Memory effects on color perception

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Introduction

Does knowledge about an object's typical color influence how we perceive the actual color of this object? For example, Germans know that a German mailbox is yellow (cf. left side of Figure 31.1). Does such knowledge influence how we see the actual color of a mailbox? Or can we perceive the color independently of our prior knowledge? These are the questions at the core of research on the so-called memory color effect.

A memory color is the typical color of an object that we memorized through our experience with the respective object (for a review, see Witzel and Gegenfurtner, 2013). In some areas of research, the term "canonical colors" is used to refer to memory colors. An object that has a memory color, such as a ripe banana or a German mailbox, is called color diagnostic because the color is informative about the identity of the object (and vice versa). For example, yellow is a character- istic feature of a ripe banana and a German mail- box. In contrast, objects that are not associated with a typical color, such as cars, may be called color-neutral to indicate that they are not color diagnostic.

Memory colors affect several aspects of color perception, including object and scene recogni- tion, color memory, color naming, and color con- stancy. The memory color effect even shows that memory colors directly influence color appear- ance. Color appearance refers to how a color subjectively appears or "looks" to the beholder. According to the idea of a memory color effect, the color of an object is not perceived indepen- dently of the object itself. Instead, the identification of the object automatically brings about the impression of its typical color.

This idea is illustrated in Figure 31.1. According to the memory color effect, the gray mailbox on the right should appear yellow to a German observer. This idea may seem surprising or even absurd since the right mailbox looks rather gray in comparison to the left mailbox in Figure 31.1. Nevertheless, numerous studies found strong evidence for such a memory color effect. Highly color diagnostic objects are per- ceived slightly tinted with their typical color, when they are actually gray (Hansen, Olkkonen, Walter, and Gegenfurtner, 2006; Olkkonen, Hansen, and Gegenfurtner, 2008; Witzel, Valkova, Hansen, and Gegenfurtner, 2011).

Memory color effects show how memory and expectations based on prior experience can influence the perception of color (see also Olkkonen, Hansen, and Gegenfurtner, 2012). Evidence for memory colors is relevant from two perspectives (e.g., Witzel et al., 2011). On the one hand, it provides insight about color perception. On the other hand, it constitutes a prime example to answer questions about the influence of learning and experience on perception in general. For this reason, memory color effects are relevant to a wide range of fundamental questions, such as functional segregation, cognitive penetrability, constructivism, and color realism. These questions span different disciplines, ranging from psy- chology and neuroscience to philosophy.

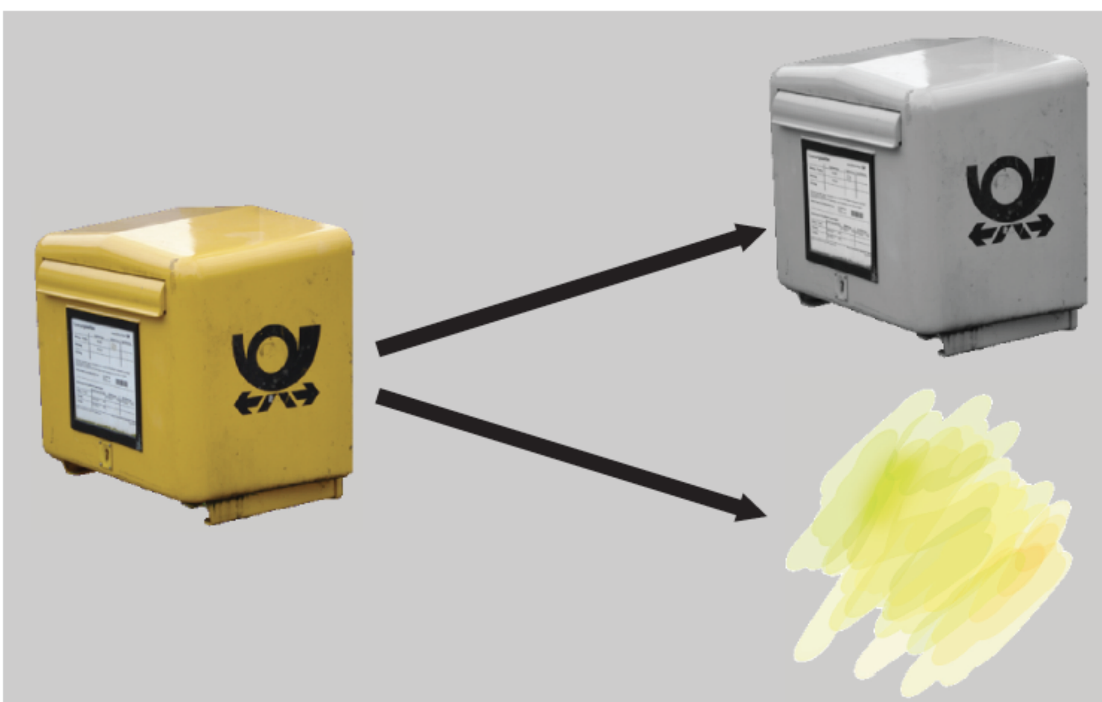

Figure 31.1 Memory color of a German mailbox. The left side shows a German mailbox in its typical color. The right side separates the object from its color. According to the memory color effect, we cannot perceive the actual color of the mailbox independently of its typical color. More precisely, a gray mailbox like the one on the top right looks slightly yellowish. This kind of memory color effect is the main topic of this chapter.

The present chapter reviews research on how memory and expectations based on prior experience can influence the perception of color. It is organized as follows. The first section gives an overview of the evidence for memory effects on color appearance. The second section outlines the effects of memory colors on other aspects of color perception, such as object recognition, color naming, memory, and constancy. Determinants of memory color effects are summarized in the third section. The fourth and final section briefly discusses how the memory color effect is related to fundamental questions about the human mind.

Memory color effects on color appearance

Already in the twentieth century, there were sev- eral empirical attempts to show memory color effects on color appearance. However, the results were contradictory and, due to methodological concerns, not unambiguously interpretable. Only during the last few years, could it be shown that "memory modulates color appear- ance" (Hansen et al., 2006).

