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Hearing Words Changes Color Perception: Facilitation of Color Discrimination by Verbal and Visual Cues

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As part of learning some languages, people learn to name colors using categorical labels such as "red," "yellow," and "green." Such labeling clearly facilitates communicating about colors, but does it also impact color perception? We demonstrate that simply hearing color words enhances categorical color perception, improving people's accuracy in discriminating between simultaneously presented colors in an untimed task. Immediately after hearing a color word participants were better able to distinguish between colors from the named category and colors from nearby categories. Discrimination between typical and atypical category members was also enhanced. Verbal cues slightly decreased discrimination accuracy between two typical shades of the named color. In contrast to verbal cues, a preview of the target color, an arguably more informative cue, failed to yield any changes to discrimination accuracy. The finding that color words strongly affect color discrimination accuracy suggests that categorical color perception may be caused by color representations being augmented in-the-moment by language.

Keywords: color, visual discrimination, top-down effects, language

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People can distinguish millions of colors (Linhares, Pinto, & Nascimento, 2008). But in the course of learning English people learn to use names like "red," "green," which apply to color categories. The question of whether there are perceptual consequences to learning and using words to categorize colors has formed a key test of *linguistic relativity*[1] because although color input does not systematically differ for speakers of different languages (Davidoff, 2015 for discussion), different languages divide the color space into categories in substantially different ways: from about a dozen basic categories at one end, to a total absence of specific color terms at the other (Kay, Berlin, Maffi, Merrifield, & Cook, 2011; Saunders & van Brakel, 1997; Wierzbicka, 2006). Here, we show for the first time that simply referring to a color using its name substantially affects people's accuracy in distinguishing different colors. We interpret these results as showing that verbal labels transiently warp color representations into a more categorical form (see Figure 1). In the General Discussion we discuss possible alternative interpretations such as postperceptual processes, attentional biases, and perceptual priming.

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The basic finding that different languages lexicalize colors differently (Berlin & Kay, 1969; Kay et al., 2011) raises three distinct questions. First, is there a consistency to the way different languages divide the color space? Second, what causes the diversity between color naming systems? Third, are there cognitive and perceptual *consequences* to the cultural practice of using language to refer to colors? The present work focuses on this third question. Before reviewing the approaches used by previous researchers to answer this question, we briefly comment on the first two questions as they relate to the present research.

Much of contemporary work on color categorization has been inspired by Berlin and Kay's seminal survey of the world's color systems (Berlin & Kay, 1969). Despite its title ("Basic Color Terms: Their Universality and Evolution") and subsequent emphasis on *universality* (e.g., Kay & Regier, 2007), the survey's results show considerable variability between how colors are named in different languages (Kay, Berlin, Maffi, Merrifield, & Cook, 2009; MacLaury et al., 1992; Saunders & van Brakel, 1997; Wierzbicka, 2006). The diversity of color systems is constrained. Some color distinctions such as red/yellow are more common than others such as blue/green. In more recent work, these constraints have been argued to result from a drive toward communicative efficiency, maximizing the similarity of colors named by the same term and maximizing the difference between colors named by different terms (Regier, Kay, & Khetarpal, 2007). While understanding why AQ: 4

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The current work was supported by NSF-PAC 1331293 to Gary Lupyan. Some results were presented at the 2017 Meeting of the Vision Sciences Society. A preprint of this work was posted to OSF along with raw data, analyses, and a video showing sample trials of the main task (https://osf.io/w3u6b/).

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[1] Whorf did not actually write about the relationship between language and color, nor between language and visual perception. Yet, from 1950s onward, the "Whorfian hypothesis" has been frequently invoked concerning the possible influences of language on color perception (e.g., Kay & Kempton, 1984 for discussion). We refer interested readers to Whorf's original works (Whorf, 1956).

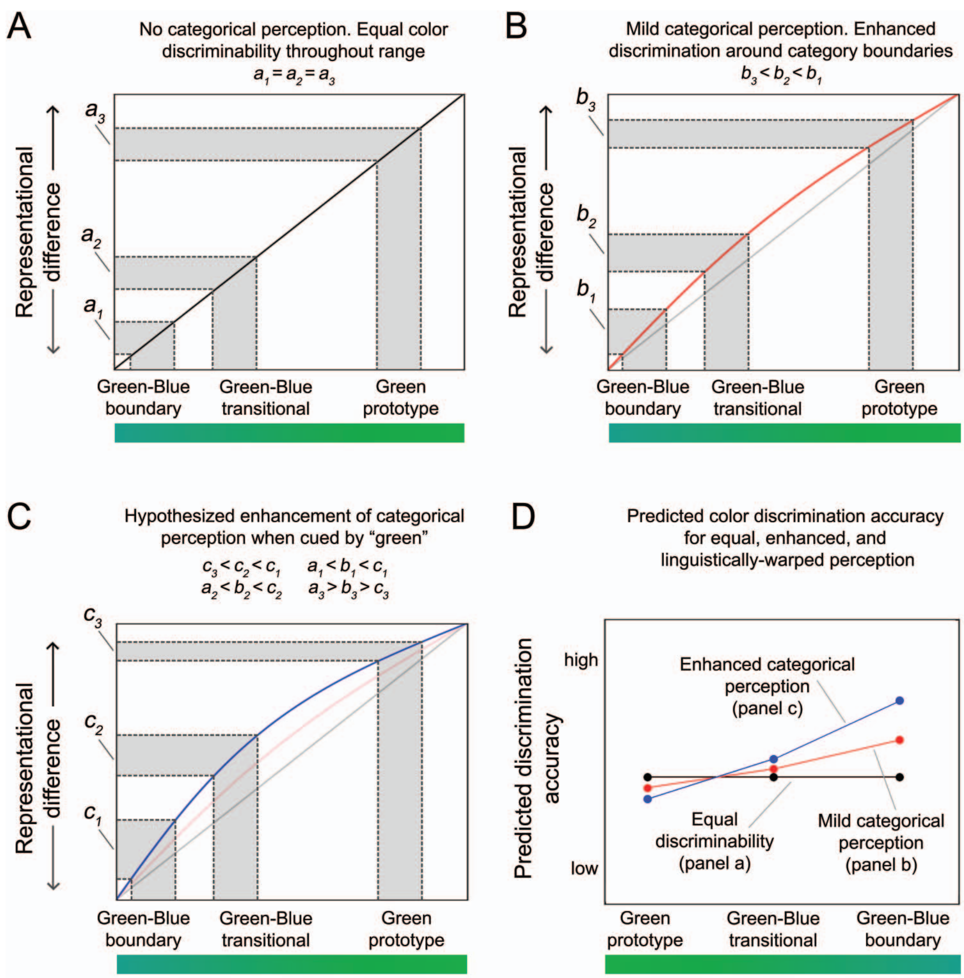

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Figure 1. A schematic showing the effects of warping the color space on discrimination judgments. (A) In a perceptually uniform space, the representational difference of a color pair spanning a category boundary (a_1) and equidistant color pairs that do not span a category boundary (a_2, a_3) is equivalent, leading to equal discriminability. (B) Expanding the color space around a category boundary and collapsing the space within a category leads to larger representational differences (better discriminability) between (b_1) than within (b_2, b_3) categories. (C) We hypothesize that processing a color label exaggerates this effect leading to enhanced categorical perception. Compared with panel B, discriminability around the boundary and for colors located about midway between two color prototypes increases while discriminability near the category prototype slightly decreases. (D) Predicted pattern of discrimination accuracy under different levels of categorical perception. Note that the color range on the *x*-axis has been reversed compared with the other panels to be more easily compared with the data presented in Figure 5. See the online article for the color version of this figure.

some color distinctions are more common than others is clearly important, such work does not detract from the more basic observation that some languages provide their speakers with ways of referring to color as a basic dimension distinct from other aspects of visual experiences, while other languages do not (e.g., Wierzbicka, 2013). What is the reason for this difference? Like other domains that show lexical variability (Majid et al., 2018), the lexicalization of color appears to track communicative need (Gibson et al., 2017). In particular, the use of dyes and mass production create situations where objects differ in their color, but not much else. This makes expressions such as "the green one" (as distinct from the yellow one) increasingly useful (Bolton & Crisp, 1979; Kay & Maffi, 1999 for discussion).

Whatever the reasons for the observed cross-cultural variability in color naming, a central question remains. What are the cognitive and perceptual *consequences* of being exposed to a particular set of named color categories. Initial attempts to answer this question focused on relatively high-level tasks such as subjective similarity judgments (Kay & Kempton, 1984) and color memory (Davidoff, Davies, & Roberson, 1999; Roberson & Davidoff, 2000; cf. Heider, 1972). These studies found that subjective difference ratings were greater and memory was better for colors that spanned a lexicalized color boundary compared with colors from the same lexicalized category, but that were (roughly) equivalently spaced in color space. One shortcoming of these studies was that they confounded effects of lexicalized color categories on perception

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with effects on higher-level nonperceptual judgments. For example, suppose one observes that people who speak a language with a lexical distinction between blues and greens rate colors that span a blue/green boundary as being more different than colors that are both named as greens or as blues. This could mean that people perceive colors spanning the boundary as more different. Or it could mean that when performing the task, participants base their similarity judgments on the difference in the names of the colors, with the lexicalization having no influence on perception itself (see Goldstone, Lippa, & Shiffrin, 2001 for a more general discussion of this "strategic judgment bias"). An analogous point has been made concerning effects of language on color memory. The basic finding is that participants show superior performance when the test requires them to match the remembered color, to colors from a different category compared with the same category (Roberson & Davidoff, 2000). This difference may be caused by language augmenting perceptual encoding of colors or warping the encoded memory traces. However, an alternate explanation is that colors provide an efficient mnemonic strategy, a point initially made by Roger Brown:

> When the color initially appears you try to give it a distinctive name. When the color is removed the name can be retained, even rehearsed. Somehow, names are responsive to volition in a way that images are not . . . When the chip is found which best deserves the name, that is recognition. (R. Brown, 1965, p. 334; cited in Lucy & Shweder, 1979)

Beyond their effects on similarity judgments and memory, verbal labels have also been implicated in how people perform when asked to sort colors into groups. The groups people tend to create are partially predicted by the labels available in their language (Davies, Corbett, Roberson, & Vandervyver, 2005). The inability to use verbal labels during the task is associated with difficulties in forming stable groups, an observation first made by Goldstein (1948) in his examination of individuals with anomia and confirmed by subsequent group and case-studies (De Renzi, Faglioni, Scotti, & Spinnler, 1972; Roberson, Davidoff, & Braisby, 1999). The chief difficulty that individuals with anomia have on such tasks appears to not lie with any difficulty in discriminating different colors, but rather a difficulty with attending to and isolating hue as a perceptual dimension. Roberson et al. (1999) describe a person with anomia (patient LEW) performing a color sorting task in the following way:

> [T]he manner in which he proceeded was to pick up two stimuli and compare them to each other. LEW looked for two stimuli that were the most perceptually similar. If satisfied that they met his criteria for grouping he placed them together, later using one of them to carry out the same procedure with another stimulus. With a large group of stimuli, this exercise took considerable time and on a number of occasions LEW declared himself dissatisfied with an emerging group and began to compare individual members to the members of other groups. The process was slow and clearly difficult in terms of decisions. (p. 9)

The approach taken by LEW is in stark contrast with what is done by control subjects, who begin by creating name-based groups (the reds go here, the yellows here, etc.)—a kind of categorical anchoring—and then placing subsequent color samples into the appropriate categories. The inability to use category names appears to make this process more difficult (a problem not limited to color categories, e.g., Cohen, Kelter, & Woll, 1980; Hjelmquist, 1989; Lupyan & Mirman, 2013).

