. 'Attractions' (+) and 'repulsions' (–) between the 40 colors of the hue circle and the five selected key words, as well as their synonyms and their antonyms. A '+' sign is shown when the corresponding standardized residual is greater than 1.96. A '–' sign is shown when the corresponding standardized residual is lower than –1.96. The horizonntal bar represents an approximate subtivision between 'warm' (upper half) and 'cool' (lower half) hues. (See Figure 4.2 for the subdivision of the Hue Circle in warm and cool hues).

	Accuracy			**Impartiality**			**Independence**			**Legality**			**Responsibility**		
	Original	**Synonyms**	**Antonyms**	**Original**	**Synonyms**	**Antonyms**	**Original**	**Synonyms**	**Antonyms**	**Original**	**Synonyms**	**Antonyms**	**Original**	**Synonyms**	**Antonyms**
G80Y		-	+					-						-	+
G90Y			+												
Y					+		+	+	-				-		
Y10R															
Y20R															
Y30R		-				+								+	
Y40R				+											
Y50R						+	+								
Y60R			+												+
Y70R								-	+						
Y80R					-	+						+			+
Y90R				-	-	+			+		-	+		-	+
R		-		-	-	+				-	-	+		-	+
R10B		-			-				+			+			+
R20B		-	+		-		-		+	-		+			+
R30B		-	+		-	+		-	+						+
R40B	-	-	+			+				-	-	+		-	+
R50B		-	+		-		-		+		-			-	+
R60B	-	-	+		-				+		-	+			+
R70B			+		-		-	-	+			+	+		
R80B	+	+	-			-							+		-
R90B		+	-		+	-		+	-	+	+	-	+	+	-
B		+	-		+	-			-	+	+	-	+	+	-
B10G	+	+	-			-		+				-		+	-
B20G		+	-		+							-		+	
B30G															
B40G	-			+	+			-							
B50G						-									
B60G								-		-					
B70G				+				-							-
B80G												-			-
B90G		+	-		+		+		-			-			-
G		+	-		+				-		+	-		+	-
G10Y		+	-	+	+	-	+				+		-		-
G20Y			-				+	+	-		+	-	+		-
G30Y	+				+	-	+		-	+	+	-			-
G40Y			-		+	-	+		-	+					-
G50Y					+										
G60Y		-	+												
G70Y			+							-					+

More generally, on considering the original words and their synonyms, we could see that positive associations emerged with blue and green colors and negative associations with red and yellow ones. The opposite was the case when the antonyms were taken into account.

These results are more evident if we count the number of '+' (attractions) and of '–' (repulsions) in Table 4.3 after having divided the hue circle into two halves (see Figure 4.2). The first half, starting with G80Y and ending with R70B, can be considered the 'warm' half of the hue circle. The second, starting with R80B and ending with G70Y, can be considered the 'cool' half of the hue circle. The original words and their synonyms attract a 'cool' color in 87.9% of cases (51 out of 58), while they repel a 'warm' color in 84.3% of cases (43 out of 51); the odds ratio is therefore 39.2. The reverse occurs when the antonyms are taken into account. They attract a 'warm' color in 93.5% of cases (43 out of 46), while they repel a 'cool' color in 97.9% of cases (46 out of 47); the odds ratio is therefore 659. Figure 4.2 shows the 40 hues of NCS hue circle, the labels of each individual hue, as well as their approximate subdivision in 'warm' and 'cool' hues.

