Signatures of Domain-General Categorization Mechanisms in Color Word Learning

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Abstract

Learning color words is a difficult problem for young children. Because color is abstract, this difficulty has been attributed to challenges in integrating over heterogeneous objects to discover color as a dimension of reference. On this account, learning that color words refer to the color dimension is slow, but subsequently mapping these words to particular shades is fast. Recent work suggests an alternative: Children may rapidly identify color as a referential dimension, but only gradually discover the precise boundaries of each color word. This alternative proposal predicts that the learning mechanisms underlying the acquisition of color words should parallel those underlying the acquisition of concrete object categories. We test this prediction, finding that children's performance in a color naming task is modulated by three factors that have previously been studied in category learning: input frequency, category size, and perceptual salience. Because it allows for precise psychophysical measurement of category properties, color presents a unique case study for investigating language acquisition and categorization more broadly.

Keywords: Language acquisition, word learning, categorization, cognitive development

Introduction

Young children can learn a surprising amount from just one encounter with a new word (Carey & Bartlett, 1978; Markson & Bloom, 1997). Notably, they will extend a new word beyond the single referent for which it was used to the *category* this referent comes from. That is, a child learning the word "ball" will extend it not just to the soccer ball at home, but also to a basketball on the television and a balloon in the sky (Clark, 1973). Using words in novel contexts is a signature aspect of children's early language use, one that gives insight into our cognitive architecture and its development.

To generalize the meaning of "ball" to other balls, children must solve two problems. First, they must infer that "ball" refers to a category organized by shape and not size or color (*dimension identification*). Second, after identifying shape as the relevant dimension, they must infer that balls are spherical or elliptical, but not rectangular (*extent identification*). Children's early vocabularies are dominated by concrete nouns like "ball" (Fenson et al., 1994), and we know a lot about how they learn these nouns. By the time they are two years old, children acquire a strong bias to extend words that refer to solid objects by whole-object shape (e.g., Landau, Smith, & Jones, 1988; Markman, 1990). This shape bias facilitates rapid, correct dimension identification, suggesting that once it is in place, the primary challenge for concrete nouns is extent identification. Indeed, children appear to fast map concrete nouns to their approximate meanings, but only slowly discover their exact extents through gradual approximation (Ameel, Malt, & Storms, 2008; Swingley, 2010). Thus, several lines of research suggest that domain-general learning and categorization mechanisms can account for children's acquisition of concrete nouns. But are more abstract words learned like concrete nouns, or are the challenges and learning mechanisms distinct for different kinds of words?

We investigate this question by taking color as a case study. In contrast to concrete nouns, color words are used correctly relatively late in development (Bartlett, 1977; Soja, 1994). This delay is surprising because two pieces of evidence suggest that identifying the extents of color words should be easy. First, these extents have been argued to reflect an optimal partitioning of color space into discrete categories, leading to cross-linguistic universals in the categories referred to by color words (Berlin & Kay, 1969). Second, children's color perception appears adult-like well before their first birthday, suggesting that they may have access to these perceptual categories by the time they are learning color words (Pitchford & Mullen, 2003). Consequently, children's relatively slow color word learning has been argued to be a problem of dimension identification; the same shape bias that facilitates dimension identification for concrete nouns hinders domain identification for color (Sandhofer & Smith, 1999; Franklin, 2006).

There are two reasons to doubt this account, however. First, even children who do not know the correct extents of any color words seem to understand that they belong to the same semantic domain: When asked about an object's color, they will produce a color word (Bartlett, 1977). Second, recent work by Wagner, Dobkins, and Barner (2013) shows that children's extent identification for color words is not all-or-none. Children who extend color words incorrectly do not use them haphazardly. Instead, their categories tend to be consistent over-extensions of adult categories. For example, children who used "blue" to label blue exemplars often also used "blue" for purple and gray exemplars.

