Title

Deterministic or probabilistic: U.S. children's beliefs about genetic inheritance

Permalink
https://escholarship.org/uc/item/72p957wh

Authors

Menendez, David
Donovan, Andrea Marquardt
Mathiaparanam, Olympia N
et al.

Publication Date
2024-01-03

DOI
10.1111/cdev.14053

Deterministic or probabilistic: U.S. children's beliefs about genetic inheritance

David Menendez[1*]

Andrea Marquardt Donovan[2]

Olympia N. Mathiaparanam[3]

Vienne Seitz[2]

Nour F. Sabbagh[2]

Rebecca E. Klapper[3]

Charles W. Kalish[2]

Karl S. Rosengren[3]

Martha W. Alibali[2]

[1]University of California-Santa Cruz

[2]University of Wisconsin-Madison

[3]University of Rochester

[*]Corresponding author

Acknowledgements

The research reported here was supported by the Institute of Education Sciences, U.S. Department of Education, through Award #R305B150003 to the University of Wisconsin-Madison. This research was also supported by a grant from the National Science Foundation (#1760940). The opinions expressed are those of the authors and do not represent views of the U.S. Department of Education or the National Science Foundation. The analyses presented here

were preregistered; The pre-registration for Study 1 can be found in here: https://osf.io/2kc3w/?view_only=00156e7728aa42a2979f6e0aa43dc0b5 and for Study 2 here: https://osf.io/ncszr/?view_only=12bd45bf7f31451ebaeac457c8c9049f. The data, analyses, and materials necessary to reproduce the analyses presented here are publicly accessible in OSF: https://osf.io/g74pa/?view_only=5270d8b6d6234580b3d9767b79a4b88a for Study 1 and https://osf.io/h74de/?view_only=3d252390c86f4a15a7ccfe1602299e37 for Study 2.

Abstract (120 words/120)

Do children think of genetic inheritance as deterministic or probabilistic? In two novel tasks, children viewed the eye colors of animal parents and judged and selected possible phenotypes of offspring. Across three studies (*N* = 353, 162 girls, 172 boys, 2 non-binary; 17 did not report gender) with predominantly White U.S. participants collected in 2019-2021, 4- to 12-year-old children showed a probabilistic understanding of genetic inheritance, and they accepted and expected variability in the genetic inheritance of eye color. Children did not show a mother bias but they did show two novel biases: perceptual similarity and sex-matching. These results held for unfamiliar animals and several physical traits (e.g., eye color, ear size, and fin type), and persisted after a lesson.

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

Deterministic or probabilistic: U.S. children's beliefs about genetic inheritance

From early elementary school, children are expected to understand that offspring will resemble, but not look exactly like, their biological parents (NGSS, 2012). In other words, children must understand that genetic inheritance is a probabilistic process that influences how organisms look and that can lead to variability among offspring as well as differences between parents and offspring. This understanding is critical for science learning, as it provides the foundation for comprehending more complex phenomena, such as within-species variation and natural selection. However, even before formal science instruction, children have naïve intuitions about inheritance (Gelman & Markman, 1987; Wellman & Gelman, 1992). Prior work has examined children's judgements of which characteristics are inherited (Johnson & Solomon, 1997; Springer, 1996; Springer & Keil, 1989) and their beliefs about how offspring will look (Terwogt et al., 2003; Williams, 2012; Williams & Smith, 2006). However, prior work has not assessed whether children's intuitive theories are probabilistic or deterministic, or whether they allow variability between parents and offspring, two aspects of such theories that might influence later genetics learning. In this paper, we examine children's thinking about inheritance and about variation between parents and offspring.

Prior literature has identified traits that children believe are inherited versus acquired. These beliefs have been measured with the *switched-at-birth* task (Springer & Keil, 1989), in which participants are asked whether an offspring raised by adoptive parents would resemble the biological or the adoptive parents. The traits in question are either genetically-based traits (e.g., height, eye color, genetic disorders) or acquired traits (e.g., language spoken, beliefs, preferences). Preschool children believe that offspring will resemble biological parents in genetically-based traits and adopted parents in acquired traits, and they differentiate between these types of traits more strongly with age (Solomon et al., 1996; Springer, 1996). Thus, children think of different types of traits as being obtained through different causal processes (e.g., *learning* for acquired traits versus *inheritance* for genetic traits). However, these studies tell us little about how children think about genetic inheritance or about variation between biological parents and offspring.

One task that has been used to assess children's understanding of biological inheritance is the *phenotypic difference* task (see Terwogt et al., 2003). In this task, children are shown two parents with different phenotypes (e.g., different eye colors), followed by multiple potential offspring with different phenotypes. Children are then asked to choose the offspring they expect the parents will have. Children choose among offspring that resemble the mother, the father, both (combined phenotype), or neither (unrelated phenotype). Before age 7, children display a *mother bias*, tending to choose offspring with the mother's phenotype, while older children tend to choose offspring that combine the parents' phenotypes (Terwogt et al., 2003; Williams, 2012).

Although the phenotypic difference task reveals biases in reasoning about biological inheritance, it is limited in how much it can reveal about children's acceptance of variability. In this task, children can choose only one offspring, even if they think that many offspring are possible. Thus, there are multiple possible interpretations of children's responses.

The interpretation offered in prior literature is that children's choices represent *the only offspring* they think is possible, which implies that children do not expect variability between parents and offspring. Based on this interpretation, some researchers have suggested that children have a deterministic model of inheritance, such that all offspring of a given set of parents must look a specific way (e.g., Johnson & Solomon, 1997). A deterministic model of inheritance is prescriptive and holds that there is only one possible phenotype for the offspring of a given set of parents. Other researchers have suggested that a deterministic concept of inheritance might be related to cognitive biases such as psychological essentialism (Gelman, 2003; Medin & Ortony, 1989). Note that holding a deterministic model is not the same as understanding that genotypes in part determine an organism's phenotype. Scientific models of inheritance incorporate the idea that an organism's genotype is shaped by a probabilistic process involving random dividing and recombination of parental DNA, an idea that is likely missing from children's intuitive theories, as they do not often reference genes (Solomon et al., 1996).

Alternatively, children's responses in the phenotypic difference task might represent *the most likely offspring*, as children may believe there could be variability between parents and offspring, but because they can choose only one offspring, they select the one they think is most likely. This interpretation suggests that children may have an intuitive understanding of the *probabilistic* nature of inheritance. A probabilistic model of inheritance maintains that genes determine the phenotype of animal but incorporates probabilistic elements by saying that there are many possible outcomes, depending on the genetic information the offspring inherited.

One way to distinguish between these alternative interpretations would be to allow children to endorse or reject a number of different offspring choices. If children endorse only one type of offspring, it would suggest that they hold a deterministic view of inheritance and expect homogeneity. If children endorse multiple offspring, it would suggest that they have a probabilistic view and accept (or even expect) variability between parents and offspring.

Prior work suggests that children may hold a deterministic view and accept only one offspring phenotype as possible. Many children believe that offspring look like smaller replicas of their parents (French et al., 2018). Further, the existence of the mother bias implies that many children think offspring can only look like their mothers (Terwogt et al., 2003). The mother bias is especially prevalent in younger children (French et al., 2018; Terwogt et al., 2003), suggesting that younger children may be especially likely to hold a deterministic view. Further, children have a strong essentialist bias, which can lead them to assume that all members of a species have the same phenotype (Gelman, 2003). This essentialist bias varies by trait and decreases with age (Taylor et al., 2009), and it is reinforced in the language used by parents (Rhodes et al., 2012), teachers (Betz et al., 2019), children's books (Gelman et al., 2013) and even curricular materials, such as science textbooks (Donovan, 2014; Jamieson & Radick, 2017). These factors might lead children to expect homogeneity among organisms of the same species, and thus expect little or no variation between parents and offspring.

It is also possible that children think that variability is possible and thus might have a probabilistic view of inheritance. Previous work shows that children accept that members of the same species can look different from one another, especially when considering superfluous traits (Emmons & Kelemen, 2015). Additionally, people rely on cognitive biases, such as essentialism, less when reasoning about familiar animals (French et al., 2018) or familiar traits (Eidson & Coley, 2014). Finally, 10- to 12-year-olds are less likely to engage in essentialist reasoning or to have a mother bias than younger children (French et al., 2018; Taylor et al., 2009; Terwogt et al., 2003), suggesting that older children might be more likely to hold a probabilistic model. Older children are also more likely to have received formal instruction on genetics, which could influence their naïve theories of inheritance (Donovan et al., 2021; Solomon & Johnson, 2000; Venville & Donovan, 2007). Based on these findings, one might expect that, at least when reasoning about familiar animals and familiar traits, children—especially older children—might accept that offspring can look different from each other.

The classic phenotypic difference task shows that variation is possible, as it displays parents that have different phenotypes. When parents have different phenotypes, children might be willing to accept more possible offspring, because the offspring could look like either parent or have a combination of the parents' phenotypes. However, when both parents have the same phenotype, it may be more challenging for children to believe that variation is possible. Trials on which the parents have the same phenotype thus provide evidence of the robustness of children's acceptance of variability—that is, whether children believe that offspring can look different from their parents, even when the parents show no variation.

