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Like Mother, Like Daughter: Adults' Judgements about Genetic Inheritance

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Authors Note

The authors wish to remember David Liu, who died before the publication of this article. David was a valued member of our research team, and his contributions were integral to this work. Olympia N. Mathiaparanam was at the University of Wisconsin-Madison while this work was conducted and is now at the University of Rochester. The study design, hypotheses, and analytic plan of the research presented in the paper were not pre-registered. All materials, data, and analysis scripts can be found at: https://osf.io/pwbja. This research was supported by the National Science Foundation (Grant 1760940) and by the U.S. Department of Education (Institute of Education Sciences, Award R305B150003 to the University of Wisconsin-Madison). The opinions expressed are those of the authors and do not represent views of the National Science Foundation or the U.S. Department of Education.

Abstract

Do people think about genetic inheritance as a deterministic or probabilistic process? Do adults display systematic biases when reasoning about genetic inheritance? Knowing how adults think about genetic inheritance is valuable, both for understanding the developmental endpoint of these concepts and for identifying biases that persist even after formal education. In two studies, we examined adults' reasoning about genetic inheritance for familiar animals (Study 1) and unfamiliar animals (Study 2). First, participants were presented with animals that varied in eye color and were asked to judge whether each could be the offspring of a particular set of animal parents that had either the same or different eye colors. The potential offspring had eye colors that were either identical to the parents, blended the parents' eye colors, or differed from the parents. Next, participants predicted how six offspring of the animal parents would look. Participants judged a variety of choices as possible—not only the ones resembling the parents—suggesting that they thought genetic inheritance was a probabilistic process. Additionally, many participants thought that female offspring would look more like their mothers and male offspring would look more like their fathers. Thus, systemic biases in reasoning about inheritance persist into adulthood.

Keywords: folk biology; genetic inheritance; variability; familiarity; intuitive theories

Public Significance Statement

We studied adults' thinking about biology and found that they had some correct knowledge (such as understanding that offspring can look different than their parents), but also some misunderstandings (such as believing that offspring will resemble the parent of the same sex). This information can be used to tailor secondary and undergraduate genetics instruction to build on the knowledge students already have while correcting the misunderstandings they might hold.

Like Mother, Like Daughter: Adults' Judgements about Genetic Inheritance

Genetic inheritance is a complex and probabilistic process, and it provides the basis for more advanced topics such as within-species variability and evolution. Despite this complexity, many children and adults seem to have a basic understanding of how genetic inheritance works (Johnson & Solomon, 1997; Springer & Keil, 1989; Weissman & Kalish, 1999) and they use this naïve understanding to make judgements about how the offspring of two parents will look (Terwogt, Stegge, & Rieffe, 2003; Williams, 2012). This folk understanding of genetic inheritance, which glosses over some of the complexities of scientific theories of genetics, has been the focus of a large body of research in developmental psychology (e.g., Solomon, Johnson, Zaitchik, & Carey, 1996; Wellman & Gelman, 1992). However, there is little research exploring how adults understand genetic inheritance and thus little information on the developmental endpoint of these concepts and whether adults' concepts have remnants of these folk understandings. In this paper, we investigate whether adults think about genetic inheritance as a probabilistic or deterministic process and whether they show any biases that might stem from early folk theories.

Assessing genetics understanding

Several studies have investigated children's conceptions of genetic inheritance. These studies present participants with a mother and a father that have different phenotypes and ask children to choose how their offspring will look using a forced-choice paradigm (for more information on this task, see Springer, 1996; Terwogt et al., 2003). They find that children around the age of seven believe that babies will resemble their mothers (a pattern called "the mother bias"), whereas older children believe that babies will have a combination of the mother's and father's phenotypes (Terwogt et al., 2003; Williams, 2012). Examining such folk beliefs in children is important for gaining an understanding of the development of inheritance concepts. However, to gain information about the developmental endpoint of such concepts (at least within a culture), comparable studies of adults' beliefs are needed (Coley, 2000).

Deterministic versus probabilistic models of genetic inheritance

Prior literature has neglected to examine whether people have a deterministic or probabilistic view of genetic inheritance. A deterministic view of genetics is a more naïve understanding of genetics, which holds that there is only one possible outcome, and all offspring will look the same. A probabilistic view of genetics is a more scientifically accurate understanding, which holds that many different phenotypes are possible, but some phenotypes are more likely than others. In past research, participants were able to select only one offspring as possible. Therefore, it is impossible to know whether responses represent *the most likely* offspring of the parents or *the only possible* offspring. If the responses represent *the most likely* offspring, they imply a probabilistic model, while if they represent *the only possible* offspring, they imply a deterministic model with no variability. Thus, past research cannot differentiate between these possible models.

On one hand, it seems likely that college educated adults in the United States hold a probabilistic model of genetics. Science education standards identify genetic inheritance as an important topic for students to understand (NGSS, 2012), and formal genetics lessons in secondary school cover dominant and recessive genes and genetic mutations that might lead parents and offspring to look different. Aside from this formal experience, adults presumably have a lot of informal experience seeing children who resemble one, both, or neither of their parents. Indeed, some recent work suggests that, when reasoning about familiar species, adults think that offspring can look quite different from their parents (French, Menendez, Herrmann, Evans, & Rosengren, 2018).

On the other hand, there are reasons to believe that adults might have a deterministic view of genetics. A deterministic view could be related to cognitive biases such as psychological essentialism

(Meyer, Roberts, Jayaratne, & Gelman, 2020). Psychological essentialism is the tendency to think of natural categories as if they have an innate substance (or essence) that gives them their properties (Gelman, 2003; Medin & Ortony, 1985). Applied to biological concepts, this means that people may think that organisms of the same species have the same essence, and so they will all have the same properties. If people think that all animals of the same species have the same properties or phenotypes, this could lead to a deterministic view of genetics, such that people think that there is only one possible outcome, and all offspring of a given set of parents will look the same. It has been argued that many adults have an essentialist model of biology that leads them to think that individuals of the same species will look similar to one another (Coley, Arenson, Xu, & Tanner, 2017; Gelman & Rhodes, 2012; Shtulman, 2006). Further, many college and high school students have difficulties understanding genetics (Bahar, Johnstone, & Hansell, 1999; Banet & Ayuso, 2000; Duncan & Reiser, 2007), so they could have other misunderstandings, such as having a deterministic view of genetics. Finally, analyses of science education materials, such as curricula and textbooks, often reinforce deterministic and essentialist beliefs about genetics (Donovan, 2014, 2017; Jamieson & Radick, 2017), and essentialist language is commonly used by biology instructors (Betz et al., 2019). Therefore, it is possible that formal instruction on genetics does not generally lead to a probabilistic view, and it might inadvertently reinforce a deterministic view.

Synthetic models

Adults might not have a uniquely deterministic or probabilistic model, but they might combine aspects of one model with folk biological theories. Prior work has shown that although adults have more biological knowledge than children, they still frequently rely on cognitive biases and folk theories (Coley et al., 2017; Coley & Tanner, 2015). This is the case, even for students who are majoring in biology or a related field (Coley & Tanner, 2015; Menendez, Rosengren, & Alibali, 2020). Therefore, undergraduate students, regardless of major, might not demonstrate a fully correct probabilistic model of genetic inheritance or a fully deterministic intuitive model. Instead, these adults might hold a *synthetic* model of genetic inheritance that combines aspects of scientific models about genetic inheritance with intuitive theories (Evans & Rosengren, 2018; Legare et al., 2012; Vosniadou, Vamvakoussi, & Skopeliti, 2008). Hence, adults could show a probabilistic model of genetic inheritance but still show biases in their choices or misconceptions in their explanations. Furthermore, adults might understand that genetic inheritance is a probabilistic process, but they might not yet understand that some phenotypes are more likely than others. Thus, they might not show a differentiated probabilistic model in which many offspring are possible, and some are more likely than others. Understanding the nature of these synthetic models, and the misconceptions that educated adults still hold, can inform scientific understanding of developmental progressions in understanding of inheritance and can highlight misconceptions that may persist even after formal biology instruction.

Potential effects of parent phenotype

Whether the parents have the same or different phenotypes might influence how adults think about genetic inheritance. It might be fairly easy for people to believe that offspring can look different from one another and from the parents when the parents have different phenotypes. For example, one offspring could look like the mother, one like the father, and one have a mix of their phenotypes. It might be more challenging for people to believe that offspring can look different from one another, and from the parents, when parents have the same phenotype. For example, recessive alleles can lead the offspring of two brown-eyed parents to have blue eyes. But even in such cases, the parent phenotype is typically more likely than other ones. Therefore, endorsing multiple offspring with different phenotypes when the parents have the same phenotype might suggest that adults have a robust probabilistic model that they use in many situations.

The phenotypes of the parents might also influence which offspring adults think are possible. When the parents have the same phenotype, adults might endorse as possible only offspring that look like the parents (or that show only slight variations). When the parents have different phenotypes, adults might endorse both of the parents' phenotypes, as well as variations and blends of those phenotypes. Therefore, participants might show different patterns of endorsements about which offspring are possible, depending on whether the parents' phenotypes are the same or different.