Thus, despite initial assumptions, learning the meaning of the word "blue" may be quite similar to learning the meaning of the word "ball." If so, the same factors that contribute to the ease or difficulty of learning concrete noun categories should also predict acquisition of color word categories. We test this proposal with three factors that are well-studied in category learning: input frequency, category size, and perceptual salience. Estimates of each of these factors for the 11 basic English color terms predict nearly all of the variance in

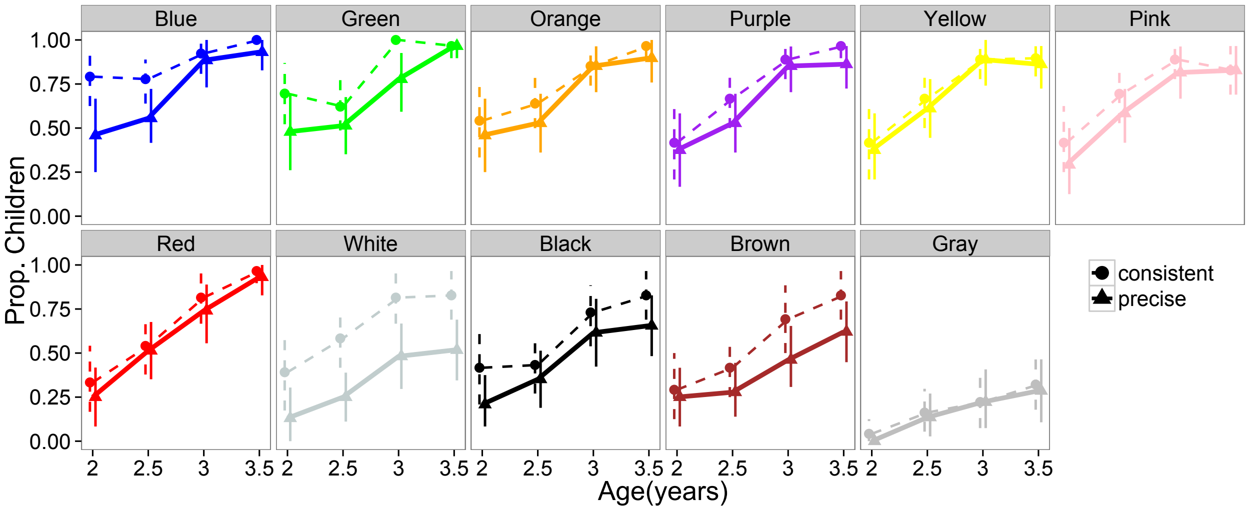

Figure 1: Children's knowledge of the extensions of the 11 basic English color terms across development. To be counted as *consistent*, a child had to always refer to the same color with the same correct term (e.g. blue always called "blue"). To be counted as *precise*, this term had to be used only for its correct color (blue called "blue," no other color called "blue"). These data show that extent identification for color words extends over several years and varies significantly from color to color. We take precise knowledge as our main measure because it is the end-state of color categorization.

children's color word acquisition in Wagner et al.'s data. This work extends our understanding of early word learning by showing that the same mechanisms responsible for learning concrete nouns also play a significant role in a more abstract semantic domain. Further, because color words allow precise psychophysical estimates of natural-language category boundaries, they present a uniquely informative new window into children's categorization more broadly.

Empirical Data

Wagner et al. (2013) tested children's color word knowledge in two simple production tasks. In each, children saw a series of uniformly-shaped but differently colored chips on a neutral black background. Each chip was shown to the child one at a time, and the child was asked "what color is it?" In one task, the chips were squares. In the other, they were shaped like fish. Children did not respond on a small proportion of trials (4.7%), which were not further analyzed. Wagner et al. (2013) tested a total of 141 children. We excluded children with a family history of abnormal color vision, or who did not cooperate on more than half of the trials, yielding a final sample was 116 children, who we separated into half-year age groups: 24 2-year-olds, 37 2.5-year-olds, 26 3-year-olds, and 29 3.5-year-olds.

Wagner et al.'s main investigation was an analysis of the systematicity of children's errors. Here, in contrast, we consider their correct responses, particularly whether they had consistent and precise extensions for each of their color words. A child's knowledge of a color word was considered *consistent* if they correctly used the English label for a color to label it in each task (e.g. called both the blue square and the blue fish "blue"). A child's knowledge was considered *precise* if they additionally did not use this term to refer to any other chip incorrectly (e.g. never called a red or orange chip "blue"). Figure 1 shows the proportion of children with consistent and precise knowledge of each of the 11 basic color words across development.