The results described so far point to some ways color names are involved in processes such as explicit similarity, short-term memory, and sorting. To establish whether color names affect more unambiguously *perceptual* processes requires using tasks that do not place substantial loads on memory and decision-making. One such task is simultaneous color discrimination. Participants are presented with an array of color swatches in which all are identical except for one. Participants simply need to indicate which color is different from the others. An accurate response requires the viewer, at minimum, to perceive the color-based difference. The better someone can perceive it, the more accurately and/or faster they can respond. Although responses also reflect a person's *decision*, this decision element is kept constant while manipulating other factors such as which colors need to be discriminated.

Experiments testing color discrimination have revealed that people who speak a language that lexicalizes a certain color boundary—for example the distinction made by Russian between синий (dark blue) and голубой (light blue)[2]—are relatively faster at distinguishing colors that span that boundary compared with colors that fall into the same lexicalized category (Winawer et al., 2007; see also Roberson, Pak, & Hanley, 2008). Electrophysiological studies examining the time course of these cross-linguistic effects show that some cross-linguistic differences can be measured less than 200 ms after stimulus onset suggesting relatively low-level differences in color representations between speakers of different languages (Maier & Abdel Rahman, 2018; Thierry, Athanasopoulos, Wiggett, Dering, & Kuipers, 2009). For native English speakers, the categorical difference between green and blue may be encoded as early as 100 ms after stimulus onset (Forder, He, & Franklin, 2017). Fn2

Further evidence that categorical color perception has a linguistic locus comes from studies showing that categorical color perception is stronger in the right visual field (which projects to the left hemisphere) presumably because language exerts a greater impact on visual processing in the left compared with the right hemisphere, at least when rapid responses are required (Drivonikou et al., 2007; Franklin et al., 2008; Gilbert, Regier, Kay, & Ivry, 2006; Roberson et al., 2008; Zhou et al., 2010).

One interpretation of results showing better discrimination for colors spanning a lexicalized boundary than for colors from the same category is that speaking a language that requires distinguishing between, for example, light and dark blue, provides speakers extra categorization practice compared with speakers of a language like English who would ordinarily refer to those colors by a common label ("blue"). On this "acquired categorical perception" account (e.g., Özgen & Davies, 2002), practice with categorizing colors (such that occurs during language learning and language use) gradually warps color representations, expanding cross-category differences and/or increasing within-category similarities. However, this account does not explain why categorical

[2] Translating синий as dark blue and голубой as light blue fail to convey that in Russian this distinction is categorical. There is not a more general term that translates to "blue", meaning that it is as invalid to translate the Russian terms as referring to light and dark blue, as it would be to translate "blue" as referring to different shades of a more basic category of "grue" (Wierzbicka, 2013).

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cross-linguistic differences in color discrimination are so flexible. For example, the relative advantage shown by Russian-speakers when discriminating between light and dark blues disappeared when language was interfered with (Winawer et al., 2007). Verbal interference also eliminated the category-advantage shown by English speakers in between-category discrimination (blues vs. greens) compared with within-category discrimination (blues vs. other blues; greens vs. other greens; Gilbert et al., 2006). Categorical perception in color discrimination has also been found to largely disappear when participants engage in a longer task involving making numerous within-category distinctions (Witzel & Gegenfurtner, 2015). These latter results hint that any warping of color representations by language, if it happens at all, is likely happening online (i.e., in the moment).

Despite the volume of research on the topic, claims about effects of language on color perception continue to be highly controversial (e.g., Bae, Olkkonen, Allred, & Flombaum, 2015; McWhorter, 2014; Witzel & Gegenfurtner, 2011). We think there are at least four reasons for this continued controversy.

First, although some studies show that people are better at discriminating colors that span lexicalized categories than colors within the same named categories, more systematic attempts to link sensitivity in color discrimination to lexical boundaries have been equivocal. When discrimination accuracy of colors around the hue circle is systematically tested, peaks in discrimination accuracy only sometimes coincide with lexicalized color boundaries (Bae et al., 2015; Witzel & Gegenfurtner, 2013, 2015). If experience naming colors induces permanent categorical perception of colors, this is unexpected. Furthermore, categorical color perception appears to be highly task-sensitive. Under testing conditions that emphasize distinguishing subtle color differences, people can be just as good at distinguishing colors within a category (e.g., different shades of green) as they are between colors that span lexicalized boundaries (e.g., greens and blues; Witzel & Gegenfurtner, 2013, 2015). Raising further questions about the causal link between categorical color perception and language is that findings of hemispheric differences in categorical processing of color—taken to imply a linguistic locus of categorical color perception—have not been consistently replicated (e.g., A. M. Brown, Lindsey, & Guckes, 2011; Suegami, Aminihajibashi, & Laeng, 2014; Witzel & Gegenfurtner, 2016). Conversely, hemispheric differences in categorical perception have also been reported for categories for which people do not have established names (Holmes & Wolff, 2012).

Second, even when peaks in discrimination coincide with lexicalized distinctions, such relationships do not imply that lexicalization *caused* the categorical perception (Bae et al., 2015; Ozturk, Shayan, Liszkowski, & Majid, 2013). Showing that verbal interference selectively affects color discrimination around lexicalized color boundaries *does* suggest a causal role for language, but the effect of verbal interference on categorical perception of color has not always replicated (Witzel & Gegenfurtner, 2011) and poses interpretational difficulties even when obtained (see Perry & Lupyan, 2013 for review). For example in both Winawer et al. (2007) and Gilbert et al. (2006), verbal interference led to the puzzling result of *faster* discrimination of within-category compared with between-category colors.[3] For domains other than color, some work finds verbal interference to selectively affect discrimination in the right visual field (Gilbert, Regier, Kay, & Ivry, 2008), while other work finds verbal interference to *increase* categorical perception in the right visual field (Franklin, Catherwood, Alvarez, & Axelsson, 2010).

Third, many of the studies claiming to show effects of language on color perception have failed to properly calibrate the colors and have tended to focus on a specific color boundary (frequently the green/blue boundary; Witzel & Gegenfurtner, 2016 for discussion) making it unclear whether the findings reflect stimulus confounds and whether the findings generalize to other regions of color space.

Fourth, several key studies examining cross-linguistic differences and effects of verbal interference (Gilbert et al., 2006; Winawer et al., 2007) have used RTs as the primary measure. This has prompted some critics to argue that the small differences in RTs, while statistically significant, are inconsequential (McWhorter, 2014).

We are, therefore, left with the unsatisfying conclusion that color discrimination may or may not be categorical, that the categorical patterns, when present, may or may not be causally related to people's experience with and use of color terms, and that even if language is causally related to color perception, the effects may be too small to be of consequence.

The Present Studies

The primary aim of our work was to investigate the influence of language on color discrimination while resolving the theoretical and methodological limitations mentioned above.

Like previous work, we use a simultaneous color discrimination task (though more difficult than what is typically used) to investigate objective color discrimination performance in a bias-free way (Witzel & Gegenfurtner, 2013). We examine four categories (red, yellow, green, and blue) and the corresponding transitions (e.g., red-yellow, yellow-green, etc.) to help ensure that our findings are not specific to a particular category. In addition, we define color categories with respect to each participant's personalized category prototypes and boundaries allowing us to test whether individual differences in the precise meanings of color words impact perceptual discrimination. Consistent with psychophysical best practices, we carefully equate color distances in the CIELUV color space using lightness and saturation in addition to hue.

Given previous results suggesting that color discrimination is being affected in-the-moment by language (i.e., the linguistic effect is an online effect), we sought to establish the causal influence of language on color discrimination by manipulating a linguistic and observing the effect of this manipulation on color discrimination. Rather than attempting to *disrupt* the involvement of language as has been previously attempted with verbal interference, we instead *exaggerate* the (theorized) involvement of language on color discrimination by cueing people on some trials with auditorily presented color names before the color-discrimination task (see, e.g., Lupyan, 2008b; Lupyan & Thompson-Schill, 2012 for other examples of this experimental logic). This cueing procedure allows us to avoid requiring participants to split their attention between two unrelated tasks and allows us to manipulate linguistic involvement on a trial-by-trial basis.

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[3] We relate these findings to the present work in the discussion of Experiment 3.

To address the concern regarding real-world consequences of small differences in RTs, our main measure is objective discrimination performance (a full analysis of RTs is presented in the online supplementary materials). Although the meaningfulness of differences in discrimination accuracy can also be debated, it is arguably easier to evaluate the consequences of a 10% difference in discrimination accuracy compared with a difference of 80 ms in RTs.

Our basic method is shown in Figure 2. On each trial participants are shown four colors, three of which are identical. The participants' task is to indicate which color (henceforth "target") is different from the others. One some trials, an auditory color word names the category of the target before the colors are shown. Finding that verbal cues affect color discrimination accuracy would provide the most direct evidence to date that color language affects in-the-moment performance on a basic perceptual task. In the next section we provide further details about why cueing people with verbal labels—and *specifically* verbal labels—is predicted to affect color discrimination, and in what way.