Current studies

In the current studies, we examined whether adults held a probabilistic or deterministic view of genetic inheritance. We investigated this issue in adults' reasoning about familiar animals (Study 1) and unfamiliar animals (Study 2). Both studies focused on eye color, a familiar trait. Addressing some critical gaps in the prior literature, we examined whether adults hold a deterministic or probabilistic model of genetic inheritance or a synthetic model that is probabilistic but includes some misconceptions. We also consider how robust adults' views are across different parent eye color combinations. Finally, we examined the distribution of offspring phenotypes that adults think are possible (similar to prior research by Terwogt et al., 2003, and Williams, 2012).

To evaluate whether adults held a probabilistic or deterministic view of genetic inheritance, we developed two tasks, and we used both in each study. In the first task, the *phenotypic judgement* task, adults were asked to judge whether two animal parents, with either the same or different eye colors, could have offspring with a specific eye color. Adults made judgements about several offspring choices. This allowed us to see if adults believed that more than one phenotypic option was possible. However, the phenotypic judgement task could not tell us if adults thought that one offspring phenotype was more likely than another. To examine this difference in likelihood, we designed a second task, the *offspring prediction* task. In the offspring prediction task, adults used the offspring choices to make predictions about the eye colors of six offspring of the same set of animal parents. By examining adults' predictions of how the six offspring would look, we could see if adults believed that certain choices were more likely than others. Thus, the *phenotypic judgement* task allows us to examine which phenotypes adults think are possible, while the *offspring prediction* task allows us to examine which phenotypes adults think are likely to occur. In both tasks, participants saw sets of parents that had the same eye color and different eye colors. This allowed us to examine whether adults believed that offspring could look different from their parents, even when the parents had the same phenotype.

We generated three hypotheses for each task. First, we hypothesized that adults would show a probabilistic view of genetics, given their educational experiences, their familiarity with eye color and the animals used in the task, and the fact that all adults have encountered variability in eye color as a trait. In the phenotypic judgement task, this would be observed by adults judging multiple offspring choices as possible. In the offspring prediction task, this would be observed by adults predicting that all offspring *would not* have the same eye color (i.e., by selecting offspring with different eye colors). Second, we expected that the distribution of eye colors that adults thought were possible would follow some systematic patterns. We hypothesized that adults would select the offspring whose eye color matched the parents' eye color more often, indicating that they believe that certain phenotypes are more likely than others. Finally, given prior work that suggests that middle-school students think that offspring will have a combination of the parents' traits (Williams, 2012), we hypothesized that adults would judge more offspring phenotypes as possible (e.g., same phenotype, blended phenotypes, different phenotypes) and select more offspring with different eye colors when the animal parents had different eye colors than when they had the same eye color.

Study 1

Method

Participants

We recruited 72 participants from an introductory psychology course during the Summer term at a large Midwestern university with moderately selective admissions criteria (see supplemental materials). We did not determine the sample size *a priori*; rather, we recruited as many participants as we could during the Summer term. We conducted a post-hoc sensitivity analysis and found that a within-subjects design with 72 participants could detect an effect size of *d* = 0.33 (an effect size smaller than the *d* = 0.72 reported in prior work by Williams, 2012) with 80% power. One participant was excluded from the analyses as they did not pass any of the attention checks. Of the remaining 71 participants, 46 identified as women and 25 identified as men. Of these 71 participants, 57.7% identified as White or Caucasian (n = 41), 29.6% identified as Asian or Asian American (n = 21), 7.0% identified as Black or African American (n = 5), 2.8% identified as Hispanic or Latinx (n = 2), 1.4% identified as Middle Eastern (n = 1), and 1.4% identified as biracial (n = 1). Twenty-eight participants (38.9%) reported majoring in a field that requires biology coursework, including neuroscience, biochemistry, and nursing (henceforth referred to as a biology-related major). On average, participants had taken 1.9 biology courses since the beginning of high school (range: 0-8). One participant was excluded from the analyses because they reported being color-blind. Participants completed the study for extra credit in an Introduction to Psychology course.

Stimuli

The stimuli were highly detailed drawings of four animals: a wolf, a fox, a beaver, and a squirrel. The drawings focused on the animals' faces in order to emphasize the animals' eye colors (see Figure 1). For each animal, we created two face shapes: one for the parents and one for the offspring. The parent and offspring faces were very similar except for some differences in facial proportions, such as the eyes of the offspring being bigger (Lorenz, 1971). For each animal, we selected two eye colors based on realistic natural variation in that species (one dark color and one light color). These colors were used for the parents. We then created four possible mother-father dyads based on these eye colors: Dark-Dark, Dark-Light, Light-Dark, and Light-Light. Participants saw one of the four dyads for each animal, with dyad type randomized for each animal for each participant. All participants saw the same four animals, but the order in which the animals were presented was also randomized.

For the offspring choices, we created six different types of eyes (see Figure 1 for an example). One was the same dark color as the parent. One was the same light color as the parent. One was a color in between the two parent colors (labeled Mix in Figure 1). One offspring had one dark eye and one light eye (labeled one-and-one in Figure 1). For one offspring, the inner part of the eye was the lighter color and the outer part of the eye was the darker color (labeled inner/outer in Figure 1). Finally, one offspring had eyes that were purple—a color that was unrelated to either parent's eye color and that is not observed in nature in any mammal species. We included the purple phenotype so we could examine whether adults endorsed every possible animal of the same species or whether they constrained their responses to what they thought was possible given the parents.

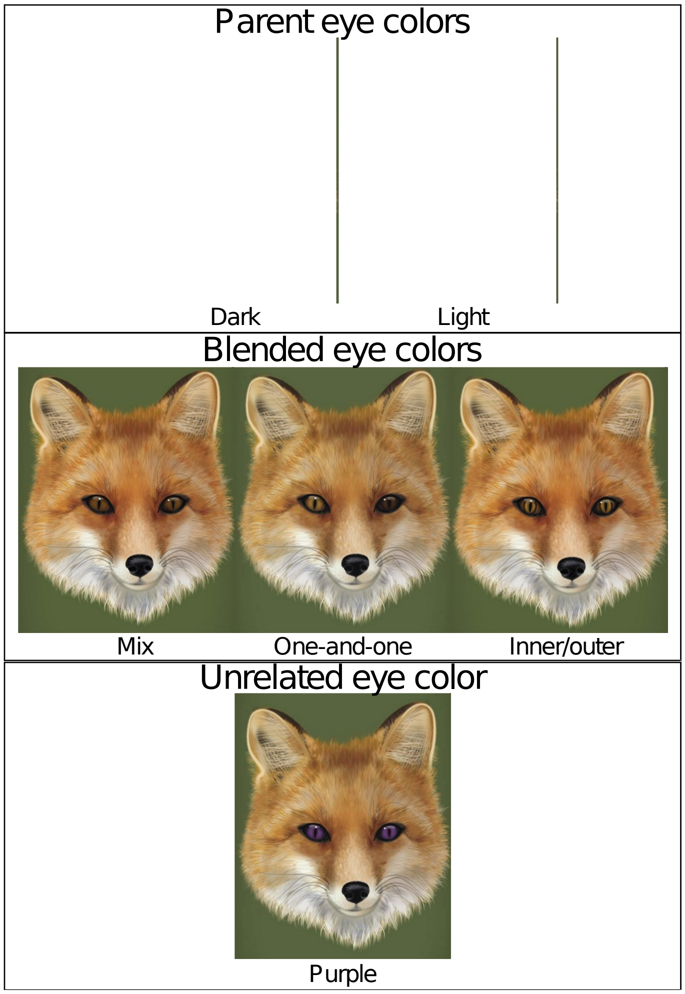

Figure 1. Fox stimuli with different eye colors.

Procedure

Participants completed the study online through Qualtrics. First, participants saw a drawing of all four animals and were asked to name them. The purpose of this naming task was to examine which animals were familiar to participants. All participants were able to correctly name the animals or named a similar type of animal (e.g., a few participants called the beaver a chipmunk, which is another rodent). Participants then completed the phenotypic judgement task followed by the offspring prediction task.

Phenotypic judgement task. For this task, participants saw the mother and father of an animal family on the top of the page and one of the possible offspring directly underneath, in between the two parents. Participants were asked whether the offspring's eye color was "like the mother," "like the father," "like a mix of both," or "like neither." This question was included to make sure that the participants noticed the differences among the eye colors. Participants were able to notice the differences between the eye colors and reliably map their relations to the parents. Data for this question are available in the supplemental materials. Participants were then asked, "Do you think these parents could have an offspring like the one on the bottom?" Participants could only answer "yes" or "no." Participants judged each of the six offspring options for one animal family before moving on to the next task. Thus, there were 6 trials per animal (one for each offspring) and participants completed this task for all four animals.