These acquisition trajectories contain a number of features that suggest an extended period of extent identification. First, for every color, both consistent and precise knowledge increase significantly across development. Second, colors vary significantly in their rates of acquisition and in the shapes of their acquisition trajectories. Finally, some colors appear to be initially overextended, characterized by a large proportion of consistent but imprecise knowers, but others colors are used precisely as soon as they are used consistently. These patterns parallel those observed in children's concrete noun category learning, raising the possibility that the same underlying learning mechanisms may be responsible for learning the meanings of these seemingly different kinds of words.

Predicting Color Word Learning

A single, domain-general account of concrete noun and color word learning would imply that factors that predict relative difficulty of different nouns should also predict relative difficulty among the color words. We investigate this hypothesis through three concrete predictors: input frequency, category size, and perceptual salience. In this analysis, we take as our primary goal the prediction of children's precise color knowledge. We return to the relationship between consistent and precise knowledge in the general discussion.

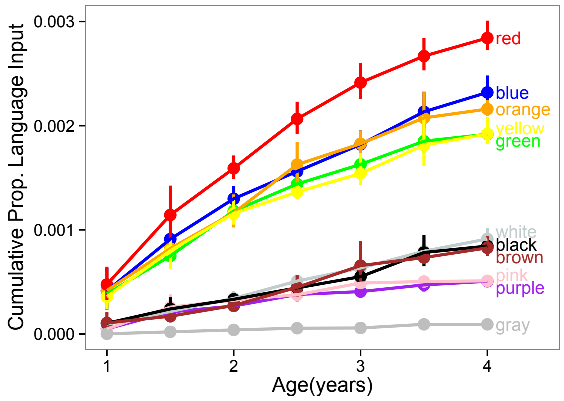

Figure 2: Cumulative proportion of input, plotted for each color word in CHILDES for children ages 1–4. Error bars indicate 95% confidence intervals computed by non-parametric bootstrap across children. Colors vary significantly in their input frequency, with the most frequent colors heard an order of magnitude more often than the least frequent color.

Input Frequency

The effect of frequency on learning rates is ubiquitous across domains and learning paradigms. In category learning, it is common to observe improved categorization accuracy across learning trials, as well as differential effects of exemplar frequency on learning rates between categories (e.g. Hayes-Roth & Hayes-Roth, 1977; Nosofsky, 1986). Frequency effects are also consistently observed in the language learning domain. For instance, Goodman, Dale, and Li (2008) estimated the frequency with which young children heard 526 different words. They showed that words' relative frequencies predicted significant variance in the ages at which children began to produce these words. This effect was particular strong for nouns ($r = .55$), although it explained some variability in the acquisition of verbs ($r = .22$), adjectives ($r = .28$), and closed class words as well ($r = .24$).

We follow Goodman et al. (2008), estimating the frequency of each of the 11 basic color words by counting their token frequency in CHILDES, a large, open database of transcribed child-directed speech (MacWhinney, 2000). All tokens produced by each North American child's mother and father were included in our estimates of input frequency. For each half-year age-bin between 1 and 4, we computed the number of tokens of each color word per 1000 words heard (Figure 2). Frequencies vary significantly from color to color. For instance, a child will hear "red" approximately 3 times as often as "brown" by the time she is 4 years old.

As our primary measure of the effect of frequency on color word learning, we include it in a mixed effects model that jointly predicts children's precise color knowledge from frequency, category size, and perceptual salience. As an interim result, however, and for comparison to Goodman et al. (2008), we estimated the correlation between cumulative input frequency at age 4 and the average proportion of all 116 children in our sample who had a precise category for each of the 11 colors. Frequency and precise color word knowledge were highly and significantly correlated ($r(10) = .79, p < .01$). Just as for concrete nouns, input frequency is significantly correlated with children's acquisition for color words.