Predictions

Why and how should color labels affect color discrimination? Our predictions stem from the label-feedback hypothesis (Lupyan, 2007, 2012a, 2012b). We begin with the simple observation that because labels are categorical, in the course of learning language, people learn to associate each color word with a range of perceptual states. This association is bidirectional: to name colors, we need to associate perceptual inputs with color names. To understand color names, we need to associate words such as "blue" with colors that are ordinarily referred to as "blue."[4] Importantly, the association between a name and a visual input is not all-or-none. Just as some dogs are more typical than other dogs (Rosch, 1973), some greens are "better" greens than others (although which greens are the best greens may vary for speakers of different languages, Uusküla & Bimler, 2016). For present purposes, a color is a good (typical) member of its named category to the extent that it is maximally associated with the label "green" compared with other color labels.

The label-feedback hypothesis makes two predictions that are relevant to the present studies. First, once labels are learned, visual experiences activate verbal labels and this activation feeds back to affect ongoing visual processing (on this perspective, verbal interference works by disrupting verbal activation or label-feedback, e.g., see Lupyan, 2009, 2012b). The main result of this representational warping is to separate category members from nearby nonmembers. For example, under the influence of the label "green", the representations of green colors move away from those of blue colors.

To better understand why a label is expected to have this warping effect, we turn to the second prediction of the label-feedback hypothesis: a label selectively activates category-diagnostic features. For example, experiencing the label "chair" applied to various chairs (comprehension) and learning to label different chairs with the same label chair (production) results in the label "chair" becoming dissociated from features like color (because chairs come in a variety of colors) and more strongly associated with a certain shape characteristic of chairs and not of other furniture (Lupyan, 2008a). As this association is established, the label chair will activate a distribution over features that highlights the features most diagnostic of chair-ness (a distribution that best matches chair "prototypes"). A subsequently presented visual input is processed in light of this categorical prior (Lupyan & Clark, 2015; see also Yang & Zelinsky, 2009). The more the visual inputs differ from this prior, the easier it will be to distinguish them. If the inputs are similar to the prior, the harder it will be to distinguish them. While this warping can be obtained when the label is activated by the visual input itself, overly presenting a label *before* the visual input exaggerates this effect because the visual input is then processed in light of the categorical prior set up by the label (Boutonnet & Lupyan, 2015; Lupyan & Thompson-Schill, 2012; see Lupyan, 2012b for a computational model).

Applied to colors, the prediction is that a color label will activate a color distribution centered on the color most strongly associated with the label (that we gloss here as the "color prototype"). The pattern of anticipated results is schematized in Figure 1. The basic prediction, therefore, is that color names will increase categorical perception. We test this prediction by examining how verbal labels affect discrimination of pairs of colors that are spaced at equivalent distances in CIELUV space, but at different locations relative to category prototypes and boundaries (see Figure 2).

What does it mean to increase categorical perception? Categorical perception is generally defined as more accurate discrimination between categories than within categories (Harnad, 1987). An increase in categorical perception can occur from an increase in between-category differentiation ("acquired differentiation"; Lawrence, 1949) and/or from within-category compression ("acquired equivalence"). As can be seen in Figure 1D, hearing green should improve discrimination between a green and a blue color more than it should impair discrimination of two (equivalently spaced) green colors. There are empirical reasons for predicting that categories produce a larger between-category differentiation than within-category compression. In phonology, a domain in which categorical perception has received the most study, experience with one's native language tends to result in much greater sensitization to between-category differences—enhancing discrimination of different phones—than on compressing within-category differences (a decreased ability to make within-category distinctions). For example, in the seminal study comparing English and Japanese speakers' discrimination of /r/ and /l/, Strange and Dittmann (1984) found that English speakers were, as expected, better than the Japanese speakers in distinguishing between /r/ and /l/ (between-category differentiation), but they were not worse than the Japanese speakers in discriminating between different /r/ exemplars and between different /l/ exemplars (i.e., they did not show acquired equivalence). Training the Japanese speakers on the /r/-/l/ distinction led to between-category improvements, but no within-category decrement. The strongest case for categorization decreasing within-category discrimination accuracy comes from vowel discrimination—the "perceptual magnet effect" (Iverson &

[4] We do not mean to suggest that our understanding of color words is reducible to a simple association between words and colors. A full account must, for example, take into account contextual factors, for example, that "red car" and "red hair" denote systematically different colors, that a bird does not need to be entirely red to be a "red bird," and that a watermelon is "red" on the inside but a "red crystal" is red throughout (Quine, 1964; Lahav, 1989; Roy & Reiter, 2005 for discussion).

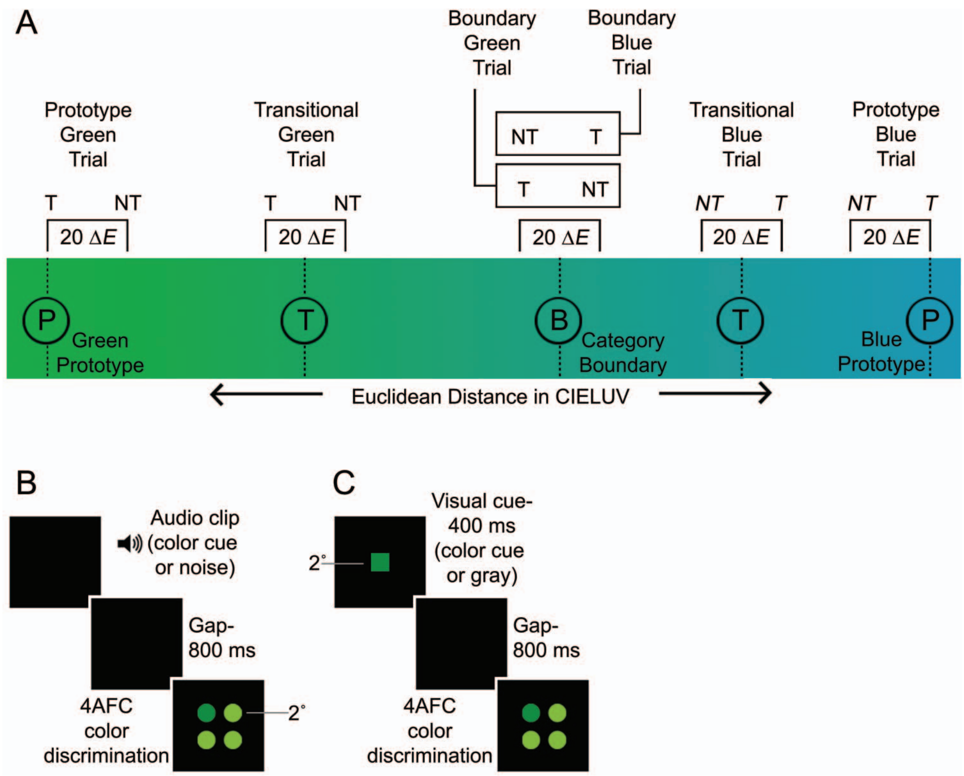

Figure 2. (A) A schematic of target and nontarget locations for the color discrimination task used in all experiments and the three trial types: (P)rototype, (T)ransitional, and (B)oundary. The perceptual distance between T (target) and NT (nontargets) on all trials was fixed. Note that the green category here is shown larger than the blue category to demonstrate that the size of each category varied across participants depending on where each participant's prototype and bounday was localized. (B) Trial procedure for the color discrimination task that used verbal labels (Experiments 1, 2, and 5); (C) Procedure for the color discrimination task that used visual cues (Experiments 3 and 4). The verbal and visual cues always related to the odd-one-out (target) color. See the online article for the color version of this figure.

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Kuhl, 1995; Kuhl, 1991)—but here too, the evidence of a decrease in sensitivity for within-category discrimination is equivocal (Lotto, Kluender, & Holt, 1998). In studies of acquired categorical perception in the visual domain—a domain more in line with the present work—categorization experience leads to clear evidence of between-category differentiation, but there is little evidence of a loss of within-category discrimination (see General Discussion for further treatment of this distinction).

Another glance at Figure 1 reveals another, somewhat counterintuitive prediction: a steeper curve increases discriminability not only at the category boundary, but also when the to-be distinguished stimuli lie approximately halfway between the prototype and boundary: colors labeled in Figure 1 as "transitional." The prediction is that hearing green should make it easier to distinguish not just greens from blues, but also more somewhat typical greens from somewhat atypical greens. This prediction is not unique to our simple model; it also comes out of models that view effects of categories on perception in terms of Bayesian inference (e.g., see Figure 2 of Feldman, Griffiths, & Morgan, 2009). This prediction has received prior support in classic work on learned categorical perception (Goldstone, 1994): learning to categorize squares according to size or according to brightness resulted in improved discrimination not only at the category boundary, but along the category-relevant dimension *within* the category as well. While consistent with this past work, the counterintuitive prediction that enhanced categorical perception should make some members of the category more discriminable from one another has never been tested in the domain of color perception.

Summary of Experiments

In Experiment 1, we examine the basic effect of verbal cueing on color discrimination at different points from the category prototype to the category boundary. In subsequent experiments, we replicate our main findings and systematically rule out some alternative explanations. In Experiment 2, we show that he effects of labels on color discrimination do not reduce to nonspecific effects of prior knowledge. In Experiments 3 and 4, we compare the effectiveness of linguistic and nonlinguistic (visual) cues. In Experiment 5, we examine the role of individualized versus average color prototypes and boundaries.

Experiment 1: Informative Verbal Cues

We began our investigation of linguistic effects on color discriminability by examining whether verbal cueing of colors affects

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color discrimination accuracy. The predictions are shown in Figure 1. If color labels exaggerate categorical color perception then when cued by a color name people should be better at discriminating the named color from nearby colors compared with when the same people are not cued by the color name. This improvement should extend to transitional trials (discriminating colors lying approximately halfway between the prototype and boundary). Verbal labels were predicted to slightly decrease accuracy in discriminating between colors closer to the prototype.

Method

Participants. Twenty-seven University of Wisconsin-Madison undergraduates (mean age = 18.7 years; age range = 18–21; 18 female) with normal or corrected-to-normal vision participated for course credit. This and subsequent studies were approved by the University of Wisconsin-Madison Institutional Review Board. All participants were screened for color vision deficiency using the Ishihara test (Ishihara, 1987). A minimum sampling size of 20 participants was chosen a priori based on the sample sizes (ranging 12 to 22 participants) used in previous research (Lupyan & Spivey, 2010; Witzel & Gegenfurtner, 2015).