The idea of memory color effects

The idea that memory and experience influence the way we perceive the colors of objects in our environment had already been suggested by Hermann von Helmholtz in 1867. He claimed that "a large part of our perceptual-image may be due to factors of memory and experience." (von Helmholtz, 1925/1867, p. 11). With respect to color, he proposed, for example, that the lightness of a white sheet of paper may be influenced by the "unconscious influence of experience" (von Helmholtz, 1924/1867, p. 131).

The actual notion of memory color was intro- duced by Hering in 1878 in a famous passage (see also Harper, 1972; Jameson and Hurvich, 1989; Olkkonen et al., 2012):

The color in which we have most consistently seen an external object is impressed indelibly on our memory and becomes a fixed property of the mem- ory image. What the layman calls the real color of an object is a color of the object that has become fixed, as it were, in his memory; I should like to call it the memory color of the object. . . Moreover, the mem- ory color of the object need not to be rigorously fixed but can have a certain range of variation depending on its derivation. . . All objects that are already known to us from experience, or that we regard as familiar by their color, we see through the spectacles of memory color, and on that account quite differently from the way we would otherwise see them. (Hering, 1964/1878, pp. 7–8).

The quotation above also highlights that Hering's original notion of a memory color already implied the idea of a memory color effect – namely, that memory colors affect how we per- ceive the colors of objects.

Classic studies

During the twentieth century, several studies pur- sued Hering's idea (Adams, 1923; Bartleson, 1960; Bolles, Hulicka, and Hanly, 1959; Bruner, Postman, and Rodrigues, 1951; Delk and Fillenbaum, 1965; Duncker, 1939; Fisher, Hull, and Holtz, 1956; Harper, 1953; Herring and Bryden, 1970; Leibovich and Paolera, 1970; sup- plementary Experiment 3 of Newhall, Burnham, and Clark, 1957; Pérez-Carpinell, Fez, Baldoví, and Soriano, 1998; Siple and Springer, 1983; White and Montgomery, 1976). These classic studies typically asked observers to pick a color that matches the memory color of a color diagnostic object (Bartleson, 1960; memory matches in Bruner et al., 1951; Newhall et al., 1957; Pérez-Carpinell et al., 1998; Siple and Springer, 1983), or to match a comparison color to the color of outline shapes (Bolles et al., 1959; perceptual matches in Bruner et al., 1951; Delk and Fillenbaum, 1965; Duncker, 1939; Harper, 1953) such as the outline shapes of a rose leaf and a donkey used by Duncker (1939). Most of these studies have shown that observers exagge- rate the saturation when the color is congruent with the typical color of the object (Adams, 1923; Bartleson, 1960; Bruner et al., 1951; Delk and Fillenbaum, 1965; Duncker, 1939; Harper, 1953; Herring and Bryden, 1970; supplementary Experiment 3 of Newhall et al., 1957; Siple and Springer, 1983; White and Montgomery, 1976). For example, they would estimate a green fabric as more saturated when shown as the outline of a rose leaf than when shown as the outline of a donkey (Duncker, 1939). However, other studies could not find such effects of memory colors (Fisher et al., 1956; Leibovich and Paolera, 1970) or found inconsistent results across objects and experimental conditions (Bolles et al., 1959;

perceptual matches in Group 4 of Bruner et al., 1951; Pérez-Carpinell et al., 1998).

Overall, these classic studies left (at least) three important questions open (e.g., Harper, 1972, pp. 137–8; Siple and Springer, 1983). Firstly, does this effect only imply a general oversaturation of the color estimation; or does it really yield an additional impression of the typical hue? Secondly, does the memory color effect directly influence perception, or could it be explained by distortions in memory or judgmental biases? Finally, why did those classic studies yield con- tradictory findings?

Recent developments

Many of the questions left open by these classic studies were due to technical difficulties in simul- taneously controlling stimulus presentation, and recording the observers' answers. With the devel- opment of lighting and computer technology, new approaches were developed at the beginning of the twenty-first century to tackle the question of memory color effects. These studies included color estimations (Yendrikhovskij, Blommaert, and Ridder, 1999), color matching (Hurlbert and Ling, 2005), hue scaling (Hansen and Gegenfurtner, 2006), and color naming (Ling, Allen-Clarke, Vurro, and Hurlbert, 2008).

For example, one of these studies used a hue- scaling technique (Hansen and Gegenfurtner, 2006). In this technique, participants are shown a color on the computer screen, and they have to estimate the proportion of yellow, red, green, and blue in the presented color. It has been shown that these four colors, the so-called unique hues, are sufficient to rate all possible hues (cf. Sternheim and Boynton, 1966). In the study on memory colors, photos of three color diagnostic objects (banana, lemon, and lettuce) were presented in each of 36 different colors. For each colored object, participants had to estimate the propor- tions of the unique hues that correspond to the appearance of these colors.

Hue scaling was also measured for the same colors, but presented as uniform disks. The disks served as control stimuli and provided the base- line of hue estimations. The difference between the hue scaling of the disks and the photos of the objects indicates systematic effects on hue esti- mation due to the presentation of objects. Results showed that, indeed, colors were estimated to contain much more yellow when shown on a banana or a lemon than when shown on a disk. For the salad vegetable, observers estimated a higher amount of green.

Another recent study (Lupyan, 2013) repli- cated the classic observation of memory color effects on afterimages (White and Montgomery, 1976) with a cancelation technique and a wide range of color diagnostic stimulus scenes. Color afterimages consist of the perception of a color (e.g., a greenish shade) in the absence of a corre- sponding stimulation that occurs after sustained fixation of an area with a complementary color (e.g., a red disk). According to Lupyan (2013) and White and Montgomery (1976), the colors of afterimages appear to be shifted towards memory colors when shown on color diagnostic objects (but see Leibovich and Paolera, 1970, for contra- dictory findings).

In sum, the results of these more recent studies confirmed that people overestimate the amount of the typical hue in color diagnostic objects (Hansen and Gegenfurtner, 2006; Hurlbert and Ling, 2005; Ling et al., 2008; Figure 5 in Yendrikhovskij et al., 1999, p. 5). Methods such as hue scaling (Hansen and Gegenfurtner, 2006) also show that memory color effects are not just a general oversaturation, but specifically increase the perceived saturation of the typical hue. Moreover, these methods do not involve any memorization, so that the effects may really be attributable to color appreciation. However, it might still be objected that these effects may be attributable to judgment bias rather than to a proper alteration of color perception.

