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Partial color word comprehension precedes production

Katherine Wagner, Jill Jergens, and David Barner

University of California, San Diego

Corresponding Author

Katherine Wagner

Department of Psychology, 0109

University of California, San Diego

La Jolla, CA 92093

kgwagner@ucsd.edu

Abstract

Previous studies report that children use color words haphazardly before acquiring adult-like meanings. The most common explanation is that children do not abstract color as a domain of linguistic meaning until several months after they begin producing color words, resulting in a stage during which children produce but do not comprehend color words. Contrary to this account, the current study provides converging evidence from multiple measures that toddlers (N=55; 18-33 mos) acquire partial but systematic color word meanings often before production, although adult meanings are acquired much later. These data support the idea that inductive processes of category formation, rather than problems abstracting color, explain the delay between children's first production of color words and mastery of adult meanings.

Keywords: adjective acquisition, categorization, color categories

Color words pose a difficult problem for children learning language (Backscheider & Shatz, 1993; Sandhofer & Smith, 1999; Kowalski & Zimiles, 2006; O’Hanlon and Roberson, 2006). As noted in a number of previous reports, children produce color words in a seemingly haphazard manner for many months before converging on adult-like meanings (Pitchford & Mullen, 2003; Sandhofer & Smith, 1999; Soja, 1994), a pattern that has also been reported in abstract domains of word learning, such as time, emotion and number (Brooks, Audet, & Barner, 2012; Busby Grant & Suddendorf, 2011; Shatz, Tare, Nguyen, & Young, 2010; Wynn, 1992; Widen & Russell, 2003). In the case of color words, many previous studies have argued that this delay between production and adult-like comprehension is due to children’s difficulty identifying color as the relevant domain of linguistic meaning. Consequently, these accounts propose that children initially produce color words (e.g., *red*, *green*, *blue*) without yet knowing whether they refer to shape, color, texture or some other property (Franklin, 2006; Kowalksi & Zimiles, 2006; O’Hanlon & Roberson, 2006; Sandhofer & Smith, 1999). The present study challenges this conclusion and shows that although children master adult like meanings of color words many months after they begin producing them, they acquire partial meanings far earlier, often before the onset of production. This suggests that the delay between production and the acquisition of adult-like meanings cannot stem from problems abstracting color, but instead is best explained by a gradual inductive process of determining the boundaries of individual color words.

In most domains of vocabulary acquisition, children acquire basic meanings for words before they begin to produce them in speech, such that in infancy and early childhood the number of words that children comprehend far exceeds the number of words that they produce (Bergelson & Swingley, 2013; Bergelson & Swingley, 2013; Tincoff & Jusczyk, 2012; Tincoff & Jusczyk, 1999; Goldin-Meadow, Seligman & Gelman, 1976; Harris, Yeeles, Chasin & Oakley,

1995; Fenson et al., 1994). However, according to some accounts there are important exceptions to this general pattern. For example, children learn to count and produce number words many months before they acquire their meanings (Wynn, 1990, 1992; Carey, 2009). Also, similar claims have been made in the domains of time (Shatz et al., 2010; Friedman, 1982; Tillman & Barner, 2013), and emotion (Widen & Russell, 2003). In each of these lexical domains, when children are asked a question – e.g., “What color is this?” or “How many are there?” they respond with domain-appropriate words (e.g., *red*, *seven*) but often select the word incorrectly (e.g., responding *red* when asked about a purple object; for discussion see Shatz et al., 2010). Across these domains, children often produce words for months – or in some cases for several years – before they acquire their adult-like meanings.

In the case of color words, the most common explanation for this lag between production and adult-like comprehension is that children struggle to abstract color as the relevant dimension of linguistic meaning. In other words, although children quickly learn to produce color words and associate them with the word “color” (Shatz et al., 2010), they struggle to identify color as the aspect of experience that this category of words encodes (e.g., Franklin, 2006; Kowalksi & Zimiles, 2006; Sandhofer & Smith, 1999). Critically, on this account, children’s difficulty is due to abstracting color rather than identifying the specific perceptual values encoded by particular words. As evidence for this view, proponents note that preverbal infants possess perceptual color categories that appear to be similar to the linguistic color categories of English-speaking adults (Franklin, Pilling & Davies, 2005; Bornstein, Kessen & Weiskopf, 1976) onto which newly acquired color words could be quickly mapped. For example, according to Shatz, Behrend, Gelman, and Ebeling (1996), “on perceptual tasks, infants treat the continuous dimension of hue categorically much as adults do. . . Thus, the apparent difficulty children have with color term

acquisition cannot be primarily because the perceptual domain is continuous whereas the lexical domain is discontinuous” (p. 178). Similarly, according to Franklin (2006), “A common theme in explaining children’s difficulty in color naming is the idea that children find it difficult to learn color names because they need to learn the boundaries of colors... [However] perceptual categories are in place even at 4 months of age” (p. 324-325). Accordingly, these accounts argue that once children identify color as the relevant dimension of meaning, they acquire color word meanings quickly, since they can easily map new color words onto pre-existing perceptual color categories: “Children seem to struggle with their first color word yet learn most of the other basic terms fairly rapidly over the next several months . . . This seems to suggest that there is some kind of ‘switch’ for children’s ability to learn and map color words correctly” (p. 324 Franklin, 2006).