Category Size

In addition to learning a category's extent, a common measure in the categorization literature is acquisition of the category's prototype: its most statistically representative exemplar. Recent work suggests that focal colors—those empirically estimated by native speakers to be the best examples of each color—are category prototypes (Abbott, Regier, & Griffiths, 2012). Consequently, we predict that children's acquisition of labels for the 11 focal colors tested by Wagner et al. (2013) should be predicted by factors that predict acquisition of category prototypes more generally.

One consistent finding with regard to category learning is that category prototypes are learned more easily and more rapidly for larger categories (Homa & Vosburgh, 1976; Hintzman, 1986). To estimate the category size of each color category, we used a dataset of judgments from adult native speakers of English in a large color naming task. Lindsey and Brown (2014) asked 51 American English speakers to provide color labels for each of 330 Munsell color chips, a set of color samples designed to densely sample color space (see Berlin & Kay, 1969).[1] To estimate the category size of each color, we computed the proportion of Munsell chips for which all speakers agreed it was the correct label (Figure 3).

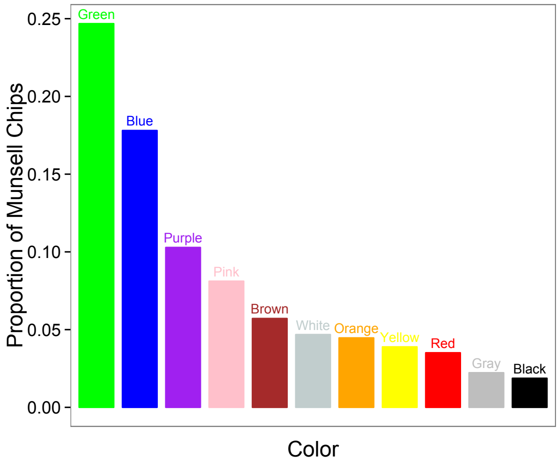

Figure 3: Proportion of the 330 Munsell chips judged by American English speakers to belong to each of the 11 basic color categories. The variance in these category sizes significantly predicts children's acquisition of these color terms.

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[1] We used Lindsey and Brown's estimates because they are more recent than those available in the World Color Survey (Berlin & Kay, 1969). However, all results remain significant using Berlin and Kay's adult judgments.

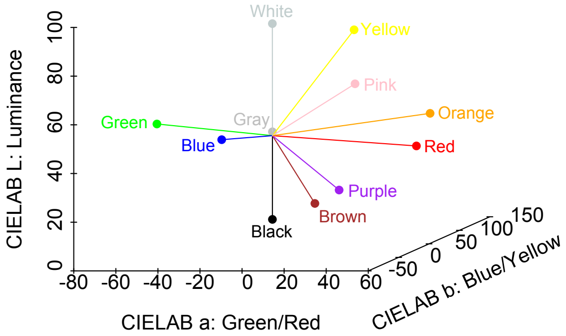

Figure 4: The position of the focal colors for each of the 11 English basic color words, plotted in CIELAB space. The salience of each color was estimated as its Euclidian distance to the origin (indicated by the line segments).

Category size was significantly correlated with children's probability of having a precise category for each color ($r(10) = .6, p < .05$; we report full model results below). Thus, as with input frequency, category size significantly correlates with rates of acquisition of color words, supporting the previous suggestion that a significant proportion of the delay in children's color word learning is due to extent identification rather than dimension identification.

Perceptual Salience

Finally, if color words are learned by a domain-general categorization process, we should expect each color's relative perceptual salience to predict that color's ease of acquisition. Across a number of categorization experiments, perceptually salient categories are reliably learned more rapidly than less salient categories (Nosofsky, 1986; Lamberts, 1998; Kruschke & Johansen, 1999).

To estimate the perceptual salience of each of the 11 basic color categories, we located each focal color's position in 3-dimensional color space. A natural space for this purpose is CIELAB—an opponent process space constructed by the French International Commission on Illumination to approximate human perceptual space. It is widely used in analyses of human color perception (Berlin & Kay, 1969; Wagner et al., 2013; Lindsey & Brown, 2014). CIELAB's three dimensions (L, a, and b) correspond to a lightness dimension, a green-red opponent process dimension, and a blue-yellow opponent process dimension. We define each color's perceptual salience as its Euclidian distance from gray at the center of the space (Figure 4). The two opponent process dimensions range from -128 to $+127$, so we picked 0 as their center. In contrast, the luminance dimension ranges from 0 to 100, so we chose 50 as the center. As with frequency and category size, perceptual salience was significantly correlated with children's precise color knowledge ($r(10) = .71, p < .05$).