Achromatic adjustments

If memory colors directly affect color perception, the color diagnostic object should result in the perceptual impression of its typical color even when the object does not have any color, such as the grayscale mailbox in Figure 31.1. An achro- matic adjustment method has been developed to test this idea (Hansen et al., 2006).

In this method, observers adjust the color of color diagnostic objects on the computer screen so that they appear to be completely achromatic – that is, gray – to them. According to the memory color effect, the achromatic gray objects should still produce the subjective impression of their typical color. If this is indeed the case, the parti- cipants have to shift the color of the objects towards the opponent color of the typical color in order to make them subjectively appear to be gray.

Figure 31.2 illustrates this idea with the exam- ple of the German mailbox. The German mailbox is typically yellow. Its achromatic adjustment is indeed slightly shifted towards its opponent color, which is blue. This implies that German obser- vers perceive the gray mailbox as slightly yellow, and counteract this impression by adding blue in order that it subjectively appear as gray.

Such memory color effects have been consis- tently shown for photos of fruits and vegetables (Hansen et al., 2006; Olkkonen et al., 2008; Witzel, 2012); for photos of color diagnostic man-made objects, such as the mailbox (Witzel, 2012; Witzel et al., 2011); and for Japanese brand logos (Kimura et al., 2013). In order to ascertain that these effects really involve color appearance, several methodological controls were implemented in the achromatic adjustment experiments, three of which will be briefly discussed below.

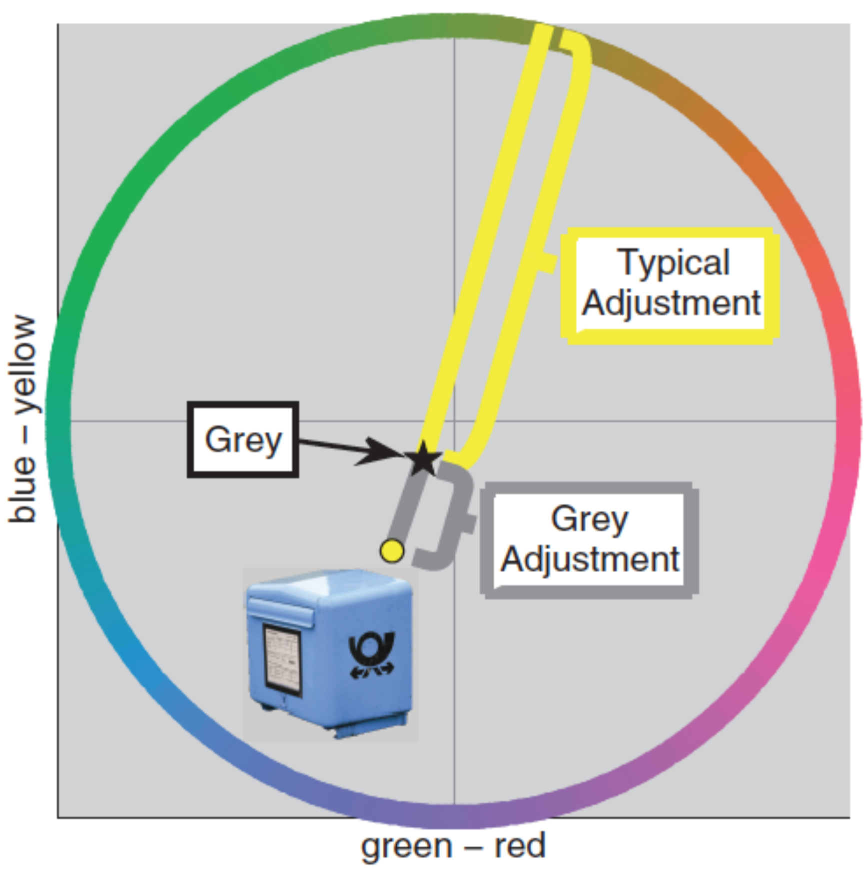

Figure 31.2 This graphic shows the average achromatic adjustment of the mailbox (yellow disk) in a cone–opponent color space (Derrington– Krauskopf–Lennie space – for details, see references). The directions in the color space represent the hues of the colors, as illustrated by the colored circle. The origin of the axes (thin gray lines) corresponds to the gray color of the background. In order to control for the possibility that the background is not perceived as completely achromatic, the subjective gray point of the observers was measured through achromatic adjustments of uniform and textured disks, which were not color diagnostic. The black star corresponds to the subjective gray point. The thick yellow line away from the star shows the hue direction of the memory color of the mailbox. The memory color has been measured separately through an adjustment task, in which observers were asked to adjust the typical color of the objects. Finally, the thick gray line away from the star towards the yellow disk indicates the hue direction of the average achromatic adjustment. The achromatic adjustment is shifted towards blue, which is opposite to the typical color. Note, however, that the bluish color of the mailbox (lower-left corner) is exaggerated for illustration purposes.

First, it was necessary to exclude the possibi- lity that effects may be due to an overshoot of adjustments. For this reason, objects were pre- sented in random colors at the beginning of each adjustment, not in their typical color. For exam- ple, a banana might be initially shown in violet in one of the trials. Hence, observers did not start their achromatic adjustments at the typical color, and could not simply adjust towards the opposite direction to reach gray. Instead, they had to adjust towards the opposite direction of the random color – for example, towards orangish-yellow if the initial color was violet. An overshoot in the direction that reduces the saturation of the initial color would not result in a shift towards the opposite direction of the typical color, because overshoots would be in random directions (oppo- site to the initial random color) and average out. Nevertheless, observers adjusted the image to the opponent color of the typical color to perceive the image as gray. In order to further control acciden- tal biases in random sampling, a still more rigor- ous method of randomization was implemented in later versions of this method (Witzel et al., 2011). Because of this initial randomization, it seems inconceivable that the evidence for mem- ory color effects could be due to an overshoot of adjustments.

Second, in order to ascertain that memory color effects involve perception and not only memory and imagination, the background of the objects corresponded to the achromatic target of the task. Participants were completely adapted to the background, and, consequently, the back- ground was the reference point for neutral gray. Hence, in these experiments, participants could directly compare and match their achromatic adjustments with the background in order to achieve the task.