Offspring prediction task. After completing the phenotypic judgement task for a given animal, we told participants that the parents had six offspring throughout their lives, three males and three females. We included that the parents had the offspring "throughout their lives," so that participants' possible knowledge of the typical litter size for each species was would not affect their responses. Participants selected how they thought the three male and three female offspring would look using the offspring possibilities from the phenotypic judgement task (displayed all at once). Participants indicated how many of the three male and three female offspring would look like each of the options. After making their choices, participants were asked to explain why they made the choices they did by typing into a text box. Participants were not able to see their offspring selections when providing their explanations. Participants completed this task for all four animals.

The order in which the animals were presented, the parent eye color combinations, and the order in which the offspring choices were presented were randomized for each participant. The parents' eye colors were the same for the phenotypic judgement and the offspring prediction task for the same animal during each of the task trials. We randomly interspersed two attention checks during the Qualtrics survey. At the end of the survey, participants reported their demographic information.

Explanation coding

To gain a deeper understanding of how participants were thinking about inheritance, we examined participants' explanations to their answers for the offspring prediction task. We coded participants' explanations into seven, non-mutually-exclusive categories: (1) *parent match*, in which participants stated that they tried to select offspring with eyes that matched the parents' eyes (see sub-codes below); (2) *sex difference*, in which participants said male and female offspring should look different; (3) *mix*, in which participants said they wanted the offspring to combine the parents' phenotypes; (4) *random*, in which participants said they responded randomly (see sub-codes below); (5) *description*, in which participants did not provide an explanation, but only a description of their offspring choices, (6) *other*, in which participants offered an explanation that did not fit one of the preceding categories; and (7) *fragment*, in which participants' responses were less than a full sentence and we could not determine their explanation. We also included sub-codes for the parent-match category: (a) *sex match*, in which participants mentioned that male offspring should look like the father and female offspring like the mother, and (b) *non-sex*, in which participants simply matched the offspring to the parents without mentioning sex or gender. We also included sub-codes for the random explanations: (a) *everything possible*, in which participants said that they chose randomly because genetics is so complex that every eye color was possible, and (b) *other*, which included any other reason for responding at random. We also separately coded whether participants mentioned *genetic information* (e.g., recessive genes). One coder coded all of the explanations and a second coder coded the explanations of 18 participants (25% of the sample). Inter-rater reliability was acceptable ($\kappa = .77$). The majority of the disagreements occurred in distinguishing the categories "other" and "fragment." Given that this distinction was not relevant for our analysis, we combined these codes. With these combined codes, inter-rater reliability was high (κ = .85). Reliability for the sub-codes (κ = .87) and for mentioning genetic information (κ = .92) was also high. All disagreements were resolved through discussion.

Transparency and Openness

All materials, including the images of the stimuli and PDF files of the Qualtrics survey are available at https://osf.io/pwbja/. The OSF project also contains all of the data and analysis scripts to reproduce the results reported here. All analyses were conducted in *R* using the *lme4* (Bates, Maechler, Bolker & Walker, 2015) and *car* (Fox & Weisberg, 2019) packages. The graphs were created using *Rmisc* (Hope, 2013) and *tidyverse* (Wickham et al., 2019) packages.

Results

We first present the results for the phenotypic judgement task, followed by results for the offspring prediction task, and finally we describe participants' explanations. An individual pattern analysis can be found in the Supplemental materials. For offspring eye color, we did not observe differences among the three "blended" phenotypes (mix, one-and-one, and inner/outer; see Figure 1), so we combined these responses into one group, which we refer to as *blend* responses. Therefore, we use offspring type as a categorical variable with four levels: dark, light, blend, and purple.

Phenotypic judgement task

First, we examined whether participants differed in how many offspring they chose, as a function of whether the parents' eye colors were the same or different. This analysis allowed us to evaluate whether participants endorsed a wider range of offspring options when parents have different eye colors compared to when they have the same eye color. We used a linear mixed-effects model to predict the number of offspring that participants endorsed (i.e., said "yes" to) from whether the parents had the same or different eye colors and whether participants were majoring in a biology-related field. We included by-subject random intercepts and by-subject random slopes for the effect of parents' eye color condition (same or different). As hypothesized, we found that participants endorsed more offspring choices (regardless of eye color) when parents had different eye colors (*M* = 4.28, *SD* = 1.09) than when they had the same eye color (*M* = 3.33, *SD* = 1.66), *b* = 1.01, *F*(1, 65.76) = 30.25, *p* < .001. There was no effect of majoring in a biology-related field, *b* = 0.17, *F*(1, 70.74) = 0.53, *p* = .468. It is worth pointing out that even when the parents had the same eye color, participants often endorsed more than one offspring option. Thus, these adults believed that there were many possible variations in how the offspring of a given set of parents could look. This indicates that, as predicted, adults believe that variability between parents and offspring is possible, even when both parents have the same eye color, suggesting they have a probabilistic model of genetics.

We also wanted to examine which specific offspring participants selected and whether these selections differed depending on whether the parents' eye colors were the same or different. To address this question, we fit a generalized linear mixed-effects model with a binomial link function predicting the probability that participants said "yes" to whether each offspring could be the baby of the animal family. We included offspring type (dark, light, blend, or purple), parent eye color condition (same or different), their interaction, and whether participants majored in a biology-related field as fixed effects. To examine the effect of offspring eye color, we used non-orthogonal contrasts with the dark eye color phenotype as the reference category. This model did not converge, so we followed the recommendations of Brauer and Curtin (2018) to simplify the model. The first model that converged included by-subject random intercepts, by-subject random slopes for the effect of parent eye color condition, three by-subject random slopes for the effect of offspring type (one for each contrast), and three random slopes for the interaction (one for each contrast), but it did not allow the random effects to correlate. We used a Kenward-Rogers approximation for the degrees of freedom.

There was no effect of majoring in a biology-related field, *OR* = 1.09, χ^2 (1, *N* = 70) = 0.07, *p* = .788. As predicted, we found an effect of offspring type, χ^2 (3, *N* = 70) = 98.70, *p* < .001, and this effect was qualified by an interaction with parent eye color condition, χ^2 (3, *N* = 70) = 23.01, *p* < .001. For example, as can been seen in Figure 2 and in line with our hypothesis, participants endorsed the blended offspring more often when parents had different eye colors rather than the same eye color. To explore this interaction in more depth, we fit the same model to the same-eye-color parent trials and the different-eye-color parent trials separately. We removed parent eye color condition and included mother/ parent eye color (light or dark) in these models.

Different parents. Out the 70 participants, 66 completed at least one trial in which the parents had different eye colors. In analyzing these trials, we found an effect of offspring type, χ^2 (3, *N* = 66) = 64.81, *p* < .001, but no effect of mother eye color, *OR* = 0.52, χ^2 (1, *N* = 66) = 0.47, *p* = .493, and no interaction, χ^2 (3, *N* = 66) = 0.96, *p* = .810. The absence of a mother eye color by offspring type interaction indicates that there was no evidence for a preference for the mother's eye color (i.e., mother bias) when the parents had different eye colors. We explored the effect of offspring type with several pairwise comparisons. Participants were equally likely to endorse offspring with light (*M* = 0.98, *SD* = 0.14) and dark eye colors (*M* = 0.96, *SD* = 0.20), χ^2 (1, *N* = 66) = 0.01, *p* = .928. Participants were less likely to endorse the offspring with blended eye colors (*M* = 0.74, *SD* = 0.44) than offspring with dark eyes, OR = 0.08, χ^2 (1, *N* = 71) = 26.60, *p* < .001. Finally, participants were less likely to endorse offspring with purple eyes (*M* = 0.13, *SD* = 0.34) than offspring with blended eye colors, OR < 0.01, χ^2 (1, *N* = 66) = 38.79, *p* < .001. See Figure 2, left panel. Taken together, these results support our hypothesis that adults' endorsements follow a systematic pattern, such that they were more likely to endorse offspring with eye colors that matched the parents' eye colors, followed by offspring with the blended eye colors, and finally offspring with the unrelated eye color.

Same parents. Out of our 70 participants, 66 completed at least one trial in which the parents had the same eye color. In analyzing these trials, we found an effect of offspring type, χ^2 (3, N = 66) = 45.90, $p < .001$, an effect of parent eye color (dark or light), OR = 154.59, χ^2 (1, N = 66) = 29.09, $p < .001$, and an interaction, χ^2 (3, N = 66) = 65.74, $p < .001$. Overall, participants were equally likely to endorse offspring with light (M = 0.67, SD = 0.47) and dark eyes (M = 0.75, SD = 0.43), OR = 0.51, χ^2 (1, N = 66) = 1.38, $p = .240$, but their likelihood of endorsement depended on the eye color of the parents, $OR < 0.01$, χ^2 (1, N = 66) = 60.78, $p < .001$. As can be seen in Figure 2, right panel, when the parents had light eyes, participants were more likely to endorse the light-eyed offspring than the dark-eyed offspring, and vice versa when the parents had dark eyes. Participants were less likely to endorse offspring with blended eye colors (M = 0.59, SD = 0.49) than offspring with dark eyes, OR = 0.15, χ^2 (1, N = 66) = 17.08, $p < .001$, and less likely to endorse offspring with purple eyes (M = 0.14, SD = 0.35) than offspring with blended eye colors, $OR < 0.01$, χ^2 (1, N = 66) = 21.53, $p < .001$. Finally, participants were less likely to endorse offspring with blended eye colors, OR = 0.46, χ^2 (1, N = 66) = 4.38, $p = .036$, and offspring with purple eyes, $OR < 0.01$, χ^2 (1, N = 66) = 7.60, $p = .006$, when the parents had dark eyes. These results show that participants' endorsements followed a systematic pattern, namely, endorsements aligned with the degree of perceptual similarity between the parents' and offspring's eye colors.