While this hypothesis offers a parsimonious account both of children’s difficulty with color words and the origin of color word meanings (i.e., as rooted in perceptual categories), it ultimately cannot explain how children converge on language-specific color word meanings. Children must be able to learn the color boundaries of any of the world’s languages, and critically, languages vary both with respect to the number of categories they encode and the precise location of the color category boundaries (Kay, Berlin, Maffi, Merrifield & Cook, 2009). For example, Berinmo, a tribal language with five basic color categories spoken in Papua New Guinea, features the colors *nol* (green, blue and purple) and *wor* (green, yellow, orange and brown). Thus, Berinmo marks a color boundary that is absent in English (i.e., a boundary within the English *green* category), but also fails to mark other boundaries that are found in English (e.g. the boundary between *blue* and *purple*; see Roberson, Davidoff, Davies, & Shapiro, 2005). Furthermore, the number of basic color terms a language has does not determine the boundaries

between colors: Korean, English, and Russian all divide the blue-green region of color space differently despite having around 11-12 basic color words (Berlin & Kay, 1969; Roberson, Hanley, & Pak, 2009; Winawer, Witthoft, Frank, Wu, & Boroditsky, 2007).

This cross-linguistic variation in the number and location of color word boundaries suggests that children must use evidence from their language input to construct language-specific color word meanings. Recent studies suggest that this inductive problem, rather than problems abstracting color, may be the primary difficulty that children have when learning color words. In one recent study, Wagner, Dobkins and Barner (2013) replicated previous reports finding that 2- to 4-year-olds produce many errors when they use color words. However, when they analyzed the nature of these errors, they found three pieces of evidence that errors were highly systematic in nature, consistent with the presence of preliminary, non-adult meanings. First, Wagner et al. found that children's errors were consistent – e.g., when children used *red* to label purple on one trial, they often did so on subsequent trials as well. Second, children's errors were perceptually proximal to the target – e.g., children were more likely to label purple as *red* rather than *green*. Finally, they found that children's errors were typically overextensions of adult categories. For example, when children used *blue* to label green, they almost always also used it to label blue. Together, these data suggest that children acquire partial meanings of color words prior to learning full adult-like meanings. Rather than having trouble identifying color as relevant to color word learning, children's main difficulty appears to be due to identifying which specific perceptual values are labeled by which words.

Wagner et al.'s (2013) study suggests that although adult-like meanings for color words are mastered much later, many children have preliminary meanings for color words as soon as they produce them. However, it remains unknown whether these preliminary meanings emerge

after production, as argued by previous studies, or if they emerge before production, as in the case of object labels (Goldin-Meadow, Seligman & Gelman, 1976; Harris, Yeeles, Chasin & Oakley, 1995). Evidence of color word meanings prior to production – even very rudimentary ones– would suggest that children can map color words onto specific regions of color space very early in the acquisition process, and that identifying the relevant dimension of meaning for color words may be no more difficult than it is for other domains of meaning.

To investigate this possibility, we tested color word knowledge in English-speaking 18- to 33-month-olds. Our objective was not to determine at what age children acquire meanings for color words – previous work has shown that this is variable and highly subject to experience (see Shatz et. al, 1996 and Franklin, 2008 for review). Instead, our objective was to test the process by which children construct their knowledge of color words by determining the order in which they acquire elements of this knowledge. Specifically, we asked whether children acquire partial comprehension of color words before they begin producing them, or vice-versa. To this end, we conducted an in-lab eye-tracking task and an in-lab assessment of color word production. These in-lab measures were corroborated by parent report regarding each child’s production and comprehension of color words. If children construct preliminary meanings for color words before production, we should find some children who exhibit partial comprehension for color words despite not yet producing them. In contrast, if children construct preliminary meanings for color words after production, we should find evidence that some children produce color words without yet having partial comprehension for them.

Methods

Participants

A total of 55 18- to 33-month-olds (24 girls; mean age = 1;11, *SD* = 3.2 mo) participated.

An additional 6 children were excluded due to a 50% chance of protanopia or deuteranopia color deficiency based on family history ($n = 1$), failure to complete the task ($n = 2$), less than 50% successful tracking ($n = 1$) and full knowledge of color terms demonstrated during the production tasks ($n = 2$). Participants were recruited from a database of interested families maintained by the Psychology Department at the University of California, San Diego. Participants lived in the greater San Diego area, and were primarily Caucasian and upper middle class. In addition, 23 adults (17 women; mean age = 21;8, $SD = 1;6$) were recruited from the student body at the University of California, San Diego.

Procedure

Parent report. Parents were asked to complete a questionnaire that asked whether children understood and/or spontaneously produced each of the eleven English basic color words (*red, orange, yellow, green, blue, purple, pink, black, brown, gray, and white*) as well as the twelve nouns used in the Comprehension Task (see below).

In-lab production task. We created eleven cards with pictures of fish, one for each of the eleven basic English colors. Prototypical exemplars of each color were chosen by the consensus of adult native speakers of English. Prior to the task, the experimenter played with the child in the lab to warm them up and encourage talking. During the task, the fish were placed colored side down in front of the child, and the experimenter flipped over each card one at a time, and asked for each card, “What color is this?” The experimenter provided neutral feedback, recorded the child’s response and placed the card to the side. This was repeated for all eleven

colors. See Table 1 for CIE L*a*b*¹ values of stimuli as measured by a Photo Research-650 SpectraScan.

Due to the young age of the children, sometimes a child's response was unclear. Responses that could not be interpreted or were clearly not a color word were recorded but not included in the analysis (e.g., *bu*, *brr*, *ga*, *fish*). Responses that could refer to colors but were not one of the English basic color words were also not included in the analysis (e.g., *puddle*, *chocolate*, *dark*).

Sometimes children would reply with two color words on a single trial, e.g., responding *purple green* when shown a green stimulus. In these cases, they were not considered to have an adult-like meaning for either color word, and both responses were included into our analysis of error types (see Results section).