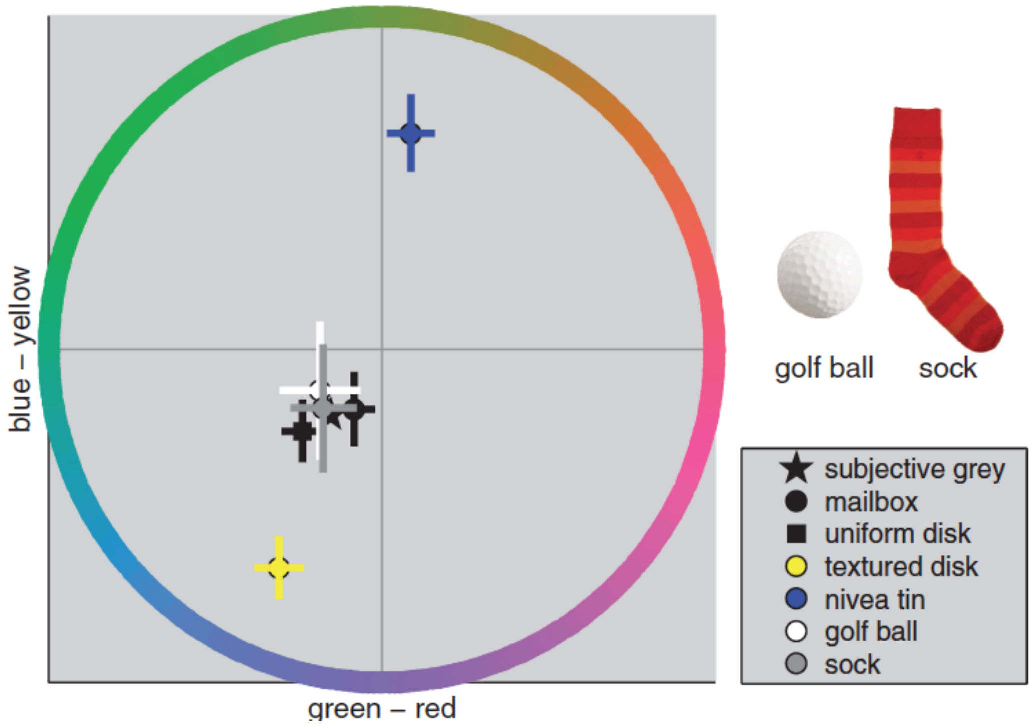

Figure 31.3 Achromatic adjustments of color-neutral objects. Achromatic adjustments of the color-neutral sock (gray circle) and the achromatic golf ball are shown together with the adjustments of the uniform and the textured disks (black symbols), and two color diagnostic objects, the blue Nivea tin (blue symbol) and the yellow mailbox (yellow symbol). Details about stimuli and results are provided in Witzel et al. (2011). The adjustments of the two disks are used to determine the subjective gray point (black star, covered by other symbols). Horizontal and vertical lines around the symbols indicate standard errors of the mean (SEM). Note that the sock and the golf ball do not differ from the subjective gray point, indicating that the shifts of the mailbox and the Nivea tin are specific to their memory colors.

The role of the background as the achromatic reference of the adjustments has been further highlighted in a follow-up study (Olkkonen et al., 2008), where the achromatic adjustments were done under different illuminations – namely, red, green, blue, and yellow. As a result, the background and the adaptation of the observer changed towards the respective illumination, and the perceptual point of reference for neutral gray became the colored background. In these experiments, memory color effects appeared relative to this background. For example, under blue illumi- nation, participants shifted their achromatic adjustment of a banana image more towards blue than their achromatic adjustments of the disks. Consequently, they shifted their adjustments to the opponent color of the typical color in order that it appears in the same color as the background. This implies that the memory color effect is guided by the perceptual comparison with the background and cannot be due to mem- ory or imagination.

Third, the observed effects were specific to memory colors. The typical colors of the different objects were very different, and hence the oppo- nent colors of the typical colors also varied depending on the object. The memory color effect was evaluated specifically in the opposite direc- tion of the typical color. The study with man-made objects sampled objects with typical colors across the whole color space, including blue and purple colors (Witzel et al., 2011). Blue and purple colors are in the opposite direction of the typical colors of fruits and vegetables. Hence, memory color effects consist of shifts of achromatic adjustments to the opposite direction for those objects than for fruits and vegetables. Nevertheless, the memory color effect also occurred for purple and blue objects. Moreover, color-neutral objects, such as a sock or a golf ball, reproduced the same sub- jective white point as the disks even though they had complex color distributions (Witzel et al., 2011). These findings are illustrated by Figure 31.3. These results show that the observed effects go in the direction determined by the memory colors, and are not unspecific biases of achromatic adjustments. Finally, memory color effects could also be produced on a monitor back- ground without an illumination chamber (Witzel, 2012). Hence the memory color effects are not bound to the set-up with the light chamber, as used in the original experiments.

In sum, the achromatic adjustment experi- ments (Hansen et al., 2006; Kimura et al., 2013; Olkkonen et al., 2008; Witzel, 2011, 2012) showed that the memory color effect occurs spe- cifically in the direction of the typical color. This implies that it is directly related to the typical color, and is not a general bias to oversaturate or overshoot. Moreover, in the color-adjustment experiments, observers could directly compare the hue of the image with the gray of the back- ground. The fact that they still exhibited memory color effects shows that memory color effects do not only consist of judgment biases but also mod- ulate color appearance.

Color discrimination

A follow-up study investigated whether memory colors influence even chromatic discrimination and sensitivity to color differences (Hansen, Giesel, and Gegenfurtner, 2008). Sensitivity is the basic ability to see differences between two colors. If memory colors affect sensitivity and chromatic discrimination, observers would be more sensitive to the typical color of color diagnostic objects and less sensitive to the color opponent to the typical color. For example, when shown colors on a banana, they would be able to discriminate particularly small differences between yellow and gray. At the same time, they would be unable to see differences between blue and gray that they would have seen when pre- sented as color-neutral objects. In this case, dis- crimination thresholds should be smaller towards the typical, and higher towards the opponent color, as compared to discrimination thresholds for disks with the same textures as the respective object. However, there was no such memory color effect on discrimination thresholds.