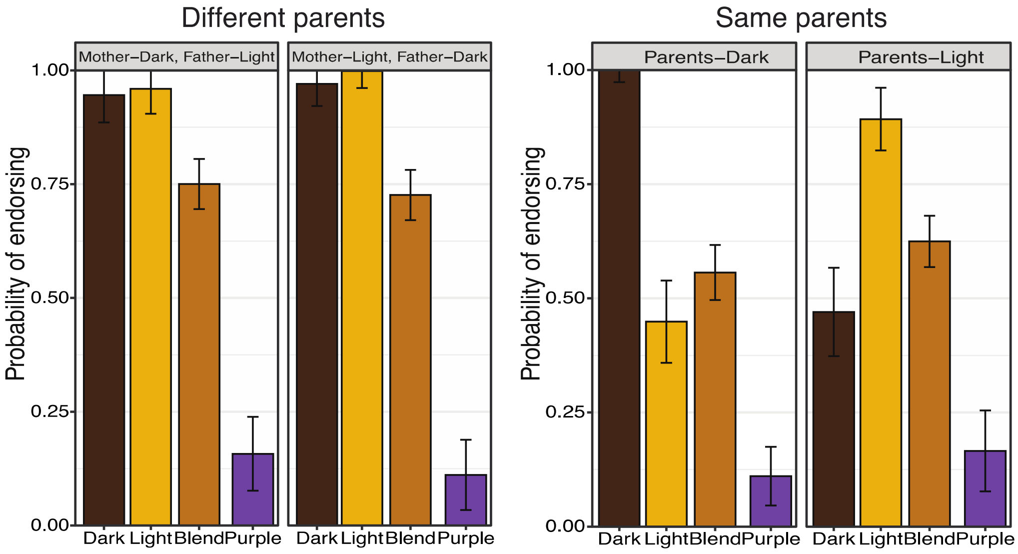

Figure 2. Probability of endorsing that a particular offspring could be the baby of the two parents in the phenotypic judgement task for Study 1. The left panel shows the results for trials on which the parents had different eye colors and the right panel shows the results for trials on which the parents had the same eye color. Error bars display the within-subject standard errors using the method described in Morey (2008).

Offspring prediction task

For the offspring prediction task, we first examined how many different offspring phenotypes participants chose. To do this, we looked at how many different options participants chose for the male and the female offspring. We used a linear mixed-effects model to predict the number of different offspring choices that participants selected (with a maximum of three, because there were three offspring of each sex). We included offspring sex, parent eye color condition (same or different), their interaction, and whether participants majored in a biology-related field. We included by-subject random intercepts and three by-subject random slopes (one each for offspring sex, parent eye color condition, and their interaction). The sole significant effect was for parent eye color condition, $b = 0.60$, F(1, 64.51) = 39.63, $p < .001$. When parents had the same eye color ($M = 1.85$, $SD = 0.92$), participants chose fewer offspring options than when parents had different eye colors (*M* = 2.47, *SD* = 0.72). However, as before, even when parents had the same eye color, participants tended to choose more than one offspring type. Thus, participants believed that not all offspring would have exactly the same eye color as the parents.

To analyze participants' choices for the offspring prediction task, we examined the set of options participants chose. We fit a generalized linear mixed-effects model with a binomial link function predicting the probability of selecting an offspring from offspring type (dark, light, blend, or purple), parent eye color condition (same or different), their interaction, and whether participants majored in a biology-related field. We also included by-subject random intercepts, and by-subject random slopes for the effect of offspring type, parents' eye color condition, and their interaction.

We found an effect of offspring type, χ^2 (3, *N* = 70) = 77.04, *p* < .001, and an effect of parent eye color condition, *OR* = 2.23, χ^2 (1, *N* = 70) = 5.33, *p* = .021, but no interaction, χ^2 (3, *N* = 70) = 5.48, *p* = .140. Additionally, participants who majored in a biology-related field (*M* = 0.34, *SD* = 0.47) were, overall, less likely to select offspring (of each type) than participants who did not major in a biology-related field (*M* = 0.38, *SD* = 0.48), *OR* = 0.69, χ^2 (1, *N* = 70) = 6.23, *p* = .013. This suggests that participants majoring in a biology-related field were more constrained in their selections.

As with the phenotypic judgement task, we examined participants' selections for the different and same parent eye color trials separately. We fit a model similar to the one described above, but we removed parent eye color condition and included offspring sex (male or female) and mother eye color (light or dark). For the model of different-parent-eye-color trials, the first model to converge had by-subject random slopes for the effects of offspring type, mother eye color, offspring sex, and all the respective interactions. For model of same-parent-eye-color trials, the first model to converge had by-subject random slopes for the effects of offspring type, parent eye color, their interaction, and offspring sex.

Different parents. We found an effect of offspring type, χ^2 (3, *N* = 66) = 93.17, *p* < .001, that was qualified by a three-way interaction with mother eye color and offspring sex, χ^2 (3, *N* = 66) = 23.88, *p* < .001. Overall, participants were less likely to select the offspring with light eyes (*M* = 0.62, *SD* = 0.49) than the offspring with dark eyes (*M* = 0.73, *SD* = 0.45), *OR* = 0.62, χ^2 (1, *N* = 66) = 4.55, *p* = .033. However, as can be seen in Figure 3, participants were more likely to select the dark-eyed than the light-eyed offspring for males when the father had dark eyes, and more likely to select the dark-eyed than the light-eyed offspring for females when the mother had dark eyes (and vice versa for light eyes), *OR* = 0.02, χ^2 (1, *N* = 66) = 22.81, *p* < .001. Additionally, participants were less likely to select the offspring with blended eye colors (*M* = 0.36, *SD* = 0.48) than the dark-eyed offspring, *OR* = 0.17, χ^2 (1, *N* = 66) = 71.47, *p* < .001. Participants were also less likely to select the purple-eyed offspring (*M* = 0.06, *SD* = 0.24) than the offspring with blended eye colors, *OR* < 0.01, χ^2 (1, N = 66) = 25.08, *p* < .001. These results indicate that participants differentiated among offspring in their selections by more often choosing the offspring that they thought were more likely. This suggests that participants were using a differentiated probabilistic model, but they still showed misconceptions, such as the idea that offspring would resemble their same-sex parent.

Same parents. We found an effect of offspring type, χ^2 (3, *N* = 66) = 69.50, *p* < .001, an effect of parent eye color, *OR* = 4.18, χ^2 (1, *N* = 66) = 30.07, *p* < .001, and an interaction between the two, χ^2 (3, *N* = 66) = 45.86, *p* < .001. Overall, we found that participants were equally likely to select the light-eyed (*M* = 0.52, *SD* = 0.50) and dark-eyed offspring (*M* = 0.56, *SD* = 0.50), *OR* = 0.90, χ^2 (1, *N* = 66) = 0.13, *p* = .721. However, as can be seen in Figure 3, they were more likely to select the light-eyed offspring than the dark-eyed offspring when the parents had light eyes, *OR* = 3.93, χ^2 (1, *N* = 66) = 14.03, *p* < .001, and vice versa when parents had dark eyes, *OR* = 0.19, χ^2 (1, *N* = 66) = 18.79, *p* < .001. Participants were less likely to select the offspring with blended eye colors (*M* = 0.24, *SD* = 0.43) than the dark-eyed offspring, *OR* = 0.12, χ^2 (1, *N* = 66) = 57.50, *p* < .001, and less likely to select the purple-eyed offspring (*M* = 0.06, *SD* = 0.24) than the offspring with blended eye colors, *OR* < 0.01, χ^2 (1, *N* = 66) = 16.89, *p* < .001. These results also suggest that participants have a differentiated probabilistic model, and that they use perceptual similarity to determine the likelihood of each offspring.