Eye-tracking comprehension task. This task assessed whether children comprehended color words by presenting a spoken color word and testing (1) whether they increased fixations to an image of the target color, and (2) whether they increased fixations to a distractor from a perceptually proximal color category. If children have overextended color categories in early acquisition, then they should fixate not only target colors but also proximal colors that may fit within their broad category.

Children viewed 24 scenes, each containing four identical pictures of an object, with the exception that each was different in color. The images were obtained from the UCSD International Picture Naming Project (Szekely et al., 2004) and included images of socks, chairs, balloons, purses, boxes, cups, cars, kites, stars, boats, books, and bows. Each object kind was

¹ CIE L*a*b* is an easily quantifiable color space designed to reflect perceptual color space in humans (Mahy, Van Eycken & Oosterlinck, 1994).

presented twice in a counterbalanced order. Prior to each trial, an attractor – centered and equidistant between all four objects – was presented to direct the child’s gaze to the center of the screen. During each trial, a voice first directed the participant’s attention to all of the objects (e.g., *Look at the socks*), and then additional information about the color of one of the objects was provided (e.g., *Look, the orange sock is my sister’s*; see Table 2 for list of colors and objects contained in each scene and the audio sentences presented with each). Each scene was presented for approximately six seconds and the target color word was spoken at the three-second mark.

Images were presented on a white background and for this reason the color *white* was not included among the test colors. Using Photoshop, the images were digitally colored with prototypical exemplars of the remaining ten basic colors in English (i.e., *red, orange, yellow, green, blue, purple, pink, black, brown, and gray*). The colors were chosen by the consensus of adult native speakers of English. The four images in each scene included two pairs of colors where the colors of each pair were perceptually adjacent to each other but distant from the members of the other pair (e.g., red and orange vs. blue and green). On each of 24 trials, one of the four colors (e.g., blue) served as the target color and was labeled by a color word (e.g., *blue*). The color perceptually adjacent to the target served as a close distractor, and the other pair of colors served as two far distractors. For each set of images, the color that served as the target was counterbalanced between children such that each of the pictures served as the target color for 25% of participants, the close distractor for 25% of participants, and one of the two far distractors for 50% of participants. Within each testing session, the location of the target and close distractor was also counterbalanced, such that each object type (i.e., target, close distractor, and far distractor) appeared in each of the four locations an equal number of times. Each of the

ten colors was targeted two to three times for each participant. The order of trials was also counterbalanced across participants.

We used Tobii Studio 3.1.6 in combination with a Tobii X120 eye tracker to track children's eye movements. Children were calibrated using Tobii Studio's standard 5-point calibration. The stimuli were presented on a Dell P2211H liquid crystal display monitor using an ATI Radeon HD 2600HT graphics card. See Table 1 for CIE L*a*b* values as measured by a Photo Research-650 SpectraScan.

Results

In-lab Production Task.²

Of the 55 participants, only 18 produced any color words during the in-lab production task (though parent reports indicated a higher number; see Table 3). These 18 children produced a total of 89 color words. 48 were used in an adult-like way. The remaining 41 were used incorrectly. Most were used incorrectly more than once, resulting in a total of 111 incorrect uses. We conducted two analyses of the errors made by these 18 children to determine if errors were systematic or haphazard. Specifically, we tested (1) whether the 41 incorrectly used labels were used in way that was consistent with overextensions of adult-like meanings, and (2) whether the 111 incorrect uses of these labels were proximal to the color targets in color space. In doing so, we sought to replicate two of the analyses reported in Wagner, Dobkins and Barner (2013). Note that the third analysis from this previous paper – i.e., consistency – could not be conducted since

² The data from the in-lab production task were not analyzed according to the groups determined by parent report, see section *Eye-tracking analysis*, because by definition, there were no Production data for children in the Comprehension-only and No-Knowledge groups. These groups were formed to only include children who are not yet producing color words. Furthermore, it was impractical to separate the two production groups (Production and Comprehension; Production-only) because the Production-only group was small and produced an average of only 0.83 color word per child on the in lab task, though parent report indicated greater production abilities, see Table 3.

in the current study each child received only one trial for each color word (due to the lower age of children in this study and the inclusion of an additional eye-tracking comprehension task).

We first asked whether children's errors reflected overextensions of adult categories. For example, a child may know that *red* refers to red objects yet have a broader meaning for *red* than adults and therefore overextend it to orange and yellow objects. Given that a child used a label incorrectly on at least one of the eleven trials we asked whether they also used that label correctly for its target color. For example, when a child used the word *red* to label orange and yellow, we asked whether they also used *red* to label red stimuli. The 18 children in this sample used a total of 41 labels incorrectly at least once, and of these 30 uses fit the definition of overextension. Using a binomial test, we found that this rate – 73% – was greater than would be expected from chance (33%, $p < 0.001$), and was almost identical to the rate reported by Wagner et al. (2013). Chance performance was defined as in Wagner et al. (2013), as follows. First, we calculated the base rates of how frequently a child produced each of the incorrect color words (e.g., if a child uses *red* to label 4 of the 11 colored fish) to calculate the probability that the word would also be used correctly (e.g., using *red* to label the red fish, 4/11 or 36%). We then took the mean of these probabilities to calculate the child's overall probability of overextension. To calculate the overall probability of overextension for each group, we calculated a weighted group mean, in which each child's individual chance rate of overextension was weighted by how many incorrect labels they contributed to the analysis.