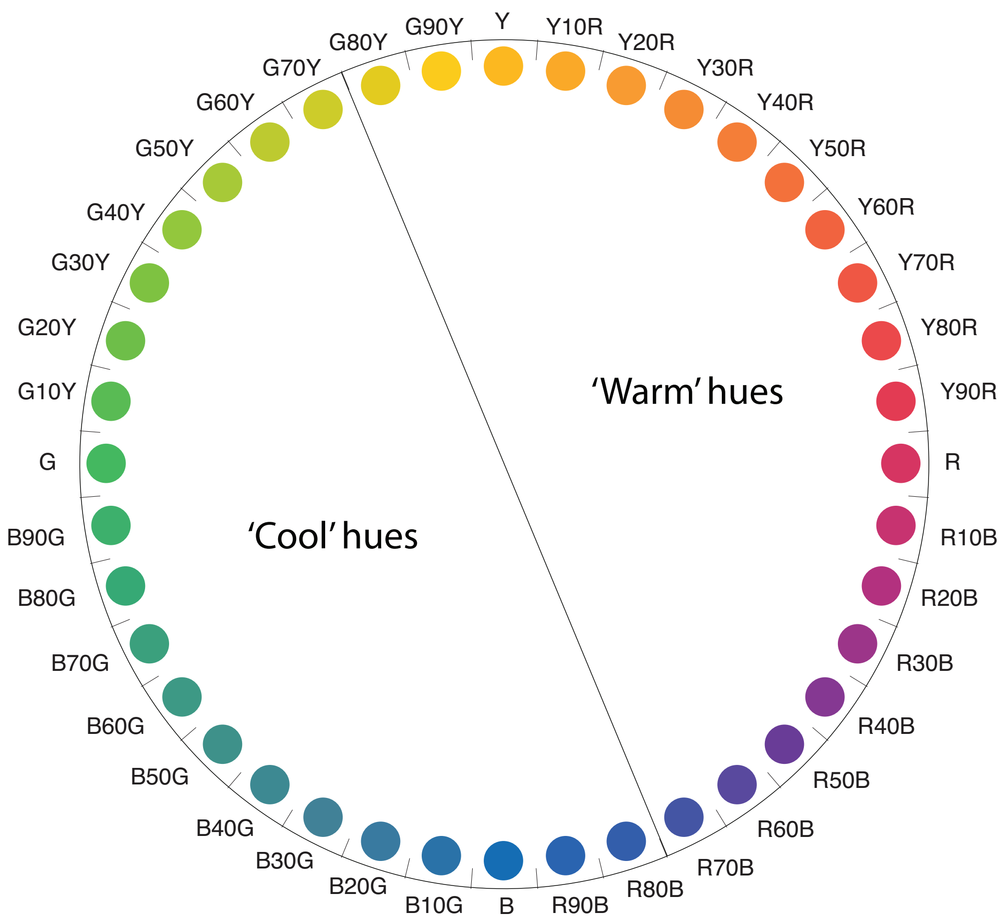


Figure 4.2. The image shows the 40 hues of the NCS Hue Circle and their labels. The thirty-six hues are identified by a letter–number combination indicating the chromatic attributes included and the relation between these (for example, Y90R is a yellow hue with 90% redness). The remaining 4 hues are identified by the letters Y (100% yellow), R (100% red), B (100% blue), and G (100% green). The circle is here divided into two halves: 'cool' hues and 'warm' hues. Indeed, we have been analyzing attractions and repulsion between abstract terms and cool and warm colors.

4.3 Discussion of Experiment 6

In this experiment, for the first time the existence of associations between specific abstract terms and specific colors was tested in the general population. We used a selection of terms related to an abstract semantic field (ethics of social behavior) to test whether different words really lead to consistent choices of colors (hues). The results show a highly significant nonrandom and remarkably systematic association between terms and hues. Our hypothesis was that a few abstract terms related to a specific semantic field (in this case, ethics in social behavior) would be associated with certain colors, and their synonyms and antonyms likewise. Owing to the high number of expected frequencies less than 5 (30%), some aggregation was mandatory. The most natural choice was to aggregate together the three synonyms of each word, as well as the three antonyms, even if some modest differences between the responses to synonyms and between the responses to antonyms appeared to exist. However, to evaluate the consistency of the results found after the aggregation, an analysis was also performed on the residuals of the 'full' contingency table (40 colors and 35 words). The results (not shown) were quite similar to those found on the aggregated words.

The main hypothesis that there appear to be 'hues of concepts' (see Albertazzi et al., 2014) was borne out by the results: the abstract terms considered were associated with blue/green (i.e. cold) colors as well as their synonyms, while their antonyms were associated with red/yellow (i.e. warm) colors. One can say that concepts can be arranged along a 'warmth continuum' between the two extremes of cold and warm (Da Pos & Valenti, 2007), suggesting the existence of perceptually cool and warm concepts, according to their consistent matching with cool and warm hues. We believe it highly unlikely that the results can be explained in terms of the visual form (e.g. Spector & Maurer 2008, 2011) of the terms representing abstract concepts. In fact, the list of the terms in Italian shows that the synonyms did not systematically start with groups of similar letters (nor the antonyms with similar letters but different from those of the synonyms of the key word in question). A possible explanation of the results lies in the positive or negative valence of the terms/concepts considered, together with the colors' warm or cold valence.