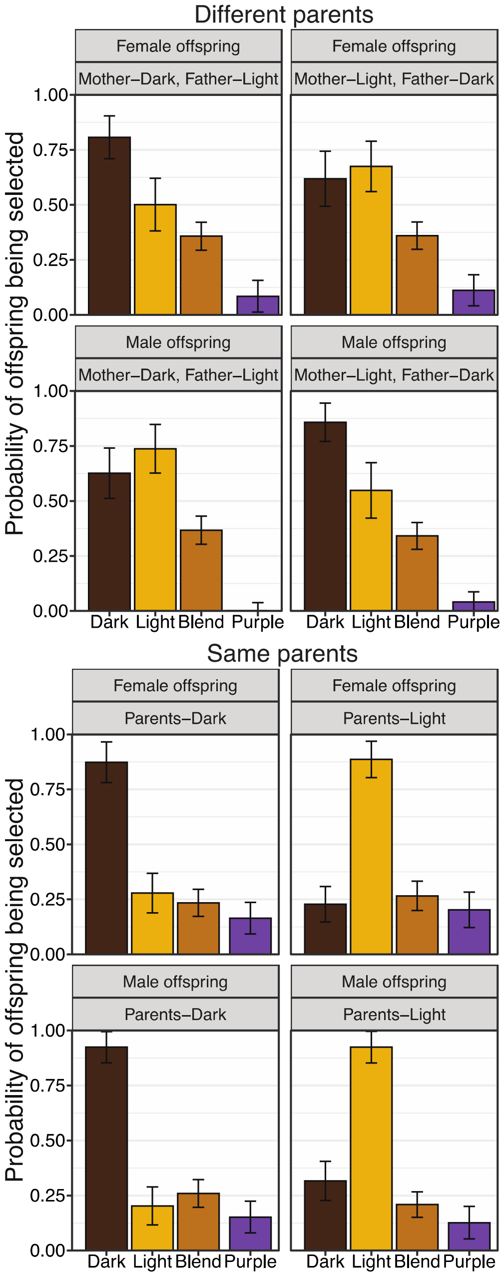

Figure 3. Probability of selecting a particular offspring during the offspring prediction task for Study 1. The top matrix shows the results for trials on which the parents had different eye colors and the

bottom matrix shows the results for trials on which the parents had the same eye color. The left panels show the results for trials on which the mother had dark eyes, and the right panels show the results for trials on which the mother had light eyes. The top panels depict selections for female offspring and the bottom panels depict selections for male offspring. Error bars display the within-subject standard errors using the method described by Morey (2008).

Explanations

In the majority of explanations, participants said that they selected offspring with eyes that matched the parents' eye colors (n = 178, 65.20% of explanations). Of these 178 explanations, 28 indicated that participants attempted to match according to sex (i.e., they selected males that looked like the father and females that looked like the mother). All but one of these sex-match explanations occurred on trials on which the parents had different eye colors (*n* = 27). Participants also sometimes mentioned a desire to mix the phenotypes of the two parents (*n* = 26, 9.52% of explanations). Again, the majority of these explanations occurred on trials on which the parents had different eye colors (*n* = 19). Some participants also mentioned that they thought that males and females would have different eye colors (*n* = 21, 7.69% of explanations). Additionally, some participants stated that they made their decisions randomly (*n* = 18, 6.59% of explanations). Some explanations were coded into multiple categories (*n* = 17, 6.23%). The most common combination involved matching the parents' eye colors for some offspring and mixing the parents' eye colors for other offspring. Finally, regardless of their primary explanation type, 41 participants (15.02%) also mentioned genetic information, such as Punnett squares or dominant or recessive alleles.

Discussion

This study shows that adults have a probabilistic view of genetics, judging multiple offspring options as possible, even when the parents had the same phenotype. Further, performance on the offspring prediction task shows that participants were more likely to select the offspring that looked like the parents than the blended eye color or purple-eyed offspring. Although adults thought many different offspring were possible, they recognized that some offspring were more likely than others, which supports the idea that adults have a differentiated probabilistic model. As predicted, participants were more likely to endorse or select an offspring choice if it had the same phenotype as one of the parents. In line with prior work, when parents had different phenotypes, many participants believed that the offspring would have a combination of the parents' phenotypes (Williams, 2012). However, the particular way in which these phenotypes were combined did not seem to matter. In the offspring prediction task, adults' choices indicated that they believed that the offspring were more likely to have the phenotype of the parent that matched their sex. Participants' explanations also reflected that they intentionally selected offspring so that the offspring resembled the same-sex parent. We saw very little influence of participant major on the results.

In Study 2, we sought to extend these findings to unfamiliar animals. Past research suggests that adults rely on cognitive biases more when thinking about unfamiliar species (French et al., 2018; Shafto & Coley, 2003) or unfamiliar traits (Arenson & Coley, 2018; Eidson & Coley, 2014). Therefore, testing participants with unfamiliar animals could indicate whether the patterns seen in Study 1 are specific to familiar animals or whether they would also be seen in how adults think about eye color inheritance more broadly. Therefore, Study 2 allowed us to examine whether the probabilistic view of genetics is adults' "default" way of thinking about animals, and it enabled us to examine the generalizability of our findings to other types of stimuli. It is particularly important to test for generalizability, given the unexpected finding in Study 1 that some adults thought that offspring would resemble the same-sex parent. Thus, the purpose of Study 2 was to test whether the results from Study 1 would replicate with unfamiliar animals.

Study 2

Method

Participants

We recruited 87 participants from an introductory psychology course at a large Midwestern university (the same university as in Study 1). Eight participants were excluded because they did not pass any of the attention checks. Of the remaining 81 participants, 44 identified as women and 35 identified as men (two did not report gender). Of these 81 participants, 76.5% identified as White or Caucasian (n = 62), 11.1% identified as Asian or Asian American (n = 9), 3.7% identified as Black or African American (n = 3), 3.7% identified as Hispanic or Latinx (n = 3), 2.5% identified as Middle Eastern (n = 2), and 2.5% identified as biracial (n = 2). Thirty-seven participants reported majoring in a biology-related field. On average, participants had taken 1.6 biology courses since the beginning of high school (range: 0-5). No participants reported being color-blind. Participants completed the study for extra credit in their Introduction to Psychology class.

Stimuli

The unfamiliar animals we used were Australian, African, or South American native animals that were not present in local zoos: a mongoose, a cuscus, a kinkajou, and a quoll. For each animal, the parents had one of two eye colors (one light color and one dark color). The possible offspring had dark eyes, light eyes, eyes in-between the light and dark eye colors, one light and one dark eye, or purple eyes. We did not include the inner/outer eye color that we had used in Study 1, as it was the most difficult eye color for participants to detect in the stimuli, and the pattern of results for this item did not differ from either of the other blended phenotypes.

Rather than the stimuli being fully randomized, as in Study 1, we created different orders, with one animal per parent eye color combination (i.e., Dark-Dark, Dark-Light, Light-Dark, and Light-Light).

This guaranteed that all participants saw sets of parents with the same eye color and sets with different eye colors.

Procedure

Participants completed the study online through Qualtrics. The procedure was nearly identical to Study 1. One difference between studies is that participants in Study 2 could have confused the unfamiliar animals depicted in the stimuli with familiar animals (e.g., participants might have thought the kinkajou was a monkey). To reduce this risk, at the outset of the study, participants were shown a drawing of all four animals and were asked to name them. Then, regardless of participants' answers, they were told the name of each animal species. Another difference is that we allowed participants to see their offspring selections for the offspring prediction task while they provided their explanations. We made this change in an effort to elicit more detailed explanations.

Explanation coding

We used the same coding scheme as in Study 1 to examine the content of participants' explanations.

Transparency and Openness

All materials, data and analysis scripts can be found at: https://osf.io/pwbja/.

Results

As in Study 1, we first present the results for the phenotypic judgement task, followed by results for the offspring prediction task, and finally we describe participants' explanations. An individual pattern analysis can be found in the Supplemental materials. To simplify the analysis, we coded whether parents had the *same* eye color (either both light or both dark, coded as -0.5) or *different* eye colors (coded 0.5). As in Study 1, we did not observe differences among the "blended" phenotypes, so we combined these responses into one group, which we refer to as *blend* responses.

Phenotypic judgement task

First, we examined whether participants differed in how many offspring they chose as a function of whether the parents' eye colors were the same or different. This analysis allowed us to see whether participants endorsed a wider range of options when parents had different eye colors compared to when they had the same eye color. We used a linear mixed-effects model to predict the number of offspring that participants endorsed (i.e., said "yes" to) from whether the parents had the same or different eye colors and whether participants majored in a biology-related field. We included by-subject random intercepts and by-subject random slopes for the effect of parents' eye color condition (same or different). As in Study 1, we found that, for unfamiliar animals, participants endorsed more offspring when parents had different eye colors ($M = 3.66$, $SD = 0.89$) than when they had the same eye color ($M = 2.91$, $SD = 1.37$), $b = 0.75$, $F(1, 78) = 43.27$ $p < .001$. There was no effect of majoring in a biology-related field, $b = -0.19$, $F(1, 77) = 1.04$, $p = .310$. As in Study 1, participants endorsed more than one offspring type, even when the parents had the same eye color.