Next, given that a child used a color label incorrectly, we asked whether the color they labeled was proximal to the color denoted by the word they used where proximity was defined in Munsell color space). For all colors except gray, an error was considered proximal if the stimulus color and the color associated with the misused label were from immediately adjacent categories

in this space, see Figure 1.³ For example, if a child labeled orange as *red*, this would be considered proximal, but if a child labeled yellow or blue as *red* this would be considered a non-proximal error. By this definition, some colors words like *green* have only two proximal colors, *blue* and *yellow*, while others like *red* have more: *orange*, *pink*, *brown*, and *purple*. Proximity was defined differently for gray because in Munsell space gray borders every chromatic and achromatic color. However, the focal regions of some colors are much more proximal to gray than those of others. Performing an analysis based solely on adjacency for gray would yield no useful distinctions and would obscure differences in proximity, i.e., would provide no distinction between children that label gray as black and those that label gray as red. Thus, we counted as proximal to gray only those colors that like gray have focal regions with low chroma – similar to saturation in other spaces (i.e., white, black, and brown).⁴

As in Wagner et al., to determine chance we calculated the probability of each label-stimulus error pair (the probability of using *red* to label an orange stimulus) as equal to the product of the base rates. For example, if 20% (0.2) of errors were in response to an orange stimulus and 80% (0.8) of errors involved using the label *red*, then the probability of using *red* to label orange would be 0.2×0.8 , or 0.16. To determine the overall chance probability of proximal errors, we summed across the probability of all label stimulus pairs that are classified as proximal. In the overextension analysis (above), we noted that the children used 41 color words incorrectly. Many of these color words were used incorrectly multiple times (e.g., using blue to refer to *green*, *purple* and black), resulting in a total of 111 errors. Of these errors, 41% were

³ Munsell Color Space was designed using higher level judgments of similarity by adults (Long & Luke, 2001; Newhall 1939; Newhall 1940), and is the standard color space used in studies examining color language and other studies of color in which precise perceptual distance between colors is not critical.

⁴ While still low in chroma, brown has a higher chroma than gray, black, or white. The outcome of the analysis does not change if we consider brown to be non-adjacent to gray.

proximal. Using a binomial test, we found that this rate was greater than chance (30%; $p = 0.006$). This replicates Wagner et al.'s result and is consistent with the hypothesis that children have partial meanings for color words before they acquire full adult-like meanings. That only 41% of errors were proximal might be taken as evidence that most of children's uses were in fact randomly generated. For children with very few color words in their lexicon, there is an upper limit on the percentage of errors that could be proximal. Consider a child who uses *red* to refer to warm colors (i.e., red, pink, brown, orange, yellow, white, and gray) but uses *blue* to refer to cool colors (i.e., blue, purple, green and black). This child would have perceptually continuous color categories – similar to those found in many languages that have only 2 basic color terms (Kay et al., 2009). Also, given that they could only produce *orange* and *blue* they would make as many proximity errors as allowed by our criteria. However, for such a child proximity errors would make up only 56% of responses. Clearly, in such a scenario, the remaining 44% of responses would not be well characterized as random. This suggests that in such cases our analysis of proximal errors underestimates the extent to which children's errors reflect broad, perceptually coherent color word categories, particularly in very young children who have only a few color words in their lexicon.

Parent Report

According to parent report, on average children's comprehension of color words exceeded their production of color words. Of the 11 basic color terms, parents reported that their children understood a mean of 4.1 words ($SD = 4.5$) and produced a mean of 2.6 words ($SD = 3.9$). However, in lab children produced a mean of only 1.7 color words ($SD = 2.9$) and produced only 0.87 words ($SD = 2.1$) with an adult-like meaning (i.e. using a word to refer to the correct color and not any incorrect colors), see Table 3 for more details. Of the words that parents

reported as produced by their child, 52% were also produced during the in-lab task (range 0-100%). Of the words that children produced in lab, 88% were also reported by parents (range 0 to 100%). Of the 12 common nouns used in the eye-tracking task, on average parents reported that their children understood 7.8 ($SD = 2.7$) and produced 4.7 ($SD = 3.9$). Thus, parent report data suggest that for most children comprehension exceeded production both for color words and for the 12 common nouns included in our study.

Eye-Tracking Comprehension Task

Participant groups. Our primary question is whether children form preliminary meanings for color words before producing them, or vice-versa. To this aim, we did not group children by age but instead divided them into four groups based both on parent report and the in-lab production task. By constructing groups of children based on both parent report and in-lab performance on the production task, we were able to take a conservative approach in identifying a group of children that is reported to comprehend color words but does not produce them according to either measure. It also allowed us to test the small group of children who were reported to produce but not comprehend any color words, to ask whether these children actually lacked meanings, or instead had preliminary meanings like those documented in error analysis above, and by Wagner et al. (2012). The remaining two groups were (1) children thought by parents to have no knowledge of color words, and (2) children who were thought to both produce and comprehend some color words.

Children who did not comprehend or produce any color words according to parent report and who also did not produce color words in lab were included in the No-Knowledge group ($n = 18$). Children who comprehended but did not produce any color words according to parent report and who did not produce any color words in lab were included in the Comprehension-Only

group ($n = 11$). Children who produced but did not comprehend any color words according to parent report were included in the Production-Only group ($n = 4$). Two additional children who had no knowledge of color words according to parent report but who produced 1 and 2 color words in lab, respectively, were also included in this group for a total of six in the Production-Only group. Critically, even with this addition, the Production-Only group was by far the smallest group in our sample, again consistent with the hypothesis that partial comprehension typically precedes production. Children who produced and comprehended color words according to parent report were included in the Comprehension-and-Production group ($n = 19$). One additional child who only comprehended color words according to parent report but who produced color words in lab was also included in this group for a total of 20 in the Comprehension-and-Production group. Note, that even the most advanced group, the Production-and-Comprehension Group, still had very limited knowledge of color words. On average, this group produced only 4.3 of 11 color words in lab (6.7 according to parent report) and demonstrated adult-like understanding of only 2.4 color words. See Table 3 for additional details on each of the groups.