These results suggest that the memory color effect is part of subjective color appearance but is not a sensory phenomenon. While the participants are able to discriminate the colors when shown simultaneously on the same objects (e.g., two bananas), they subjectively appear to be different when seen in isolation. This also explains why the gray mailbox in Figure 31.1 does not appear yel- low when it can be directly compared to the "strongly" (i.e., highly saturated) yellow mailbox. Color contrast has a strong effect on color appear- ance (e.g., Lotto and Purves, 2002), while the memory color effect is comparatively small. For this reason, the strong color-contrast effect most probably counteracts the weak memory color effect on color appearance in Figure 31.1.

Neurobiological evidence

Recent neurobiological evidence further supports the idea that memory colors directly affect color appearance. Although some studies suggested that the cortical areas that subserve the retrieval of memory color knowledge are distinct from those that subserve color perception (e.g., Chao and Martin, 1999; for review, see Tanaka, Weiskopf, and Williams, 2001), other studies pro- vided evidence that some cortical regions are involved in both color perception and memory color retrieval, indicating a certain degree of "common coding" of color perception and mem- ory (e.g., Hsu, Frankland, and Thompson-Schill, 2012; Simmons et al., 2007).

In particular, a recent study (Bannert and Bartels, 2013) has shown color-specific brain activity when observers see grayscale images of color diagnostic objects – that is, images without chromatic information apart from association of the objects with their memory colors. This study used color diagnostic objects for which a memory color effect was shown at the behavioral level in previous studies, including the images of a banana, a lettuce, and a strawberry (Olkkonen et al., 2008), and the images of a Nivea can, a German traffic sign, a Coca-Cola can, and a tennis ball (Witzel, 2012; Witzel et al., 2011). Grayscale, achromatic versions of these images produced color-specific responses in the primary visual cor- tex (V1). There was also some evidence for con- nections between the primary visual cortex and extrastriate cortical structures, more precisely the human visual area 4 (hV4) and the ventral occipi- tal lobe. Since the primary visual cortex processes fundamental aspects of color perception, these results provide neurobiological evidence that memory colors produce a perceptual impression of color (see also Vandenbroucke, Fahrenfort, Meuwese, Scholte, and Lamme, in press).

Memory color effects on other aspects of color perception

Apart from the effects on color appearance, mem- ory colors affect color vision in scene and object recognition, in color memory, in color naming, and in color constancy.

Scene and object recognition

Since color is a characteristic feature of color diagnostic objects, memory colors interfere with color perception in scene and object recognition. Object recognition is better (faster and/or more accurate) when color diagnostic objects are presented in their typical color than in an atypical color or in grayscale (Goffaux, Jacques, Mouraux, Oliva, and Schyns, 2005; Nagai and Yokosawa, 2003; Naor-Raz, Tarr, and Kersten, 2003; Nicholson and Humphrey, 2004; Rossion and Pourtois, 2004; Tanaka and Presnell, 1999; Therriault, Yaxley, and Zwaan, 2009; Uttl, Graf, and Santacruz, 2006). For example, the iden- tification of a banana is faster when it is shown in yellow than in violet. Memory colors also support the recognition of material changes, such as the decay of fruits (Yoonessi and Zaidi, 2010).

Moreover, the presence of typical colors improves scene recognition (Gegenfurtner and Rieger, 2000; Oliva and Schyns, 2000; Wichmann, Sharpe, and Gegenfurtner, 2002). While some studies did not find any particular effect of color diagnosticity on object and scene recognition (e.g., Wurm, Legge, Isenberg, and Luebker, 1993), the majority of studies suggest that memory colors increase the importance of color for scene recognition. The presence of color in scenes has a stronger impact on object and scene recognition when the objects are color diagnostic (Bramao, Reis, Petersson, and Faisca, 2011; Tanaka et al., 2001). Finally, memory colors also affect eye movements during scene exploration (e.g., Ho-Phuoc, Guyader, Landragin, and Guérin-Dugué, 2012). In sum, memory colors improve object and scene recog- nition when objects and scenes are seen in their typical colors (for review, see Bramao et al., 2011; Tanaka et al., 2001).

In addition, the object-color associations of memory colors have more far-reaching effects on the role of color in object identification. When observers are exposed to these object- color associations, memory colors prepare them to perceive certain objects, and they direct their attention towards particular colors and objects in a scene. In particular, the presence of a certain object automatically directs the observer's atten- tion to its typical color in the scene even if it occurs on other objects (Huettig and Altmann, 2011). Moreover, the color-object associations of memory colors produce several kinds of prim- ing effects. In particular, seeing a color affects the recognition of grayscale color diagnostic objects (Lewis, Pearson, and Khuu, 2013), and the recog- nition of words that refer to such objects (Nijboer, van Zandvoort, and de Haan, 2006). Such interference effects have also been found in chil- dren at the age of 3.5 years with an object-Stroop paradigm (Prevor and Diamond, 2005), and for 2–3-year-old children in a free-looking paradigm (Johnson and Huettig, 2011; Johnson, McQueen, and Huettig, 2011). However, these priming and attentional effects do not necessarily involve color perception; instead they may occur on a purely semantic basis, as in semantic priming (Joseph and Proffitt, 1996; Naor-Raz et al., 2003; Nijboer et al., 2006; Yee, Ahmed, and Thompson-Schill, 2012).

Color memory

Color memory consists of memorizing a particu- lar color over time. There is some evidence that appropriate colors that agree with the memory color of an object are remembered more accu- rately (Ratner and McCarthy, 1990; Van Gulick and Tarr, 2010). For example, an orange color is recalled more accurately than other colors when shown on a Halloween pumpkin, which is typi- cally orange. Moreover, as with color appearance, color memory exaggerates the saturation of the color when it is shown on a color diagnostic fruit or vegetable. However, shifts of memorized col- ors towards the typical hue were not observed (Siple and Springer, 1983).