Genetics knowledge

The goal of this research was to characterize children's intuitive theories about genetic inheritance. We consider the possibility that children may combine intuitive theories with aspects of the scientific theory of genetics, as they do for some other scientific concepts (Legare et al., 2012).

In the United States, the earliest that genetics is taught is in the fifth grade; therefore, most research on genetics understanding has focused on adolescents (e.g., Donovan et al., 2021). Thus, little research has addressed possible relations between children's intuitive and scientific theories of inheritance. Although instruction on different aspects of genetics can lead to changes in children's theories (Solomon & Johnson, 2000; Venville & Donovan, 2007), there has been little consideration of how children's intuitive theories might support (or inhibit) their learning of scientific theory. For example, understanding that parents and offspring can be different might help children make sense of the concept of genetic mutations.

Children are also exposed to information about genetics outside of formal schooling. Cultural messages around genes are pervasive (Nelkin & Lindee, 2010) and parents sometimes discuss genetic concepts with their children (Shtulman et al., 2020). Therefore, children might know and use words related to genetics before they learn their scientific meanings, and they might sometimes use them incorrectly (Smith & Williams, 2007; Venville et al., 2005). Therefore, we also examined whether children incorporate genetic terms into their reasoning.

The role of instruction in genetics learning

Genetics instruction typically occurs in middle and high school. Although most students receive genetics instruction, many children struggle to understand the material (Lewis et al., 2000; Venville & Donovan, 2007). Many students have misconceptions about the relations among genes, proteins, and phenotypes (Stern & Kampourakis, 2017), and these misconceptions often persist after instruction (Thomas, 2000). Traditional genetics instruction may also promote essentialist views (Stern & Kampourakis, 2017; Thomas, 2000). Given these challenges, new learning progressions have been proposed (Duncan et al., 2009) that emphasize that all organisms have genetic information in their cells that contains instructions for the structure of proteins, proteins connect genes to traits, and organisms transfer their genetic information to the next generation. This learning progression also emphasizes that genes and traits are correlated, and certain patterns are more likely than others to occur, but the environment may affect how genetic information is expressed. Recent educational interventions, such as the Humane Genomics Intervention, have shown that children in middle and high school and adults do revise their beliefs and misconceptions about genetics in response to instruction (Donovan et al., 2021). Interventions for younger children are often much more simple, focusing on the causal role of genes (Solomon & Johnson, 2000; Venville & Donovan, 2007).

Many genetics lessons use visual representations, such as media (Solomon & Johnson, 2000), manipulatives (Venville & Donovan, 2007), or diagrams, such as pedigree diagrams (Mathiaparanam et al., 2022). Visual representations have been found to promote learning of science concepts (Mayer, 2009); however their effectiveness depends on many factors, including their perceptual features (Rey, 2012). Perceptually rich visualizations (e.g., realistic images) often help students learn the information presented in the lesson, but might not help them generalize to other material (Rey, 2012; Skulmowski, 2023). In contrast, perceptually bland representations (e.g., images that are more schematic), often promote generalization by conveying that the information in the lesson extends beyond the specific exemplar used in the lesson (Menendez, 2023; Menendez et al., 2020). Therefore, it is possible that teaching children about genetics using bland visual representations might promote generalization beyond the exemplars used in the lesson.

In the present paper, we are interested in how receiving additional knowledge about genetic inheritance influences children's models of inheritance, and whether it might lead them to revise their beliefs for the specific trait mentioned in the lesson, and also more broadly for other traits that were not mentioned. To address this goal, we gave a brief lesson to children about genetic inheritance in eye color, and then examined how they thought about genetic inheritance, not only for eye color, but also for ear size and fin type. This tested whether learning about one trait would generalize to other traits, and it also probes whether children can revise their models of genetic inheritance.

Current studies

In the current studies, we used two novel tasks to characterize children's intuitive theories about inheritance, the *phenotypic judgement task* and the *offspring prediction task*. Preliminary studies with these tasks with adults have shown that adults expect variability between parents and offspring (Authors, YEAR). These tasks are modeled after the phenotypic difference task, but they allow participants to endorse or select more than one offspring.

In the *phenotypic judgement task*, children see drawings of two animal parents that have either the same or different phenotypes. They are then shown many offspring choices, one at a time, and asked if they think each is a *possible* offspring of that parent pair. This task allows us to examine whether children think that only one option is possible (a deterministic model) or many options are possible (a probabilistic model). This task also allows us to examine which options children think are possible and how these judgements change depending on characteristics of the parents. We used this task in Studies 1 and 2.

In the *offspring prediction task*, children are shown a parent pair, and they are asked to predict phenotypes for six offspring. Children can select multiple offspring of a given type; thus, this task can reveal which offspring children think are most likely. Children were also asked to explain their answers, and their explanations allowed us to assess whether they integrated aspects of genetic theory into their intuitive theories. We used this task in Studies 1B and 2.

In both tasks, we varied the eye colors of the parents. Eye color is not caused by variation in a single gene, but rather it is a polygenic trait (White & Rabago-Smith, 2011). Eye color has been used in prior studies assessing children's understanding of inheritance (e.g., Springer & Keil, 1989; Williams, 2012) and is familiar to children. Parent pairs had either the same eye color (i.e., both light-colored or both dark-colored eyes) or different eye colors (i.e., one parent with light-colored eyes and one with dark-colored eyes). The offspring choices had either light-colored eyes, dark-colored eyes, an eye color in between the light and dark eye colors, one dark-colored eye and one light-colored eye, or purple eyes (a color unrelated to both parents). We included both familiar and unfamiliar animals, as prior research suggests familiarity might influence children's beliefs (French et al., 2018).

In Study 2, we also examined how children reason about other physical traits (i.e., ear size and fin type), and whether these beliefs change after a lesson. We presented students with a short lesson about genetics using wolf families as examples. The lesson stated that: (1) all organisms have genetic information, (2) this genetic information is in their cells, (3) this genetic information determines how an organism will look, (4) parents pass genetic information to their offspring, (5) an offspring gets half of their genetic material from each parent, and (6) the offspring may resemble either parent or could look different from either parent. These topics have been proposed as key topics in learning progressions for genetics (Duncan et al., 2009). We then presented children with several examples of wolves with various eye colors. We presented these examples using pedigree diagrams, which are common in educational materials for genetics (Mathiaparanam et al., 2022). Students received the lesson with either a perceptually rich or a perceptually bland diagram, so that we could determine whether children generalized more if they saw the bland diagram.

Study 1

We hypothesized that children would judge more offspring as possible when parents had different eye colors than when parents had the same eye color. We also hypothesized that children would endorse the offspring that had the same eye color as the parents more frequently and would endorse the offspring with purple eyes less frequently. Finally, we hypothesized that children would endorse offspring with blended eye colors (i.e., offspring with the eye color in-between the light and dark eye colors, and offspring with one dark-colored eye and one light-colored eye) more frequently when parents had different eye colors. We did not have a specific hypothesis about animal familiarity, because eye color is a familiar trait.

Method

Participants

The target sample size was determined with a power analysis based on prior work by Williams (2012), which reported an effect of offspring type of $\chi^2(N = 182) = 21.1$ (converted into R^2 using an online calculator), indicating that participants selected different offspring options at different rates and exhibited a mother bias. We used modelPower in R which indicated a minimum sample size of 63 participants to detect an effect of offspring type of comparable size with 80% power. Given differences in our design, we decided to oversample and aimed to collect 90 participants.

In Fall 2019 and early 2020, we recruited 91 children from a children's museum in a mid-size Midwestern city (M age = 6.71, SD = 2.12). There were 30 4- to 5-year-olds, 30 6- to 7-year-olds, 19 8- to 9-year-olds, and 12 10- to 12-year-olds. Parental reports indicated that 52 were girls, 38 were boys, and 1 participant was non-binary. In addition, parental reports indicated that 57.1% were White ($n = 52$), 1.1% were Asian or Asian American ($n = 1$), 3.3% were Black or African American ($n = 3$), 9.9% were Hispanic or Latinx ($n = 9$), 1.1% were Native American ($n = 1$), and 5.5% were bi- or multi-racial ($n = 5$); 22.0% declined to report race or ethnicity ($n = 20$). Children received a small toy for participating.

Stimuli

The stimuli were highly detailed drawings of animals' faces (see Figure 1). Three animals (fox, beaver, bear) were expected to be familiar, and three animals (cuscus, kinkajou, quoll) were expected to be unfamiliar. The unfamiliar animals were species native to Australia or South America that were not present at nearby zoos. Each participant saw four of the possible six animals, two from the familiar set and two from the unfamiliar set. Based on natural variation in eye color, we selected two eye colors for each species (one dark and one light) that were easily distinguishable. These colors were used for the animal parents. This yielded four possible mother-father eye color combinations (Dark-Dark, Dark-Light, Light-Dark, and Light-Light) for each animal.