Apparatus. All stimuli were displayed on a 22" ViewSonic VX2268WM LCD monitor (Brea, CA; color resolution: 8 bits/channel; spatial resolution: 1680 × 1050; refresh rate: 120 Hz) and viewed at an approximate distance of 57 cm. Participants were tested in a dark room; the only source of light was the monitor. Luminance and chromaticity coordinates were established with a i1Display Pro colorimeter (X-Rite, Grand Rapids, MI). Look-up tables were formulated based on these coordinates to convert between linear and γ-distributed RGB values. For conversions in CIELUV space the chromaticities of the gray buttons used in the first two tasks (see below) were used as the white point. These buttons were metameric with illuminant D65; $x = 0.313$, $y = 0.329$) and luminance (14 cd/m^2). These same gray values were used for all the written instructions. We deliberately presented all color stimuli on a black rather than a gray background to avoid any of the colors approaching isoluminance with the background. Color discrimination is known to be better when distinguishing isoluminant colors compared with nonisoluminant colors and nonsystematic imbalances across participants on this dimension because of variation in the location of prototypes across participants could have biased discrimination performance in some areas of color space. The use of a black background likely affected the absolute locations of the prototype and boundary colors (see Figure
F3 3), but because the background was held constant across all participants and experiments and the factors of interest are within-subject manipulations, we do not believe the choice of background is an explanatory factor of our main results.

Establishing color prototypes: Stimuli and procedure. We began by establishing each participant's individual red, yellow, green, and blue prototypes using an adaptive-color picker task in the perceptually uniform CIELUV color space. At the start of the task, participants saw 27 color swatches arranged in a grid
F4 (see Figure 4). Participants subsequently homed in on a specified color over multiple trials. Final selections are shown in Figure 3A–C. Further methodological details are provided in *SI Establishing color prototypes*.

Establishing color category boundaries: Stimuli and procedure. After obtaining estimates of color prototypes, we sought to measure the location in color space marking the boundary between the colors. On each boundary-location trial, participants viewed a single circular swatch and used the mouse-wheel to adjust its color along an arc in CIELUV space projected between the two prototypes. They could adjust the color of the swatch back and forth as much as they wanted (adapted from Malkoc, Kay, & Webster, 2005). Final selections for all experiments are shown in Figure 3D–3F. Further methodological details are provided in *SI Establishing color category boundaries*.

Color discrimination: Stimuli and procedure. After locating individual color prototypes and boundaries, participants completed a four-alternative forced-choice (4AFC) color discrimination task modeled after Witzel and Gegenfurtner (2013). On each trial participants viewed four circular color swatches, one of which—the target—was a different color from the others—the nontargets. participants needed to distinguish which swatch was the odd-one-out. The perceptual color distance between the target and nontargets was maintained around a fixed level of 20 ± 1 Δ*E* units in CIELUV on all trials (see Figure 2A).

Figure 2B shows the design of the color-discrimination task. Before seeing the to-be-discriminated colors, participants heard an auditory cue—either a verbal label naming the color category of the upcoming target or an uninformative burst of white-noise. All cues were of equal duration and amplitude. Using auditory noise bursts as a control ensures that participants receive alerting benefits of auditory stimulation on all trials (e.g., Lupyan, 2008b; Lupyan & Spivey, 2010; Lupyan & Ward, 2013).

The color label always named the color category of the target. The target's location was counterbalanced and trial order was randomized within subjects. Participants responded using a keyboard and were asked to respond as quickly as possible without sacrificing accuracy. No accuracy feedback was provided. Because our primary interest was in investigating the effects of color names on typical color discrimination, we did not assess sensitivity at the very limits of human perception by measuring just-noticeable differences. Further methodological details are provided in *SI Color Discrimination*. A video showing several experimental trials is available at (https://osf.io/w3u6b/).

We tested our prediction that verbal labels influence objective discrimination accuracy by measuring discrimination performance for colors that spanned individual participants' lexicalized color boundaries (*boundary trials*), colors in between prototypes and boundaries (*transitional trials*), and colors near the participants' *prototypes* (see Figure 2A). If hearing color names produces more categorical color representations, the expected effect on color discrimination is a benefit on boundary trials, a smaller benefit on transitional trials, and a small decrement in accuracy on prototype trials.

Analytic approach. We analyzed color discrimination by modeling accuracy (likelihood of correct response) using logit mixed-effects logistic regression and modeled response time (incorrect responses removed) using mixed effects linear regression (R Version 3.3.1; lme4 Version 1.1–12); *p* values were computed using Satterthwaite approximations (lmerTest package). Unless specified, fixed effects (centered) included the cue-type (label vs.

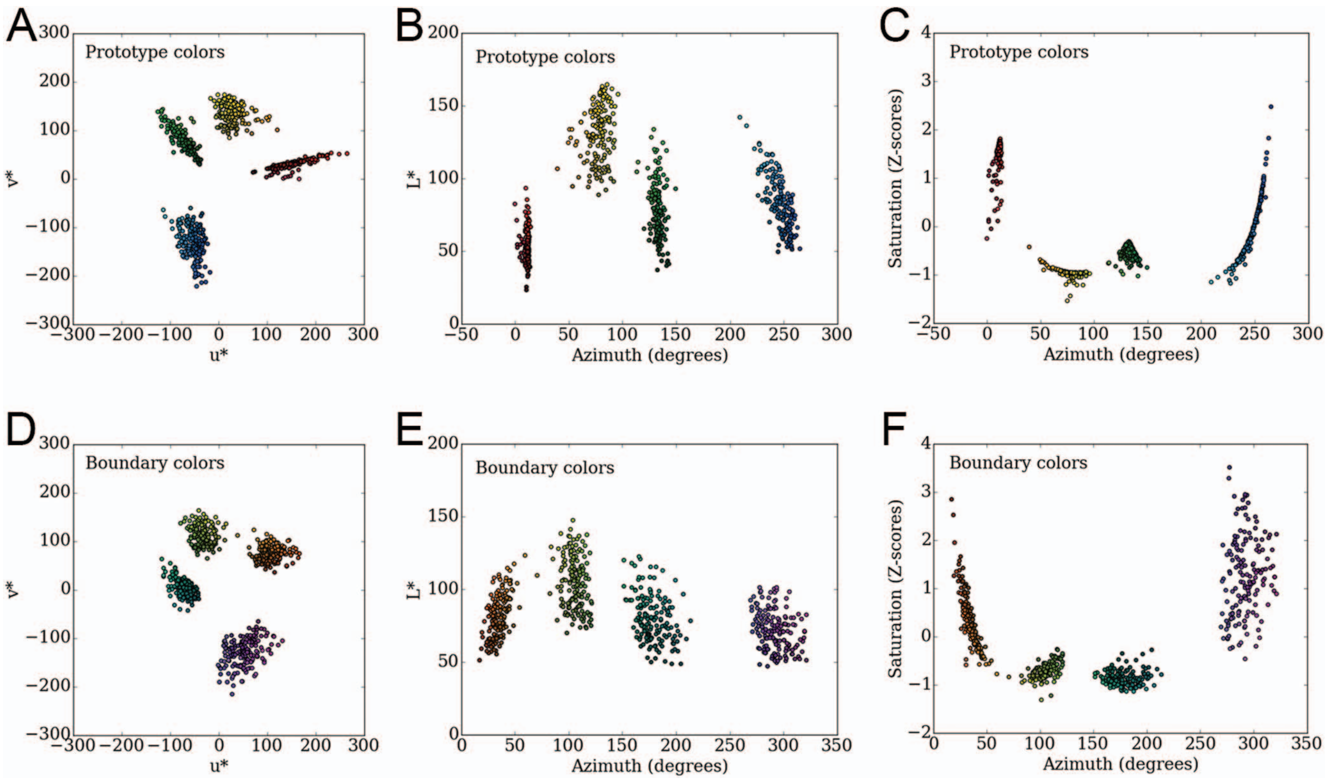

Figure 3. Final color selections of the best exemplars (A–C) and boundaries (D–F) of red, green, yellow, and blue. Each dot represents a participant (n = 161[5]). Colors are plotted in CIELUV space. The plots illustrate that the relatively high agreement in hue combined with substantial individual differences in the lightness and saturation of best exemplars and boundaries. See the online article for the color version of this figure.

noise), trial-type (prototype, transitional, boundary—modeled as ordered factors), and their interaction. We modeled subjects and color category (red, yellow, green, and blue) as random intercepts and included a by-subject random slope for cue-presence. Additional analyses are presented in *SI Experiment 1: Additional Analyses.*

Results

The results from the prototype and boundary localization tasks (see Figure 3) reveal levels of agreement comparable to earlier studies of unique hues (Webster, Miyahara, Malkoc, & Raker, 2000). Of note is the rather large variability in the lightness and saturation of people's selections. Although people roughly agree on which hues correspond to the best examples of blue, green, red, and yellow and the boundaries between them, they agree considerably less about the lightness and saturation of the best exemplars and boundaries.

The effects of hearing the cue on color discrimination are shown in Figure 5A. Hearing a target's color name immediately before the color display substantially improved overall color discrimination from M = 79.6% to M = 86.2%, b = 0.63, 95% confidence interval (CI) [0.47, 0.80], z = 7.49, $p < .0001$. The effect of labels was selective and depended on trial-type: Labels facilitated visual discrimination when the target and nontargets spanned a category boundary (increasing accuracy from 74.8 to 89.9%), b = 1.23, 95% CI [0.99, 1.47], z = 9.98, $p < .0001$, and when discriminating more from less typical "transitional" colors (from 82.0 to 88.7%), b = 0.80, 95% CI [0.51, 1.10], z = 5.32, $p < .001$. When the target was the category prototype and the nontarget was also relatively typical, cues slightly decreased accuracy (from 82.1 to 79.9%), b = −.18, 95% CI [−41, .04], z = 1.61, p = .11), leading to a significant cue-by-trial-type interaction, b = 0.75, 95% CI [0.61, 0.89], z = 10.56, $p < .0001$. Trial-type was a significant predictor of accuracy on label trials, b = 0.50, 95% CI [0.39, 0.61], z = 9.06, $p < .0001$. This was because of significantly higher performance when the colors spanned a category boundary compared with discriminating prototypical colors, b = 0.47, 95% CI [0.36, 0.57], z = 8.70, $p < .0001$, and when discriminating more from less typical transitional colors compared with discriminating prototypical colors, b = 0.85, 95% CI [0.64, 1.06], z = 7.87, $p < .0001$. Trial-type was also predictive of performance on no-label trials, b = −0.26, 95% CI [−0.35, −0.17], z = −5.73, $p < .001$. This was due to color discrimination being significantly worse around category boundaries compared with discrimination around category prototypes, b = −0.25, 95% CI [−0.34, −0.16], z =

5 This number includes 16 participants who completed the identical prototype and boundary selection and then proceeded to perform a study not reported here. We include their data in Figure 3 as it further improves the estimates for color prototypes and boundaries.