Other aspects highlighted by our results concern the internal structure of the semantic field considered. Indeed, the associations of the words with colors could yield information about the relative 'positions' of the abstract concepts in the semantic field, and about their different 'weight' and prototypicality. For example, the word 'emancipation' (as a synonym for 'independence') was associated with red, contrary to the other synonyms for the key words, which were usually associated with blues and greens. One may therefore ask whether the semantic value of the word 'emancipation' as a synonym for independence is less than that of the other synonyms considered—autonomy, freedom, and legitimacy (all associated with blue). Or, as regards antonyms, one observes that, because 'negligence' and 'carelessness' (antonyms of 'accuracy') or 'subjection' and 'subordination' (antonyms of 'independence') had mixed associations with red and blue, they had less value than other antonyms of the same key words—'imprecision' and 'dependence', respectively. As for the question of how this information complements (or otherwise) information on word usage, on the basis of the results obtained it seems possible to conclude that linguistic use does not always correspond to the real synonymic value of a word in a particular semantic field. It seems that some terms, within a particular semantic field, have stronger/more prototypical nuclei of meaning than others. One might therefore consider revising the dictionary terms in light of the associations that our experiment revealed. To do this, however, the analysis should be extended to a larger number of semantic fields. In turn, the colors associated with the words also do not have the same significance. For example, 'responsibility' (as well as its synonyms) shows most of the positive residuals associated with the unique hue 'blue' and with its contiguous colors; likewise, 'blue residuals' are predominant for 'accuracy'. On the other hand, green colors are predominant for 'independence'. This means that, in the case of cold colors, there is a characterization of the words towards the different unique colors.

The results obtained may contribute to the debate on the status of concepts, a key topic in cognitive science, the point at issue being whether (and how) abstract concepts can be traced back to empirical ones. Color space, and specifically the hue circle, can also be considered a viable spatial modelling framework for the semantic space of concepts, and for the relative weights of the terms of a semantic field: for example, it may assist in establishing which, among certain words, is the covering term (header) of that field. In our case, for example, the word 'responsibility', which has the highest residual, could be considered the 'header' because it shows the highest evidence against the hypothesis of a random association.

The field of analysis opened up by this type of inquiry is obviously very extensive, and further research may both specify our experiments in more detail and engage in new ones. For example, we did not analyze all the aspects of the color–concept relation, but restricted our inquiry to a particular relation—that between colors (hues) and abstract terms in one semantic field. Other studies might extend the range of terms for the semantic field considered or investigate different abstract semantic fields. Further analyses might also develop cross-cultural and cross-linguistic studies, also considering less industrialized societies. Finding consistency across cultures, in fact, would confirm the existence of an association between the words/concepts and color, supporting the hypothesis that color is a strong concept descriptor from a universal viewpoint. Our findings may also be relevant to a series of disciplines, such as ergonomics, and specifically the design of graphic interfaces as regards the use of colors more closely matching particular contexts/meanings that the graphic interface wants to convey, thus ensuring that the words appearing on the website are not haphazardly chosen. Finally, the results may guide the search for neural correlates of the associations in the abstract domains of conceptualization.

CHAPTER 5

General conclusion

5.1 What have we learned?

The study of cross-modal and cross-dimensional associations in non-synesthetes has become an increasingly popular research topic in recent times (see Spence, 2011, for a review). The main purpose of our research was to test whether non-synesthetes also exhibit systematic associations between two different dimensions of the visual domain: shape and color. Because shape and color were the focus of our research, some aspects of the present studies could also be related to art and, in particular, to the theory developed by the abstract artist Wassily Kandinsky on shape-color correspondences. As explained in the General Introduction, the project consisted of six experiments (see Table 5.1 for an overview), some of them (Experiments 1-3 and 6) carried out in the Experimental Psychology Labs at the University of Trento under the supervision of Prof. Liliana Albertazzi, and the others (Experiments 4-5) carried out in the Visual Perception and Aesthetics Lab at the University of California Berkeley, under the supervision of Prof. Stephen Palmer.