Complete Model

So far, we have shown that input frequency, category size, and perceptual salience are each significant predictors of children's knowledge of the meanings of color words at the aggregate level. We now return to the rich dataset that motivated these predictions: the variable trajectories of individual color words across development (Figure 1). Although our three predictors are typically varied independently in studies of categorization, they are correlated in many natural categories, including those referred to by color words. We can thus ask whether frequency, category size, and perceptual salience each account for independent variance in learning.

We fit a mixed-effects logistic regression to the full dataset, predicting whether each child had a precise color category for each color word. We included in the model the number of times each color appeared in the input for a child of that age (Figure 2), each color's category size (Figure 3), and each color's perceptual salience (Figure 4). Frequency and category size were both log-transformed, based on prior evidence that learning scales in the log of input (Anderson & Schooler, 1991). All three factors were highly significant predictors of children's color knowledge (Table 1).

To visualize the effect of adding each factor, we plot model predictions against children's knowledge as each predictor is included (Figure 5). The top panel shows a control model that uses children's age to predict their precise color-word knowledge. This model captures the global increase in precise knowledge across development. A global increase across all color-words could in-principle be predicted by a dimension-identification account that included performance limitations. That is, global improvement could arise from early precise categories combined with developmental changes in motivational and/or attentional factors that lead older children to be more engaged in and thus better at our task. However, neither this model nor any such account can capture either the aggregate differences in difficulty among the colors, or their idiosyncratic patterns of acquisition across development.

Using a single category predictor—the number of times each color word appears in children's input at each age—substantially improves fit of the model, allowing it capture some of the differences in difficulty. In addition, it allows us to correctly predict different growth trajectories for each color based on non-linearities in their cumulative frequency across development (Figure 2). Category size and salience

Table 1: A mixed-effects logistic regression predicting children's precise color word knowledge from category learning predictors. The model was specified as `precise` $\sim$ `log(frequency)+log(size)+salience+(1|subj)`

Predictor	Estimate (SE)	z-value	Sig.
Intercept	-1.71 (.46)	-3.69	$p < .001$
Log(Frequency)	.54 (.14)	3.97	$p < .001$
Log(Size)	.71 (.12)	5.73	$p < .001$
Salience	.018 (.004)	3.96	$p < .001$