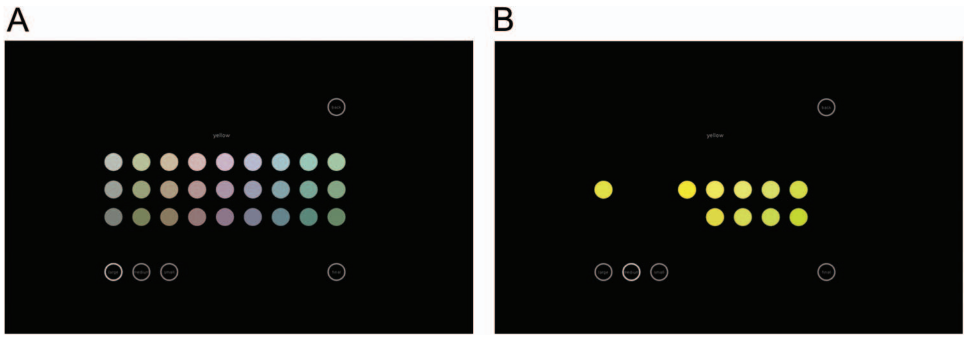

Figure 4. Sample trials from the color-picker task to establish color prototypes. Here, participants are asked to locate the best "yellow." The swatches in (A) resemble the swatches at the start of the trial. The swatches in (B) resemble those that would be displayed after making a number of selections toward yellow. Note that the perceptual distance between colors is larger in (A) than in (B) showing participants homing in on their color prototypes. The missing swatches in (B) occur when a color falls outside the range of colors that the monitor could display. See the online article for the color version of this figure.

5.62, $p < .001$, and being significantly worse around boundaries compared than on transitional colors, $b = -0.49$, 95% CI [−0.66, −0.31], $z = 5.47$, $p < .001$. For analyses of response times, see *SI Experiment 1: Additional Analyses* and Figure 3A in supplemental material.

Discussion

Immediately after hearing a color name (e.g., green), participants were more accurate in discriminating between targets and nontargets when they spanned a color boundary, for example, a green among blues (boundary trials), and in distinguishing typical greens from atypical greens (transitional trials). Performance on prototype trials was numerically poorer following verbal labels, though not significantly so. Overall, this pattern is consistent with the prediction that color labels transiently induce more categorical color representations.

We also observed an absence of categorical perception on uncued trials. Performance on uncued trials was actually poorest when discriminating colors spanning a color boundary. This result is consistent with discrimination threshold data on a comparable 4-AFC task (Witzel & Gegenfurtner, 2013) that showed performance around some color boundaries is worse compared with around some color prototypes (see also Hill, Roger, & Vorhagen, 1997; Mahy, Van Eycken, & Oosterlinck, 1994). We return to this result in our discussion of Experiment 3.

Experiment 2: Redundant Verbal Cues

We have argued that the effect of color names in Experiment 1 derives from color names transiently making color representations more categorical by acting as a categorical prior. Experiments 2 and 3 investigate whether knowledge of the target's color, delivered in other ways has a similar effect. Whereas in Experiment 1 the color name informed participants of the category of the upcoming target, in Experiment 2 we blocked trials by category, making the labels informationally redundant. Blocking trials by color category meant that participants knew ahead of time the color category of the upcoming target, for example, they knew that on a green block, the target would be either the only green color or the best green color. This experiment allowed us to test whether hearing a color name affects color discrimination *even when* participants already knew the color category of the upcoming target. A positive finding would provide added evidence for the claim that color names enhance categorical color perception.

Method

Participants. Twenty-nine University of Wisconsin-Madison undergraduates (mean age = 18.9 years; age range = 18–28; 16 female) participated in for course credit.

Procedure. The procedure was identical to Experiment 1 except that the trials were now blocked by color category rendering the labels informationally redundant (as in e.g., Lupyan & Spivey, 2010). There were four blocks (red, yellow, green, and blue) containing 96 trials each. Block order was randomized between subjects. On a random half of the trials in each block, participants heard a color label (e.g., "blue" for the blue-target block); on the remaining half, participants heard a noise cue. Cues and trial-types (prototype, transitional, and boundary) were randomized within each block.

Results

With color categories blocked such that participants knew the color category of the upcoming target, there was no main effect of verbal labels on discrimination accuracy (M_{cued} = 88.6%; M_{uncued} = 87.8%), $b = 0.07$, 95% CI [−0.09, 0.22], $z = 0.84$, $p = .40$. However, there was a significant cue-by-trial-type interaction, $b = 0.17$, 95% CI [0.03, 0.32], $z = 2.18$, $p = .030$ (Figure 5B). As in Experiment 1, verbal cues selectively affect discrimination accuracy for the boundary and transitional trials (M_{cued} = 90.9%; M_{uncued} = 89.1%), $b = 0.22$, 95% CI [0.01, 0.43], $z = 2.07$, $p = .039$ while yielding a nonsignificant decrease in accuracy on prototypical colors (from 85.3 to 84.0%), $b = -.21$, 95% CI [−.45, .03], $z = 1.68$, $p = .09$. As in Experiment 1, hearing a color name before making a discrimination judgment enhanced categorical perception. There was a significant effect of trial-type on label trials, $b = 0.38$, 95% CI [0.27, 0.49], $z = 6.87$, $p < .001$, and this effect was larger than on trials without labels, $b = 0.21$, 95% CI

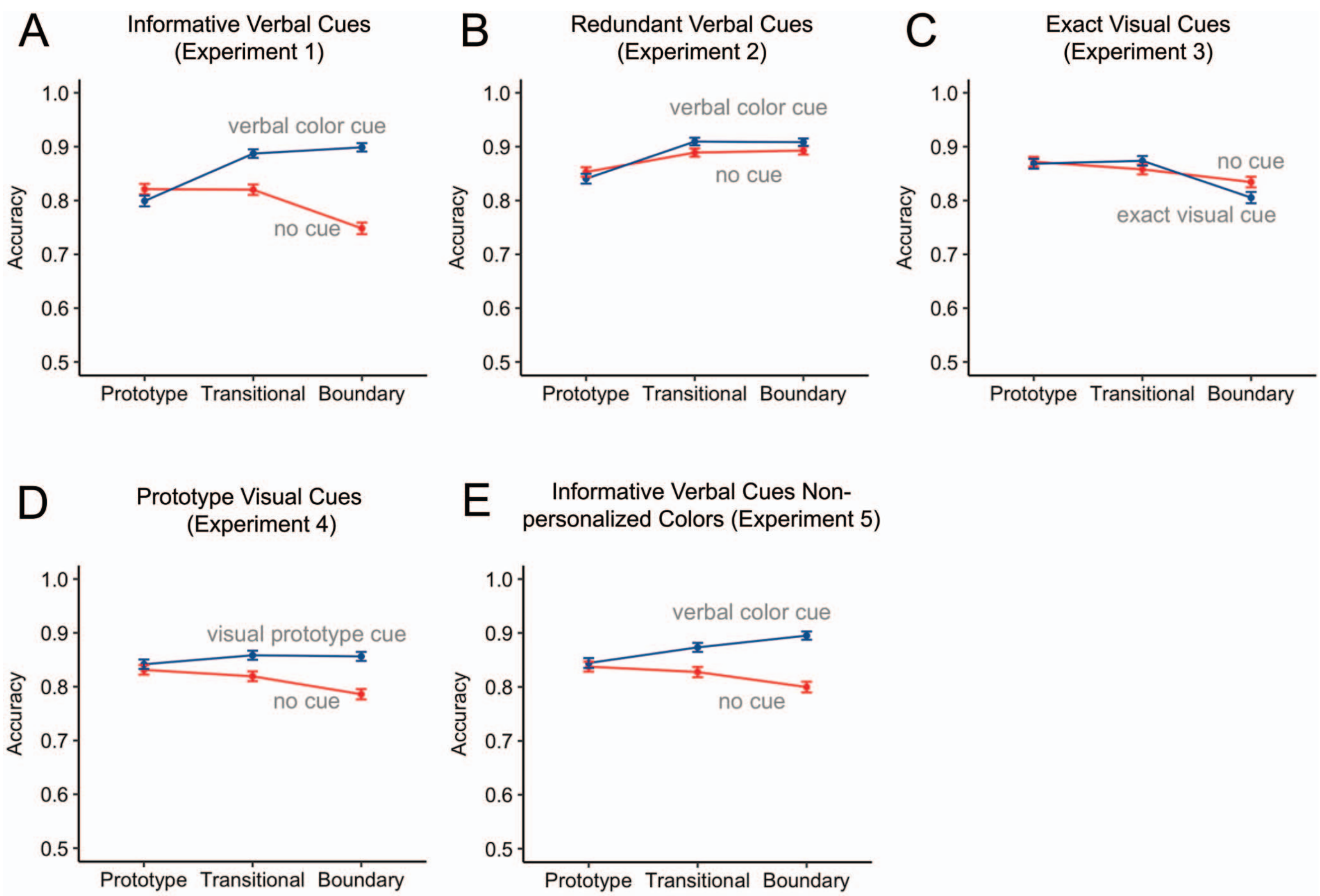

Figure 5. The results showing participants' discrimination accuracy on a 4AFC color discrimination task following different types of verbal and visual cues (A–D). The specific colors each participant saw were based on their individual color selections in the preceding tasks; (E) Participants saw the same the colors. Error bars are ±1 *SE* of the within-subject condition differences (Morey, 2008). See the online article for the color version of this figure.

[0.11, 0.32], $z = 3.96$, $p < .001$. For analyses of response times, see *SI Experiment 2: Additional Analyses* and Figure 3B in the supplemental material.