Experiment 1 provided striking initial evidence that people tend to systematically match certain hues to certain simple geometric shapes, in line with other recent evidence of cross-modal and cross-dimensional associations in non-synesthetes. Strong relations were found for instance between a circle or a square and reds, a triangle or a pyramid and yellows, a hexagon and red-blues, and a parallelogram with blues. Early analyses suggested a role of color temperature in the association of particular hues with particular shapes, as well as a role of the natural lightness of hues: the triangle and the circle were the “warmest” shapes, whereas the parallelogram was the “coolest”; the triangle and the circle were the “darkest” shapes, as opposed to the pyramid and the cone, which were the “lightest”. Experiment 2 confirmed the overall pattern of shape-to-color associations that emerged in Experiment 1 with a different group of participants and showed that such shape-color associations are independent of a shape’s size, area/perimeter, and gravitational stability. Chen et al. (accepted) replicated Experiment 1 in Japan using the same method, and showed that systematic shape-to-color associations are observed in Japanese too. It is worth noting that some associations—such as the ones between circle and red and triangle and yellow—were the same that we found for Italian participants. Kandinsky’s theory that a triangle is yellow, a square is red, and a circle is blue, seems to be supported only in part by our findings: a triangle was associated with yellow, and a square was associated with red, but a circle did not turn out to be associated with blue.

Kandinsky also suggested that the relations between certain shapes and colors would be driven by the shapes' angles. A further experiment (Experiment 3) was then conducted to examine the relation between angles and hues, showing that participants also systematically established an association between such parts of shapes (i.e., angles) and hues. Overall, participants tended to match acute angels with warm hues and obtuse angles with cool hues. Some of the strongest relations were, for instance, the one between the angle of 22.5° and yellows and the one between the angle of 157.5° and red-blue. Experiment 3 also allowed us to conduct comparisons with the results obtained in the previous experiments, in order to determine *a posteriori* whether angles could be decisive for the association between certain geometric shapes and colors: for example, whether the presence of acute angles in a triangle or of right angles in a square influences the association of the overall figure with a particular hue. The presence of specific angles in a shape did not seem to explain the results so far obtained for the overall geometric shapes in their entirety. For instance, it is true that the overall triangle which is characterized by acute angles, mainly matched to yellow, was associated to yellow; whereas the overall square which is characterized by right angles, mainly matched to green-yellow and yellow-red, was associated to red. Since the angles of a shape alone did not explain the choice of the color to be matched with the overall shape, we extended the study to a wider variety of shape-features of the global shapes.

Experiment 4 and 5 extended the study of shape-to-color associations in non-synesthetes to color attributes other than the hue (i.e., saturation and lightness) and to a wider variety of shapes and shape-features. Two sets of stimuli were employed—a set of line-shapes in Experiment 4 and a set of closed geometric shapes in Experiment 5—which were manipulated to vary systematically with respect to a series of geometric shape-features, including their pointedness, symmetry, concavity, intersections, and number of generating-points. Subjective perceptual ratings of such shape-features were also obtained from our participants. The results showed that at least some of the shape-features studied influenced at least some of the color attributes (saturation, lightness, redness/greenness, and yellowness/blueness) of the associated colors. The objective geometric and the subjective perceptual features of a shape could predict the color appearance of the associated colors to similar degrees. In particular, a shape's pointedness seemed to be the factor that most strongly influenced color choices in both experiments: more angular line-shapes, as well as pointier closed geometric shapes, produced color choices that were on average more saturated and redder with respect to color choices for curved ones. Other specific associations between shape-features and color-attributes could be observed; for instance, intersections of line-shapes as well as symmetry-axes of closed geometric shapes, produced color choices that were more saturated and redder.