The color words that were produced and comprehended varied considerably between children. Thus, we tailored our analysis of the eye-tracking comprehension data on an individual basis. Although all children received the same trials during the experiment, in the following analyses we exclusively targeted words that children were reported to produce only, comprehend only, or both comprehend and produce. We used data from parent report and in-lab color naming to determine which colors met these criteria and thus should be included in the analysis for each child. Trials were included for the analysis as follows: for each child in the Production-Only group, we included trials for color words that the child produced either in lab or according to

parent report; for each child in the Comprehension-Only group, we included trials that tested color words that the child comprehended according to parent report; for each child in the Production-and-Comprehension group, we included trials that tested color words that the child produced and comprehended either in lab or according to parent report. Finally, for the No-Knowledge and Adult groups, all trials were included. See Table 3 for details on how many words children in each of these groups know according to parent report and performance on the in-lab comprehension task.

Predictions for each participant group. If children always acquire partial meanings of color words before producing them, then three of the four groups of children should exhibit some color word meanings. First, the two groups who already produce some color words – the Production-Only and the Production-and-Comprehension groups – should shift their attention to a labeled focal hue more than to a far distractor. Evidence for this would suggest that even Production-Only children have preliminary meanings, and thus that their caregivers may be more conservative in ascribing knowledge to their children. Second, children in the Comprehension-Only group should also exhibit knowledge of some color word meanings. This would provide especially strong evidence that comprehension precedes production. Finally, we had no predictions for the so-called “No Knowledge” group. Some of these children, despite not yet producing color words, may actually have some preliminary meanings. On the other hand, these children may genuinely lack any knowledge of color words, and may therefore perform randomly.

Children may also fixate the close distractor in addition to the target if their preliminary meanings are overextended. Wagner, Dobkins & Barner (2013) found that children overextended color word meanings from the time they first begin producing color words until the time they

master adult like meanings for color words. Based on this prior work, we predict that both groups that are already producing color words (Production-Only and Production-and-Comprehension) should fixate the close distractors in addition to the targets. However, because close distractors may be secondary members of the children's color word categories and because there is likely to be individual variability in the particular overextensions children make, we expect fixations to the close distractor to be less pronounced and occur later in the trial.

Children in the Comprehension-Only group may also fixate the close distractors if children's form meanings prior to production and these earliest meanings are also overextended. Alternatively, children may form meanings prior to production but overextension may not occur until children start production color words in speech (Reich, 1976; Barrett, 1978; Bendict, 1979). In this case, children in the Comprehension-Only group may only fixate the target and not the close distractors.

Main analyses. Eye movements were successfully tracked 81% ($SD = 15.4\%$) of the time for children and 92% ($SD = 4.4$) of the time for adults.

Total fixation durations from the eye-tracking task were binned into four time periods. The first time period was used as a baseline and it ranged from the beginning of each trial to the onset of the color word. The second time period ranged from 251ms after the color word was spoken to 1000ms, the third from 1001ms to 2000ms and the fourth from 2001ms to 3000ms. We divided the post color word time period into three time bins (instead of one large bin) because (1) prior evidence suggests that toddlers' fixations to the target peak and then decline after a target word is spoken (for discussion, see Fernald, Zangl, Portillo, & Marchman, 2008), and (2) we wished to test for differences in timing for fixations to the target and close distractor.

In order to directly compare the time spent fixating the two far distractors to the time spent fixating the close distractor and the target, we calculated the average proportion of time spent fixating the two far distractors, and compared this to proportion of time spent fixating the close distractor and the target during each of the four time periods. Under the null hypothesis of random looking behavior, these proportions would be equal to 0.25.

For each group of participants (including adults and the four groups of children), we performed a 4 (time: baseline, 251-1000ms, 1001-2000ms, 2001-3000ms) x 3 (fixated image: target, close distractor, far distractor) repeated measures ANOVA to determine whether participants' looking behavior (i.e., the proportion of time spent fixating each of the image types) changed after the target color word was spoken.

Interactions between time and fixated image were found for the Adult group ($F(6,242)=164, p<0.001$), the Comprehension-Only group ($F(6,110) = 2.62, p = 0.021$), the Comprehension-and-Production group ($F(6,209) = 2.68, p = 0.016$) as well as the Production-Only group ($F(6,55) = 2.64, p = 0.026$). No interactions or main effects were observed in the No-Knowledge group (all F s < 1.5 , p s > 0.18). These interactions indicate that the relative looking behavior between the images changed over time in response to the presentation of the spoken color word.

Planned comparisons. We next explored these interactions by conducting planned comparisons using Wilcoxon's signed rank tests to determine if the changes observed in the participants' looking behavior were consistent with partial comprehension of the target color words. Exclusively testing looking to the target could be accomplished by comparing target fixation before and after the use of the color word. However, a more sophisticated metric is required to examine fixations to the close distractor. This is because as children increase

fixations to the target, they may decrease fixation to both the far distractor and the close distractor, while still looking at the close distractor more than the far distractors. To be sensitive to this type of differentiation between distractor types, the critical metric must then look at fixations of the target and close distractor relative to the far distractor. Thus, we calculated a difference score by subtracting the average proportion of fixations to the far distractors from the proportion of fixations to the target. In a second analysis, we calculated a similar difference score comparing fixations to the close distractor to those to the far distractors. We expected that difference scores after the color words were presented would be greater than during baseline if children comprehended (or partially comprehended) the words in question. For each planned comparison, we conducted a one-tailed exact Wilcoxon Signed Rank Test. Two-tailed tests were not employed because there was no hypothesis according to which any of the groups would decrease fixations to the target (or close distractor) relative to the far distractors after the color word was spoken.