Color naming

In color naming, colors are assigned to color terms that define color categories, such as red, pink, purple, etc. Colors are named differently when shown on color diagnostic objects. In parti- cular, the yellow category is extended in size when colors are shown on a banana (Ling et al., 2008). Moreover, when an ambiguous color is shown on a color diagnostic object, observers adapt, or "recalibrate," their linguistic categories to include this color in the category that corre- sponds to the object's memory color (Mitterer and de Ruiter, 2008). For example, if an ambig- uous orange-yellow color is shown on a banana, observers widen their yellow category to include this color, and begin to call it yellow even when it is shown on a color-neutral sock.

However, object-specific effects on color nam- ing are not simply due to a shift towards the memory color. They also occur for language- specific associations between objects and color names. Even though the middle, yellow traffic light has the same color in Germany and the Netherlands, it is called differently in German and Dutch – namely, yellow and orange, respec- tively. Consequently, in a color-naming task with yellow-orange colors, Germans call more colors yellow than Dutch people when they are pre- sented on the middle traffic light (Mitterer, Horschig, Musseler, and Majid, 2009).

Color constancy

Color constancy refers to the stability of color appearance across changes of illumination. It has been suggested that the comparison between actual and memory colors allows for estimating the color change that is due to the illumination (for a discussion, see Hurlbert and Ling, 2005; Ling and Hurlbert, 2006; Olkkonen et al., 2008). For example, the presence of a banana could help to compare the greenish yellow under a green illumination in a given scene with the typical yellow under a white illumination in memory.

However, evidence in support of this idea is ambiguous. On the one hand, there is evidence that color constancy improves in the presence of color diagnostic objects. Color diagnostic objects seem to serve as cues when estimating colors under water (Emmerson and Ross, 1987) and matching colors simultaneously across strongly different illuminations (Granzier and Gegenfurtner, 2012). On the other hand, color constancy barely improves in successive matches of colors in the presence of a banana (Kanematsu and Brainard, 2014). In addition, the presence of color diagnostic objects does not improve the recognition of illuminations (Pearce, Crichton, seems to be some impact of memory colors on color constancy, but the effect is small compared to other determinants of color constancy.

Summary and implications

In addition to the classic memory color effects on color appearance, memory colors also automati- cally influence how color information is used in perceptual tasks. They constitute points of refer- ence for several kinds of visual evaluations and judgments, and hence interfere with the percep- tual information about color. In natural environ- ments, where objects usually appear in their typical color, the interference effects strengthen color information about objects. When color information is used in everyday life, there are considerable levels of uncertainty. Features of objects and materials may vary across different instances of these objects and materials (e.g., different examples of apples). Moreover, comparing object colors across time involves the uncertainty of memory. Finally, changes of illumination introduce another source of variabil- ity about object colors. The effects of memory colors help to deal with the uncertainty that arises from these sources of noise and variability.

Determinants of memory color effects

Memory color effects do not occur to the same extent for all objects. Some objects have been repeatedly shown to produce particularly strong memory color effects. This is the case for the banana, for which achromatic adjustments were shifted up to 17% (Olkkonen et al., 2008, and still higher in preliminary pilot studies), and which also yielded particularly strong memory color effects in other studies (e.g., Lewis et al., 2013). In contrast, there is barely any evidence for memory colors for red objects, such as a heart (Harper, 1953; Witzel et al., 2011) or a strawberry (Olkkonen et al., 2008). Several factors modulate the strength of memory color effects.

Mackiewicz, Finlayson, and Hurlbert, 2014). When the evidence is taken together, there

Perceptual information and recognizability

Memory color effects directly depend on percep- tual information other than color. In this context, perceptual information refers to perceptual char- acteristics that allow the observer to recognize and identify the object. These characteristics comprise the two-dimensional outline shape, sur- face texture, three-dimensionality, and polychro- maticity (i.e., the fact that object surfaces consist of color distributions rather than uniformly colored areas).

Outline shapes, such as those used in classic studies of memory color effects, are void of texture and three-dimensional cues. Memory color effects have been shown to be much weaker for outline shapes than for photos of fruits in hue scaling (Hansen and Gegenfurtner, 2006) and in achro- matic adjustment (Olkkonen et al., 2008). Moreover, Olkkonen and colleagues also mea- sured memory color effects for photos of painted fruits, which do not have natural texture (Olkkonen et al., 2008). Memory color effects were highest for the original photos with most perceptual infor- mation, while they were least for the outline shapes with the least perceptual information.

These effects of perceptual information are further clarified by the finding that memory col- ors of fruits are more accurate and more precise for representations that are three-dimensional, textured, and polychromatic (Vurro, Ling, and Hurlbert, 2013). The fact that impoverished representations, such as outline shapes, imply only vague memory colors explains why their memory color effects are comparatively weak. Moreover, as with memory color effects, three-dimensional polychromatic images of bananas still have more accurate memory color associa- tions than other fruits (Vurro et al., 2013).

However, what is important for memory color effects is not the mere fact that stimuli are three-dimensional, textured, and polychromatic. The fact that memory color effects also occurred for artificial objects shows that these effects are not particular to natural objects and natural color distributions. The man-made objects that pro- duced memory color effects included two-dimensional objects with uniform color areas, such as an image of a smurf. Finally, there is evidence that low rather than high spatial fre- quencies are important for memory color effects in color priming of achromatic fruits. This finding further undermines the idea that texture, which is defined by high spatial frequencies, is central to memory color effects (Lewis et al., 2013).

Hence, memory color effects depend neither on three-dimensionality nor on color distribu- tion, but rather on the recognizability of the object. Recognizability refers to how clearly the characteristic features of the object are visi- ble so that the object (e.g., a particular banana) can be identified as an instance of its object class (e.g., bananas). This idea is supported by the observation that performance in reporting mem- ory colors for gray representations of the objects increases with increasing recognizability (Witzel et al., 2011).

Color diagnosticity and familiarity

Color diagnosticity has an objective and a sub- jective side (Witzel and Gegenfurtner, 2013). On the objective side, an object or object class is color diagnostic when instances of these objects vary in a limited range of colors that defines their typical color. On the subjective side, an object is only color diagnostic if the observer is familiar with that object, and knows its typical color. Not surprisingly, subjective color diagnosticity is cor- related with the strength of memory color effects (Witzel et al., 2011). Objects with low color diag- nosticity are unlikely to produce memory color effects (Kimura et al., 2013; Witzel et al., 2011).