Discussion

When color categories were blocked, making the labels completely redundant, the labels nevertheless led to an increase in categorical perception. When color discrimination was preceded by a color name, participants (a) showed better performance on boundary than prototype colors, and (b) showed a selective improvement in discrimination on trials where the target was more typical of the cued category than the nontargets. Comparing Figure 5A and Figure 5B reveals that color discrimination in the no-cue condition of the present study was similar to the verbal-cue condition of Experiment 1. This is not surprising. Blocking the color categories reinforces the categories and allows participants to, in effect, cue themselves (Lupyan & Swingley, 2012). Nevertheless, actually hearing the label further exaggerated categorical perception (albeit slightly). This result lends further support to the causal link between color terms and categorical color perception.

Experiment 3: Visual Cueing of Color

Experiment 1 showed that hearing color words improved color discrimination around color boundaries and in between prototypes and boundaries. Experiment 2 showed a similar, though smaller effect even when they the color labels were informationally redundant. These results leave open the question of whether the cueing effect is specific to color words or whether *any* trial-by-trial cueing of the target color would have the same effect on color discrimination (as may be predicted by a feature-based attentional account). If the cueing effect observed in Experiments 1 and 2 is not specific to linguistic cues, then presenting participants with an even more informative cue—a preview of the exact target color—should be even more effective. Alternatively, the observed effect of linguistic cues on color discrimination may hinge on the cues being *categorical*. Whereas a visual cue is necessarily specific (e.g., a green cue has to be a specific shade of green), a label abstracts away from specific exemplars (here, particular shades of the color) and in so doing promotes the activation of a more categorical representation (Boutonnet & Lupyan, 2015; Edmiston & Lupyan, 2015). If it is this categorical nature of verbal labels

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that is responsible for its effect on color discrimination, then visual cues may be ineffective in altering color discrimination precisely because they are overly specific.

Method

Participants. Thirty-one University of Wisconsin-Madison undergraduates participated for course credit. The final sample was $n = 25$ (mean age = 19.4 years; age range = 18–23; 22 female). Five participants were eliminated for having performance below 50% and one participant did not begin the color discrimination task because of time constraints. Four participants did not complete all 384 trials of the color discrimination task, but are included as they completed >75% of the task. Removing these participants did not substantively change the results.

Procedure. The procedure was the same as Experiment 1 except that the cues were now visual rather than verbal. On cued trials the cue was a square swatch ($\sim 2° \times 2°$) presented at the center of the screen colored with the exact color of the upcoming target. On uncued trials, the cue was a square outlined in gray. The cues were shown for 400 ms to match the duration of the auditory cues in Experiment 1.

Results

Unlike verbal cues, visual cues did not facilitate performance (M_{cued} = 84.9%, M_{uncued} = 85.5%), $b = -.008$, 95% CI [−.19, .17], $z = .08$, $p = .93$, Figure 5C. Unlike Experiments 1 and 2, in the present experiment there was no significant cue-by-trial-type interaction, $b = -.11$, 95% CI [−.26, .03], $z = 1.49$, $p = .135$. There was a significant effect of trial-type, $b = -0.22$, 95% CI [−0.29, −0.15], $z = 5.91$, $p < .0001$. Color discrimination was slightly more accurate around prototypical colors (M = 87.0%) and transitional colors (M = 86.6%) than around color category boundaries (M = 82.0%). That is, in the absence of verbal labels, participants' performance failed to show any evidence of a categorical advantage (indeed, performance was slightly better within category than between), mirroring performance on the uncued trials of Experiment 1. We comment on this result in the Discussion.

Comparing Experiment 3 directly to Experiment 1 revealed a significant cue-by-experiment-by-trial-type interaction, $b = 0.87$, 95% CI [0.66, 1.07], $z = 8.31$, $p < .0001$ showing that the cue was most effective for the transitional and prototype trials in Experiment 1, but did not affect performance differently for the three trial-types in Experiment 3. We also found a reliable cue-by-experiment interaction, $b = 0.62$, 95% CI [0.40, 0.85], $z = 5.35$, $p < .0001$, showing that the cue was more beneficial in Experiment 1 than in Experiment 3. For analyses of response times, see *SI Experiment 3: Additional Analyses* and Figure 3C in the supplemental material.

Discussion

We have interpreted the results of Experiments 1 and 2 as showing that verbal labels activate a "categorical prior" within which the subsequent discrimination task is then performed. (Boutonnet & Lupyan, 2015; Schmidt & Zelinsky, 2009; Yang & Zelinsky, 2009). However, are words special in this regard? Could a categorical prior be deployed using a nonverbal cue? In the present study we used visual cues that exactly matched the color of the upcoming target. These visual cues were completely ineffective in altering discrimination accuracy, leading to a pattern of discrimination very similar to that of the no-cue condition of Experiment 1 (cf. Figures 5A/5C and supplemental Figure 2A/2B). These results provides further evidence that some of the power of verbal labels to augment discrimination lies in their ability to *abstract* from any specific exemplar of the category (Edmiston & Lupyan, 2015). On this view, it is *because* a color name such as "green" can abstract away from specific greens that it induces more categorical color perception. Note also that the ineffectiveness of visual color cues in altering color-discrimination accuracy speaks strongly against any account of the present effects based on a low-level perceptual-priming mechanisms—a point to which we return in the General Discussion.

The color cues used in the present experiment conveyed precise information about the color of the upcoming target. However, they *also* conveyed categorical information. According to the label-feedback hypothesis, seeing a visual cue should have activated the color's name that should then feed back and activate a more categorical color representation affecting subsequent color discrimination. If so, why did visual cues not affect discrimination? Consider that the visual cues that are expected to be easiest to label—those showing the prototypical colors—were precisely the trials on which labeling was not expected to help. Conversely, the trials on which an increase in categorical perception was expected to have the largest effect (boundary trials) were precisely those that have cues that are hardest to label. Finally, on transitional trials, the cue should have a relatively strong and selective association with one color category. Indeed, performance was slightly better on visually cued transitional trials compared with no-cue trials, but not significantly so. This reduced effect of endogenous cues is consistent with theoretical prediction and past work (Lupyan, 2008b, 2012b; Lupyan & Spivey, 2010).

An unexpected result is that overall discrimination accuracy in the present study was poorest around the color boundaries. This was also the case for the no-cue condition of Experiment 1. In the absence of verbal cues, rather than showing *reduced* categorical perception, participants showed *poorer* discrimination around category boundaries than elsewhere. More insight into this puzzling result can be obtained by examining Figure 2A and 2B in the supplemental material that show that on no-cue and visual-cue trials the classic categorical perception effect was observed for *some* combinations of target-color and color-transitions such as locating blue targets among green nontargets (though not green targets among blue nontargets). Note also that despite these differences in baseline discrimination, verbal cues consistently increased accuracy for transitional and boundary trials.

The most parsimonious explanation for why performance on no-cue and visual-cue trials does not always show the expected categorical advantage is that the CIELUV space, although designed to be perceptually uniform, has known distortions (A. M. Brown et al., 2011; Witzel & Gegenfurtner, 2011) and some color boundaries fall in regions of color space in which CIELUV distances overestimate people's discrimination ability. This observation may help explain the puzzling result in several studies that down-regulating linguistic involvement during color discrimination via verbal interference did not simply reduce categorical perception, but reversed it, leading to faster RTs on within-category trials compared with between-category trials (Gilbert et al., 2006; Winawer et al., 2007).

Experiment 4: Visual Cueing Using Color Prototypes

Experiments 1 and 2 showed that verbal color labels labeling the target color changed color discrimination accuracy—increasing accuracy around the prototype and in the middle of the category while slightly decreasing accuracy around the prototypes—the pattern expected if color labels activate more categorical color representation. Experiment 3 showed that discrimination accuracy was unchanged when instead of using verbal cues, participants were cued to the exact identity of the target color with a visual cue. We have interpreted this difference as stemming from verbal cues being categorical and visual cues being exact. However, there are other differences between the two cueing conditions such as modality: auditory for Experiments 1 and 2 and visual for Experiment 3. The goal of Experiment 4 was to examine whether making visual cues more categorical (i.e., more word-like) leads to a similar pattern of results obtained with verbal cues.

Fn6 Although perceptual cues cannot avoid conveying precise perceptual information (Edmiston & Lupyan, 2015),[6] we reasoned that using a color that matches the participant's prototype is the closest perceptual analogue to a verbal cue. In this experiment we test whether such "quasi-categorical" perceptual cues affect color discrimination similarly to verbal cues.

Method

Participants. Thirty University of Wisconsin-Madison undergraduates (mean age = 18.6 years; age range = 18–24; 22 female) participated for course credit.

Procedure. The procedure was identical to Experiment 3 except (a) the visual color cue now matched the participant's computed color prototype and (b) the visual cue was identical for all trials within a color category. For example, all the cued *red* trials were preceded by a centrally presented red square matching the participant's red prototype.

Results

Prototypical visual cues significantly increased discrimination performance from 81.2 to 85.2%, $b = 0.28$, 95% CI [0.11, 0.45], $z = 3.23$, $p < .001$. As in Experiments 1 and 2, this effect interacted with trial-type, $b = 0.24$, 95% CI [0.11, 0.37], $z = 3.65$, $p < .001$ (Figure 5D). Like Experiments 1 and 2, the visual prototype cues significantly facilitated discriminating category members from noncategory members (from 78.6 to 85.6%), $b = 0.56$, 95% CI [0.30, 0.82], $z = 4.2$, $p < .0001$, and more from less typical transitional colors (from 81.9 to 85.8%), $b = 0.36$, 95% CI [0.10, 0.63], $z = 2.7$, $p = .007$. Unlike past studies, the cues led to a nonsignificant increase in accuracy when discriminating prototypical colors from slightly less prototypical colors ($M_{uncued} = 83.1\%$; $M_{cued} = 84.2\%$), $b = -.03$ 95% CI [−.26, .80], $z = .26$, $p = .80$.