Adults showed increased fixations to the target (relative to the far distractors) when compared to baseline during all three of the post-color word time windows (all W s = 0; all p s < 0.001; r s = 0.62), but they did not show increased fixations to the close distractor relative to baseline during any of the three post-color word time windows (all p s > 0.35), see Figure 2.

Relative to adults, the children in our sample are likely to have color word meanings that are preliminary and imprecise. Furthermore, prior work suggests that children are slower in online word recognition tasks than adults (Fernald, Pinto, Swingley, Weinberg & McRoberts, 1998; Fernald, Thorpe & Marchman, 2010). Thus we expect children's fixations to the target to be noisier and occur later in the trial when compared to adults, see time course graphs of fixations in Appendix A.

As predicted, the Production-and-Comprehension group showed increased fixations towards the target, relative to the far distractors, that peaked during the 1001-2000ms ($W = 22$, $p < 0.001$, $r = 0.49$) but were also statistically significant during the 2001-3000ms ($W = 58$, $p = 0.041$, $r = 0.28$), see Figure 3. Also as predicted, they exhibited increased fixations to the close distractor that peaked later than fixations to the target, during the 2001-3000ms time window ($W = 46$, $p = 0.013$, $r = 0.35$). Fixations to the close distractor also approached significance during the earlier 1001-2000ms time window ($W = 61$, $p = 0.053$, $r = 0.26$), see Figure 3, suggesting that the children in this group may have overextended meanings of the color words. In sum, the Production-and-Comprehension group increased fixations to the target soon after the color word was spoken and later in the trial, fixations to the target were replaced with fixations to the close distractor, see Figure 3. If children in the Comprehension-Only and Production-Only group also increase fixations to the target and close distractor, we expect them to do so in a similar time course, first fixating the target and then later fixating the close distractor.

We predicted that the data from Production-Only group would be qualitatively similar to the Production-and-Comprehension group. Although a significant interaction between time and fixated image was observed for the Production-Only group (see *Main Analyses* section above), none of the planned comparisons reached statistical significance due to the very low number of participants that qualified for this group. However, as in the Production-and-Comprehension Group, this group exhibited increased fixations to the target of a comparable effect size early in the trial during the 1000ms to the 2000ms time period ($W = 5$, $p = 0.16$, $r = 0.33$), though they began one time period earlier ($W = 5$, $p = 0.16$, $r = 0.33$), during the 251 to 1000ms time window. Also like the Production-and-Comprehension group, the Production-Only group exhibited increased fixations to the close distractor of a comparable effect size during the later

2001-3000ms time window, though again this was not statistically significant ($W = 5$ $p = 0.16$, $r = 0.33$), see Figure 3. Furthermore, although these effects did not reach statistical significance, the effect sizes were comparable to those observed in the Production and Comprehension Group. Ideally, a larger sample of Production-Only children would be tested. Unfortunately, increasing the number of participants in this group by even 10 participants would require running at least 100 additional children given their relative rarity. In the overwhelming majority of cases, parents who report that their children produce a word also believe that their children comprehends that word, too – an intuition which is strongly supported by our data. Given the similarities in their performance on the eye-tracking comprehension task, the Production-Only group may not be qualitatively different from the Production-and-Comprehension Group. Instead, their parents may simply use more stringent criteria in assessing their children's comprehension.

Finally, like the Production-and-Comprehension Group, the Comprehension-Only Group showed increased fixations towards the target that peaked during the time window 1001-2000ms after the target color word was spoken ($W = 11$, $p = 0.027$, $r = 0.42$). However, unlike the Production-and-Comprehension Group, the Comprehension-Only Group did not show increased fixations to the close distractor during any of the time windows (all $ps > 0.71$). Thus, these children, like adults, exclusively increased fixations to the target despite failing to produce any color words, see Figure 3.

Discussion

We investigated color word knowledge in a group of young English-speaking children, including a subset who had yet to produce any color words. Replicating previous reports (Pitchford & Mullen, 2003; Sandhofer & Smith, 1999; Soja, 1994), we found that children make many errors when labeling colors, but that these errors are non-random: children appear to learn

preliminary, non-adult-like, meanings for color words very early in the acquisition process, often before they begin producing them in speech (Wagner, Dobkins, & Barner, 2013; Bartlett, 1978). These data provide evidence against the idea that the delay between color word production and the acquisition of adult-like meanings stems from a failure to abstract color as a domain of meaning (Franklin, 2006; Kowalksi & Zimiles, 2006; O’Hanlon & Roberson, 2006; Sandhofer & Smith, 1999). Instead, our data suggest that children identify color as relevant to color word meanings very early and that adult meanings emerge late due to a gradual inductive learning process.

Several pieces of evidence support these conclusions. First, replicating Wagner, Dobkins, and Barner (2013), a color word production task found that when children made color labeling errors, they were highly systematic. For example, when children made errors, they were often overextensions: when children used a word like *red* to label orange, they very often also used the same word to correctly label its target color (e.g., the color red). Also, children’s errors were often to colors that were directly adjacent to the target color, again consistent with the hypothesis that they initially overextend their color words beyond the adult color boundaries. Like the data from Wagner et al., these findings suggest that the delay between color word production and acquisition of adult-like meanings is due primarily to a gradual inductive process of identifying adult-like category boundaries.

