Shared understanding of color among sighted and blind adults

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Empiricist philosophers such as Locke famously argued that people born blind might learn arbitrary color facts (e.g., marigolds are yellow) but would lack color understanding. Contrary to this intuition, we find that blind and sighted adults share causal understanding of color, despite not always agreeing about arbitrary color facts. Relative to sighted people, blind individuals are less likely to generate "yellow" for banana and "red" for stop sign but make similar generative inferences about real and novel objects' colors, and provide similar causal explanations. For example, people infer that two natural kinds (e.g., bananas) and two artifacts with functional colors (e.g., stop signs) are more likely to have the same color than two artifacts with nonfunctional colors (e.g., cars). People develop intuitive and inferentially rich "theories" of color regardless of visual experience. Linguistic communication is more effective at aligning intuitive theories than knowledge of arbitrary facts.

color | intuitive theories | blindness | language

What and how do we learn from others, and what must we see for ourselves? A common intuition is that sensory phenomena have to be experienced directly to be fully grasped. Locke (1) and Hume (2) argued that an understanding of color was inaccessible to people born blind. More recently, Frank Jackson (3, 4) suggested that Mary, a fictional color scientist living in a black-and-white room, would miss out on essential elements of color understanding that could only be gained through first-person experience (see also ref. 5). Many contemporary theories of cognition, including embodiment theories, link knowledge of sensory phenomena to first-person experience. According to such views, visual experience is central to concepts like "red" (6–12). Once created, the original sensory trace is activated by language and thinking. When one speaker says to another, "This car is red," mutual understanding makes use of a sensory common ground (i.e., prior visual experiences of "red"). Consistent with this idea, hearing color words activates brain regions involved in color perception (e.g., refs. 13–15). Such views propose that people with different sensory experiences have different conceptual representations of sensory phenomena (e.g., each person's concept of "red" reflects the specific "reds" they have seen) (7, 11, 14). Exactly what aspects of sensory knowledge come from sensory experience remains an open question.

In domains other than sensory phenomena, we gain much of our knowledge from other people through cultural transmission rather than from direct sensory experience (e.g., refs. 16 and 17). Humans are highly adept at sharing knowledge within a society and across generations (18–22). Part of what makes cultural transmission so effective is language, a uniquely human and remarkably efficient communication system. Religious beliefs, internal contents of people's minds, and social categories (e.g., gender) are among the many things we learn from others through language (e.g., refs. 23–27). Here, we ask what kind of understanding of sensory phenomena is transmitted via language by comparing knowledge of color among people who are blind and sighted living in the same culture.

As noted above, a longstanding view in philosophy and psychology is that color knowledge in blindness is fragmented and empty (1, 2, 28, 29). However, unlike Mary, the lone color scientist living in a black-and-white room, people born blind engage in ordinary linguistic communication with sighted people who experience color. What does such communication convey? Landau and Gleitman (30) were the first to challenge the idea of deficient "visual" knowledge in blindness, by showing that a congenitally blind 4-y-old, Kelli, applied color words to concrete objects but not mental entities (e.g., ideas) and understood that color could only be perceived visually, unlike texture or size. Blind and sighted adults also share knowledge of similarities between colors (e.g., "green" and "blue" are similar but different from "orange" and "red"), although this knowledge is more variable among blind individuals (31–33).

Potentially consistent with the idea that sensory experience is necessary, several recent studies have identified substantial differences in blind and sighted people's color knowledge. Sighted people can report the colors of many objects (e.g., hippos are "gray", and strawberries are "red") and show high agreement; by contrast, agreement is lower among people who are blind and between sighted and blind people (29, 34). Moreover, agreement is lower among blind adults for color relative to other physical dimensions, such as shape, texture, and size (34). Even when people who are blind agree with the sighted on the canonical color of an object (e.g., strawberries are "red"), blind individuals are less likely to use color as a dimension during semantic similarity judgments, leading to the suggestion that such knowledge is "merely stipulated" for blind but not sighted people (29). Converging

Significance

We learn in a variety of ways: through direct sensory experience, by talking with others, and by thinking. Disentangling how these sources contribute to what we know is challenging. A wedge into this puzzle was suggested by empiricist philosophers, who hypothesized that people born blind would lack deep knowledge of "visual" phenomena such as color. We find that, contrary to this prediction, congenitally blind and sighted individuals share in-depth understanding of object color. Blind and sighted people share similar intuitions about which objects will have consistent colors, make similar predictions for novel objects, and give similar explanations. Living among people who talk about color is sufficient for color understanding, highlighting the efficiency of linguistic communication as a source of knowledge.

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evidence for the idea that language is limited in what it transmits about color comes from text corpus analyses, which are less successful at extracting color information from text, relative to other physical dimensions (e.g., shape) and abstract properties (e.g., taxonomy) (35, 36). One interpretation of these results is that despite a rich vocabulary of color terms in English, everyday linguistic communication is limited in what it conveys about color.

However, these prior studies may underestimate the capacity of language to transmit color information. Like most studies of color knowledge in sighted people, these studies focused on knowledge of associative color facts such as that strawberries are "red", rather than on inferentially rich, causal understanding of color (e.g., refs. 37–41). Such color factoids might be least likely to be culturally transmitted since, for both sighted and blind people alike, they are inferentially shallow and disconnected from other things we know about objects. Little follows specifically from the fact that strawberries are "red", as opposed to "blue" or "purple."

In addition to such associative links between objects and their colors, even young children have causal-explanatory intuitions about color (42, 43). These intuitions are a part of broader frameworks, often referred to as "intuitive theories" about physical objects (e.g., refs. 44–50). Children expect an object's relationship with color to differ depending on whether it is a natural kind (e.g., plant, animal, gem) or an artifact (e.g., machine, tool). In response to "Why is this object yellow?" children prefer explanations that appeal to biological mechanisms for natural kinds but human intentions for artifacts (43). In contrast to associative color facts, causal object–color links are both explanatory and can generate predictions about objects that have not previously been experienced. When asked, "Could something still be a Glick even if it was a different color?," 5-y-old children are more likely to say yes for an artifact than for an animal. By contrast, two instances of a natural kind (e.g., two strawberries) and two instances of an artifact (e.g., two cars) are judged equally likely to have consistent shapes (42). Causal object–color relationships also differ among artifacts in ways that are related to human intentions, although this type of knowledge has not previously been tested. For artifacts such as stop signs and paper, color plays a functional role and is therefore consistent across tokens. Stop signs are red for visibility and recognizability, and paper is white to make markings visible. By contrast, for artifacts like cars and mugs, color is not related to function (e.g., transportation and holding liquid) and therefore can vary freely.

Is first person sensory experience instrumental to acquiring such causal-explanatory color knowledge? One possibility is that seeing stop signs, paper, mugs, and cars is necessary for viewers to infer causal object–color relationships and to generalize such knowledge to novel instances, just like seeing animals appears to be highly useful to learning their specific colors (34). Here, we predicted instead that linguistic communication would be more effective at transmitting causal-explanatory color knowledge than associative color facts. Laboratory experiments suggest that children and adults are better at learning such causal-explanatory knowledge (51–53). Adults remember lists of features better if they can be related to each other and recall the same events and facts better if they are presented as coherent stories with causal structure (52–56). People naturally search for explanatory information by asking "why" (57–63). The process of explaining itself can boost memory for causal information: After being prompted to explain, children remember objects' features better when there is a link between it and how the object works, as opposed to when the relation is an arbitrary association (51, 64). These laboratory experiments suggest that causal-explanatory knowledge is learned more effectively than isolated facts. The case of color knowledge in blindness offers a test case of whether linguistic communication transmits causal-explanatory knowledge more effectively in naturalistic settings.