A reliable cue (cue-present vs. cue-absent) by experiment (Experiment 3 vs. Experiment 4) interaction, $b = 0.34$, 95% CI [0.11, 0.57], $z = 2.91$, $p = .004$ showed that prototypical visual cues were significantly more effective than exact visual cues. The overall benefit of the prototypical visual cues, however, was significantly smaller than the overall benefit of the verbal cues in Experiment 1, $b = 0.48$, 95% CI [0.30, 0.67], $z = 5.08$, $p < .001$. Examining the interaction between cue, trial-type, and a dummy-contrast between Experiment 1 (verbal cues) and the present study (prototype visual cues) showed that the verbal cues of Experiment 1 led to significantly more categorical responding than the prototype-visual cues of Experiment 4, $b = .48$ 95% CI [.30, .67], $z = 5.10$, $p < .0001$. This interaction remained reliable when prototype-trials were removed from the analysis, $b = .38$, 95% CI [.006, .76], $z = 1.99$, $p = .047$. For an analysis of response times, see *SI Experiment 4: Additional Analyses* and Figure 3D in the supplemental material.

Discussion

While seeing a preview of the exact target color (Experiment 3) did not affect color discrimination, using each subject's color prototype as a visual cue for all trials of that category (present study) facilitated discrimination similarly to the verbal cues (Experiment 1), but to a significantly smaller extent. This result shows that it is possible to cue people to process colors in a more categorical way using a nonverbal cue. It remains possible that although visual cues were used in this study, the effect is nevertheless mediated by language. Viewing the visual cue may have activated the color label which in turn acted as a categorical prior. As mentioned in the discussion of Experiment 3, this type of endogenous activation of the label is expected to have the same though weaker effect than an overtly presented label (see Lupyan, 2012b for a model). Alternatively, the visual cue may be having a more direct effect, independent of the participants' knowledge of verbal category names.

Experiment 5: Comparing Individualized to Average Prototypes and Boundaries

As evident in Figure 3, participants varied in the precise location in color space of their color prototypes and boundaries. To the extent that hearing a color label activates a categorical representation centered on the color prototype (thereby accentuating representational differences around the boundary), we thought it was important to use prototypes and boundaries individualized for each participant. If this is correct, then the effect of the verbal cue should decrease if we use group-averages of color prototypes and boundaries instead of individualized ones.

Method

Participants. Twenty-eight University of Wisconsin-Madison undergraduates (mean age = 18.6 years; age range = 18–23; 17 female) received course credit for participating.

Procedure. Like Experiment 1, participants first completed the prototype color-picker task and the boundary color adjustment

[6] Although this is true in general (one cannot have an image of a dog, *in general*), the color domain may offer some ways to convey categorical information using strictly visual cues by using a cloud of points that span range of colors corresponding to the desired category. We leave this manipulation for future work.

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task. However, instead of using personalized color boundaries, we used the same colors for each participant, based on the group averages (see Table 1 in the supplemental material for chromaticity coordinates).

Results

Hearing a target's color name immediately before the color display significantly improved overall color discrimination from $M = 82.2\%$ to $M = 87.1\%$, $b = 0.42$, 95% CI [0.29, 0.56], $z = 6.10$, $p < .001$ (see Figure 5E). We expected that the facilitatory effect of verbal cues on color discrimination would increase with increasing color distance from prototypes. This prediction was supported by a significant Cue-Presence × Color-Distance interaction, $b = 0.40$, 95% CI [0.16, 0.65], $z = 3.24$, $p = .001$. On label-cued trials performance marginally increased with increasing distance from the category prototype, $b = 0.19$, 95% CI [−0.01, 0.40], $z = 1.84$, $p = .066$. On no-cue trials, accuracy significantly decreased, $b = -0.39$, 95% CI [−0.56, −0.22], $z = 4.52$, $p < .001$. These results are a replication of Experiment 1.

To test whether the facilitatory effect of labels on color discrimination was more pronounced when individual color prototypes and boundaries were used, we compared the effects of the cue observed here to that observed in Experiment 1. The two-way Cue × Experiment interaction was not significant, $b = 0.15$, 95% CI [−0.04, 0.35], $z = 1.55$, $p = .12$, but the Three-Way Cue × Trial-Type × Experiment interaction was highly significant, $b = 0.35$, 95% CI [0.16, 0.55], $z = 3.54$, $p < .001$. In line with our predictions, this was driven by a greater effect of labels around category boundaries when targets were aligned with each participant's personalized color selections (Experiment 1; $\text{label}_{\text{boundary-accuracy}} - \text{uncued}_{\text{boundary-accuracy}} = 15.1\%$) compared with when they were not aligned (Experiment 5; $\text{label}_{\text{boundary-accuracy}} - \text{uncued}_{\text{boundary-accuracy}} = 9.5\%$). This same trend was observed in a weaker form when discriminating more from less typical transitional colors (Experiment 1: 6.7%; Experiment 5: 4.6%). Whereas accuracy around prototype trials was numerically decreased in Experiment 1, the use of averaged prototypes in Experiment 4 led to virtually identical performance on cued and uncued trials (Experiment 1: $\text{label}_{\text{prototype-accuracy}} - \text{uncued}_{\text{prototype-accuracy}} = -2.2\%$; Experiment 5: $\text{label}_{\text{prototype-accuracy}} - \text{uncued}_{\text{prototype-accuracy}} = 0.6\%$). Thus, hearing verbal color labels induced greater categorical perception when stimuli were more aligned with the participant's individual location of color category prototypes and category boundaries. For an analysis of response times, see *SI Experiment 5: Additional Analyses* and Figure 3E in the supplemental material.

Discussion

We replicated the facilitatory effect of verbal cues when using averaged rather than individualized prototypes and boundaries. However, verbal cues had a larger effect on discriminating colors closer to the *individual's* boundary than on colors closer to the *averaged* boundary. This result is important for two reasons. First, it shows that individual differences in color categories relate to differences in the effects of language on color discrimination. Second, it suggests that further research into how color names augment color processing may safely use group-averaged color prototypes and boundaries provided that the effect being investigated is sufficiently large. Investigating smaller effects may benefit from locating individualized prototypes and boundaries.

General Discussion

Does language affect color perception? Despite considerable prior work on the topic, the answer has remained unclear for both methodological and theoretical reasons. The current studies sought to address the question by applying best-practices of color psychophysics to a set of predictions generated by the label-feedback hypothesis (Lupyan, 2012a, 2012b). We predicted that color names would activate categorical color representations such that when asked to discriminate colors within the "categorical prior" set up by the label, people would show increased accuracy for distinguishing colors that span a lexicalized boundary, and between relatively typical and relatively atypical members of the named category. Hearing a color name was predicted to lead to a small decrease in accuracy when discriminating between relatively typical instances of the named category.

The results (see Figure 5) were consistent with these predictions. Immediately after hearing a color label, people were more accurate at distinguishing between a color that matched the named color category and colors from a neighboring category (boundary trials), and when distinguishing between typical and atypical members of the named category (transitional trials). On trials when participants had to distinguish between two typical shades of the named color, verbal labels led to a small (and nonsignificant) decrease in performance. These results are consistent with color labels transiently inducing greater categorical perception of color (schematized in Figure 1).

Unlike the effects of verbal labels which are—by definition—categorical, *visual* cues conveying precise information of the target's upcoming color did not change discrimination accuracy (Experiment 3). Cueing color using the participant's previously identified color prototype (Experiment 4) mimicked the beneficial effect of the verbal cue, but was significantly less effective than cueing people with a verbal label. Finally, Experiment 5 showed that the effect of verbal cues was strongest around individualized rather than group-averaged color-boundaries lending further support to the causal influence of labels on color discrimination.

These results are consistent with the label feedback hypothesis according to which words become associated with category-diagnostic features and begin acting as categorical priors (Boutonnet & Lupyan, 2015; Edmiston & Lupyan, 2015; Lupyan, 2012a). While color representations can be activated with or without language, a color label like red is able to induce a more categorical representation of redness with consequences for performance on an objective visual discrimination task. Combined, our results offer the strongest evidence to date that the cultural practice of referring to colors influences accuracy on an objective color-discrimination task.

Our results showing that color words induce more categorical color representations mirror in some ways two recent reports showing categorical effects on both delayed and simultaneous color matching (Bae et al., 2015; Cibelli, Xu, Austerweil, Griffiths, & Regier, 2016). In these papers, participants' errors in color matching were biased in a way consistent with categorical perception roughly in line with named color categories. These results were interpreted by the authors as arising from an integrative process wherein analog/continuous perceptual representation of color are combined with discrete/categorical representations. This distinction between an interactive/top-down account in which a higher level representation alters lower-level representations and an integrative/bottom-up account in which an intermediate system integrates input from multiple sources, is analogous to the debate that took place in attempts to understand influences of word knowledge on speech perception (McClelland, Mirman, & Holt, 2006; Norris, McQueen, & Cutler, 2000; Samuel, 1996).

Our results bear on this debate in two ways. First, regardless of whether categorical effects in color perception stem from an integrative/bottom-up mechanism or interactive/top-down mechanism, there is a question of *where* the categorical information comes from. In Cibelli et al. (2016) account these are verbal in nature. Bae et al. (2015), on the other hand are inclined to a
Fn7 nonverbal source.[7] The present results support a linguistic locus of categorical effects in that categorical perception was transiently changed by the presentation of verbal cues (although we cannot rule out additional nonlinguistic contributions to categorical color perception, e.g., long-term experience with human artifacts produced to have discrete colors). Second, although it is difficult to distinguish between the interactive and integrative accounts based on purely behavioral data (and none of our empirical findings hinge on this distinction), one aspect of our results is difficult to explain on the integrative account. Whereas both accounts predict that categorical inputs would increase discriminability between categories and decrease discriminability within categories, the interactive account predicts that a categorical prior would also increase discrimination within parts of the category (the so-called transitional trials; see Figure 1) because the influence of the labels depends on the typicality of the items that are being discriminated. Although it is possible to accommodate this finding in an integrative account by modeling category inputs as continuous, doing so begins to merge the distinctions between the two accounts to a point at which they no longer meaningfully differ.

There remains the possibility that color representations at some early level of visual processing are entirely immune to linguistic influences. However, what our results show is that basic visual discrimination evidently does not rely on these immune visual representations and instead is strongly influenced by in-the-moment use of language.