For each animal, we created one face shape for the parents and one face shape for the offspring. These shapes differed slightly, based approximately on typical developmental changes in proportions (Lorenz, 1971). We then created five offspring that varied only in eye color (see Figure 1). One offspring had the dark color from the parents, one had the light color from the parents, one had a mix of light and dark eye colors (labeled *mix* in Figure 1), one had one dark eye and one light eye (labeled *one-and-one* in Figure 1), and one had purple eyes—an eye color that was unrelated to either parent and that is not found in any mammalian species. The mix and one-and-one options represent different ways of combining the parents' phenotypes. These options were meant to mimic forms of co-dominance and incomplete dominance that, although rare, are possible in the natural world (although not necessarily possible for eye color inheritance in every animal in the study). We included the purple phenotype to examine children's judgements of an eye color that was not related to either of the parents.

Procedure

Participants completed the study in a private room at the museum. Parents provided consent and participants assented to participation. We used a 2 (familiarity condition: familiar, unfamiliar) x 2 (parent condition: same, different eye color) within-subjects design.

Identification task. First, we presented two parents of an animal family that had either the same or different eye colors. Participants were asked if they knew what the animal was. Most participants knew the familiar animals but not the unfamiliar animals (see Supplemental materials).

[Insert Figure 1 here]

Figure 1. Offspring stimuli for the cuscus in the left panel. Example of the phenotypic judgement task (Studies 1 and 1B; top right panel) and the offspring selection task (Studies 1B and 2; bottom right panel) for the cuscus. The directions were spoken rather than written.

Phenotypic Judgement task. First, the experimenter pointed to the mother and father and told the participant whether the parents had the same or different eye colors. Next, the experimenter showed the possible offspring to the participant one at a time. Offspring were presented in the following fixed order: dark or light offspring, light or dark offspring, mix offspring, purple offspring, and one-and-one offspring. Whether the light or dark offspring was presented first depended on the eye color of the parents, such that the first offspring presented always matched the eye color of at least one of the parents. When parents had different eye colors, the order of the light and dark offspring was determined at random. For each offspring, the experimenter stated the relation between the offspring eye color and the parents' eye color (e.g., when the offspring had the same eye color as the mother, the experimenter said "this [animal name] has the same eye color as the mom," and when the offspring was a mix of the parents' eye colors, the experimenter said "this [animal name] has eyes that are a mix of the mom's and the dad's eye color"). After the experimenter explained the relation, they asked, "Do you think this (points to the offspring) could be the baby of this mom and dad [animal name]?" Participants answered "yes" or "no" for 6 potential offspring. Participants completed all judgements for one animal before they were shown the next animal. We consider judging each offspring alternative for one animal as a trial; therefore, each participant completed 4 trials, with a total of 24 judgements. The experiment took approximately 10 minutes.

Results

Pre-registered analyses

We first examined which specific offspring participants endorsed. We did not observe any differences in endorsements of the two types of eye color blends. The offspring with an eye color that was a mix of the parents' eye colors was endorsed on 64.4% of trials and the offspring with one eye of each color was endorsed on 62.4% of trials, which aligns with college students' judgements (Authors, YEAR); therefore, we combined these categories in our analyses. We fit a generalized linear mixed-effects model with a binomial link function predicting participants' endorsements for each trial. We included offspring type (dummy coded, with dark eyes as the reference group), parent condition (coded -0.5 for same eye color and 0.5 for different eye colors), familiarity (coded -0.5 for unfamiliar and 0.5 for familiar), age (mean-centered), and all possible interactions. We also included by-subject random intercepts and by-subject random slopes for the three-way interaction of offspring type, parent condition, and familiarity, and all the respective lower-order effects. We followed the recommendations of Brauer and Curtin (2018) to achieve convergence. The first model to converge did not allow the random effects to correlate. Here we report statistics only for key hypothesized effects; please see the supplemental materials for tables with full model statistics.

As hypothesized, there was a significant effect of offspring type, $\chi^2(3, N = 91) = 73.55$, $p < .001$. Participants were equally likely to endorse offspring with light eyes ($M = 0.76$, $SD = 0.43$) and dark eyes ($M = 0.77$, $SD = 0.42$). They were more likely to endorse offspring with dark eyes than offspring with blends ($M = 0.63$, $SD = 0.48$), and more likely to endorse offspring with blends than offspring with purple eyes ($M = 0.25$, $SD = 0.43$). Also as hypothesized, participants were significantly more likely to judge an offspring as possible when parents had different eye colors (*M* = 0.68, *SD* = 0.47) than when they had the same eye color (*M* = 0.54, *SD* = 0.50), *OR* = 2.37, $\chi^2(1, N = 91) = 8.56$, $p = .003$. As hypothesized, there was also an interaction of offspring type and parent condition, $\chi^2(3, N = 91) = 9.58$, $p = .022$. Participants were more likely to judge offspring with blends as possible when parents had different eye colors than when parents had the same eye color, as shown by a significant simple interaction of parent condition and the dark eyes versus blends contrast, $\chi^2(1, N = 91) = 4.41$, $p = .036$. No other effects or interactions were significant.

Post-hoc analyses

In addition to the pre-registered analyses, we analyzed offspring choices when parents had the same and different eye colors separately, to more fully examine the interaction of offspring type and parent type. These analyses revealed how participants' beliefs about offspring depended on the parents' characteristics. We also tested the number of offspring participants endorsed and whether this number was significantly above the deterministic value of 1.

Different parents. As can be seen in Figure 2, when parents had different eye colors, participants were equally likely to endorse offspring with light and dark eyes, regardless of the mother's eye color. We tested this by examining participants' endorsements on trials on which parents had different eye colors. We fit a generalized linear mixed-effects model predicting endorsement from offspring type (dark or light), mother eye color (light or dark), age, and their interactions. We also included by-subject random intercepts and by-subject random slopes for the interaction of offspring type and mother eye color, and all lower-order effects. We did not include familiarity, as the previous analyses had not revealed any effects. None of the effects were significant. Critically, there was no indication of an offspring type by mother eye color interaction, $\chi^2(1, N = 91) = 0.05$, $p = .829$. Thus, there was no evidence that participants were more likely to endorse offspring that matched the mother than the father.

[Insert Figure 2 here]

Figure 2. Probability of endorsement by offspring type (x-axis). The left panel shows trials on which the parents had different eye colors, and the right panel shows trials on which the parents had the same eye color. Within each panel, the left graph shows trials on which the mother had dark eyes, and the right graph show trials on which the mother had light eyes. The error bars show the within-subject standard errors of the means.

Same parents. As can be seen in Figure 2, when parents had the same eye color, participants were more likely to endorse the eye color that matched the parents. We fit a generalized linear mixed-effects model with a binomial link function predicting participants' endorsements for trials on which parents had the same eye color. We included offspring type (dummy coded, with dark eyes as the reference group), parent eye color (coded -0.5 for light and 0.5 for dark), age (mean-centered), and all possible interactions. We also included by-subject random intercepts and by-subject random slopes for the interaction of offspring type and mother eye color and all lower-order effects, but we did not allow them to correlate. We did not include familiarity, as the previous analyses had not revealed any effects. There was a significant offspring type by parent eye color interaction, $\chi^2(3, N = 90) = 13.84$, $p = .003$. Participants most frequently endorsed offspring with the eye color that matched the parents' eye color (e.g., dark when both parents had dark eyes), followed by offspring with blends, then offspring with the alternative eye color (e.g., light when both parents had dark eyes), and finally offspring with purple eyes. This pattern reflects more frequent endorsement of the offspring when there is greater perceptual similarity between the offspring eye color and parents' eye color, as the blends are perceptually more similar to the parents' eyes than the alternative eye color, and the alternative eye color is perceptually more similar to the parents' eyes than purple. We also found an offspring type by age interaction, $\chi^2(3, N = 90) = 11.90$, $p = .008$, such that younger participants were more likely to endorse offspring with purple eyes, $\chi^2(1, N = 91) = 9.95$, $p = .002$.

Number of offspring endorsed. To examine whether participants accepted any variability in the possible offspring (i.e., if they thought that more than one offspring type was possible), we examined whether the total number of offspring that participants endorsed for each trial was significantly different from 1 (range 0-5). In both the same ($M = 2.66$, $SD = 1.43$) and different parent conditions ($M = 3.38$, $SD = 1.18$), participants endorsed significantly more than one response, $F(1, 89.66) = 137.03$, $p < .001$, and $F(1, 89.97) = 450.87$, $p < .001$, respectively. Of the 91 participants, only two participants (2.2%, one 6-year-old and one 10-year-old) did not accept any variability (defined as endorsing more than one option) on any of the trials. Three participants (3.3%) accepted variability on only one trial (two 6-year-olds and one 7-year-old, all on different-parent trials). Eleven participants (12.1%) accepted variability on only two trials (with nine of them doing so only on different-parent trials). Finally, 20 participants (22%) accepted variability on three trials and 55 participants (60.4%) accepted variability on all four trials. Thus, over 80% of participants accepted variability on most trials.