In the current study, we probed sighted and congenitally blind people's associative and causal-explanatory knowledge of color in three experiments. Experiment 1 first queried associative memory for real objects' colors by asking participants to generate "a common color of X" (Fig. 1). We next asked participants to judge how likely two instances of the same object are to have the same color, for natural kinds (e.g., two bananas) and artifacts (e.g., two cars). We reasoned that if people share intuitive theories about the relationship between color and object kind, blind and sighted people would make similar inferences about color consistency, even while disagreeing on associative facts (i.e., the particular colors of objects). We predicted that people would judge natural kinds and artifacts with function-relevant color (e.g., stop signs), but not artifacts with function-irrelevant color (e.g., cars), to have high color consistency across instances. For artifacts, to ask whether blind and sighted people make color consistency judgments by reasoning about the causal relationship between the object and its color, we additionally obtained judgments about the relevance of color to artifact function. We predicted that the color consistency ratings would correlate with functional relevance.

The ability to support generalization to novel instances is a key test of whether knowledge is inferentially rich (e.g., refs. 47 and 65). In experiment 2, we thus asked participants to make inferences about color consistency for novel objects (natural kinds, artifacts with function-relevant color, and artifacts with function-irrelevant color) in an imaginary island scenario (Fig. 1). If knowledge about the origins and causes of color is shared, then blind and sighted participants might make systematic predictions for color consistency for novel objects on the basis of object category (e.g., creature, gem, or gadget, coin). Finally, in experiment 3, we elicited open-ended explanations for why objects have their colors (e.g., "Why is a carrot orange?"). This allowed us to probe the specific nature of blind and sighted people's knowledge of the causal mechanisms that give rise to object colors.

Results

Knowledge of Specific Object Colors among Sighted and Blind Participants. Blind and sighted participants were asked to name a common color of 54 real objects (experiment 1, 30; experiment 3, 24; collapsed for the current analysis) (Fig. 2*A*). For both sighted and blind groups, color naming agreement was higher for natural kinds (NK) (e.g., lemon) than for artifacts with nonfunctional colors (A-NFC) (e.g., car), but similar to artifacts with functional colors (A-FC) (e.g., stop signs) (Fig. 2*B*; Simpson's diversity index for sighted, NK: mean [M] = 0.86, 95% CI [0.77, 0.95]; A-NFC: M = 0.49, 95% CI [0.35, 0.63]; A-FC: M = 0.74, 95% CI [0.61, 0.87]; blind NK: M = 0.5, 95% CI [0.38, 0.62]; A-NFC: M = 0.24, 95% CI [0.2, 0.28]; A-FC: M = 0.48, 95% CI [0.36, 0.6]). Naming agreement was substantially higher for sighted compared to blind participants across all object types, and there was no group-by-object kind interaction [result of regression, effect of group: $\chi^2(1) = 71.11$, $P < 0.001$, $\omega_p^2 = 0.57$; effect of object type: $\chi^2(2) = 20$, $P < 0.001$, $\omega_p^2 = 0.25$; object-type-by-group interaction: $\chi^2(2) = 1.49$, $P = 0.5$].

Color Consistency Inferences in Blind and Sighted Individuals: Real Objects. Sighted and blind participants judged the likelihood that two objects (e.g., two lemons), randomly chosen from the same object category, would have the same color for 10 natural kinds (NK, e.g., lemon), 10 artifacts with nonfunctional colors (A-NFC, e.g., car) and 10 artifacts with functional colors (A-FC, e.g., stop sign) (henceforth color consistency judgment). Participants rated consistency likelihood on a scale of 1–7 (1: not

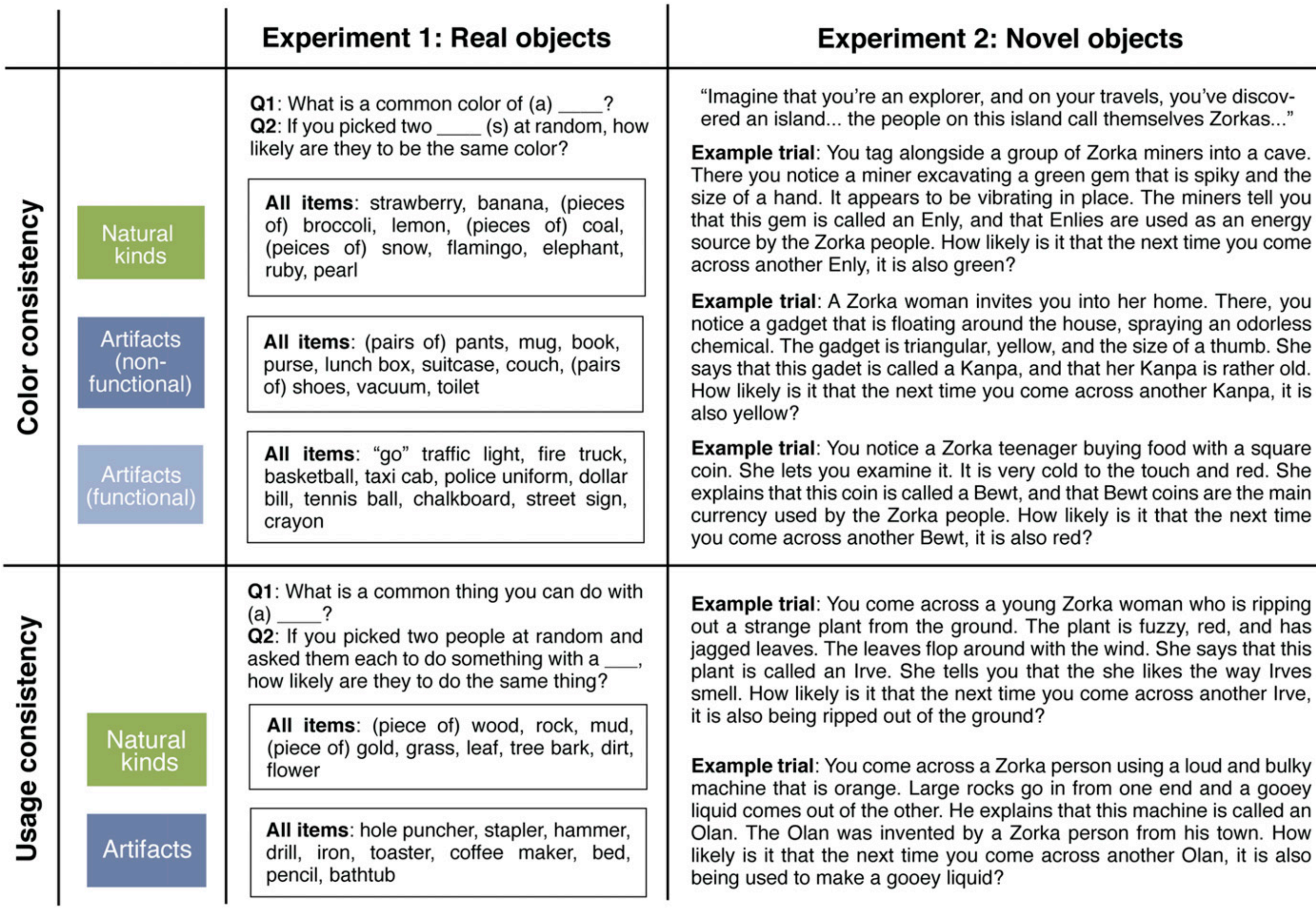

Fig. 1. Experimental conditions and trials for color consistency inference. Participants were asked about color and usage consistency for real (experiment 1) and novel (experiment 2) objects. In both experiments, color trials asked about natural kinds, artifacts with nonfunctional colors, and artifacts with functional colors, while usage trials asked about natural kinds and artifacts. Different items were used in every trial. For experiment 1, all items used are listed, and for experiment 2, one sample trial (an appendix with full list of trials can be found in *SI Appendix*).

likely; 7: very likely). As a control, participants judged the likelihood that two people chosen at random would do the same thing with an object (e.g., a leaf vs. a car) (henceforth usage consistency judgment). Usage consistency was tested for 10 natural kinds (NK) and 10 artifacts.