However, there is no study in which memory color effects occurred for object-color associa- tions that were acquired under controlled condi- tions. For example, in an additional study, we familiarized observers with a novel object. The novel object was a yellow, woolen pompom that was put on the office desk of the observers for 2–3 months. However, this familiarization procedure seems not to have been sufficient. Although mea- sures of subjective color diagnosticity and mem- ory color effects tended to be higher for the familiarized observers than for a control group that saw the object only briefly before measure- ments, these tendencies were not statistically sig- nificant (Witzel, 2012). Another unpublished follow-up study by Gesche Huebner and Martin Giesel (personal communication) trained obser- vers to associate particular colors with geometri- cal shapes (circles, triangles, and squares), but did not find memory color effects with these acquired memory colors either. In summary, memory color effects in achromatic adjustments could be shown only for the most color diagnostic objects with which observers had been familiar throughout their lives.

Daylight axis and asymmetries of color space

Memory color effects on color appearance occur most strongly along the daylight axis, which cor- responds to a curve that goes approximately through typical blue and yellow (Witzel et al., 2011). Adjustments of achromatic colors (gray levels) vary most strongly along the daylight axis, even for color-neutral objects, such as the disks, the golf ball, and the sock. Due to the uncertainty along the daylight axis, memory col- ors may have a stronger effect on color appear- ance. In fact, a recent study even showed that observers are particularly insensitive to changes of colors in the blue direction of daylight (Pearce et al., 2014). The insensitivity of the changes towards blue also explains the systematic bias of the subjective white point towards blue (cf. the black star in Figures 31.2 and 31.3), since varia- tion in this direction produces shifts of the mean into that direction.

Adaptation and measurement precision

The light chamber used in the original achromatic adjustment studies enhances adaptation, and hence the precision of color appreciation (also shown for color naming by Hansen, Walter, and Gegenfurtner, 2007). The study without the light chamber yielded much weaker memory color effects, even for stimuli that were the same as in previous studies, such as the mailbox or the banana (Witzel, 2012). These findings highlight the fact that the control of adaptation and the precision of color-appearance measurements affect the measurement of memory colors.

Summary and implications

In sum, the characteristics of stimuli and material strongly modulate the strength of memory color effects. Variation in stimulus and material may also explain why some of the classic experiments in the past found consistent memory color effects (e.g., Delk and Fillenbaum, 1965; Duncker, 1939), and some did not (in particular, see Bolles et al., 1959; Bruner et al., 1951; Fisher et al., 1956; Leibovich and Paolera, 1970; Pérez- Carpinell et al., 1998). Low perceptual informa- tion and recognizabilty result in weak and unstable memory color effects. In particular, the weak memory color effects for outline shapes explain why some of the classic studies that used outline shapes yielded inconsistent findings. The lack of rigorous control of color diagnosticity provides another explanation of why classic stu- dies may have yielded inconsistent results. The role of the daylight axis for memory color effects also suggests that those classic studies might have obtained weaker and less stable memory color effects because they concentrated on objects with red (Bruner et al., 1951; Fisher et al., 1956) and green (Bolles et al., 1959) memory colors. Finally, incomplete adaptation and measurement imprecision may also yield inconsistent results for memory color effects across studies.

At the same time, some differences across objects still remain unexplained. It is unclear why bananas yield particularly strong memory color effects since they did not seem to be parti- cularly recognizable or color diagnostic (cf. Figure 1 in Witzel et al., 2011). It seems that bananas have a particularly characteristic three- dimensional shape and polychromatic texture, supporting the accuracy of the association between bananas and their typical yellow (Vurro et al., 2013). This might explain why bananas yield the highest memory color effects.

Moreover, memory color effects were particu- larly rare for objects with red memory colors throughout a wide range of studies. This was the case even though red objects, such as the straw- berry and the heart, yielded particularly high per- formances in the measurement of subjective color diagnosticity (Witzel et al., 2011). Moreover, the effect of the daylight axes cannot explain why red objects yield even lower memory color effects than green objects. However, the lack of memory color effects for those red objects seems not to be simply related to the color red since red brand logos seem to produce memory color effects (Kimura et al., 2013).

Broader implications and conclusions

Memory colors affect several aspects of color perception. The observation of such effects has implications for questions about functional seg- regation, about modularity and cognitive penetr- ability, about the influence of learning and the origin of perceptual features, and about whether color corresponds to a physical, objective, or a psychological, subjective reality.

Functional segregation

Functional segregation in high-level vision is a major topic in color research (Gegenfurtner, 2003; Gegenfurtner and Kiper, 2003). Functional segregation refers to the idea that color is perceived independently of other elemen- tary visual attributes, such as shape, texture, or depth. In particular, this idea implies that infor- mation about color is processed by cortical cells that are functionally separable from those that process other visual attributes (Miceli et al., 2001; Wandell, 1995).

Memory color effects contradict this idea (Ling and Hurlbert, 2004; Naor-Raz et al., 2003; Olkkonen et al., 2008; Witzel et al., 2011). They show that color perception depends on the objects on which the colors are shown. Consequently, color is not perceived independently of other visual features that determine the identity of the objects. The evidence from neuroimaging (Bannert and Bartels, 2013) shows that the effects of object identity may even interact with color vision in the primary visual cortex, in a very early stage of color processing.

Modularity and cognitive penetrability

More generally, memory color effects undermine the idea that psychological functions and phenomena, such as perception, cognition, memory, and consciousness, are necessarily modular. Similar to functional segregation, modularity refers to the idea that different psychological phenomena are independent of each other and correspond to separate neural processes and structures (Stokes, 2013). Contrary to the idea of modularity, memory color effects suggest that memory and perception are not independent func- tions and phenomena.

Since knowledge and memory are considered to be part of cognition, memory color effects have been taken as evidence for the cognitive penetrability of visual perception (Lyons, 2011; MacPherson, 2012; Siegel, 2012; Toribio, 2014). Cognitive penetrability refers to the idea that perception may be influenced or "penetrated" by cognition (Collins and Olson, 2014; Deroy, 2013; Lyons, 2011).