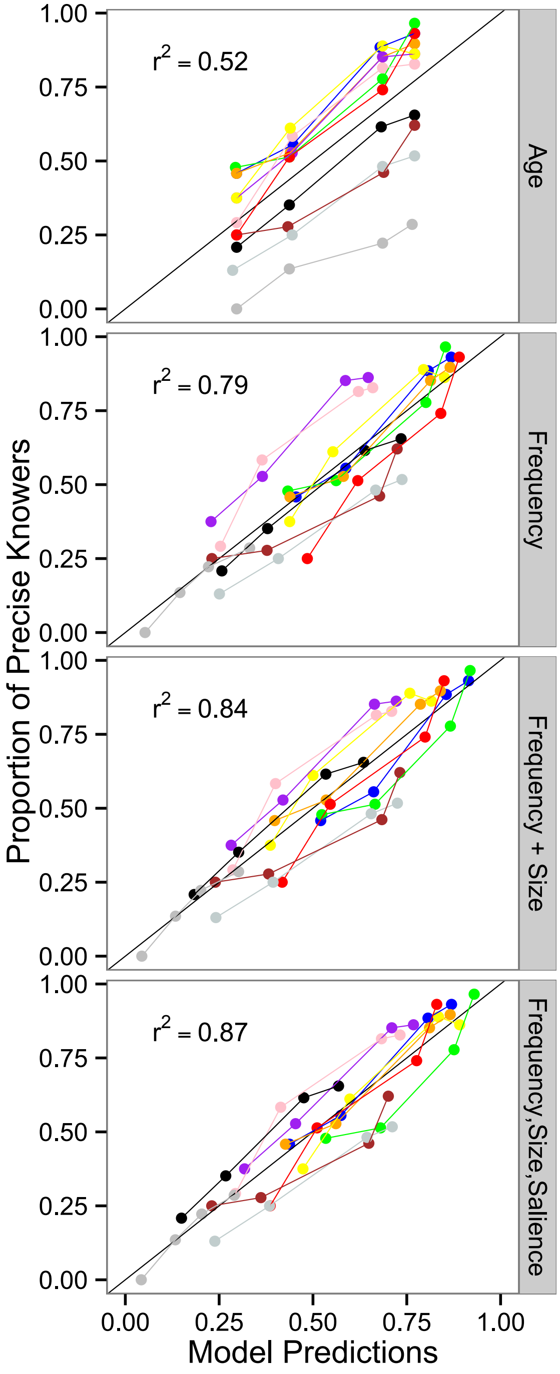

Figure 5: Model predictions compared to children's precise color word knowledge for each of the 11 basic colors and 4 age groups in Wagner et al. (2013). Each point represents one age group for one color, lines connect the four age groups for each color. Each panel shows the model's fit as an additional predictor is added to the mixed-effects model; the last panel shows the full model. Distance between the points and the diagonal is a visual indicator of goodness of fit. When all three factors were included, the model predicted nearly all of the variance in children's color word knowledge.

each contribute a small but significant amount of predictive power to the model, adding up to capture 87% of the variance in children's knowledge across color and age.

General Discussion

Children learn the meanings of color words significantly later than they learn the meanings of equally frequent concrete nouns. For instance, "blue" is 150% as frequent as "ball" in CHILDES, but children do not seem to have a precise meaning for "blue" until they are 3 or 4 years old. This relative delay has led to the consensus that these two different kinds of words must present different challenges for the learner. In particular, the consensus account holds that children rapidly identify shape as the correct dimension on which to extend concrete nouns, but only slowly discover that color is a relevant dimension for generalization.

Our analyses cast doubt on this interpretation by providing evidence that the rates of acquisition of the meanings of individual color words are predictable from with their individual category properties. This result suggests that even if domain identification is more difficult for color words than concrete nouns, it is not the primary reason for their relative delay. Thus, a single, domain-general learning mechanism may account of learning for both kinds of words. Of course, these results are fundamentally correlational; they cannot uniquely identify the mechanism responsible for color word learning (Glymour, 1998). Nonetheless, they provide strong prima facie evidence that our theory of color word learning may need to be reconsidered, as has happened with dimension identification theories of delay for other kinds of abstract words (Widen & Russell, 2008).

If domain identification is not the primary barrier for learning the meanings of color words, but rather extent identification, why is their acquisition so slow relative to equally frequent concrete nouns? We propose that this question may be ill-posed; children may acquire color words no more slowly than concrete nouns. Because color is such a densely packed semantic domain, it is relatively easy for both researchers and caregivers to identify imprecisions in children's category boundaries (Hidaka & Smith, 2010). In contrast, children could have equally imprecise category boundaries for concrete nouns, but their use of these words could be indistinguishable from use by adults in typical contexts. That is, just as there is a lag between children's consistent use of color words and their precise use of these same words, there is likely to be a similar lag for concrete nouns. Indeed, explorations of children's categories in equally restricted domains of concrete nouns—e.g. the meanings of "cup," "bowl," and "plate" find developmental change in category boundaries well into late childhood and even young adulthood (Andersen, 1975; Ameel et al., 2008). Put another way, 2-year olds may have the same imprecision in their "ball" category as in their "blue" category.

Because the color domain is amenable to precise psychophysical estimation of natural language category boundaries, it is ideal for identifying changes in children's word meanings from inconsistent, to consistent, to precise over early development. Color words provide a powerful new setting in which to investigate early learning and generalization mechanisms, one that promises to unify our models of language acquisition with our models of categorization.

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