Sighted participants judged natural kinds (e.g., lemons) to have lower usage consistency but higher color consistency, relative to artifacts (with nonfunctional colors, e.g., cars) (Fig. 3; sighted usage NK: M = 3.67, 95% CI [2.96, 4.38]; usage A: M = 5.66, 95% CI [4.99, 6.33], Wilcoxon matched-pairs signed rank test for usage NK vs. A, two-tailed: $z = -3.82$, $P < 0.001$, $r = 0.88$; color NK: M = 6.2, 95% CI [5.7, 6.7], color A-NFC: M = 3.34; 95% CI [2.57, 4.11]; color NK vs. A-NFC, $z = 3.78$, $P < 0.001$, $r = 0.87$). Sighted participants' color consistency ratings for artifacts with functional colors (e.g., stop signs) were higher than those for artifacts with nonfunctional colors and lower than those of natural kinds (color A-FC: M = 5.17, 95% CI [4.36, 5.98], comparing A-FC vs. A-NFC: $z = 3.8$, $P < 0.001$, $r = 0.87$; A-FC vs. NK: $z = -3.66$, $P < 0.001$, $r = 0.84$). For all artifacts, we obtained ratings of an object color's relevance to its function from a separate group of sighted Amazon Mechanical Turk participants. These function relevance judgments for artifacts were positively correlated with sighted participants' color consistency judgments (Spearman's rank correlation: rho = 0.55, $P = 0.01$; Fig. 4).

The same effect of object type on color and usage consistency judgments was observed in the blind group. Blind participants again judged natural kinds to have lower usage consistency but higher color consistency, compared to artifacts (blind usage NK: M = 3.87, 95% CI [3.16, 4.58]; A: M = 6.19, 95% CI [5.69, 6.69]; Wilcoxon matched-pairs test for usage NK vs. A: $z = -3.92$, $P < 0.001$, $r = 0.88$; color NK: M = 5.66, 95% CI [4.99, 6.33]; A-NFC: M = 3.32, 95% CI [2.68, 3.96]; NK vs. A-NFC: $z = 3.92$, $P < 0.001$, $r = 0.88$). Artifacts with functional colors were judged to have higher color consistency than artifacts with nonfunctional colors, but lower than natural kinds (color A-FC: M = 5.38, 95% CI [4.59, 6.17]; comparing A-FC vs. A-NFC: $z = 3.92$, $P < 0.001$, $r = 0.88$; A-FC vs. NK: $z = -1.98$, $P = 0.048$, $r = 0.44$). Blind participants' consistency judgments for artifacts were positively also correlated with MTurk participants' ratings of color's relevance to object function (Spearman's rho = 0.6, $P = 0.005$; Fig. 4).

When groups were compared directly to each other, object kind and trial type did not interact with group (mixed ordinal logistic regression, group (blind vs. sighted) × trial type (color vs. usage) × object kind (NK vs. A-NFC), with sighted group, usage trial, and A-NFC treatment coded as baselines, no three-way interaction ($\beta = -0.24$, SE = 0.38, $z = -0.63$, $P = 0.5$). We also analyzed color judgments separately (group [blind vs. sighted] × object kind [NK vs. A-NFC vs. A-FC], with sighted and A-NFC as baseline). There was no significant interaction between group and object kind when comparing artifacts with functional color to artifacts with nonfunctional color ($\beta = 0.45$, SE = 0.27, $z = 1.65$, $P = 0.1$), although the interaction was

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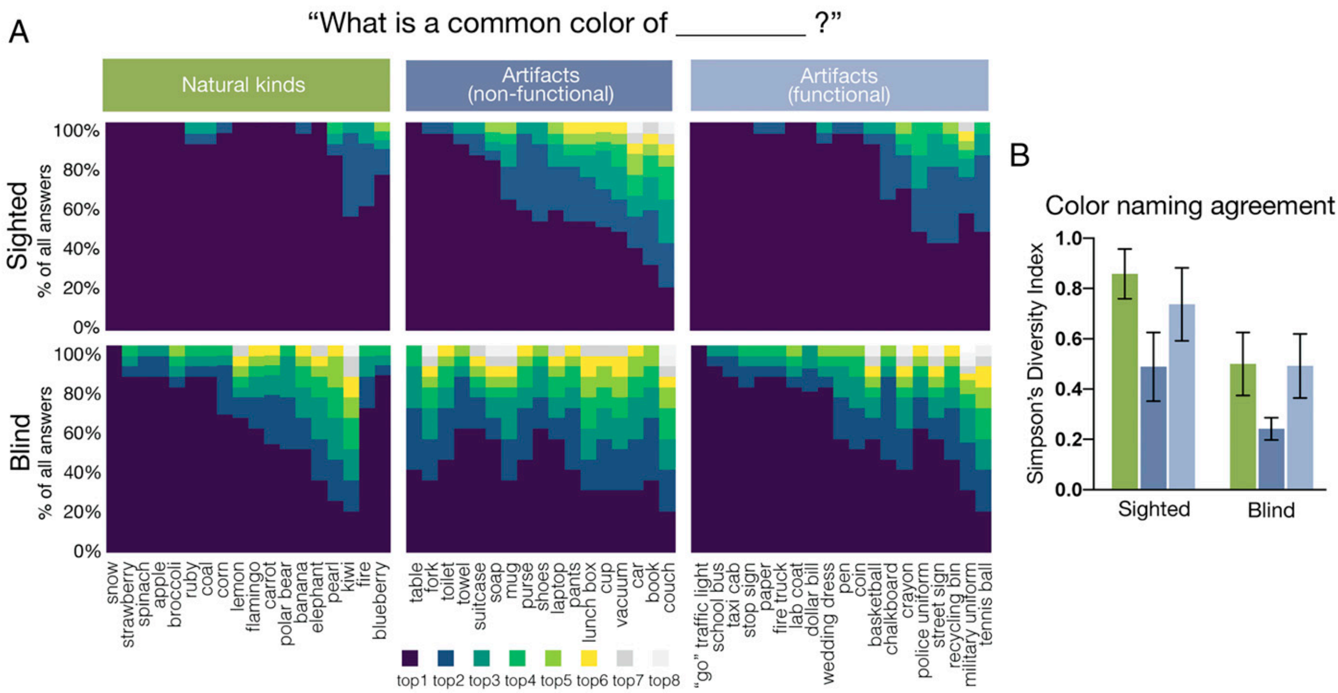

Fig. 2. Object color naming agreement. Blind and sighted participants were asked to name common colors of real objects (experiments 1 and 3). (*A*) Stacked bars show the frequency of the eight most frequent colors provided for each object. Frequency for each unique color word is shown as a proportion of all words provided for an object. (*B*) Bar graph showing naming agreement (Simpson's diversity index calculated for individual objects). Mean ± 95% CIs (across objects).

significant when comparing natural kinds to artifacts with nonfunctional color ($\beta = -1.02$, SE = 0.27, $z = -3.78$, $P < 0.001$). Although both groups showed higher color consistency judgments for natural kinds than artifacts with nonfunctional colors, the sighted, compared to blind group, the difference in ratings for natural kinds and artifacts with nonfunctional color is higher, and post hoc tests show that this is driven by higher consistency ratings for natural kinds in the sighted (Wilcoxon test for sighted vs. blind NK: $z = 2.48$, $P = 0.013$, $r = 0.4$; for artifacts FC: $z = 1.15$, $P = 0.3$).