A second objective of Experiments 4-5 was to explore the role of emotion as a possible mediator in shape-to-color associations. In particular, we tested the Emotional Mediation

Hypothesis or "EMH" (Palmer et al., 2013) for shape-to-color associations, according to which people would match colors to shapes on the basis of their shared emotional associations. Results were consistent with the "EMH": for instance, colors rated as being "angry" or "harmful" were chosen as going best with shapes that were rated as being "angry" or "harmful" by our participants; similarly, colors rated as being "happy" were chosen as going best with shapes that were rated as being "happy". The angriness/harmfulness emotional dimension was the one that more strongly characterized both sets of stimuli, whereas happiness seemed to partially characterize closed geometric shapes but not line-shapes. The emotional space of shape-stimuli could be seen as constituted by two main dimensions that roughly reflect their high/low potency (angriness/harmfulness) and positive/negative valence (happiness), which are the two main dimensions that constitute the emotional space of colors too (Wright & Rainwater, 1962; D'Andrade, Egan, 1974). Even though the present findings are totally consistent with the "EMH", they do not allow us to establish whether there is a causal role of emotions in producing the pattern of shape-to-color associations emerged. Future research should attempt to clarify the relative contributions of perceptual and emotional factors, as well as the way they relate to each other. Moreover, the potential role played by further factors (such as preference, or object-mediated conscious/subconscious associations) could be explored.

Finally, Experiment 6 consisted of a collateral study aimed at assessing a further kind of systematic association in the general population: the association between words related to abstract concepts and hues. Even though this experiment departs from the main (perceptual) aims of the present project, it provides a valuable example of how studies of this kind can be applied to a variety of fields and shed light on other processes, such as language. In the present experiment, systematic associations were found between a series of terms related to the frame of ethics in social behavior and hues. More precisely, results showed that the series of key-terms studied (accuracy, impartiality, independence, legality, and responsibility) and their synonyms were matched to blue-green (cool) colors, whereas their antonyms were matched to yellow-red (warm) colors. The association provides information about the nature of abstract concepts and their relationship with perception.

Altogether, the present project provides additional examples of associations in the non-synesthetic population. We suggest that this new trend of research, in general, could improve the study of human perception, cognition, and language, and guide collateral studies on the neural correlates of the results. We also hope that the specific line of research that we started could help bridge the gap between shape and color, which are often studied separately in visual perception, as well as to find possible applications in a variety of disciplines, including ergonomics, art, and design.

Table 5.1. Overview of Experiments 1-6. The table summarizes the main findings of each Experiment and how they relate to each other.

Experiment 1	• people systematically match **hues** to **shapes**, • Kandinsky's art theory on shape-color correspondences is partly supported by our results (i.e., a triangle was associated with yellow, and a square was associated with red, but a circle did not turn out to be associated with blue), and • additional associations between shapes and hues are described.
Experiment 2	• evidence from Experiment 1 is replicated with another group of participants, and • the shape-color associations found previously are independent of a shape's size, area/perimeter and stability.
Experiment 3	• people systematically match **hues** to **angles**, and • the results suggest that the angles may play a role in determining some of the shape-color associations found in Experiments 1 (e.g., the association between triangle and yellow could be explained by the presence of acute angles which are associated with yellow)
Experiments 4	• non-synesthetes systematically match line-shapes and colors, • specific **features** of **line-shapes** influence specific **color attributes** of the associated colors (e.g., more angular line-shapes produce more saturated, darker, and redder color choices), and • the results are consistent with the Emotional Mediation Hypothesis, (e.g., "angry" colors are associated with "angry" lines)
Experiments 5	• the results of Experiment 4 are extended to closed geometric shapes, • specific **features** of **closed geometric shapes** influence specific **color attributes** of the associated colors (e.g., pointier closed geometric shapes produced more saturated, redder, color choices), and • the results are consistent with the Emotional Mediation Hypothesis, (e.g., "harmful" colors are associated with "harmful" shapes)
Experiment 6	• people systematically match **hues** to **words** pertaining to an abstract semantic field: a series of key-terms and their synonyms were matched to blue-green (cool) colors, whereas their antonyms were matched to yellow-red (warm) colors.

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Appendix 2.1. CIELAB values of the printed Hue Circle used in Experiment 1. L*, a*, b* are the coordinates of the CIE (Commission Internationale d'Eclairage) 1976 color space (CIELAB). The illuminant is approx. 3200K (halogen lamp) for printed colors.