We next examined the number of offspring participants endorsed. We fit a linear mixed-effects model predicting the number endorsed from parent condition (coded -0.5 for same eye color and 0.5 for different eye colors), familiarity (coded -0.5 for unfamiliar and 0.5 for familiar), age (mean centered), and all the respective interactions. We included by-subject random intercepts as well as by-subject random slopes for the effects of parent condition, familiarity, and their interaction, and we allowed the random effects to correlate. As can be seen in Figure 3, participants endorsed more offspring when parents had different eye colors (*M* = 3.38, *SD* = 1.18) than when they had the same eye color (*M* = 2.66, *SD* = 1.43), *F*(1, 87.98) = 45.48, $p < .001$. No other effects were significant.

[Insert Figure 3 here]

Figure 3. Model predictions for the number of offspring endorsed in the judgement task (y-axis), for parents who had the same or different eye colors (x-axis) and for familiar animals (circles) and unfamiliar animals (diamonds). The error bars show the within-subject standard errors of the point estimates.

Discussion

Study 1 introduced a new task for examining intuitive theories about inheritance that includes a more comprehensive assessment of endorsement of biological variability than tasks used in prior research. This study showed that, for eye color, participants had a probabilistic model of genetic inheritance, as they accepted several different offspring phenotypes as possible. Participants showed this pattern, regardless of whether parents had the same or different eye colors, but they accepted more offspring phenotypes as possible when parents had different eye colors. When parents had different eye colors, participants endorsed the mother's and father's eye colors at similar rates, showing no indication of the *mother bias* that has been previously reported in the literature. When parents had different eye colors, participants were more likely to endorse offspring that combined the two eye colors. Finally, when parents had the same eye color, participants appeared to base their judgements on perceptual similarity, as the likelihood of an offspring being endorsed increased for offspring eye colors that were perceptually more similar to the parents.

Study 1 shows that children believe that many different offspring phenotypes are possible and they attend to the parents' phenotypes when determining which offspring are possible. Thus, children constrain the variability they accept, based on their knowledge of the phenotypes of the parents. However, a critical question is whether children also recognize that certain phenotypes are *more likely*. Children may broadly accept variation by endorsing many different phenotypes, but they may also constrain this variation by believing that some phenotypes are more likely than others. In Study 1, we cannot ascertain which possible offspring phenotypes children thought were *more* likely. To address this question, in Study 1B, reported in the supplemental materials, we introduced the *offspring prediction task*, in which children predicted how six offspring of an animal family would look. We had planned to obtain a sample size similar to that in Study 1, but due to the onset of the COVID-19 pandemic, data collection for this study had to be halted after only 30 participants. In Study 1B, children completed the phenotypic judgement task used in Study 1, followed by the *offspring prediction task*. Briefly, Study 1B shows largely similar results in children's responses to the phenotypic judgement task. It also demonstrated that children could successfully complete the *offspring prediction* task. Moreover, the results suggested that children select offspring that have different traits and that children tend to select offspring that resemble the parent of the same sex. We coded children's explanations and saw that children were intentionally selecting offspring that looked different from the parents, and they were intentionally matching the offspring to the same sex parents. We also coded for the use of genetic language and found that some children used genetic terms in their explanations (e.g., “genes”, “dominant”). The results from this study are presented in full in the supplemental materials.

Given the limited sample size in Study 1B, in Study 2 we collected a larger sample of children using both the phenotypic judgement task and the offspring prediction task. We also wished to test whether the biases we identified would shift after a brief lesson that included a genetic diagram, and we were interested in whether the perceptual features of the diagrams used in the lesson would influence generalization from the lesson. Prior work has shown that undergraduate students generalize more broadly when they learn with bland diagrams (Menendez et al., 2020), suggesting that children might be more likely to generalize from a lesson on eye color to other traits when they learn with a bland diagram. We randomly assigned children to receive a lesson with either a rich (i.e., drawing containing realistic details) or bland (i.e., line drawing without details) diagram (see Figure 4). Based on prior work, we hypothesized that those who received the bland diagram would endorse more offspring after the lesson than those who saw the rich diagram. Finally, in this study, we also examined whether the perceptual similarity pattern and the sex-matching bias would extend to features other than eye color, such as ear size or fin shape.

Study 2

Method

Participants

We pre-registered that we would run 224 children, with 32 participants in each grade from 1 through 7 (roughly 5 to 13 years of age), based on a power analysis using the diagram effect from Menendez, Rosengren, and Alibali (2020), which had an odds ratio of 0.61 (d = -0.2725). Using this Cohen's d, we determined that we needed 213 participants to have 80% power to detect the effect. However, due to an error on the experimenters' part, 232 children participated in this study (including 28 in Grade 1, 42 in Grade 2, 33 in Grade 3, 34 in Grade 4, 27 in Grade 5, 37 in Grade 6, and 31 in Grade 7) from July 2020 to June 2021. Many parents did not report their children's age, but all parents reported their children's grade levels (to confirm eligibility); therefore, in the remainder of the paper we use child grade rather than age in our statistical models. Among participants whose parents reported age, the average age was 9.54 years (*SD* = 2.03, range = 5.57, 13.04). Per parental reports, 95 participants were girls, 119 were boys, and 1 was non-binary; 17 parents did not report their child's gender. Parental reports indicated that 72.8% of participants were White (*n* = 169), 3.0% were as Asian or Asian American (*n* = 7), 2.2% were Black or African American (*n* = 5), 4.7% were Hispanic or Latinx (n = 11), 0.4% were Native American (*n* = 1), and 6.5% were bi- or multi-racial (n = 15); 10.3% did not report race or ethnicity information (*n* = 24). Participants received $15 for completing the study.

Offspring prediction task

As in Study 1, participants first completed the phenotypic judgement task and then the offspring prediction task. During the offspring prediction task, the experimenter presented a PowerPoint slide with the mother and father of the animal family on top. Below the parents were six empty spaces and at the bottom of the slide there were five stacks of images, one stack for each of the five offspring types. Each stack contained six identical images. The experimenter first explained that the animal parents had six babies throughout their lives, and that three were male and three were female. The experimenter then said that the babies were "all grown up" now, and the asked the participant to use the images to show how they thought the six offspring would look. The experimenter explained that each stack had offspring with the same eye color and that there were six images in each stack, so the participant could make any combinations they chose. After the participant selected the images, the experimenter asked them to explain their choices. We coded participants' explanations for a variety of themes (see supplemental materials), including whether they used genetic terms, such as "genes," "dominant," or "mutation."

Design and Procedures

The study took place in one 45-minute Zoom session, and it had a pretest-lesson-posttest design. At pretest, participants completed the phenotypic judgement and offspring prediction tasks for two animal families: wolf parents with the same eye color (light eyes), and beaver parents with different eye colors (mother with dark eyes, father with light eyes). For the offspring prediction task, participants were randomly assigned to place male offspring under the mother and female offspring under the father or vice versa. Participants were then randomly assigned to receive a brief lesson about inheritance of eye color with either a perceptually rich or perceptually bland diagram (see Figure 4). The lesson conveyed that animals have a "code inside them" that determines how they look, and that they get half of this code from each parent. The lesson then walked participants through the 3 families shown in the pedigree. The diagram depicted one set of parents with the same eye color and one with different eye colors. Participants were told that both families had offspring that looked like one of the parents (or both parents, in the same eye color family). Participants were told that these two offspring (that had different eye colors) got together and had four offspring, one having the father's eye color, one having the mother's eye color, and two having different eye colors. The lessons were identical except for the diagram that participants saw.

[Insert Figure 4 here]

Figure 4. Rich (top panel) and bland (bottom panel) pedigree diagrams used in the lesson about genetic inheritance of eye color. For expanded versions, see OSF.

At posttest, participants completed the phenotypic judgement and offspring prediction task for two animals: wolf parents with the same eye color (light eyes), and fox parents with different eye colors (mother with dark eyes, father with light eyes). They then completed the phenotypic judgement task for two additional animals with other traits: fennec fox parents with different ear sizes (mother with large ears, father with small ears), and bass (fish) parents with the same fin type (spikey fins). For the fennec fox, the offspring had either two large ears, two small ears, two medium ears, one small and one large ear, or two bat ears. For the bass, the offspring had either two spikey fins, two smooth fins, two fins that were in-between spikey and smooth, one spikey and one smooth fin, or two goldfish fins. These options were analogs of the options for eye color. Participants completed all the tasks for one animal before moving on to the next animal. In the posttest, the first animal was the same as the animal in the lesson (the wolf), and each subsequent animal was progressively more dissimilar: fox eye color (mammal with same trait as in the lesson), fennec fox (mammal with different trait), and bass (non-mammal with different trait). This allowed us to assess participants’ generalization.

Results

We first present the results for the phenotypic judgement task and then the offspring prediction task. Analyses of participants’ explanations can be found in the supplemental materials. Means and standard deviations reported throughout this section are unadjusted.

Additional pre-registered analyses of the pretest can be found in the supplemental materials. In addition, tables with full model statistics can be found in the supplemental materials.