To compare blind and sighted individuals' reliance on artifact color-function relevance for judging color consistency, we further ran an ordinal regression model with consistency ratings as the DV and group and relevance ratings as predictors. Consistent

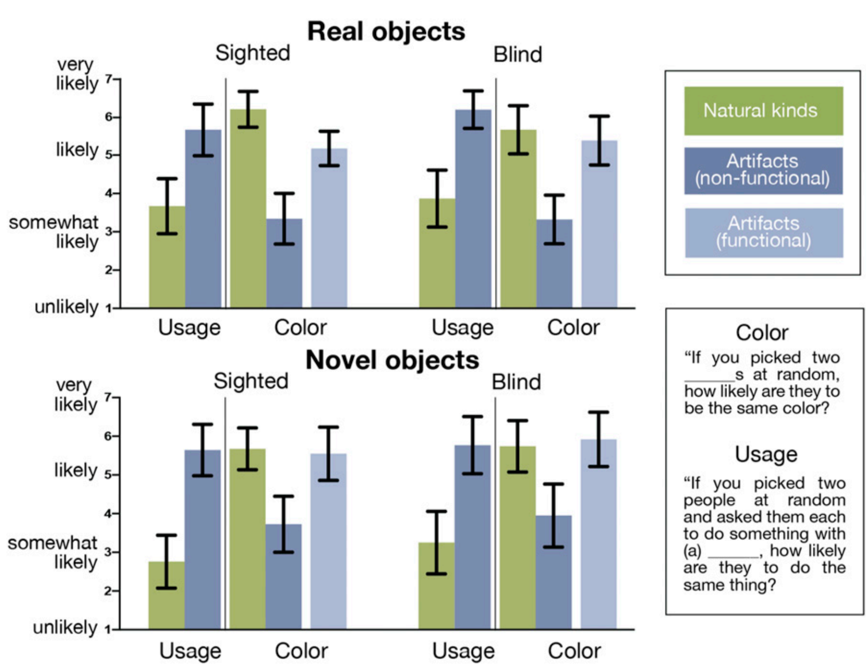

Fig. 3. Inferences about color and usage consistency across instances of an object. Consistency judgments for real (experiment 1) and novel (experiment 2) objects. Bars are mean ± 95% CIs.

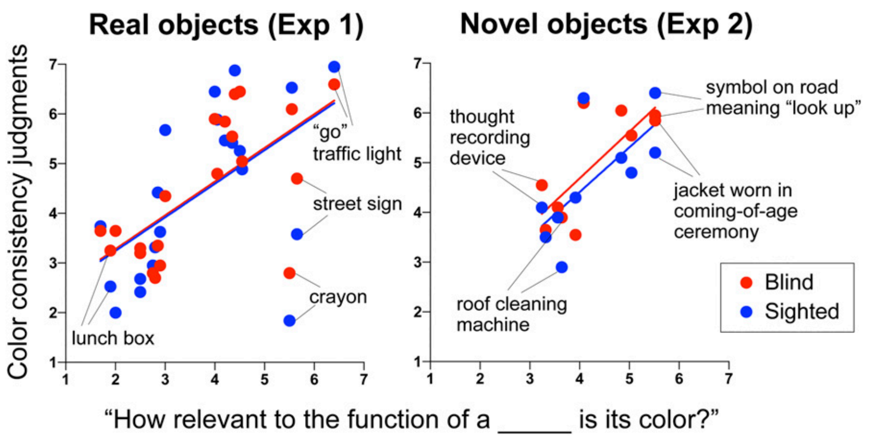

Fig. 4. Relationship between functional relevance of color and consistency judgments for artifacts. Functional relevance judgments were obtained from separate groups of (sighted) participants on Mechanical Turk. Color consistency judgments are from experiments 1 (real artifacts) and 2 (novel artifacts). Red, blind; blue, sighted.

with the high correlations reported above, there was a significant effect of relevance ratings ($\beta = 1.16$, SE = 0.3, $z = 3.83$, $P < 0.001$) but no effect of group ($\beta = 0.12$, SE = 0.53, $z = 0.23$, $P = 0.8$) or a group by function-relevance interaction ($\beta = -0.07$, SE = 0.11, $z = -0.63$, $P = 0.5$) (Fig. 4).

Color Consistency Inferences in Blind and Sighted Individuals: Novel Objects. For real familiar objects, blind and sighted individuals could make color consistency judgments based on knowledge of their actual color frequencies (e.g., learned from seeing or hearing that bananas are often yellow but that cars can be red, blue, black, etc.). Alternatively, or in addition, people may use a general understanding of the relationship between object kind (e.g., natural kind vs. artifact) and color (i.e., intuitive theories), to infer color consistency. Indeed, although on the whole color consistency judgments for real objects were similar across blind and sighted adults, people who are blind rated color consistency for natural kinds slightly lower than the sighted, possibly because of differences in associative object color-knowledge. To more directly test knowledge of general object–color relationships, we collected color consistency judgments for novel objects, for which neither blind nor sighted participants could have directly experienced their color. Participants were presented with "explorer on an island" scenario and judged the consistency of color and usage for novel natural kinds (e.g., gem, plant) (five objects), novel artifacts with non-function-relevant colors (e.g., cleaning gadget, speaking device) (five objects), and novel artifacts with function-relevant colors (e.g., coin, ceremonial clothing) (five objects).

As with real objects, both groups judged artifacts to be more likely to have consistent usage than natural kinds (sighted usage NK: M = 2.76, 95% CI [2.12, 3.4]; A: M = 5.64, 95% CI [5.02, 6.26]; Wilcoxon matched-pairs signed rank test for NK vs. A: $z = -3.82$, $P < 0.001$, $r = 0.88$; blind usage NK: M = 3.25, 95% CI [2.49, 4.01]; A: M = 5.77, 95% CI [5.08, 6.46]; NK vs. A: $z = -3.92$, $P < 0.001$, $r = 0.88$). For color trials, consistency