We then examined the specific offspring that participants endorsed. To do so, we fit a generalized linear mixed-effects model with a binomial link function predicting the probability that participants said "yes" to whether each offspring could be the baby of the animal family from offspring type (dark, light, blend, or purple), parent eye color condition (same or different), their interaction, and participant major (biology-related field or not). We also included by-subject random intercepts, and three by-subject random slopes (one for the effect of offspring type, one for the effect of parent eye color condition, and one for their interaction). To examine the effect of offspring eye color, we used non-orthogonal contrasts, with the dark eye color phenotype as the reference category. The first model to converge did not include random intercepts and did not allow the random effects to correlate.

As in Study 1, there was no effect of majoring in a biology-related field, χ^2 (1, N = 79) = 0.22, *p* = .635. As predicted, we found an effect of offspring type, χ^2 (3, N = 79) = 78.03, *p* < .001, which was moderated by an interaction with parent condition, χ^2 (3, N = 79) = 14.66, *p* = .002. As in Study 1, to explore this interaction in more depth, we fit the same model to the same parent eye color trials and the different parent eye color trials separately. For these analyses, we removed parent eye color condition and we included mother/parent eye color (light or dark).

Different parents. In analyzing the different-parent-eye-color trials, we found an effect of offspring type, χ^2 (3, *N* = 79) = 55.93, *p* < .001, but no effect of mother eye color, *OR* = 1.00, χ^2 (1, *N* = 79) < 0.01, *p* > .999, and no interaction, χ^2 (3, *N* = 79) = 0.06, *p* = .96. Thus, participants did not show a mother bias for unfamiliar animals on this task. This is similar to the results of Study 1 with familiar animals for this task. Participants were equally likely to endorse offspring with light (*M* = 0.97, *SD* = 0.16) and dark eye colors (*M* = 0.97, *SD* = 0.16). Participants were more likely to endorse dark-eyed offspring than offspring with blended eye colors (*M* = 0.79, *SD* = 0.41), *OR* > 1000, χ^2 (1, *N* = 79) =14.25, *p* < .001. Finally, participants were less likely to endorse offspring with purple eyes (*M* = 0.13, *SD* = 0.33) than offspring with blended eye colors, OR < 0.01, χ^2 (1, *N* = 79) = 35.25, *p* < .001. See Figure 4. The pattern replicates the results of Study 1 with unfamiliar animals. Adults' endorsements followed a systematic pattern, such that they were most likely to endorse offspring with eye colors that matched the parents' eye colors, followed by offspring with blended eye colors, and finally offspring with the unrelated eye color (purple).

Same parents. We found an effect of offspring type, χ^2 (3, *N* = 79) = 48.64, *p* < .001, an effect of parent eye color, *OR* = 25.44, χ^2 (1, *N* = 79) = 26.20, *p* < .001, and an interaction, χ^2 (3, *N* = 79) = 41.09, *p* < .001. Overall, participants were equally likely to endorse the light-eyed offspring (*M* = 0.76, *SD* = 0.43) and the dark-eyed offspring (*M* = 0.73, *SD* = 0.44), *OR* = 1.61, χ^2 (1, *N* = 79) = 0.64, *p* = .422, but the likelihood of endorsement depended on the eye color of the parents, *OR* < 0.01, χ^2 (1, *N* = 79) = 39.37, *p* < .001. As can be seen in Figure 4, when the parents had light eyes, participants were more likely to endorse the light-eyed offspring than the dark-eyed offspring, and vice versa when the parents had dark eyes. Participants were more likely to endorse the dark-eyed offspring than the offspring with blended eye colors (*M* = 0.64, *SD* = 0.48), *OR* > 1000, χ^2 (1, *N* = 79) = 14.25, *p* < .001, and less likely to endorse the purple-eyed offspring (*M* = 0.14, *SD* = 0.35) than the offspring with blended eye colors, *OR* < 0.001 , χ^2 (1, *N* = 79) = 35.25, *p* < .001. This pattern replicates the findings of Study 1 with unfamiliar animals, in that participants' endorsements aligned with the degree of perceptual similarity between the parents' and offspring's eye colors.

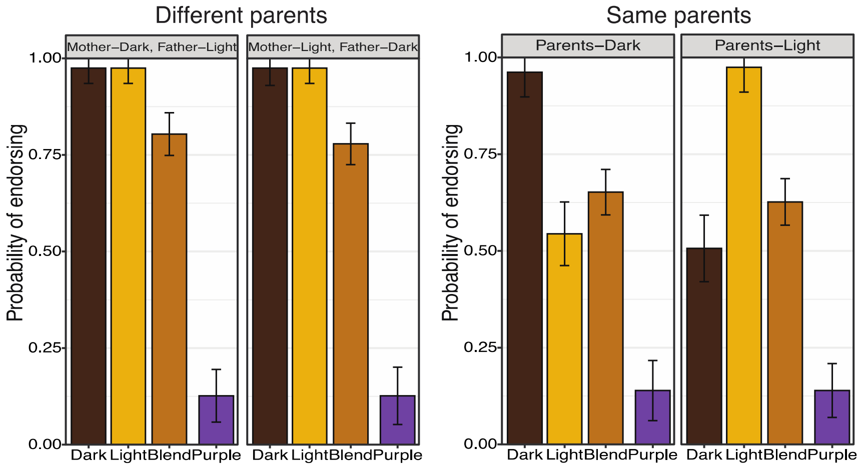

Figure 4. Probability of endorsing that a particular offspring could be the baby of the two parents in the phenotypic judgement task for Study 2. The left panels show the results for trials on which the parents had different eye colors and the right panels show the results for trials on which the parents had the same eye color. Error bars display the within-subject standard errors using the method described in Morey (2008).

Offspring prediction task

For the offspring prediction task, we first examined how many different offspring phenotypes participants chose. To do this, we looked at how many different offspring options participants chose for the male and the female offspring. We used a linear mixed-effects model to predict the number of different offspring choices that participants selected (with a maximum of three, because the parents had three offspring of each sex). As predictors, we included offspring sex, parent eye color condition (same or different), their interaction, and whether participants majored in a biology-related field. We included by-subject random intercepts and three by-subject random slopes (one for each effect). This model did not converge, so we removed the covariances between the random effects. As in Study 1, we found only an effect of parent eye color condition, $b = 0.45$, $F(1, 78) = 37.23$, $p < .001$. When parents had the same eye color ($M = 1.80$, $SD = 0.85$), participants chose fewer offspring options compared to when the parents had different eye colors ($M = 2.25$, $SD = 0.79$). In addition, as in Study 1, even when unfamiliar animal parents had the same eye color, participants tended to choose more than one offspring type.

To analyze participants' choices for the offspring prediction task, we examined the set of options participants chose. We fit a generalized linear mixed-effects model with a binomial link function predicting the probability of selecting an offspring from offspring type (dark, light, blend, or purple eyes), parent eye color condition (same or different), their interaction, and whether participants majored in a biology-related field. We also included by-subject random intercepts and by-subject random slopes for the effect of offspring type (one for each dummy code), the effect of parent condition, and their interaction (one for each dummy code).

We found effects of offspring type, χ^2 $(3, N = 79) = 130.61$, $p < .001$, and parent eye color condition, $OR = 1.74$, χ^2 $(1, N = 79) = 8.59$, $p = .003$, but no interaction, χ^2 $(3, N = 79) = 1.69$, $p = .638$. Unlike Study 1, there was no effect of majoring in a biology-related field, $OR = 0.84$, χ^2 $(1, N = 79) =$

1.20, $p = .273$. As in Study 1, we examined participants' selections for the different-parent-eye-color and same-parent-eye-color trials separately. We fit a similar model as the one described above, but we removed parent eye color condition and included offspring sex (male or female) and mother eye color (light or dark). In each case, the first model to converge had by-subject random slopes for the effects of offspring type, mother eye color, offspring sex, and all the respective interactions.

Different parents. In the different-parent-eye-color trials, we found an effect of offspring type, χ^2 (3, $N = 79$) = 223.07, $p < .001$, that was qualified by a three-way interaction with mother eye color and offspring sex, χ^2 (3, $N = 79$) = 71.39, $p < .001$. Overall, participants were more likely to select the dark-eyed offspring ($M = 0.71$, $SD = 0.45$) than the light-eyed offspring ($M = 0.67$, $SD = 0.47$), OR = 143.67, χ^2 (1, N = 79) = 27.19, $p < .001$. However, as can be seen in Figure 5, participants were more likely to select the dark-eyed than the light-eyed offspring for males when the father had dark eyes, and more likely to select the dark-eyed than the light-eyed offspring for females when the mother had dark eyes (and vice versa when the same-sex parent had light eyes), $OR < 0.01$, χ^2 (1, $N = 79$) = 54.93, $p < .001$. Additionally, participants were less likely to select the offspring with blended eye colors (M = 0.31, $SD = 0.46$) than the dark-eyed offspring, $OR = 0.14$, χ^2 (1, $N = 79$) = 101.46, $p < .001$. Participants were also less likely to select the purple-eyed offspring ($M = 0.24$, $SD = 0.43$) than the offspring with blended eye colors, $OR < 0.01$, χ^2 (1, $N = 79$) = 75.72, $p < .001$. These results replicate those of Study 1 but with unfamiliar animals, and they show that adults tend to select offspring they believe are more likely, suggesting a differentiated probabilistic model. These results also replicate the same-sex bias shown in Study 1, and they show that this bias extends to unfamiliar animals.