Pre-registered analyses

Phenotypic judgement task: Number of offspring. As in Study 1, participants endorsed more than one offspring for all animals, both at pretest and posttest, and participants selected more offspring when parents had different phenotypes than when parents had the same phenotype (see Figure 5). We fit two linear mixed effects models, one for the wolf and one for the other animal with eye color as the trait (beaver or fox). We included test time, diagram type, grade, and their interactions as predictors, and we included by-subject random intercepts and by-subject random slopes for the effect of test time. Participants endorsed more offspring at posttest than pretest, both when parents had the same, $F(1, 228) = 46.93$, $p < .001$, and different eye colors, $F(1, 228) = 27.69$, $p < .001$, suggesting that the lessons led participants to accept more offspring as possible. When parents had different eye colors, older participants endorsed more offspring phenotypes, $F(1, 228) = 11.99$, $p < .001$. There was also an interaction of test time and diagram richness. Contrary to our hypothesis, participants in the rich condition increased the number of offspring they endorsed from pretest to posttest more than participants in the bland condition. No other effects were significant.

[Insert Figure 5 here]

Figure 5. Number of offspring endorsed in the phenotypic judgement task for the wolf (first panel), beaver/ fox (second panel), fennec fox (third panel) and bass (fourth panel), broken down by diagram condition, with the bland condition in gray and the rich condition in red. For the wolf

and beaver/fox, results are also broken down by test time. Error bars represent the within-subject standard error of the mean.

We also examined how many offspring participants endorsed for the ear size and fin type trials. For each trait, we fit a linear regression with grade, diagram type, and their interaction as predictors. Again, participants endorsed more than one offspring for both traits, suggesting that their reasoning about these traits was similar to their reasoning about eye color. Of note, participants' responses for these traits were very similar to their responses for eye color at pretest (with bass, which had parents with the same phenotype, similar to the same-parents pretest trials, and fennec fox, which had parents with different phenotypes, similar to the different-parents pretest trials), suggesting that participants did not generalize from the eye color lesson to other traits. See Figure 5. No effects were significant.

Phenotypic judgement task: Offspring endorsed. We then examined the specific offspring participants endorsed for each animal. As pre-registered, we fit one mixed-effects logistic regression per animal comparison. We included offspring type, diagram condition, grade, and the respective interactions for all models. For the wolf and the beaver/ fox models, we also included test time and allowed it to interact with the other predictors. We kept the random effect structure maximal and followed the recommendations of Brauer and Curtin (2018) in cases of non-convergence. For each animal, full model statistics are included in the supplemental materials.

[Insert Figure 6 here]

Figure 6. Probability of endorsement by offspring type (x-axis) for the wolf (first panel), beaver/

fox (second panel), fennec fox (third panel) and bass (fourth panel), broken down by test time (different shapes). The error bars show the within-subject standard errors of the means.

Wolf (Same parents). The first model to converge did not include by-subject random intercepts and did not allow the random effects to correlate. We found an effect of offspring type that was qualified by an interaction with test time. As can be seen in Figure 6, at pretest participants showed a perceptual similarity bias, with participants being more likely to endorse offspring with light eyes (which matched the parents) than offspring with blends, more likely to endorse offspring with blends than offspring with dark eyes, and more likely to endorse offspring with dark eyes than offspring with purple eyes. After the lesson, participants were more likely to endorse all offspring types, but the increase was greatest for the offspring with dark eyes. Participants in higher grades were also more likely to endorse each offspring type. No other effects were significant.

Beaver/ Fox (Different parents). The first model to converge included only by-subject random slopes for the effect of test time and the test time by offspring type interaction. We found an effect of offspring type and an effect of test time, but no interaction, suggesting that the lesson led participants to endorse all of the offspring types more frequently. As can be seen in Figure 6, participants were equally likely to endorse offspring whose eyes matched those of the two parent phenotypes, less likely to endorse offspring with blends than offspring with dark eyes, and less likely to endorse offspring with purple eyes than offspring with blends. As grade level increased, participants were more likely to endorse all offspring types, but they reached ceiling (i.e., consistent endorsement) at an earlier grade for the two parent phenotypes, which was reflected in the offspring type by grade interaction. No other effects were significant.

Fennec fox (Different parents). The first model to converge did not include by-subject random intercepts and did not allow the random slopes to correlate. There was an effect of offspring type, as can be seen in Figure 6. As for eye color, participants were equally likely to endorse offspring that matched the two parent phenotypes (i.e., long and short ears), less likely to endorse offspring with medium ears (the blend) than offspring with long ears, and more likely to endorse offspring with medium ears than offspring with bat ears. No other effects were significant.

Bass (Same parents). The first model to converge did not allow the random slopes to correlate. There was an effect of offspring type; see Figure 6. As for eye color, participants showed a perceptual similarity bias, being more likely to endorse offspring with spikey fins (which matched the parents) than offspring with blended fins, more likely to endorse offspring with blended fins than offspring with smooth fins, and more likely to endorse offspring with smooth fins than offspring with goldfish fins. No other effects were significant.

Offspring prediction task: Number of offspring. We first examined how many different types of offspring participants selected for each trial, and then examined which offspring they selected. As a reminder, participants completed the offspring prediction task for the wolf and beaver at pretest and the wolf and fox at posttest. Consistent with Study 1, participants selected more than one offspring for all animals, both at pretest and posttest, with participants selecting more offspring when the parents had different phenotypes than when parents had the same phenotype (see Figure 7). We fit two linear mixed effects models, one for the wolf and one for the other animal with eye color as the trait (beaver/ fox). We included test time, offspring sex, diagram type, grade, and their interactions as predictors, and we included by-subject random intercepts and by-subject random slopes for the effects of test time and offspring sex. We found that for the wolf (for which parents had the same eye color), participants in higher grades selected *fewer* different types of offspring. No other effects were significant; see the supplemental materials.

[Insert Figure 7 here]

Figure 7. Number of different types of offspring participants selected in the prediction task, broken down by offspring sex (males in orange, females in green) and test time. The error bars show the within-subject standard errors of the point estimates.

Offspring prediction task: Offspring selected. Next, we examined the specific offspring that participants chose. We fit two mixed-effects logistic regressions, one for each animal, predicting participants' selections from offspring type, test time, diagram condition, grade, and their interactions. We included by-subject random intercepts and by-subject random slopes for the effects of offspring type and test time.

Wolf (Same parents). There was an effect of offspring type that interacted with test time. As can be seen in Figure 8, participants relied on perceptual similarity at both pretest and posttest, but after the lesson, participants were more likely to select the offspring that matched the parents (light eyes). There was also an effect of grade that interacted with offspring type. As grade level increased, participants were more likely to select the offspring that matched the parents (light eyes), and less likely to select the purple-eyed offspring.

[Insert Figure 8 here]

Figure 8. Probability of selection by offspring type (x-axis), broken down by test time (circle

for pretest and diamond for posttest). The left panel shows the results for the wolf and the right panel for the beaver/ fox. The error bars show the within-subject standard errors of the means.

Beaver/Fox (Different parents). Again, there was an effect of offspring type that interacted with test time. Participants were less likely to select the offspring with the blended eye color at posttest. There was also a grade by offspring type interaction. Similar to the wolf, older participants were more likely to select the offspring types that matched the parents (i.e., dark-eyed and light-eyed), and less likely to select the purple-eyed offspring.

Post-hoc analyses

Given that the lesson conveyed that offspring receive the same amount (half) of their DNA "code" from each parent, we wanted to examine whether participants would be less likely to engage in sex-matching after the lesson. To address this question, we added offspring sex to the model for the beaver/ fox (as those parents had different eye colors). As can be seen in Figure 9, participants engaged in sex-matching both at pretest and posttest. Critically, the three-way interaction of offspring type by offspring sex by test time was not significant, $\chi^2(3, N = 232) = 3.64$, $p = .303$; thus, there was no evidence that sex-matching was influenced by the lesson. We also did not find that sex-matching varied across grade levels, $\chi^2(3, N = 232) = 1.41$, $p = .702$. Participants mentioned sex-matching in 16.7% of explanations and genetic terms in 6.3% of explanations. Older participants were less likely to mention sex-matching, OR = 0.75, $\chi^2(1, N = 216) = 11.23$, $p < .001$, and more likely to use genetic terms, OR = 2.09, $\chi^2(1, N = 230) = 23.64$, $p < .001$. For further information, see the supplemental materials.

[Insert Figure 9 here]

Figure 9. Probability of selecting an offspring, broken down by offspring type (x-axis), offspring sex (left panels for females, right panels for males), and test type (top panels for posttest, and bottom panels for pretest). The error bars show the within-subject standard errors of the point estimates.

Discussion

Like Study 1, Study 2 showed that children think that more than one offspring is possible, and they use perceptual similarity and sex-matching to decide which offspring are possible. Study 2 additionally showed that these biases extend to other traits, like ear size and fin type. However, given that ear size and fin type were only assessed after the lesson, it is unclear whether responses for these traits were influenced by the lesson. Although the lesson led participants to revise their beliefs on perceptual similarity (at least for the trait in the lesson), it did not lead to changes in children's sex-matching responses, suggesting that the sex-matching bias might be more resistant to change than the perceptual similarity bias. To be clear, we are not stating that all educational interventions would be ineffective at changing children's beliefs about genetics, but only that our brief intervention did not lead to changes in participants' sex-matching. Indeed, prior work has shown that adults and teenagers modify their beliefs and misconceptions about genetics when those are clearly addressed during instruction (Donovan et al., 2021; Jamieson & Radick, 2017). Based on our findings, we suggest that some misconceptions, such as the assumption that all traits are sex-linked, might be more entrenched than others and thus more difficult to modify.