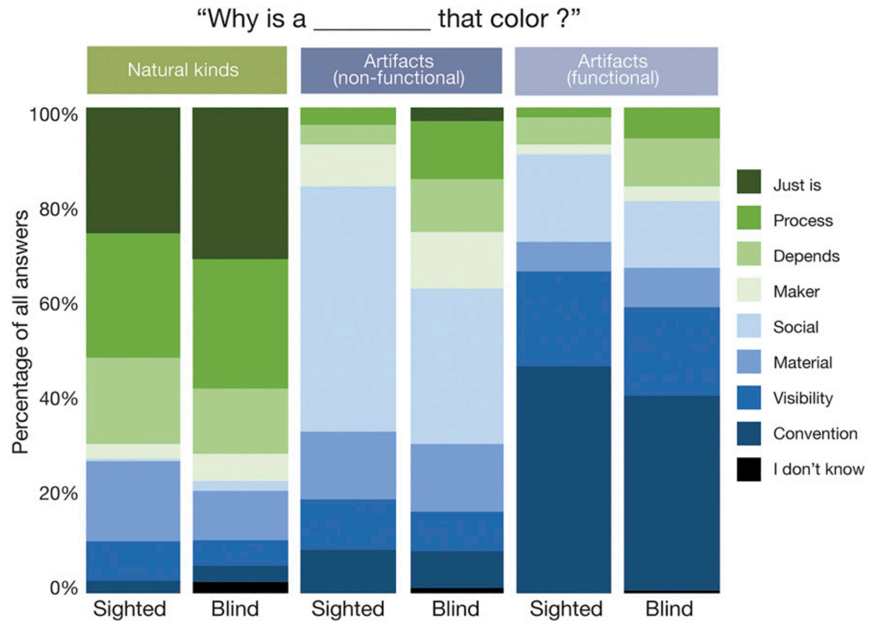

Fig. 5. Explanations about object color. Explanation types were coded by five different coders who were blind to group and object. Stacked bar shows the frequency of each explanation type as a proportion of all explanations provided for an object (within object type) across participants (within a group). A detailed key of explanation types can be found in *SI Appendix*.

was again judged to be higher for natural kinds than for artifacts with nonfunctional color by both groups (sighted color NK: M = 5.67, 95% CI [5.17, 6.17]; A-NFC: M = 3.73, 95% CI [3.06, 4.4]; NK vs. A-NFC: $z = 3.81$, $P < 0.001$, $r = 0.84$; blind color NK: M = 5.74, 95% CI [5.12, 6.26]; A-NFC: M = 3.95, 95% CI [3.19, 4.71]; NK vs. A-NFC, $z = 3.72$, $P < 0.001$, $r = 0.85$). For both groups, artifacts with functional colors were judged as likely to have consistent colors as the natural kinds but more likely compared to artifacts with nonfunctional colors (for sighted color A-FC: M = 5.55, 95% CI [4.74, 6.36]; NK vs. A-FC: $z = -0.65$, $P = 0.52$; A-NFC vs. A-FC: $z = 3.78$, $P < 0.001$, $r = 0.87$; for blind color A-FC: M = 5.92, 95% CI [5.26, 6.58]; NK vs. A-FC: $z = 1.03$, $P = 0.3$; A-NFC vs. A-FC: $z = 3.9$, $P < 0.001$, $r = 0.87$).

The interaction between group, question type, and object kind was nonsignificant (mixed ordinal logistic regression, three-way interaction: $\beta = -0.11$, SE = 0.52, $z = -0.2$, $P = 0.8$). The group-by-object kind interaction for color trials only were also not significant (for NK vs. A-NFC: $\beta = -0.07$, SE = 0.36, $z = -0.18$, $P = 0.9$, for A-FC vs. A-NFC: $\beta = 0.52$, SE = 0.39, $z = 1.39$, $P = 0.2$).

For novel artifacts, both blind and sighted groups' consistency ratings were again positively correlated with function relevance ratings obtained from a separate group of sighted participants on Mechanical Turk (rho = 0.73, $P = 0.03$; for blind group: rho = 0.57, $P = 0.1$; Fig. 4). As with real objects, when consistency judgments were compared in one model with group and function relevance judgments as predictors, there was a significant effect of relevance ratings ($\beta = 1.41$, SE = 0.49, $z = 2.87$, $P = 0.004$) but no effect of group ($\beta = 1.22$, SE = 1.13, $z = 1.07$, $P = 0.3$) or a group by function-relevance interaction ($\beta = -0.43$, SE = 0.26, $z = -1.65$, $P = 0.1$) (Fig. 4).

Blind and Sighted People's Causal Explanations of Object Color (Experiment 3). In experiment 3, blind and sighted participants were asked to explain why each object has its particular color. The explanations were coded according to what type of information they appealed to: process, depends on…, just is that way, material, social, maker of the object, visibility, and cultural convention (see *SI Appendix* for coding details). Both blind and sighted participants provided rich and coherent explanations of the cause of object color (Fig. 5). Both groups tended to provide different explanations for natural kinds, artifacts with nonfunctional colors, and artifacts with functional colors. For natural kinds, both groups most often said "it just is that way" (sighted, 32% of participants; blind, 31%) or appealed to a process that give the object its color (sighted, 32%; blind, 31%). For example, participants often described how the process of photosynthesis makes plants green. By contrast for artifacts with nonfunctional colors (e.g., cars), both blind and sighted participants appealed to people's social and esthetic preferences (sighted, 64%; blind, 44%), and referred to the material of which the object was made (sighted, 18%; blind, 13%). For example, people frequently stated "personal preference" as a cause for cars, and for cup, mentioned that they could be different colors depending on whether they are made of plastic, porcelain, or metal. For artifacts with functional colors, participants most often appealed to cultural convention (sighted, 57%; blind, 51%) and visibility (sighted, 24%; blind, 23%). For example, for school bus, participants frequently mentioned tradition and history, and for stop sign, that the color makes it easy to see.

We examined how similar explanations were across groups by computing Spearman's correlation across groups within object kind. The frequencies of explanations by type were highly correlated across groups for all three kinds of objects (natural kind: rho = 0.99, $P < 0.001$; artifacts with nonfunctional color: rho = 0.72, $P = 0.03$; artifacts with functional color: rho = 0.97, $P < 0.001$). Correlations across object kinds within each group were comparatively much lower (within sighted group: natural vs. A-NFC: rho = −0.31, $P = 0.4$; natural vs. A-FC: rho = −0.27, $P = 0.5$; A-NFC vs. A-FC: rho = 0.78, $P = 0.01$; within blind group: natural vs. A-NFC: rho = −0.02, $P = 1$; natural vs. A-FC: rho = −0.37, $P = 0.3$; A-NFC vs. A-FC: rho = 0.28, $P = 0.5$).

Discussion

A straightforward idea is that we acquire color knowledge through seeing. Consistent with this intuition, we find that people who have never seen are less likely to agree with each other and with sighted people about associative color facts: Although 100% of blind participants generate the label "white" for snow, only 50% say "yellow" for bananas (compared to 100% and 95% of sighted people) (see also refs. 29 and 34). This observation suggests that direct visual access is more effective than linguistic communication at transmitting object–color associations.

By contrast, we find that causal and inferentially rich color knowledge is shared among blind and sighted individuals—blind and sighted participants alike judge that two instances of a natural kind (e.g., two bananas or two gems) are more likely to have the same color than two instances of an artifact (e.g., two cars or two mugs). Blind and sighted people also provide similar explanations of why real objects have the colors that they do, and these explanations vary systematically across natural kinds and artifacts. For natural kinds, both blind and sighted appeal to an objects' intrinsic nature (e.g., "that's just how it is," "that's nature") or describe processes such as photosynthesis, growth, or evolution. For artifacts, participants consistently cite individuals' or groups of people's needs and intentions (e.g., culture, aesthetic preference, visibility). Blind individuals produce coherent explanations for object color even when they do not agree with the sighted about the typical color of that particular object type. For example, while both groups' explanations for the color of polar bears mention their arctic habitat, almost all sighted participants explain that their white fur allows camouflage in the snow while some blind participants explain that polar bears are black to absorb heat in the cold. (Polar bears indeed have black skin underneath their white fur, and these features are thought to have evolved for camouflage and heat absorption, respectively) (66). Such cases provide an illustration of causal understanding of color that is independent of knowing object–color associations.