Same parents. In the same-parent-eye-color trials, we found an effect of offspring type, χ^2 (3, N = 79) = 103.00, $p < .001$. There was no main effect of parent eye color, OR =1.07, χ^2 (1, $N = 79$) = 0.11, $p = .742$, but there was an interaction between offspring type and parent eye color, χ^2 (3, $N = 79$) =

95.15, $p < .001$. Overall, we found that participants were equally likely to select the light-eyed offspring ($M = 0.57$, $SD = 0.50$) and the dark-eyed offspring ($M = 0.59$, $SD = 0.49$), $OR = 1.18$, χ^2 (1, $N = 79$) = 0.28, $p = .597$. However, as can be seen in Figure 5, they were more likely to select the light-eyed than the dark-eyed offspring when the parents had light eyes, $OR = 26.32$, χ^2 (1, $N = 79$) = 98.06, $p < .001$, and vice versa when the parents had dark eyes, $OR = 0.02$, χ^2 (1, $N = 79$) = 101.98, $p < .001$. Participants were also less likely to select the offspring with blended eye colors ($M = 0.24$, $SD = 0.43$) than the dark-eyed offspring, $OR = 0.13$, χ^2 (1, $N = 79$) = 69.40, $p < .001$, and less likely to select the purple-eyed offspring ($M = 0.16$, $SD = 0.37$) than the offspring with blended eye colors, $OR = 0.01$, χ^2 (1, $N = 79$) = 12.00, $p < .001$. Therefore, as in Study 1, the pattern of data suggests that participants used a differentiated probabilistic model, and that they used perceptual similarity to determine the likelihood of each offspring.

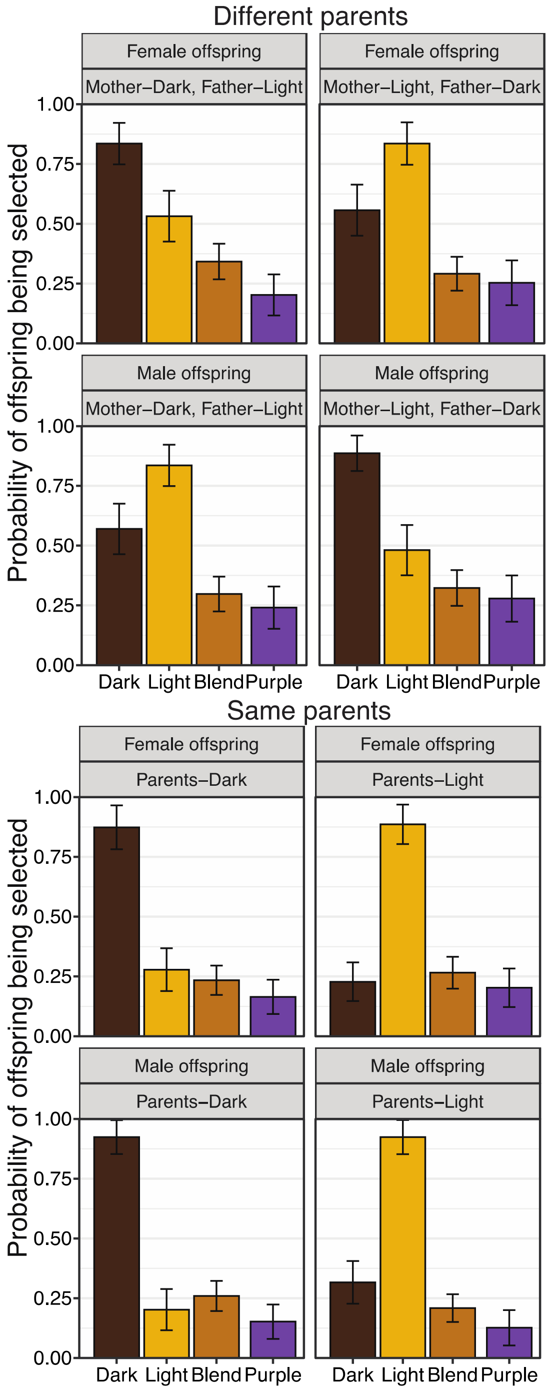

Figure 5. Probability of selecting a particular offspring during the offspring prediction task for Study 2. The top matrix shows the results for trials on which the parents had different eye colors and the bottom matrix shows the results for trials on which the parents had the same eye color. The left panels show the results for trials on which the mother had dark eyes, and the right panels show the results for trials on which the mother had light eyes. The top panels depict selections of female offspring and the

bottom panels depict selections of male offspring. Error bars display the within-subject standard errors using the method described in Morey (2008).

Explanations

As in Study 1, in the majority of explanations, participants stated that they selected the offspring to match the parents' eye colors (*n* = 185, 59.7% of explanations). Of these 185 explanations, 28 indicated that participants attempted to match according to sex (i.e., they selected male offspring that looked like the father and female offspring that looked like the mother). Nearly all of these sex-match explanations occurred on trials on which parents had different eye colors (*n* = 26). Participants also frequently mentioned a desire to mix the phenotypes of the two parents (*n* = 62, 20.0% of explanations). Again, many of these explanations occurred on trials on which the parents had different eye colors (*n* = 49). Notably, the proportion of mix explanations in Study 2 (20%) was more than double the proportion of mix explanations in Study 1 (9.4%). Some participants also mentioned that they thought that male and female offspring would have different eye colors (*n* = 39, 12.6% of explanations). Additionally, some participants stated that they made their decisions randomly (*n* = 5, 1.6% of explanations). Many more explanations were coded into multiple categories in Study 2 (15.5%, *n* = 48) than in Study 1 (6.5%). As in Study 1, the most common combination involved matching the parents' eye colors for some offspring and mixing the parents' eye colors for other offspring. Finally, regardless of their primary explanation category, 73 explanations (23.5%) mentioned genetic information, such as Punnett squares or dominant or recessive alleles.

Discussion

Overall, the results of Study 2 were very similar to those of Study 1, suggesting that adults have a differentiated probabilistic view of genetics that they use to reason generally about the genetic inheritance of eye color—for familiar and unfamiliar animals. Participants tended to select offspring that looked like the parents, but they also accepted offspring that looked slightly different. Once again, we saw that, when the parents had different eye colors, participants thought that the offspring were more likely to have the eye color of the same-sex parent (i.e., the females would have the mother's phenotype, and the males would have the father's phenotype). Participants' responses also did not depend on whether they were majoring in a biology-related field.

General Discussion

Our findings suggest that adults have a differentiated probabilistic view of genetics. In the phenotypic judgement task, participants judged many different offspring as possible, showing that they understood that genetic inheritance can lead to variability across offspring. This was the case, even when parents had the same eye color, suggesting that they believed animals have some genetic information that they do not express. In the offspring prediction task, participants were more likely to select offspring that looked like the parents, suggesting that adults differentiate between offspring they think are likely and offspring they think are possible but unlikely. We showed that adults used this differentiated probabilistic model for both familiar and unfamiliar animal species, suggesting that this view is used broadly when reasoning about eye color inheritance.

We also found evidence of two misconceptions: a perceptual similarity bias and a same-sex bias. When parents had the same eye color, participants were biased to think that eye colors that were similar to the parents' eye colors were more likely. Although intuitive, basing likelihoods on perceptual similarity is not always accurate. More problematic is our finding that many participants thought offspring were more likely to have the phenotype of their same-sex parent. This tendency was pervasive, as participants displayed it with both familiar and unfamiliar animals, and some participants explicitly stated it in their explanations. Given that many of our participants had received formal instruction in biology, our results suggest that this misconception might not be easily corrected through current instructional practices but might need to be specifically targeted.

Theoretical implications

By using novel methods to assess adults' beliefs about genetic inheritance, our studies present a different view of genetic inheritance than that presented in past research. Prior work found that adolescents believe that offspring would have a combination of the parents' phenotypes (Williams, 2012). However, by allowing participants to select more than one offspring, we found that participants endorsed the offspring that had the same phenotypes as one of the parents more often than the offspring that combined the parents' phenotypes. This suggests that prior work on children's understanding of genetics might not be representative of what children think is possible in the domain of genetics. Instead, like the adults in our studies, children might understand that multiple different-looking offspring are possible.