This study also revealed interesting developmental differences between the tasks. In the phenotypic judgement task, children in higher grades endorsed *more* offspring phenotypes, while in the offspring prediction task, children in higher grades selected *fewer* offspring phenotypes. This suggests that with age, children realize that more phenotypes are biologically possible, but they also recognize that some phenotypes are *more likely* than others. Thus, older children endorse a higher number of different phenotypes, but they correctly judge that those that match the parents are most likely. This developmental trend is in line with work on children's judgements of "possibility" in biology and other domains (Shtulman & Carey, 2007).

Contrary to our pre-registered hypothesis, we did not find that the bland diagram was better than the rich diagram for promoting learning or generalization. The only effect of diagram richness that we observed pointed in the opposite direction—children who received the lesson with the *rich* diagram showed a greater increase in the number of offspring types they endorsed for the wolf and the beaver/ fox. This result suggests that the rich diagram helped children learn about eye color inheritance more than the bland diagram. Although contrary to our hypothesis, this result aligns with other recent work by Menendez et al. (2022), who found that children in first and second grade learned better from a lesson on metamorphosis with a rich diagram than from a lesson with a bland diagram. Other work has suggested that elementary school children generalize facts about animals more broadly when they see them with a rich image (Menendez, 2023). Children in this age range are exposed more frequently to rich visualizations in their science materials, and this may make rich visualizations easier to process (Menendez, 2023). Additionally, although we found that the lesson influenced children's judgements of the animal in the lesson (the wolf) and to a smaller extent, the trait (eye color) that was the focus of the lesson, we did not see evidence that children generalized to other traits, as their endorsements for novel traits were comparable to their pretest endorsements for eye color.

General Discussion

These studies show that children have a probabilistic model of inheritance and that they accept that there can be variability between parent and offspring phenotypes. Children generally believed that more than one offspring phenotype was possible, and this was reflected in their responses to both the *phenotypic judgement* and *offspring prediction* tasks. Further, children most often selected offspring that looked like the parents, suggesting that they recognized that offspring tend to look like their parents. This suggests that children as young as 4 think that offspring can look different from their parents, yet they believe that certain offspring types are more likely than others. Thus, even 4-year-olds may recognize the probabilistic nature of genetic inheritance.

Although children showed evidence of a probabilistic model and endorsed variability, some response patterns indicate biases not attested in prior work. Prior studies have reported that children have a mother bias, which is the tendency to think offspring will look like the mother (Terwogt et al., 2003). Although this bias has been found in 3- to 5-year-old children, it is worth noting that Study 1 included 4- and 5-year-olds, and they did not show this bias. We suggest that the mother bias might have been an artifact of the methodology used in prior work, or it might be present only for very young children. Instead of a mother bias, we found that when given information about the sex of the offspring, children selected offspring so that female offspring resembled the mother and male offspring resembled the father. This sex-matching was also evident in children's explanations. For example, an 11-year-old boy said, "The boys will probably relate to the dad and girls will relate to the mom." Although many traits are sexually dimorphic (e.g., feather coloration in many bird species) or sex-linked (e.g., male pattern baldness), eye color is neither sexually dimorphic nor sex-linked in any of the animals in these studies or in humans. Therefore, we suggest that children exhibit a bias to match the phenotype of the offspring to that of the same-sex parent. This bias has also been found in adults' selections and explanations (Menendez et al., 2023), suggesting that it might be present early in development and persist through formal instruction in biology. It is possible that this bias is related to children's essentialist beliefs about gender. It is also possible that children believe that offspring receive more genetic information from the parent of the same sex.

Children's responses suggest that they used perceptual similarity to constrain their acceptance of variability. When parents had the same phenotype, children appeared to judge the possibility of offspring phenotypes based on perceptual similarity to the parents' phenotype. This pattern does not align with eye color inheritance in humans (e.g., although rare, parents with brown eyes can have a child with blue or green eyes). This constraint has also been observed in research on lifespan changes, for which children are more likely to accept small changes in only one feature (e.g., size) than more drastic changes in multiple features (e.g., size and proportions; French et al., 2018). Children may be willing to accept slight variations in many areas of biology, but they may require instruction to accept more drastic variations.

Children's intuitive theory of inheritance

These studies suggest that children have a much more complex intuitive theory of inheritance than previously believed. The general claim that children expect offspring will resemble their parents still holds true. In their explanations, some children appealed to genetics by stating that parents pass on their genes. This correct understanding could be supported by children's essentialist reasoning, the belief that a parent's essence is transmitted to the offspring (Gelman, 2003; Solomon, 2002). Although children could ascribe this essence to many internal properties (e.g., the heart, Meyer et al., 2017, or blood, Waxman et al., 2007), by ascribing the essence to genes (known as genetic essentialism, Cheung et al., 2014; Dar-Nimrod & Heine,

2011) essentialist reasoning might support children's scientifically appropriate understanding that genetic material is passed down from parents to offspring. Children also believed that there could be slight variations between parents and offspring. This acceptance of variability is a novel finding. We show that children accept that there can be variability between parents and offspring, but that their acceptance depends on the degree of perceptual similarity.

When parents have different phenotypes, children believe that offspring can resemble either parent, but they are more likely to resemble their same-sex parent. This pattern might be rooted in children's gender essentialism, or the belief that girls resemble one another more than they resemble boys (Taylor et al., 2009). Another belief that could be supported by essentialism is the belief that parents' phenotypes would be combined. Some children explained that parents' genes "mixed" and noted that this could result in the offspring expressing both phenotypes (e.g., offspring with one eye that matched the mother's eye color and one eye that matched the father's eye color) or a combination of the two (e.g., offspring with an eye color between the mother's and father's eye color). Organisms *can* express phenotypes that are a mix of the phenotypes of the parents, like the blended and one-and-one phenotypes, particularly in cases of incomplete dominance or co-dominance. But children in this age range are not typically taught the concepts of incomplete dominance or codominance, and these patterns are relatively infrequent in the natural world, suggesting children might not have a lot of experience seeing them. These issues suggest that the idea of mixing genes might stem from children's intuitive theories leading them to believe that the essences of the parents are combined (Williams, 2012). Children frequently endorsed the one-and-one phenotype, which is very infrequent in the natural world, could also be a manifestation of theory-based reasoning, as it may be based on the idea that each parent contributes exactly one-half of the offspring's genes. More research is needed to understand which aspects of children’s intuitive theories might support their learning of scientific models of genetics, and which aspects might hinder this learning.

Based on our findings, we characterize children’s intuitive theory of inheritance as a probabilistic model that uses essentialism and perceptual similarity to constrain what they believe is likely. The probabilistic nature of children’s theories (the idea that many variations of offspring are possible) and the idea of parents’ phenotypes mixing can serve as a starting point for instruction that explains that genetic information from both parents is passed on to offspring, but the process by which a particular allele is passed from parent to child is a probabilistic one.

With age, this theory becomes more fully developed. Older children endorsed more offspring, but rejected extreme options (e.g., purple eyes). We also found that some children incorporated genetic terminology in their explanations, though not always correctly. This suggests that a short genetics lesson might not be enough to change children’s beliefs. Indirect support for this idea comes from studies with college students (who have received genetics instruction) who also still showed the perceptual similarity and sex-matching biases (Menendez et al., 2023). Direct support for this lack of change is found in Study 2, in which children (at all ages) still showed a sex-matching bias, even after a lesson that highlighted offspring get half of their DNA from each parent.

It is worth pointing out these studies focused on physical traits, in particular eye color. In Study 2, we found similar results for eye color, ear size, and fin type, suggesting that our findings might generalize to other physical traits. Our findings may also generalize to psychological traits, as prior work suggests that children think about physical and psychological traits similarly (e.g., Johnson & Solomon, 1997; Williams, 2012). The familiarity of the animals did not influence children’s performance, suggesting that children use a probabilistic model of genetic inheritance for all animals. However, the characteristics of the trait itself could influence children's reasoning. For example, it is possible that if children received information about the functional utility of a trait, their judgements might be more deterministic, favoring the more functionally advantageous phenotype (Emmons & Kelemen, 2015). Additionally, past research has shown that children make more deterministic judgements for internal traits or ones tied more closely to the essence of the animal category (Brandone et al., 2012). Future work that systematically varies traits and the information children receive about traits may enhance our understanding of how far these beliefs extend.