A second piece of evidence came from parental report. On average, parents reported that children comprehended more color words than they produced. Parents of only four of the 55 children who participated reported that their child produced color words without comprehending them. In contrast, parents of 12 children reported that their children comprehended color words without producing them. This was not simply because we sampled from children who were too

old, and thus had advanced color word knowledge: We also found 20 children who neither produced nor comprehended color words according to parent report. These data are clearly at odds with previous claims that children use color words randomly for months before mastering adult-like meanings (Pitchford & Mullen, 2003; Sandhofer & Smith, 1999; Soja, 1994).

However, our data also suggest that parent report data should be interpreted with caution.

Although we found that children frequently had meanings for color words before they produced them – consistent with what parents reported – they are not yet full, adult-like, meanings at this stage. As noted above, children in the Production-only and Production and Comprehension groups did not accurately use color words to label colors in our in-lab labeling task (often overextending to adjacent colors). Children in the Comprehension-only group did not use any words in the in-lab task. Yet, all three groups *did* systematically look to the appropriate target color for these same words in the eye-tracking task. Also, despite often fixating correct colors in the eye-tracking task, many children also fixated perceptually close distractor colors. In sum, our findings suggest that although parents are likely right that their children have acquired *some* meaning for their color words, their judgments should not be interpreted as evidence for full adult-like meanings.

Our eye-tracking data support the conclusion that partial meanings often precede color word production. Consistent with parent report, children whose parents indicated that they both produced and comprehended color words looked significantly longer to target colors when target words were presented. Likewise, we found that children who did not produce color words but whose parents said they comprehended them also showed evidence of comprehension in the eye-tracking task. Finally, the small group of children who produced color words but were reported by parents to not understand them also tended to look more towards the target colors when target

words were presented, though this result was only marginally significant due to the limited number of parents who classified their children as only producing color words – a fact which itself is consistent with the hypothesis that production only rarely precedes partial comprehension. In sum, our eye-tracking data suggest that children usually have meanings (even if partial and non-adult-like) for the color words that they produce, and frequently have meanings even for color words that they do not yet produce.

Consistent with the idea that the delay between production and adult-like comprehension of color words is due to a gradual inductive process (rather than a problem with abstraction), our eye-tracking data also suggest that many young children construct overly broad meanings for color words which must be narrowed over time. For example, unlike adults, the group of children who were reported to both produce and comprehend some color words frequently made fixations to close distractors (e.g., to green on “blue” trials). This corroborates the data from our in-lab production task, which found that many children overextended color words to adjacent colors (see also Wagner et al., 2013). Data from the eye-tracking task suggest that this overextension of color words is not merely pragmatic in nature (i.e., using incorrect words to fill lexical gaps, see Clark, 1978), but reflects a broad meaning – or at the least uncertainty about the category boundaries (for similar findings, see Wagner et al., 2013). Interestingly, not all groups showed this effect. In contrast to the Production-and-Comprehension group, the Comprehension-Only group showed increased fixations to the target after the color word was spoken, but not to the close distractor. This result is consistent with the previously reported observation that children’s meanings for words become overextended only *after* they have begun producing them (Reich, 1976; Barrett, 1978; Benedict, 1979). On this hypothesis, children might begin the color word acquisition process with conservative meanings and only overextend after experiencing a

relatively large database of examples from which to generalize. Alternatively, rather than receptive experience driving overextension, it may be driven by children's own use of words. Specifically, as children search for words to describe the colors around them to their listeners, they may pragmatically extend their meanings to include these colors, resulting in changes to the actual color word semantics.

Our finding that children identify color as relevant to word meaning early in acquisition is, at first pass, inconsistent with previous reports that children at this stage have difficulty abstracting color (e.g., Kowalski & Zimiles, 2006; Sandhofer & Smith, 1999). In one study, Sandhofer and Smith (1999) found that children were unable to match based on color until after they could successfully label colors. However, such studies often specifically avoid referencing color (Sandhofer & Smith, 1999; Kowalski & Zimiles, 2006; for further critical discussion see Soja, 1994). While these studies interestingly demonstrate that children do not preferentially attend to color early in development, our results suggest that children nonetheless can abstract color from an early age if color is highlighted linguistically. In fact, in studies where color properties are highlighted, evidence of color abstraction has been found in infants as young as five to twelve months of age (Catherwood, Crassini & Freiberg, 1989; Waxman, 2007; Wilcox, Woods & Chapa, 2008; Wilcox, 1999).

In sum, evidence from parental report, an in-lab production task, and an eye-tracking comprehension measure together suggest that, contrary to the conclusions of many previous reports, color words resemble other early-acquired words: meanings frequently emerge before children produce color words in speech though it takes some time before children's meanings become adult-like. Color words may be unique only in that children's color word errors are more easily observed in naturalistic settings because the perceptual space is more compressed and

intermediate exemplars are more frequent. Emerging evidence suggests that children may acquire early partial meanings for a variety of words before they acquire full adult-like meanings, including number words (Barner & Bachrach, 2010; Brooks, Audet, & Barner, 2012; Condry & Spelke, 2008; Sarnecka & Gelman, 2004), time words (Tillman & Barner, 2013), emotions words (Widen & Russell, 2003), and object labels (Ameel, Malt & Storm, 2008). Children may be able to fast map words to their referents but they require considerable time to converge on full-fledged adult meanings (Carey & Bartlett, 1978).