Blind and sighted people's intuitions about the relationship between kind and color go beyond the natural kind/artifact distinction (67). Among artifacts, people give higher color consistency ratings for those that have functionally relevant colors (e.g., paper, stop signs) as opposed to those that do not (e.g., cars, mugs). Ratings of how important color is to an artifact's function are highly correlated with blind and sighted participants' ratings of color consistency. Explanations produced by sighted and blind adults also vary systematically by artifact type. For household and personal items such as mugs and cars, participants appeal to aesthetic preferences. For institution-related objects like police uniforms and dollar bills, participants cite social need for recognition. For stop signs, participants appeal to visibility (e.g., "red because red jumps out and warns people to stop"). Across artifacts, sighted and blind alike appeal to a range of causes such as camouflage, recognizability, cultural convention, symbolism, history, and aesthetic preference.

Finally, sighted and blind people make similar color consistency inferences for novel objects with which neither group has visual or linguistic experience. For example, both blind and sighted participants judge that two instances of a novel gem (natural kind) would be more likely to have the same color than two instances of a novel household gadget (artifact). Blind and sighted people also make distinctions within novel artifacts, intuiting which are most likely to have functionally relevant and therefore consistent colors (e.g., coins, toxic waste containers). As with real objects, ratings of color's relevance to object function for novel artifacts predicted color consistency ratings. Neither blind nor sighted people have had the opportunity to learn the statistics of color consistency for these novel types, since they have only heard their color specified once during the experiment (e.g., a noise-emitting, oval-shaped orange toxic waste container called a Bollop that people regularly use). Systematic judgments for these objects depend on causally connecting their function with color as well as possibly analogizing to existing objects' causally relevant dimensions (e.g., reasoning about the toxic waste container's color by thinking about the purpose of recycling bin colors). Together, this evidence suggests that people living in the same culture develop similar intuitive theories of color regardless of their visual experience, and use these theories to make inferences that go beyond the data.

The present work leaves several open questions about color knowledge of sighted and blind people. First, it is worth noting that the present results do not speak to the issue of phenomenology (i.e., what it is like to see color), a key piece of knowledge said to be missing for Mary, the color scientists (4). Indeed, such phenomenological or qualia knowledge might be empirically intractable (e.g., ref. 5). With regard to intuitive theories of color, although we find substantial shared knowledge among sighted and blind people, further work is needed to fully characterize this knowledge in both populations. The present results do not rule out the possibility of some differences in color inferences as a function of perceptual experience. Although the overall pattern of color consistency judgments was highly similar between sighted and blind people, we observed slightly higher color consistency judgments for natural kinds among sighted as compared to blind people. We may also have failed to detect other small differences due to the relatively small sample size of the current study. The present results clearly show, however, that if differences in intuitive theories of color do exist between people who are sighted and people who are blind, these differences are more subtle than the robust differences in associative color knowledge. Finally, the present results are not inconsistent with the possibility of other color knowledge, not studied here, that differs among sighted and blind people. Indeed, recent evidence suggests both neural similarities and differences between blind and sighted people's representations of color: While objects with similar colors show similar patterns of activity in the anterior temporal lobe of both blind and sighted individuals, color perception regions in visual cortex additionally encode color similarity in sighted individuals (68–70). The full typology of color knowledge in sighted and blind people remains to be fully described. Importantly, the present results demonstrate that there is much more to color knowledge than verbal facts and sensory (visual) representations.

Within the domain of causal, intuitive-theoretic color knowledge, much remains to be uncovered in both sighted and blind people. We hypothesize that, like in other domains, the intuitive theories of color of both blind and sighted individuals will differ in substantial ways from formal scientific color theories (67, 71). Participants' explanations of object colors did sometimes cite scientifically studied processes (e.g., photosynthesis), but more commonly consisted of informal justifications lacking mechanistic detail (e.g., "that's just how it grows," "it's nature," "God made it that way," "manufacturer decided to paint it that way," "the material it's made of"). When more specific causes and processes are mentioned, they are often social and historical, and unlikely to be taught through formal education (e.g., both blind and sighted participants mentioned personality of the owner for cars and "the patriarchy" for the color of wedding dresses). During development, sighted children's beliefs about color depart systematically from scientific knowledge. Children mistakenly believe that an object will continue to have the same color even when the lighting source is changed, that objects emit their own shadows, and that a green object will have a green shadow (72–75). Children's explanations about such phenomena omit crucial components, such as the source and nature of light illuminating an object (72). Similar inconsistencies between scientific and intuitive theories have been observed in numerous other knowledge domains (e.g., physics: ref. 76; biology: ref. 77; psychology: ref. 78). Even when educated adults and experts report strong confidence in their own understanding, their explanations for how things work are coarse and incomplete (79). Future work is needed to understand the ways in which intuitive theories of color among sighted and blind people share features with and depart from scientific color theories.

Importantly, the present evidence demonstrates that linguistic communication is highly adept at facilitating understanding of sensory phenomena, including color. Previous studies with blind adults and text corpus analyses reported that object colors are less well transmitted by linguistic communication than other physical (e.g., shape, texture) and abstract dimensions (e.g., taxonomy) (35, 36, 80). Proposed explanations for this observation include color not being accessible through modalities other than sight and/or being less talked about (34–36). Here, we show that unlike associative color facts, those aspects of color knowledge that are causal and inferentially rich are transmitted with high fidelity by linguistic communication. These findings suggest that color knowledge per se is not less linguistically accessible. Instead, language preferentially transmits causal, inferentially rich information over associative facts. This hypothesis parsimoniously explains both the current findings and the previous observation that associative color facts are less likely to be transmitted than other physical dimensions, since previous work focused on those aspects of color knowledge that are less causally linked to objects than other aspects of physical appearance. For example, people who are blind were less likely to agree with sighted people on color, than on shape or texture of animals. Relative to color, texture and shape are both more causally linked to an animal's taxonomic group and habitat. If we know that an animal lives in water, we can infer it is shaped like other sea-dwelling creatures, and if it is a bird, it is likely to have feathers (34). By contrast, both swans and polar bears are white, despite having no taxonomic or habitat relationship. Together, these data suggest that language preferentially transmits causally relevant and inferentially rich appearance knowledge.

The present results also provide insight into why text corpus analyses do better at extracting some kinds of perceptual information than others (e.g., 80). Although text corpus analyses do not build causal models or show preferential memory for causal material, we hypothesize that they are more likely to learn causally relevant perceptual features from text because these features are more attested in the linguistic signal and more correlated with other object properties. For example, text corpus analyses can guess that two animals have the same shape if they generally occur in similar linguistic contexts. By contrast, such guessing will not work for animal color because color is not causally linked to the object and therefore not predicted by contextual similarity. Evidence from people who are blind highlights the differences between how people and current text analysis algorithms learn about appearance through language. Unlike such algorithms, people incorporate linguistic information into causal intuitive theories through inference (see also refs. 81 and 82). The constructed theories enable people to make predictions about objects they have never encountered and to produce explanations (65, 83). This is also in part what enables humans to learn more about real object appearance from the linguistic signal: by filling in gaps in the data through inference.