Implications for psychology and education

Some theorists have argued that children's understanding of the biological world is constrained by early cognitive biases, including psychological essentialism (Medin & Ortony, 1989; Shtulman & Schulz, 2008), teleology (Kelemen, 2012), and anthropocentrism (Arenson & Coley, 2018). These biases lead people to infer that animals of the same species will be highly similar to one another (essentialism), to infer that animals acquire their traits for a specific purpose (teleology), and to reason about animals depending on their similarity to humans (anthropocentrism). It has been argued that these biases are pervasive because people use them across development and in a variety of biological domains (Eidson & Coley, 2014; Kelemen et al., 2013; Shtulman & Valcarcel, 2012).

However, some studies have shown that even though these biases are present, they are not applied in all situations (Arenson & Coley, 2018), and children and adults can inhibit them to display more scientific knowledge (Ronfard et al., 2021; Young & Shtulman, 2020). In line with this work, our studies show that children do not always rely on essentialist reasoning when thinking about inheritance as, at least for physical traits. Children accept that parents and offspring can look different, and they expect some variability.

It is possible that these biases arise primarily when reasoning about species or other categories, rather than about individuals. Children may accept more variation when thinking about individual parents and offspring than when thinking about species. Indeed, several studies have demonstrated lower acceptance of variation at the species level (Emmons & Kelemen, 2015; Rhodes & Brickman, 2010). Explanations of how parent-offspring variation relates to variation at the species level might make children more accepting of variation at the species level. This could have implications for science education, as within-species variation is a key concept (Walck-Shannon et al., 2019) and is foundational for understanding evolution through natural selection (Shtulman, 2006; Shtulman & Schulz, 2008).

Our studies provide some guidance on potential topics to address in genetic lessons, as without instruction, some biases might persist into adulthood (Menendez et al., 2023). Our results suggest that genetics lessons should directly address when sex does or does not influence the phenotype of the offspring, as this might decrease students' tendency to sex-match for all traits. Lessons should also stress that phenotypes that are perceptually similar to the parents are not *necessarily* more likely than phenotypes that are perceptually dissimilar. Instead, the likelihood of a particular phenotype depends on the inheritance patterns of the trait in question. Additionally, these studies show that children have some understanding of genetic inheritance at an earlier age than this topic is typically taught. This suggests that genetics instruction could occur in earlier grades, provided the materials convey the information in an age-appropriate manner, as has been done with other complex biological topics (e.g., evolution, Ronfard et al., 2021).

Limitations

Our findings must be considered in light of the studies' limitations. Study 1 included mostly children from a highly educated community. These children may have parents with a stronger science background than the general population in the United States, and this might influence children's probabilistic views of inheritance. For Study 2, we recruited children from many areas of the United States, but we do not know if the sample differs in certain demographic characteristics (such as parent education) from the sample in Study 1. Therefore, it is possible that the results may not generalize to other communities within the U.S. or worldwide. We also examined only physical traits, and because ear size and fin type were queried only after the lesson, it is unclear if children's responses to these items were affected by the lesson. Future work should consider additional traits, including unfamiliar, functional, and internal traits. Additionally, we examined only how children reasoned about relatively simple traits in non-human animals. Therefore, we do not know whether these results generalize to more complex traits or human traits, which are often the focus of genetics instruction in high school and college. Finally, it is possible that by including the labels "mom" and "dad" in our questions, children might have assumed that the animals were the parents of the animals shown. We included these labels because, to examine the mother bias, we needed to specify which parent was the mother, and these labels had been used in previous studies (Solomon & Johnson, 2000; Springer, 1996; Williams, 2012; Williams & Smith, 2006). Future studies might examine whether eliminating these labels influences children's responses.

Conclusion

We examined beliefs about inheritance among predominantly White U.S. children with two novel tasks, the phenotypic judgement task (Studies 1-2) and the offspring prediction task (Studies 1B-2). These tasks allowed children to provide multiple responses about how offspring might look, allowing us to obtain a comprehensive view of how children think about genetic inheritance. Across three studies, children displayed a probabilistic view of genetic inheritance. They viewed multiple phenotypes as possible, and they viewed some as more likely than others. Children also displayed some misconceptions, such as sex-matching and perceptual similarity biases. Characterizing children's understanding of inheritance as probabilistic and accepting of variability presents a different picture of the development of biological reasoning than was evidenced in past research. This understanding generalized to different types of animals and to different physical traits, and the biases were resistant to change after a brief lesson. Children's probabilistic understanding of inheritance can provide a foundation for understanding a range of biological processes, and this understanding could be leveraged in early science education.

References

Arenson, M., & Coley, J. D. (2018). Anthropocentric by Default? Attribution of Familiar and Novel Properties to Living Things. *Cognitive Science*, *42*(1), 253–285. https://doi.org/10.1111/cogs.12501

Betz, N., Leffers, J. S., Thor, E. E. D., Fux, M., de Nesnera, K., Tanner, K. D., & Coley, J. D. (2019). Cognitive Construal-Consistent Instructor Language in the Undergraduate Biology Classroom. *CBE—Life Sciences Education*, *18*(4), ar63. https://doi.org/10.1187/cbe.19-04-0076

Brandone, A. C., Cimpian, A., Leslie, S.-J., & Gelman, S. A. (2012). Do lions have manes? For children, generics are about kinds rather than quantities. *Child Development*, *83*(2), 423–433. https://doi.org/10.1111/j.1467-8624.2011.01708.x

Brauer, M., & Curtin, J. J. (2018). Linear mixed-effects models and the analysis of nonindependent data: A unified framework to analyze categorical and continuous independent variables that vary within-subjects and/or within-items. *Psychological Methods*, *23*(3), 389–411. https://doi.org/10.1037/met0000159

Cheung, B. Y., Dar-Nimrod, I., & Gonsalkorale, K. (2014). Am I my genes? Perceived genetic etiology, intrapersonal processes, and health. *Social and Personality Psychology Compass*, *8*(11), 626–637. https://doi.org/10.1111/spc3.12138

Dar-Nimrod, I., & Heine, S. J. (2011). Genetic essentialism: On the deceptive determinism of DNA. *Psychological Bulletin*, *137*(5), 800–818. https://doi.org/10.1037/a0021860

Donovan, B. M. (2014). Playing with fire? The impact of the hidden curriculum in school genetics on essentialist conceptions of race. *Journal of Research in Science Teaching*, *51*(4), 462–496. https://doi.org/10.1002/tea.21138

Donovan, B. M., Weindling, M., Salazar, B., Duncan, A., Stuhlsatz, M., & Keck, P. (2021). Genomics literacy matters: Supporting the development of genomics literacy through genetics education could reduce the prevalence of genetic essentialism. *Journal of Research in Science Teaching*, *58*(4), 520–550. https://doi.org/10.1002/tea.21670

Duncan, R. G., Rogat, A. D., & Yarden, A. (2009). A learning progression for deepening students' understandings of modern genetics across the 5th–10th grades. *Journal of Research in Science Teaching*, *46*(6), 655–674. https://doi.org/10.1002/tea.20312

Eidson, R. C., & Coley, J. D. (2014). Not So Fast: Reassessing Gender Essentialism in Young Adults. *Journal of Cognition and Development*, *15*(2), 382–392. https://doi.org/10.1080/15248372.2013.763810

Emmons, N. A., & Kelemen, D. A. (2015). Young children's acceptance of within-species variation: Implications for essentialism and teaching evolution. *Journal of Experimental Child Psychology*, *139*, 148–160. https://doi.org/10.1016/j.jecp.2015.05.011

French, J. A., Menendez, D., Herrmann, P. A., Evans, E. M., & Rosengren, K. S. (2018). Cognitive constraints influence an understanding of life-cycle change. *Journal of Experimental Child Psychology*, *173*, 205–221. https://doi.org/10.1016/j.jecp.2018.03.018

Gelman, S. A. (2003). *The essential child: Origins of essentialism in everyday thought*. Oxford University Press.

Gelman, S. A., & Markman, E. M. (1987). Young children's inductions from natural kinds: The role of categories and appearances. *Child Development*, *58*(6), 1532–1541. https://doi.org/10.2307/1130693

Gelman, S. A., Ware, E. A., Manczak, E. M., & Graham, S. A. (2013). Children's sensitivity to the knowledge expressed in pedagogical and non-pedagogical contexts. *Developmental Psychology*, *49*(3), 491–504. https://doi.org/10.1037/a0027901

Jamieson, A., & Radick, G. (2017). Genetic Determinism in the Genetics Curriculum. *Science & Education*, *26*(10), 1261–1290. https://doi.org/10.1007/s11191-017-9900-8

Johnson, S. C., & Solomon, G. E. A. (1997). Why Dogs Have Puppies and Cats Have Kittens: The Role of Birth in Young Children's Understanding of Biological Origins. *Child Development*, *68*(3), 404–419. https://doi.org/10.1111/j.1467-8624.1997.tb01948.x

Kelemen, D. (2012). Teleological minds: How natural intuitions about agency and purpose influence learning about evolution. In K. S. Rosengren, S. K. Brem, E. M. Evans, & G. M. Sinatra (Eds.), *Evolution challenges: Integrating research and practice in teaching and learning about evolution* (pp. 66–92). Oxford University Press.