Critics of the idea of cognitive penetrability have argued that memory color effects are evidence for increased object sensitivity at a per- ceptual rather than cognitive level (Deroy, 2013). In this case, the knowledge about the color diagnostic object, including its memory color, that allows the recognition of the object is included in perception. Other critics have argued that memory color effects in achromatic adjust- ments are due to changes in the criterion of jud- ging the presence or absence of a color, rather than to changes in sensitivity (Zeimbekis, 2013). However, this argument implies that low-level sensory sensitivity is the main element of percep- tion. With respect to these arguments, it is crucial to clearly distinguish between what belongs to perception and what to cognition (Stokes, 2013).

Empirically, there is no evidence that memory colors affect low-level sensory perception in terms of discrimination thresholds (Hansen et al., 2008). Hence, observers are able to see when the color changes from gray to the opponent direction independently of the memory color. Nevertheless, a banana and a German mailbox subjectively look gray when they are shown in a slightly bluish color, but not when they are in exactly the same gray color as their background (Hansen et al., 2006; Olkkonen et al., 2008; Witzel et al., 2011). Consequently, memory colors affect how “higher-level” perception uses sensory information to determine the subjective impression of color.

In contrast to a modular conception, percep- tion and cognition could be the result of the same, or at least overlapping, brain functions. In this case, cognition is not independent of perception, but is situated or grounded in sensor- imotor experience (Barsalou, 2008; King, 2000; O’Connor and Glenberg, 2003). In particular, the idea of neural network models illustrates that memory and knowledge might be an emer- gent property of perception itself (Fuster, 1997; Versace et al., 2014). In this case, memory color effects would be inherent in the learning of the statistical regularities that takes place during perception. Neurobiological results that find overlaps between neural processing of color perception and memory (Bannert and Bartels, 2013; Hsu et al., 2012) could be explained by this idea.

Perceptual learning and constructivism

Memory color effects support the idea that learn- ing and experience influence or even shape per- ception (Adams, 1923; Baker and Mackintosh, 1955; Bruner et al., 1951; Duncker, 1939; Fisher et al., 1956; Harper, 1953; Hering, 1964/1878; von Helmholtz, 1925/1867). Memory color effects are due to the association between object and color. The association between an object and its memory color must be due to the experience of the observer with this object. This is particularly clear for man-made objects that are specific to a certain cultural context and do not exist in nature (Witzel et al., 2011). Hence, memory color effects support the idea that learning and experi- ence influence perception.

Past experiences with regularities in the environment produce expectations about what kinds of events and regularities are most likely to happen in the future. Experience with sys- tematic associations between an object (e.g., a banana or a mailbox) and a certain range of typical colors (e.g., different shades of yellow) produce expectations about the possible colors of a new instance of that object class. For exam- ple, from experience that ripe bananas are mainly yellow, it might be unexpected that, under some circumstances, bananas are actually blue (Moser et al., 2008). Memory color effects support the idea that such expectations shape and modulate conscious perception (Cheung and Bar, 2012; Gosselin and Schyns, 2003; Panichello, Cheung, and Bar, 2012).

Visual experience shapes perception through perceptual learning (Fahle, 2009; Goldstone, 1998; Lu, Hua, Huang, Zhou, and Dosher, 2011). Perceptual learning may even occur during mere exposure to statistical patterns (e.g., Watanabe, Náñez, and Sasaki, 2001). Hence, per- ceptual learning may explain how the repeated experience of objects (e.g., bananas or mail- boxes) in particular colors (e.g., shades of yellow) produces a bias in color perception.

The effects of past experience and perceptual learning also explain why a beholder perceives stable object features in the first place. In parti- cular, perceptual learning of regularities in the visual environment may create features that may be used to identify objects (e.g., Dorffner, 1998; Rumelhart and Zipser, 1985; Schyns, Goldstone, and Thibaut, 1998; St. Julien, 1997). Which features these are, and to what extent they are a product of perceptual learning or of innate properties of the visual system, are empirical ques- tions. The memory color effect shows that even the basic feature of color is malleable to visual experience, and hence it supports the general idea that features are shaped, and may be produced through learning and experience. In this way, it also supports the constructivist idea that per- ceived reality is shaped through interaction with the physical and social environment (Watzlawick, 1984; Wittgenstein, 1953).

Concept of color and color realism

The impact of learning and prior experience on color perception also implies that color perception is influenced by subjective experience. In this way, memory color effects highlight the subjective dimension of color perception. For example, red might be a memory color of the banana, if the beholder was familiar, not with yellow Cavendish bananas, but with red Dacca bananas (Witzel and Gegenfurtner, 2013). For this reason, memory color effects are also relevant to the understanding of what color actually is. This question is discussed in the debate on color realism (e.g., Byrne and Hilbert, 2003). Color realism claims that color is a property of the physical environment (Broackes, 1992; Byrne and Hilbert, 2003; Hyman, 2005; Ross, 2001). In contrast, color subjectivism claims that color is a purely psychological phenomenon (Hardin, 1988), and color relationalism postulates that color is defined by the relationship between physical properties and the observer (e.g., Cohen, 2006). In both the last two cases, color is assumed to be relative to the observer.

Although memory color effects indicate that color appearance changes with the observer's personal experience, they do not imply that color appearance is completely subjective and arbitrary. The influence of memory colors on color appearance goes in a direction that stabi- lizes the association between the perceptual impression of color and the characteristics of objects in the environment. In this way, memory color stabilizes the perception of the object as it naturally occurs in the visual environment. It reduces uncertainty about object and color iden- tity by combining different kinds of information so as to yield the most likely percept. From this perspective, memory color effects make color perception more realistic by reinforcing the link between perceived colors and other object prop- erties. Hence, they increase the reliability of reference between the subjective impression and the physical characteristics of objects in the envir- onment (Witzel, 2011, 2012).

For the concept of color, the observation of memory color effects suggests that the nature of color is not the subjective impression alone, inde- pendent of stimulation through the visual envir- onment, nor is it a characteristic of the physical environment (e.g., Cohen, 2006; Wright, 2010). Instead, it may be understood as the product of "unconscious inference" (von Helmholtz, 1925/ 1867) that establishes a link between the physical environment and the subjective impression. The reliability of this link constitutes the reality of color. Research on the memory color effect high- lights how this link is "constructed" through the experience of the visual system with the visual environment.

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