Unlike most corpus-analysis algorithms, humans also make use of grammatical information (e.g., refs. 30 and 84). In the case of object color consistency, generics are one relevant type of grammatical construction. Hearing "this car is red," as opposed to "tomatoes are red" and "stop signs are red," could provide

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evidence about color consistency. Generic constructions are likely to be important since object–color cooccurrence in text alone does not faithfully reflect color consistency. Most objects are equally like to co-occur with canonical and noncanonical colors in text (36). For example, "crow" co-occurs with "black" and "white" with similar frequencies, presumably because noting unusual colors is more pragmatically useful (85). Sighted children use generic language to infer that a property is pervasive to an object type, as opposed to specific to a particular instance of that object (e.g., refs. 86–88). Likewise, people who are blind could use generics as a cue to color consistency. Generics could also facilitate learning specific object colors. Although people who are blind are less likely to agree with sighted people on specific animal colors than shapes, blind participants, but not text corpus analyses, are still most likely to generate the canonical color (89). In sum, the richness of information humans glean from language about appearance implies use of linguistic evidence in sophisticated ways to transform intuitive theories through inference (18, 88, 90).

The present results raise new questions concerning the role of language as opposed to sensory observation in the development of intuitive theories of color. One possibility is that for sighted people, language and vision convey redundant information, such that the same knowledge blind people acquire through language can be learned through vision by sighted people. If so, while blind and sighted people living in the same culture end up with similar theories by adulthood, there may be different trajectories in knowledge acquisition during development, with blind children showing later acquisition of the same information. Furthermore, if language and vision are completely redundant, we would expect those with typical color experience but limited early access to language (e.g., deaf children born to parents who do not sign) to have theories equivalent to those of sighted and blind people reported here. Alternatively, it remains possible that language conveys unique information about color. Future work is needed to uncover precisely how blind and sighted people use language as a source of information when constructing intuitions about color. Studies of acquisition in blind children and work with populations with different language access would provide important insight into how, and with what information such intuitions are constructed.

In summary, we find that blind and sighted individuals alike possess theory-like, inferentially rich knowledge about the relationship between objects and their colors. These intuitive theories of color support consistent generalizations in the face of limited information (e.g., for novel objects), invoke deep causes (e.g., object function), support the generation of sophisticated explanations, apply to broad categories (e.g., all plants) as well as to specific instances (e.g., polar bears), and are specific to color. Interestingly, such structured and inferentially rich color knowledge appears to be more resilient to the lack of first-person sensory experience than knowledge of associative color facts. This observation directly contradicts the common intuition that blind people's knowledge of color consists of meaningless arbitrary facts. Language appears to support the updating of causal models much more robustly than it does the acquisition of arbitrary facts.

The case of color knowledge in blindness illustrates the capacity of testimony to transmit in-depth understanding of sensory phenomena. It also provides complementary support for the idea that language is a powerful source of information for intuitive theory construction. For many previously studied domains of knowledge, language-induced learning could in principle piggyback on preexisting structured knowledge built through sensory observation. For example, learning that the Earth is round might piggyback on learning roundness through vision and touch (91). Even in the case of mental phenomena, simulation of one's own feelings and thoughts has been offered as a source of "first-person" information about others' minds (92, 93). Analogously, a sighted person might construct a representation of a novel animal described as blue and large by referencing physical knowledge previously built up through sensory experience of color and size (34). In the case of color knowledge among blind individuals, there is no directly pertinent sensory information. Nevertheless, inferentially rich knowledge is constructed through inference from linguistic communication. The current findings also support the claim that language is especially adept for cultural transmission of causal intuitive theories (94–96). In this regard, the current findings are consistent with evidence from laboratory experiments showing that children and adults remember facts better when they are linked by causes than when they are merely statistically associated (51, 64). Evidence from color knowledge in blindness complements these findings by showing that language preferentially conveys inferentially rich, causal knowledge in naturalistic cultural transmission.

Methods

Participants. Twenty congenitally blind (14 females/6 males; age: M = 30.85, SD = 10.59, years of education: M = 15.4, SD = 2.23) and 19 sighted (14 females/5 males; age: M = 31.21, SD = 11.21, years of education: M = 15.79, SD = 1.82) participants took part in the study (participant table can be found in *SI Appendix*, Table S1). All blind participants reported no experience with color, shape, or motion, and had at most minimal light perception. All blind participants were tested at the 2018 National Federation of the Blind Convention in Orlando, FL. Age- and education-matched sighted participants were then recruited and tested in person in-laboratory (in Baltimore, MD). Subtests of the Woodcock Johnson III Tests of Achievements (Word ID, Word Attack, Synonyms, Antonyms, and Analogies) were administered to sighted and blind participants, and anyone scoring below 2 SDs from their own group's mean was excluded from further analyses. This resulted in one sighted participant (participant 20) being excluded. The study consisted of three experiments administered to all participants within the same session. Experimental procedures were approved by the Johns Hopkins Homewood Institutional Review Board, and all participants provided informed consent.

Experimental Procedures Overview. Experiment 1 and 3 queried knowledge of and inferences about the colors of real objects (30 objects in experiment 1; 24 in experiment 3). In experiment 2, participants made color inferences about 15 novel objects. Experiment 2 was always administered first to prevent the real object judgments from influencing inferences made about novel objects. Within each experiment, two different trial orders were used, one for half of the participants within each group. Experimenters read aloud instructions and trials, and participant answers were audio-recorded and later transcribed for scoring. The full list of stimuli and instructions can be found in *SI Appendix*.

Experiment 1: Knowledge of Real Object Colors. In each trial of experiment 1, participants were asked two questions about an everyday object (Fig. 1). Three types of questions were asked: color consistency (30 objects), usage consistency (20 objects), and fillers (20 objects). Objects used for color trials were either natural (10 objects) or man-made (20 objects), and man-made artifacts could have function-relevant color (FC, 10 objects) or non-function-relevant color (NFC, 10 objects). Usage trials consisted of 10 natural kinds and 10 artifacts. On filler trials, participants were asked questions about noncolor features (size, shape, and texture). Filler trials consisted of 5 natural kinds and 15 artifacts in order to balance the overall number of natural kind and manmade trials. The full list of items used in color and usage trials can be found in Fig. 1.

On color trials, participants were first asked, "What is one common color of (a) [object name]?", followed by, "If you picked two [object name]s at random, how likely are they to be the same color? Rate on a scale of 1 to 7 (1: 'unlikely', 3: 'somewhat likely', 5: 'likely', 7: 'very likely')."

For usage trials, the questions were, "What is one common thing you can do with (a/some) [object name]?" and, "If you picked two people at random and asked them each to do something with (a/some) [object name], how likely are they to do the same thing, on a scale of 1 to 7?" Usage trials served as a control condition to ensure blind and sighted participants showed equivalent performance and were willing to rate artifacts as having some consistent properties.

Experiment 2: Color Inferences about Novel Objects. In experiment 2, in order to elicit inferences about novel objects parallel to in experiment 1, participants were first presented an "Explorer on an Island" scenario:

"Imagine that you're an explorer, and on your travels, you've discovered an island in a remote corner of the world… You learn that the people on this island call themselves Zorkas… The Zorka people appear to have a highly advanced culture. They have their own language, tools, machines, buildings, vehicles, foods, customs, and so on. The ecology on this island is also different from what we're used to: it has its own plant and animal life, unusual rocks, minerals, and so on. You're trying to learn about how things work on this island…."