N	L*	a*	b*	N	L*	a*	b*
1	49.61	21.41	-10.18	21	83.11	-8	43.97
2	57.37	33.73	2.83	22	78.92	-10.95	37.78
3	57.27	35.79	9.63	23	69.94	-19.3	28.82
4	58.52	36.64	16.16	24	65.24	-22.46	11.51
5	55.98	36.61	16.41	25	57.22	-29.52	-0.49
6	59.09	38.23	23.06	26	47.50	-35.5	-7.1
7	61.15	41.14	29.36	27	47.84	-35.4	-12.56
8	66.01	38.57	32.56	28	46.95	-34.52	-16.99
9	68.65	34.91	34.12	29	48.70	-34.84	-23.22
10	70.68	31.75	33.76	30	49.41	-34.82	-24.68
11	71.85	29.53	38.87	31	50.29	-34.56	-27.39
12	72.83	27.56	45.73	32	48.21	-34.68	-24.37
13	76.40	22.31	49.92	33	49.39	-32.56	-36.56
14	78.73	18.59	54.73	34	48.26	-31.57	-40.11
15	81.33	14.02	58.36	35	51.25	-30.09	-43.8
16	85.93	5.54	63.61	36	48.52	-27.56	-48.6
17	88.53	0.5	62.95	37	45.66	-25.48	-46.89
18	88.91	0.02	60.79	38	43.59	-21.74	-41.64
19	88.59	-1.38	59.91	39	45.86	-13.75	-36.27
20	85.31	-4.36	55.3	40	42.88	-4.07	-27.79

Appendix 2.2. CIELAB values of the Hue Circle used in Experiment 2 and in Experiment 3. L*, a*, b* are the coordinates of the CIE (Commission Internationale d'Eclairage) 1976 color space (CIELAB). The illuminant is approx. D65 (6500K) for colors observed on the screen.

N	L*	a*	b*	N	L*	a*	b*
1	86.34	0	81	21	50.01	-2	-45.5
2	84.52	-10	79	22	48.20	5	-50
3	82.71	-18	76	23	46.38	14.5	-51
4	80.89	-24	72	24	44.57	25	-48
5	79.07	-32	67	25	42.75	32	-41
6	77.26	-40	61	26	45.47	39.5	-31.5
7	75.44	-47	55	27	48.20	45	-23
8	73.63	-51	46	28	50.92	51.5	-13
9	71.81	-54	38	29	53.65	55	0
10	69.99	-54	29	30	56.37	56	12
11	68.18	-51.5	20	31	59.10	55	25
12	66.36	-48	12	32	61.82	53	35
13	64.54	-43	6	33	64.55	51	43
14	62.73	-37	0	34	67.27	48	51
15	60.91	-32.5	-5.5	35	70.00	43	57
16	59.10	-27	-12	36	72.72	37	63
17	57.28	-20	-18	37	75.44	31	70
18	55.46	-16	-25	38	78.17	25	74
19	53.65	-12.5	-32	39	80.89	16	77.5
20	51.83	-9	-40	40	83.62	8	80

Appendix 3.1. CIE 1931 values for the 32 chromatic colors of the Berkeley Color Project (Palmer & Schloss, 2010; Schloss & Palmer, 2011) and CIE 1931 values for the four achromatic colors with CIE Illuminant C (Schloss, Poggesi, & Palmer, 2011) used in Experiments 4–5. The first letter in the color name refers the ‘‘cut’’ [saturated (S), light (L), muted (M), and dark (D)]. The second letter in the name refers to the hue [red (R), orange (O), yellow (Y), chartreuse (H), green (G), cyan (C), blue (B) and purple (P)].