Our studies also revealed novel biases that have not been previously reported in the literature. Contrary to prior literature, adults endorsed the offspring that matched each parent at very high rates, showing no overall preference for the mother's phenotype (a tendency displayed by children in prior studies, Johnson & Solomon, 1997; Terwogt et al., 2003). At the same time, we did find that many adults tended to select male offspring that had the same eye color as the father and female offspring that had the same eye color as the mother (see pattern analysis in the Supplemental materials. We also saw this pattern in participants' explanations, as some participants mentioned selecting offspring that resembled the same-sex parent, suggesting that this response pattern is intentional and reflects how many adults think about inheritance. To our knowledge, this is the first study to show adults using a sex-matching strategy in making judgements about genetic inheritance. The prediction that offspring will resemble their same-sex parent more than their opposite-sex parent is not always correct—in fact, it is only correct for sexually dimorphic species and sex-linked traits. Although certain traits are sex-linked and sexual dimorphism is present in many animals, it is important to highlight that eye color is not sex-linked for any of the species included in this study, nor is it sex-linked in humans. Therefore, there was little reason for adults to assume that eye color was a sex-linked trait in this study. Instead, sex-match responses might be due to a misconception that the same-sex parent contributes more of the genetic material. Sex-match responses could also be based on the belief that males and females should look different from one another (Taylor, Rhodes, & Gelman, 2008). Future work should examine whether children also show this bias and should examine the reasoning behind adults' tendency to sex-match.

Our findings suggest that adults have a synthetic model of genetic inheritance that combines scientific and intuitive theories (see, e.g., Evans & Rosengren, 2018). Our studies suggest that, regardless of college major, adults hold a differentiated probabilistic model, such that they think that many offspring are possible, and some are more likely than others. However, they also show biases in how they decide which phenotypes are more likely. When parents had the same eye color, they based their judgements on perceptual similarity. When parents had different eye colors, they believed that the mother's phenotype was more likely for females and the father's phenotype was more likely for males.

Integrating our studies with prior literature suggests a possible developmental progression for concepts of genetic inheritance. Prior work with preschoolers suggests that they have a deterministic model, such that they believe that offspring will look like their mothers (Springer, 1996). Then, between the ages of 7 and 10, children begin to understand that offspring do not have to look like their mothers (Williams, 2012), which might signal the emergence of a probabilistic model, in which children believe that many offspring are possible. By adulthood, people recognize that different phenotypes have different likelihoods of occurring, but their reasoning about the differences in likelihoods might not always be scientifically accurate, as we have shown here. Future research should examine how children respond to the phenotypic judgement task and offspring prediction task with both familiar and unfamiliar animals, to yield further insight into the developmental progression of understanding of genetic inheritance.

The idea that adults have a probabilistic view of genetics could suggest that adults do not rely on essentialist thinking as often as previously thought. Essentialist reasoning would bias people towards a deterministic view of genetics (Dar-Nimrod & Heine, 2011). It may be that people still rely on essentialism when reasoning about genetics under time pressure or when reasoning about novel traits (Arenson & Coley, 2018; Eidson & Coley, 2014), but our study shows that essentialism had little influence on adults' thinking about eye color, even for unfamiliar animals. This is surprising, as past work suggests that adults often combine genetic and essentialist reasoning (Dar-Nimrod & Heine, 2011). Contrary to essentialist views, our participants thought that offspring could look different from their parents, even when the parents had the same phenotype, and some justified this idea by talking about recessive genes—thus acknowledging that the genotype contains information not expressed in the phenotype. The idea that there could be a part of the genetic code (or essence) that does not influence an organism's properties is contrary to simple essentialist beliefs. Further research is needed to examine how people understand the relation between genotype and phenotype.

Practical implications

Our studies have implications for how genetics instruction for secondary and undergraduate students should be designed. We found that, even though most adults in our sample had received formal instruction on genetics, many still held misconceptions. It is possible that these misconceptions could be corrected by explicitly addressing them in lessons. For example, lessons could focus on directly on the relations between genotype and phenotype and on the implications for perceptual similarity and sex matching. However, it may be challenging to design lessons to address the sex match bias, given that some traits are in fact sexually dimorphic. Future research is needed to examine what sorts of instructional activities can help learners reason more appropriately about traits that are sexually dimorphic and traits that are not.

Our studies also have implications for adults' understanding of biological variability. The idea that animals of the same species can look different from one another is critical in biology education (Batzli et al., 2016; Walck-Shannon et al., 2019). In particular, the concept of within-species variability is fundamental for understanding evolution through natural selection (Shtulman & Schulz, 2008). However, it has been documented that people, especially children, struggle to understand within-species variability (Emmons & Kelemen, 2015; Gelman & Rhodes, 2012). We found that adults are more accepting of within-species variability than previously believed, as they accepted that offspring can look different from their parents. However, our studies also suggest that adults think these differences must be small. When parents had the same eye color, adults judged offspring based on perceptual similarity to the parents' eye color. Specifically, they were most likely to endorse offspring with the eye color that was a perfect match, followed by offspring with blended eye colors, then offspring with the alternative eye color, and finally offspring with purple eyes. The idea that the scope of biological variation is relatively small aligns with prior research on adults' endorsement of life cycle changes (French et al., 2018; Menendez et al., 2020). Therefore, although adults might be more open to variability than previously believed, instruction should emphasize that these differences between organisms of the same species are not always subtle.

We also found that, for both familiar and unfamiliar animals, when parents had different eye colors, participants were more likely to select the offspring with the darker eye color than the offspring with the lighter eye color. It is possible that participants held a dark-is-dominant bias such that they assumed that the darker eye color was more likely to be a dominant phenotype. Indeed, some participants expressed this idea in their explanations. For example, a biology major in Study 1 wrote, "I selected the majority to have black eyes because I believe that is the dominant eye color in this pairing." This was also seen with the unfamiliar animals in Study 2, as a non-biology major wrote, "The dominant color would be the dark brown." This assumption could be due to darker colors, such as brown eyes, often being used as examples for dominant phenotypes in genetics instruction. This assumption could also come from visual biases that darker colors represent greater quantities (Schloss et al., 2019), but more work is needed to identify the root of this assumption. Regardless of its origin, instruction on genetics should use a variety of examples (including ones in which dark colors are not dominant) to prevent this assumption.

Our studies suggest that genetics instruction should highlight that the phenotype of the offspring does not have to be similar to that of the parents, if they have alleles that lead them to be dissimilar. Additionally, genetics instruction should stress that parents contribute the same amount of genetic material to all offspring and that offspring can resemble either of their parents. It is also possible that including this type of genetics instruction in earlier grades might help correct misconceptions before they become entrenched (Kelemen, 2019). Therefore, we suggest that genetics instructors should be aware of the common misconceptions that people hold, in order to tailor their instruction appropriately.

Limitations

It is also important to highlight some limitations of this work. First, because these studies were conducted online, we had no control over the screen size or the screen settings that participants used. Some of the animals had fairly small eyes, so it is possible that some participants did not notice the differences between the offspring possibilities. However, participants' responses in the identification task suggest that they were able to discriminate among the offspring and to discern how their eye colors mapped to the parents' eye colors.

Second, our study considered only eye color. Participants might make different judgements about other traits, such as fur color or even psychological traits. In our studies we focused on physical traits, as they tend to be the focus of genetics instruction in schools and participants can reasonably assume that they are genetically inherited. Prior research has suggested that children treat physical and psychological traits, such as extraversion, similarly (Johnson & Solomon, 1997; Williams, 2012). However, future studies should examine how characteristics of the traits influence people's judgements.

Third, it is possible that our results were due to participants thinking that eye color is a superfluous trait. Prior work that has examined how people think about biological kinds suggests that people expect less variation in traits that are internal to the animal and traits that have a specific function (Emmons & Kelemen, 2015). It is possible that if we had used a different type of physical trait or if we had told participants that eye color had a particular function, then participants may have been less likely to think that the offspring could look different from the parents. However, other aspects of our results might not change with the functionality of the trait. For example, participants' bias to match the offspring's trait to the same-sex parent might not be influenced by whether the trait is functional or not. Future research is needed to test this possibility.

Finally, our study sample was made up of undergraduate students in the United States, and the participants were primarily White and primarily young adults. It is unclear how these results would generalize to other age groups or cultural groups or to adults with differing levels of formal schooling. However, the fact that nearly all of our participants had had some formal biology instruction makes it even more surprising that we found consistent misconceptions across our studies.

Conclusions

Our findings provide important new information about adults' understanding of genetic inheritance. We showed that adults have a probabilistic view of genetic inheritance, both for familiar and unfamiliar animals. Additionally, we discovered previously unattested patterns in adults' performance. In particular, when the sex of the offspring was not specified, adults matched offspring traits to either parent's phenotype. When the offspring's sex was specified, they often matched the offspring's phenotype to the same sex parent's phenotype. This new information regarding adults' beliefs about genetic inheritance provides developmental psychologists with new information about the developmental endpoint for reasoning about genetic inheritance among U.S. primarily White college-educated adults. Our results provide a nuanced picture of people's understanding of genetic inheritance, revealing new misconceptions and areas of strength that can inform both psychological theory and curriculum development.

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