Participants then heard 35 short vignettes, each of which described an encounter with a novel object (natural kind, artifacts with functional color, and artifacts with nonfunctional color; Fig. 1). In each trial, several appearance features were noted (e.g., "green gem that is spiky and the size of a hand"). The object was then named (e.g., "The miners tell you that this gem is called an Enly").

As in experiment 1, participants were next asked to rate the likelihood that another instance of the same object would have the same color (e.g., "How likely is it that the next time you come across another Enly, it is also green? "). In usage trials, the question asked the likelihood that the novel object would be used in the same way if encountered at another time (e.g., "How likely is it that the next time you come across another Irve, it is also being ripped out of the ground?"). In addition, there were 10 filler trials (seven natural kind, three man-made objects), in which participants were asked about the likely repeat occurrence of a noncolor feature (e.g., shape, texture, size).

Color trials consisted of five natural kinds (plant, algae, gem, liquid from a plant, fruit), five artifacts with function-relevant color (coin, road symbol, toxic waste container, ceremonial clothing, clear substance being used to build a wall), and five artifacts with function-irrelevant color (an odor-emitting gadget, roof cleaning machine, two devices with ambiguous functions).

Usage trials consisted of five natural kind (creature, boulder, stone, flower, plant) and five artifacts (machine that makes square holes, storage device, toy, machine that turns stones into goo, and one contraption with ambiguous function).

Filler trials contained seven natural kind (fruit, two creatures, rock, two plants, gem) and three artifacts (game device, type of pool, one contraption with ambiguous function).

Experiment 3: Explanations about the Cause of Object Color. For an additional list of 24 real objects (8 natural kind, 9 manmade with functional color, 7 function-irrelevant color), we asked participants to report their common colors (as in experiment 1). Common color reports for these 24 objects are collapsed with those from experiment 1 in Fig. 2. For these objects, we additionally asked why objects had the particular color (or colors) that the participant provided: "Why are [object name]s that/those color[s]?" Participants were instructed to provide whatever explanation felt right to them. Participants were also asked whether the object has different colored parts, and if an object's color varies across instances, to report the other colors. The answer to these questions were not analyzed for the present study.

Quantifying Color Naming Agreement for Real Objects. Across experiments 1 and 3, participants named the color of 54 objects (Fig. 1) (experiment 1: 30 objects, "What is one common color of…?"; and experiment 3: 24 objects, "What is the most common color of…?"). For each object, we quantified naming agreement by using the Simpson's diversity index (SDI) (34, 97). For unique color words (1 to R) provided for each object across all participants within a group (blind or sighted), a naming agreement score was calculated according to the equation below. N is the total number of words used across participants for each object, and n is the number of times each unique word (1 to R) was provided. The index ranges for 0–1, where 0 indicates that the same color word was never used by two participants (i.e., low color naming agreement), and 1 suggests all participants provided the same color (i.e., high naming agreement):

$$\mathrm{SDI} = \frac{\sum_{i=1}^{R} n_i(n_i - 1)}{N(N-1)}.$$

Although participants were instructed to provide one color, a few participants provided multiple colors (at most three, e.g., "red, white, and blue"). All of these colors were included in the analysis. Furthermore, a small proportion of participants said "I don't know" or provided words that were not typical color terms (dark, light, beige, neon). These responses were treated the same as color terms ("I don't know" was counted as one word, coded "IDK"). Since SDIs were not normally distributed, they were log-transformed. To examine differences in color naming agreement across groups, we then performed linear mixed effects regression on log-transformed SDIs, using lmer in R (98), with objects as random effects.

Color Consistency Inference Analysis. Consistency likelihood judgments were analyzed using ordinal logistic regression using the ordinal (99) package in R. Participants and objects were always included as random effects, and separate models were used in each analysis described (e.g., for real vs. novel objects).

We first compared group differences for natural kinds and artifacts with nonfunctional color only, since artifacts with functional color are a special category. This also allowed us to look at a group (blind vs. sighted) × object kind (natural vs. artifact) × trial type (color vs. function) three-way interaction. Baselines were coded as sighted group, usage trial, and artifact. We then compared across groups for color trials only, this time including all three kinds of objects (natural, artifact with functional color, artifact with nonfunctional color), with sighted group and artifact with nonfunctional color as the baseline.

Correlation with Functional Relevance of Color for Artifacts. We obtained ratings from Amazon Mechanical Turk for the functional relevance of color to artifacts separately for real (n = 20) and novel (n = 25) objects. Participants were asked, "How important is the color of a [object] to its function?" and had to rate on a scale of 1 to 7 (not at all to very relevant). For novel objects, participants were provided with the same "explorer on an island" scenario as in the main experiment. Artifacts designated as "artifacts with functional colors" were those that received an average rating of 4 or above, and artifacts "nonfunctional colors" all had ratings below 4 (*SI Appendix*, Tables S2 and S3). We correlated the average functional relevance ratings for each object with the average color consistency judgments, for blind and sighted groups separately (Spearman correlation). To compare across groups, we used ordinal logistic regression with group and relevance judgments as fixed effects and participants and items as random effects.

Analysis of Explanations. Explanation types were decided by the experimenters based on examining all the explanations (while blind to group and object). We decided on nine types of explanations: "process," "depends on," "just is," "material," "social/aesthetic," "maker," "visibility," "convention," and "I don't know." A key of explanations can be found in *SI Appendix*, Table S3.

Explanations were coded by four coders who did not know which object or group each explanation came from. Note, however, that in a small number of instances participants said the object's name in their explanations, and at other times, it was fairly easy to discern the object from the explanation.

There was large variability in how many words participants used in their explanations (range = 1–165 words; M = 13 words). This meant that each explanation (i.e., what one participant said for one object) could contain multiple explanation types. For example, a participant's answer that the color of a wedding dress is due to "symbolism, or personal style," was coded as containing "convention" (for symbolism) and "social/aesthetic" (for personal style) explanations. However, the same word or phrase (e.g., "personal style") was never coded for more than one explanation type.

Some participants gave lengthier explanations than others, without necessarily providing additional information (e.g., often telling anecdotal stories to make a point). For wedding dress, for instance, another participant explained: "Well, there's something about tradition, and white being associated with purity and virginity and all that, but beyond that it's just a matter of demand, if you want a baby barf green wedding dress that's your problem." This explanation was also coded with "convention" and "social/aesthetic."

Coding was then filtered according to the criteria that at least three out of four coders have to agree. The first author (fifth coder) made some additional changes, again keeping group and objects blind, and overruled tagging for <5% explanations. After this process, the number of explanation types per explanation (again, a single explanation from one participant for one object) only ranged from 1 to 3 (M = 1.26).

We compared explanations across groups within each object kind. Within a group and kind (e.g., sighted group, natural kinds), we calculated how frequently participants (across all participants within group) used each of the nine explanation types. The counts were then calculated as a percentage of all explanations (within group and object kind). We then computed Spearman's correlations over the percentages (for nine types) across groups, as well as across object kinds within groups.

Data Availability. Anonymized behavior data have been deposited in the Open Science Framework (https://osf.io/2u7zn/) (100). All data, code, and materials used in the analysis have been deposited in GitHub (https://github.com/judyseinkim/Intuitive-Theories-of-Color), and a detailed description of analyses can be found at https://rpubs.com/judyseinkim/color_theory.

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