Color	x	y	Y (cd/m2)
SR	0.549	0.313	22.93
LR	0.407	0.326	49.95
MR	0.441	0.324	22.93
DR	0.506	0.311	7.60
SO	0.513	0.412	49.95
LO	0.399	0.366	68.56
MO	0.423	0.375	34.86
DO	0.481	0.388	10.76
SY	0.446	0.472	91.25
LY	0.391	0.413	91.25
MY	0.407	0.426	49.95
DY	0.437	0.450	18.43
SH	0.387	0.504	68.56
LH	0.357	0.420	79.90
MH	0.360	0.436	42.40
DH	0.369	0.473	18.43
SG	0.254	0.449	42.40
LG	0.288	0.381	63.90
MG	0.281	0.392	34.86
DG	0.261	0.419	12.34
SC	0.226	0.335	49.95
LC	0.267	0.330	68.56
MC	0.254	0.328	34.86
DC	0.233	0.324	13.92
SB	0.200	0.230	34.86
LB	0.255	0.278	59.25
MB	0.241	0.265	28.90
DB	0.212	0.236	10.76
SP	0.272	0.156	18.43
LP	0.290	0.242	49.95
MP	0.287	0.222	22.93
DP	0.280	0.181	7.60
White	0.310	0.316	116.00
Black	0.310	0.316	0.30
Dark Gray	0.310	0.316	12.34
Med. Gray	0.310	0.316	31.88
Light Gray	0.310	0.316	63.90

Appendix 3.2.

Synesthesia Battery prescreening questionnaire. All participants answering 'Often' or 'All the time' to one or more items, or reporting to experience any other kind of unusual sensory experience in the last two questions, were required to take the whole Synesthesia Battery by Eagleman et al. (2007) online (www.synaesthete.org). Data from participants who classified as synesthetes according to the Battery were excluded.

1. Does seeing, thinking of, or hearing a number cause a perception of color?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

2. Does seeing, thinking of, or hearing a letter cause a perception of color?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

3. Does the concept of days such as Monday or Tuesday, and so on, trigger a color?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

4. Do the concepts of months, such as January and February, and so on, trigger a color?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

5. Do Chinese numbers cause a perception of synesthetic colors?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

6. Do you visualize numbers, letters or time units like weekdays or months as being spread out in a 3D space around you?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

7. Do individual keys on a piano or other instrument cause color perception?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

8. Do different musical chords cause perception of different colors?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

9. Do different musical instruments cause perception of different colors?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

10. Does seeing a Chinese character cause a perception of color?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

11. Do tastes trigger a color for you? For example, does the taste of chocolate, citrus, or banana trigger a color?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

12. Do smells trigger a color for you? For example, does the odor of steak or fries cause the perception of a color in you?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

13. Does pain trigger a color for you? For example, do different levels of pain you experience at different times, say while having a headache, cause you to perceive color?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

14. Does seeing or thinking of a person make you perceive a color?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

15. Do tactile sensations trigger a color for you? For example, when you experience touch sensations of different kinds, on different parts of your body, do you also perceive color?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

16.Do heat and cold trigger colors in you? For example, does touching cold water or feeling warm water in a shower cause you to perceive different colors?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

17. Do seeing, thinking of, or hearing a Czech letter cause a perception of color?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

18. Do you perceive different colors while experiencing a sexual orgasm?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

19. Do different emotions like joy, gloom cause perception of color?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

20. Does seeing a picture or a scene also cause you to hear a sound?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

21. Does hearing a sound cause a distinct odor, like the noise of water gushing arouses the smell of a rose?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

22. Does seeing an object or a scene cause you to perceive a distinct smell?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

23. Does hearing a sound cause a sensation of touch for you? For example, does hearing an airplane fly past cause a distinct sensation of touch?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

24. Does hearing a sound cause a sensation of taste for you? For example, does the ticking of a clock cause a sour taste in your mouth?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

25. Does seeing a picture, object, or a scene cause the sensation of a taste for you?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

26. Does the American Sign Language cause a perception of color for you?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

27. Does the British Sign Language cause a perception of color for you?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

28. Does the Cyrillic Alphabet cause experiences of color for you?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

29. Does the Greek Alphabet cause experiences of color for you?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

30. Does the Hebrew Alphabet cause experiences of color for you?
☐ Never ☐ Rarely ☐ Sometimes ☐ Often ☐ All the time

31. We have described a few types of synesthesia. Many other unusual blendings of the senses have been reported. Do you suspect that you experience an unusual blending that other people do not have (other than the ones listed above)? Those could include automatically hearing a sound when you see movement, or the sense of a shape being triggered by a taste, or experiencing a color when feeling pain.

☐ Yes, I believe I may have other forms of unusual sensory experiences
☐ Not that I know of

32. Please describe any other unusual blending of the senses that you think you might have and that other people do not have. If you would like to add any comments about the experiences that are mentioned in this survey as well, feel free to do so.