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Table 1: CIE L*a*b* values for production and comprehension tasks. Fish stimuli used for the in-lab production task are on the left and for the stimuli presented on screen during the in-lab eyetracking comprehension task are on the right.⁵

Color	Production Task			Comprehension Task		
	L*	a*	b*	L*	a*	b*
Red	58.5	60.4	43.4	59.6	67.3	59.5
Orange	68.2	48.1	54.9	77.3	41	49.7
Yellow	96.7	-2.1	76.7	88.2	-6.2	67.9
Green	65.0	-33.3	24.0	50.1	-38.5	30
Blue	40.9	-4.8	-42.5	28.9	2.4	-107.5
Purple	44.8	20.6	-23.2	37.5	41.5	-56.5
Pink	70.4	48.0	3.9	68.1	48.0	-8.5
Brown	55.5	24.8	34.8	43.7	15.7	27.3
Black	37.6	1.1	4.8	*		
White	99.2	0.2	1.0	**		
Gray	67.4	2.8	4.1	68.7	-0.9	-3.2

* The black color that was presented on screen was too dim to be picked up by the PR-650 Spectrascan.

** White was not included on the eye-tracking comprehension task, see methods.

⁵ The comprehension task was presented on a computer monitor so that we could collect data with an eyetracker, and the production task was carried out with real, non-electronic cards. The values are not identical between tasks because equating color values between a computer monitor and real stimuli is an exceptionally challenging task. However, stimuli for both tasks were chosen as prototypical exemplars by consensus of adult native speakers of English.

Table 2: Audio and visual stimuli used in the eye-tracking task. All participants saw all 24 scenes, 4 scenes for each of the 6 color groups below. Each scene contained 4 differently colored but otherwise identical objects. The 4 colors included 2 pairs of colors, where the colors of each pair were perceptually adjacent to each other, but distant from the members of the other pair (e.g. red and orange vs. blue and green). Which color served as the target for each scene was counterbalanced between participants.

Colors in scene		Audio Sentences
Pair 1	Pair 2	
yellow	gray	"Look at the cups, look the <target> cup has water inside."
orange	black	"Look at the socks, look the <target> sock is my sister's."
		"Look at the boxes, look the <target> box has a surprise inside."
		"Look at the chairs, look the <target> <i>color</i> chair is comfy."
red	green	"Look at the balloons, look the <target> balloon is my favorite."
orange	blue	"Look at the bows, look the <target> bow is pretty."
		"Look at the boxes, look the <target> box has a toy inside."
		"Look at the purses, look the <target> purse is my friend's."
yellow	red	"Look at the balloons, look the <target> balloon is from the zoo."
green	pink	"Look at the purses, look the <target> purse is my mom's."
		"Look at the socks, look the <target> sock is my brother's."
		"Look at the kites, look the <target> kite is awesome."
blue	orange	"Look at the cars, look the <target> car is going to the store."
purple	brown	"Look at the stars, look the <target> star is pretty."
		"Look at the boats, look the <target> boat is fancy."
		"Look at the chairs, look the <target> chair is old."
brown	green	"Look at the bows, look the <target> bow is new."
black	blue	"Look at the books, look the <target> book is funny."
		"Look at the stars, look the <target> star is awesome."
		"Look at the boats, look the <target> boat is my dad's."
gray	pink	"Look at the kites, look the <target> kite is new."
brown	purple	"Look at the cups, look the <target> cup has soup inside."
		"Look at the books, look the <target> book is exciting."
		"Look at the cars, look the <target> car is going to school."

Table 3: Means of production and comprehension data for the four groups of children. Children were classified into group based on both their performance on the in-lab production task and parent report. Here we present the average number of words comprehended and produced according to parent report as well as the average number produce in lab. We also report the number of adult-like color word meanings a child appeared to have during the in-lab task. Children were considered to have an adult meaning of a word if they used it to label the correct color (e.g., using *red* to label the red fish) on the in-lab production task and did not use it to label any incorrect stimuli. All other words that were produced during the in-lab task were produced incorrectly at least once. Standard Deviations are in parentheses.

	No Knowledge	Comprehension Only	Production Only	Comprehension and Production
N	18	11	6	20
Age in mos	22.3 (3.0)	23.6 (3.6)	21.2 (3.0)	22.8 (3.2)
Parents: Words Comprehended	0	7.0 (3.21) range: 2-11	0	7.5 (3.8) range: 1-11
Parents: Words Produced	0	0	2.1 (1.8) range: 0 to 5	6.7 (3.8) range: 0-10
In-lab: Words Produced	0	0	0.83 (1.2) range: 0 to 3	4.3 (3.4) range: 0 to 10
In lab: Adult Meanings	0	0	0	2.4 (2.9) range: 0 to 8

Figure 1: Representation of Munsell color space (Long & Luke, 2001). Hue is represented by position around the ring, Chroma (similar to saturation in other color spaces) is represented by positions on each spoke and Value (similar to brightness in other color spaces) is represented along the vertical axis. As in Wagner, Dobkins & Barner (2013), for all colors but gray, an error was considered proximal if the color category of the incorrect label and the color shade being labeled were adjacent in this color space, see text for more details.

Figure 2: Fixations in adult participants during each time bin. The proportions of fixation time spent on the target and close distractor, plotted with the average proportion of fixation time spend on the far distractors.

Figure 3: Fixations in the four groups of children during each time bin. The proportions of fixation time spent on the target and close distractor, plotted with the average proportion of fixation time spend on the far distractors.

Appendix I

Figure A2: Time course of fixations in adult participants. The proportions of fixation time spent on the target and close distractor during the time course of the six second trials, plotted with the average proportion of fixation time spend on the far distractors.

Figure A2: Time course of fixations in the four groups of children. The proportions of fixation time spent on the target and close distractor during the time course of the six second trials, plotted with the average proportion of fixation time spend on the far distractors.