Between-Category Differentiation Versus Within-Category Equivalence in Categorical Color Perception

The changes to categorical perception that we observed here was revealed as an improvement in between-category differentiation rather than as within-category equivalence. In the beginning of the article, we described that between-category differentiation is more common than within-category equivalence in other domains such as speech. At the urging of a reviewer, we examined whether some of the previously reported cases of categorical color perception stem from within-category equivalence, between-category
T1 differentiation, or both. A summary is presented in Table 1. The results paint a mixed picture. While the majority of findings show greater effects on between-category differentiation (e.g., speeding up of between-category discrimination), some findings do show greater categorical perception stemming from within-category equivalence (as revealed by slower responses). The conditions that give rise to one pattern or the other remain unclear.

Is This an Attentional Effect?

Is the observed effect of verbal cues on visual discrimination an effect of attention? The answer depends on how one defines attention (Anderson, 2011; Lupyan, 2017). Neither verbal nor visual cues contained any useful information concerning the location of the target and so the effects cannot be explained by appeal to spatial attention. Could the effect of verbal cues be explained as featural attention operating across the visual field (e.g., Maunsell & Treue, 2006; Zhang & Luck, 2009)? On a feature-based attention account, the improved visual color discrimination following verbal cues involves modulation of visual representations (as also argued by the present account). Feature-based attention is not an alternative to our account, but rather a possible mechanism. Our results suggest that verbal cues may be uniquely effective at deploying attention to perceptual *categories* (Lupyan, 2008b; Yang & Zelinsky, 2009) and raise the possibility that the ability to direct people's attention to perceptual dimensions like shape and color may importantly rely on their having previously learned labels (such as color names and the word "color" itself) that then become highly effective cues for attentional guidance (Lupyan, 2008b; Nako, Wu, Smith, & Eimer, 2014).

Is This Just a Priming Effect?

Can the observed findings be viewed as a type of priming? The answer again depends on the precise definition of priming. Although we used the term "cues" when referring to the stimuli presented before the color discrimination task, they could just as well be called "primes". The key question is, what *kind* of priming explains the present results. The results of Experiment 3 suggest that color discrimination (at least when moderately difficult) is not affected by visual previews (a condition that effectively implements a perceptual prime). This ineffectiveness is at odds with the usefulness of visual previews in conventional visual search tasks (e.g., Vickery, King, & Jiang, 2005), which is to be expected. In a visual search task in which a participant's task is to find a particular image such as a motorcycle, seeing an exact preview of the motorcycle helps by preactivating relevant visual representations leading to faster rejection of nonmatching items and/or faster identification of the target. In the present task, however, preactivating the hue matching the target color swatch does not necessarily make its representation stand out from that of other swatches leaving accuracy unaffected. If the present results are construed as an instance of priming, it would be an instance of *categorical* priming (see Lupyan, 2017; Nako et al., 2014). The main conclusion remains that verbal labels are acting as categorical cues (primes) influencing discrimination accuracy.

[7] The primary reason appears to be that the authors view verbal effects as stemming solely from explicit verbal rehearsal, which they think is unlikely to be occurring in a study involving simultaneous color matching. On the label-feedback account, verbal effects are not limited to such explicit verbal rehearsal and can occur because of automatic (and implicit) activation of verbal labels from visual inputs.

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Table 1
Summary Results From Some Previous Research on Categorical Color Perception of Wheher Changes in Categorical Color Perception Stem From Within-Category Equivalence, Between-Category Differentiation, or Both

Reference	Task	Manipulation	Based on inspecting	Manner in which categorical perception is affected
Gilbert, Regier, Kay, and Ivry (2006)	Odd one out visual search	Right vs. left visual field: baseline (Exps. 1 and 2).	Figures 1c, 2b	Both, but larger effect for between-category in right vs. left visual field.
Gilbert et al. (2006)	Odd one out visual search	Right visual field: baseline vs. verbal interference (Exps. 1 and 2)	Figures 1d, 2c	Larger effect on between-category responses that are slowed by verbal interference in the right visual field.
Gilbert et al. (2006)	Odd one out visual search	Right vs. left visual field: nonverbal interference (Exp. 2)	Figure 2b–2d	Faster for between category in the right visual field.
Winawer et al. (2007)	Simultaneous color match	Verbal interference	Figure 2-left	Between-category matches slowed by verbal interference
Drivonikou et al. (2007); Reanalysis of Daoutis et al. (2006), Exp. 1	Odd one out visual search	Right vs. left visual field	Figure 1c	Slower within-category in right visual field.
Drivonikou et al. (2007); Reanalysis of Daoutis et al. (2006), Exp. 2	Odd one out visual search	Right vs. left visual field (blue vs. green trials)	Figure 2c	Both, but larger effect for between-category differentiation in the right visual field.
Drivonikou et al. (2007); Reanalysis of Daoutis et al. (2006), Exp. 2	Odd one out visual search	Right vs. left visual field (blue vs. purple trials)	Figure 2e	Faster between category differentiation in the right visual field.
Franklin et al. (2008)	Odd one out visual search	Right vs. left visual field; infants vs. adults.	Figure 2	Slower within-category[a] differentiation.
Roberson, Pak, and Hanley (2008)	Odd-one out visual search	Right vs. left visual field; Korean vs. English speakers	Figure 4-left	Approximately equal within-category equivalence and between-category differentiation.

Note. Exp. = experiment.
[a] This pattern is unlikely to be caused by acquired equivalence because the visual-field difference for within-category discrimination is stronger for infants than for adults.

Open Questions

Our work leaves open several questions. The first concerns the developmental trajectory of color categories. If language causes categorical color perception, then the presence of color categories in young infants, as has been reported by a number of studies (Clifford, Franklin, Davies, & Holmes, 2009; Franklin & Davies, 2004; Ozturk et al., 2013; Skelton, Catchpole, Abbott, Bosten, & Franklin, 2017), presents an obvious puzzle. One possibility is that adult-calibrated color spaces such as Munsell and CIELUV do not accurately reflect infant color vision. Color distances that are equated for adults may not be equated for infants. If so, then the results used to support categorical color perception in infants may instead reflect infants picking up on perceptual discontinuities in the materials (Ocelák, 2016; cf. Franklin, Skelton, & Catchpole, 2014). Another possibility is that there are indeed preverbal color categories that are gradually modified by learning the color terms of specific languages.

Our work also leaves open the question of the neural mechanisms by which language augments color representations. We have suggested that words affect color discrimination performance by transiently warping visual color representations via top-down feedback. Being a purely behavioral study, our work does not directly test this proposed mechanism, but a number of functional magnetic resonance imaging (fMRI) and electroencephalogram (EEG) results suggest that such top-down modulation is occurring. For example, Brouwer and Heeger (2013) used fMRI to estimate categorical tuning of color representations throughout visual cortex while subjects either named the colors or performed an attention-diverting two-back task. Categorical representation of color was observed only during the color naming task and in two regions: ventral V4 (V4v) and a visual region at the ventral-occipital-temporal border (VO1). Further evidence that color categories warp visual representations come from studies using EEG which show that categorical relationships between visual stimuli are being represented during early visual processing (Clifford, Holmes, Davies, & Franklin, 2010; Forder et al., 2017; Maier & Abdel Rahman, 2018; Thierry et al., 2009). However, we would be remiss to ignore several conflicting studies showing that categories influence only later, higher-level processes (Clifford et al., 2012; He, Witzel, Forder, Clifford, & Franklin, 2014; see also Francken, Meijs, Hagoort, van Gaal, & de Lange, 2015). Some of the differences between these and studies showing more direct influences on visual processing may be caused by stimulus confounds (Forder et al., 2017 for discussion). Another source of discrepancy may be because of the degree to which different tasks emphasize categories. As the present studies show, the extent to which people perceive colors in a categorical fashion is quite flexible: it can be modulated on a trial-by-trial basis by language. Categorical perception can also be enhanced when trials are blocked by color category (Experiment 2), a manipulation that may be emphasizing the category via more sustained top-down feedback from the category label (see Lupyan & Spivey, 2008, for a computational model).

Notwithstanding some of the above-mentioned physiological evidence that perceptual representations appear to be influenced by cognitive processes, some critics of the idea that perception is "cognitively penetrable" (e.g., Firestone & Scholl, 2016) may wonder whether the current results can be explained as language affecting only "postperceptual" processes with genuine perception left untouched. If this is the case, one must then conclude that standard psychophysical methods of the kind used here simply reflect postperceptual processing. If true, then a considerable body of psychophysical research, claiming to reveal facts about the workings of perception should be reclassified as studies of post-perceptual processing. We are skeptical that psychophysics could be so grossly mistaken (see Lupyan, 2016a for discussion).

Beyond Color

While the focus of the present work is on the effect of language on color discrimination, language has been found to influence performance in many other putatively nonverbal domains ranging from how people encode and remember events (Athanasopoulos & Bylund, 2013; Boroditsky, Ham, & Ramscar, 2002), to object recognition (Lupyan & Thompson-Schill, 2012), temporal cognition (Boroditsky, Fuhrman, & McCormick, 2011; Bylund & Athanasopoulos, 2017), visual search (Lupyan, 2008b), motion detection (Francken, Kok, Hagoort, & de Lange, 2015; Meteyard, Bahrami, & Vigliocco, 2007), and abstract reasoning (Baldo, Paulraj, Curran, & Dronkers, 2015; DeShon, Chan, & Weissbein, 1995). While the measures and methods used in these studies vary too greatly to be explained by a single mechanism, they offer converging evidence of language rapidly and often automatically modulating performance in domains traditionally thought to operate independently of linguistic influence. At the same time, these studies show that such linguistic influences are dynamic and highly flexible, a far cry from the language-as-straitjacket caricature of Whorfian effects that is sometimes invoked by critics (for discussion see, Borghi & Binkofski, 2014; Boroditsky, 2010; Bylund & Athanasopoulos, 2017; Casasanto, 2008; Lupyan, 2016b).

Conclusion

We set out to examine whether there are perceptual consequences to the use of color names. We found that verbal cues—hearing color names such as "red" and "blue"—had substantial effects on accuracy with which people distinguished colors in an untimed simultaneous discrimination task. The accuracy pattern was consistent with labels inducing more categorical color representations. Subsequent experiments showed that verbal labels appear to play a privileged role in inducing this more categorical state. These results suggest that categorical effects shown in some color discrimination tasks (e.g., Bae et al., 2015; Witzel & Gegenfurtner, 2015) may be partly due to the involvement of verbal labels. Whereas all perceptual experiences of blueness are necessarily specific, color names allow us to transcend this specificity, leading to improved discrimination in regions of color space most relevant for linguistic communication.

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