Kelemen, D., Rottman, J., & Seston, R. (2013). Professional physical scientists display tenacious teleological tendencies: Purpose-based reasoning as a cognitive default. *Journal of Experimental Psychology: General*, *142*(4), 1074–1083. https://doi.org/10.1037/a0030399

Legare, C. H., Evans, E. M., Rosengren, K. S., & Harris, P. L. (2012). The coexistence of natural and supernatural explanations across cultures and development. *Child Development*, *83*(3), 779–793. https://doi.org/10.1111/j.1467-8624.2012.01743.x

Lewis, J., Leach, J., & Wood-Robinson, C. (2000). Chromosomes: The missing link — young people's understanding of mitosis, meiosis, and fertilisation. *Journal of Biological Education*, *34*(4), 189–199. https://doi.org/10.1080/00219266.2000.9655717

Lorenz, K. (1971). *Studies in Animal and Human Behaviour* (Vol. 2). Methuen.

Mathiaparanam, O. N., Donovan, A., Menendez, D., Jones, C., Yoo, S. H., Alibali, M. W., Kalish, C. W., & Rosengren, K. (2022). Perceptual features in visual representations: A content analysis of inheritance diagrams. *Proceedings of the Annual Meeting of the Cognitive Science Society*, *44*(44), 4061.

Mayer, R. E. (2009). *Multimedia learning* (2nd ed). Cambridge University Press.

Medin, D., & Ortony, A. (1989). Psychological essentialism. In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning*. Cambridge University Press.

Menendez, D. (2023). Cues to generality: Integrating linguistic and visual information when generalizing biological information. *Journal of Educational Psychology*. https://doi.org/10.1037/edu0000812

Menendez, D., Mathiaparanam, O. N., Seitz, V., Liu, D., Donovan, A. M., Kalish, C. W., Alibali, M. W., & Rosengren, K. S. (2023). Like mother, like daughter: Adults' judgments about genetic inheritance. *Journal of Experimental Psychology: Applied*, *29*(1), 63. https://doi.org/10.1037/xap0000436

Menendez, D., Rosengren, K. S., & Alibali, M. W. (2020). Do details bug you? Effects of perceptual richness in learning about biological change. *Applied Cognitive Psychology*, *34*(5), 1101–1117. https://doi.org/10.1002/acp.3698

Menendez, D., Rosengren, K. S., & Alibali, M. W. (2022). Detailed bugs or bugging details? The influence of perceptual richness across elementary school years. *Journal of Experimental Child Psychology*, *213*, 105269. https://doi.org/10.1016/j.jecp.2021.105269

Meyer, M., Gelman, S. A., Roberts, S. O., & Leslie, S.-J. (2017). My heart made me do it: Children's essentialist beliefs about heart transplants. *Cognitive Science*, *41*(6), 1694–1712. https://doi.org/10.1111/cogs.12431

Nelkin, D., & Lindee, M. S. (2010). *The DNA Mystique: The Gene as a Cultural Icon*. University of Michigan Press.

Rey, G. D. (2012). A review of research and a meta-analysis of the seductive detail effect. *Educational Research Review*, *7*(3), 216–237. https://doi.org/10.1016/j.edurev.2012.05.003

Rhodes, M., & Brickman, D. (2010). The role of within-category variability in category-based induction: A developmental study. *Cognitive Science*, *34*(8), 1561–1573. https://doi.org/10.1111/j.1551-6709.2010.01137.x

Rhodes, M., Leslie, S. J., & Tworek, C. M. (2012). Cultural transmission of social essentialism. *Proceedings of the National Academy of Sciences*, *109*(34), 13526–13531. https://doi.org/10.1073/pnas.1208951109

Ronfard, S., Brown, S., Doncaster, E., & Kelemen, D. (2021). Inhibiting intuition: Scaffolding children's theory construction about species evolution in the face of competing explanations. *Cognition*, *211*, 104635. https://doi.org/10.1016/j.cognition.2021.104635

Shtulman, A. (2006). Qualitative differences between naïve and scientific theories of evolution. *Cognitive Psychology*, *52*(2), 170–194. https://doi.org/10.1016/j.cogpsych.2005.10.001

Shtulman, A., & Carey, S. (2007). Improbable or Impossible? How Children Reason About the Possibility of Extraordinary Events. *Child Development*, *78*(3), 1015–1032. https://doi.org/10.1111/j.1467-8624.2007.01047.x

Shtulman, A., & Schulz, L. (2008). The Relation Between Essentialist Beliefs and Evolutionary Reasoning. *Cognitive Science: A Multidisciplinary Journal*, *32*(6), 1049–1062. https://doi.org/10.1080/03640210801897864

Shtulman, A., Share, I., Silber-Marker, R., & Landrum, A. R. (2020). OMG GMO! Parent-child conversations about genetically modified foods. *Cognitive Development*, *55*, 100895. https://doi.org/10.1016/j.cogdev.2020.100895

Shtulman, A., & Valcarcel, J. (2012). Scientific knowledge suppresses but does not supplant earlier intuitions. *Cognition*, *124*(2), 209–215. https://doi.org/10.1016/j.cognition.2012.04.005

Skulmowski, A. (2023). Realistic details impact learners independently of split-attention effects. *Cognitive Processing*, *24*(2), 187–198. https://doi.org/10.1007/s10339-022-01123-z

Smith, L. A., & Williams, J. M. (2007). "It's the X and Y thing": Cross-sectional and longitudinal changes in children's understanding of genes. *Research in Science Education*, *37*(4), 407–422. https://doi.org/10.1007/s11165-006-9033-6

Solomon, G. E. A. (2002). Birth, kind and naïve biology. *Developmental Science*, *5*(2), 213–218. https://doi.org/10.1111/1467-7687.00223

Solomon, G. E. A., & Johnson, S. C. (2000). Conceptual change in the classroom: Teaching young children to understand biological inheritance. *British Journal of Developmental Psychology*, *18*(1), 81–96. https://doi.org/10.1348/026151000165580

Solomon, G. E. A., Johnson, S. C., Zaitchik, D., & Carey, S. (1996). Like Father, Like Son: Young Children's Understanding of How and Why Offspring Resemble Their Parents. *Child Development*, *67*(1), 151–171. https://doi.org/10.1111/j.1467-8624.1996.tb01726.x

Springer, K. (1996). Young Children's Understanding of a Biological Basis for Parent-Offspring Relations. *Child Development*, *67*(6), 2841–2856. https://doi.org/10.1111/j.1467-8624.1996.tb01891.x

Springer, K., & Keil, F. C. (1989). On the Development of Biologically Specific Beliefs: The Case of Inheritance. *Child Development*, *60*(3), 637–648. https://doi.org/10.2307/1130729

Stern, F., & Kampourakis, K. (2017). Teaching for genetics literacy in the post-genomic era. *Studies in Science Education*, *53*(2), 193–225. https://doi.org/10.1080/03057267.2017.1392731

Taylor, M. G., Rhodes, M., & Gelman, S. A. (2009). Boys will be boys; cows will be cows: Children's essentialist reasoning about gender categories and animal species. *Child Development*, *80*(2), 461–481. https://doi.org/10.1111/j.1467-8624.2009.01272.x

Terwogt, M. M., Stegge, H., & Rieffe, C. (2003). Children's understanding of inherited resemblance: The case of two parents. *International Journal of Behavioral Development*, *27*(4), 366–374. https://doi.org/10.1080/01650250344000037

Thomas, J. (2000). Learning about Genes and Evolution through Formal and Informal Education. *Studies in Science Education*, *35*(1), 59–92. https://doi.org/10.1080/03057260008560155

Venville, G., & Donovan, J. (2007). Developing Year 2 Students' Theory of Biology with Concepts of the Gene and DNA. *International Journal of Science Education*, *29*(9), 1111–1131. https://doi.org/10.1080/09500690600931079

Venville, G., Gribble, S. J., & Donovan, J. (2005). An exploration of young children's understandings of genetics concepts from ontological and epistemological perspectives. *Science Education*, *89*(4), 614–633. https://doi.org/10.1002/sce.20061

Walck-Shannon, E., Batzli, J., Pultorak, J., & Boehmer, H. (2019). Biological Variation as a Threshold Concept: Can We Measure Threshold Crossing? *CBE—Life Sciences Education*, *18*(3), ar36. https://doi.org/10.1187/cbe.18-12-0241

Waxman, S., Medin, D., & Ross, N. (2007). Folkbiological reasoning from a cross-cultural developmental perspective: Early essentialist notions are shaped by cultural beliefs. *Developmental Psychology*, *43*(2), 294–308. https://doi.org/10.1037/0012-1649.43.2.294

Wellman, H. M., & Gelman, S. A. (1992). Cognitive development: Foundational theories of core domains. *Annual Review of Psychology*, *43*(1), 337–375. https://doi.org/10.1146/annurev.ps.43.020192.002005

White, D., & Rabago-Smith, M. (2011). Genotype–phenotype associations and human eye color. *Journal of Human Genetics*, *56*(1), Article 1. https://doi.org/10.1038/jhg.2010.126

Williams, J. M. (2012). Children and adolescents' understandings of family resemblance: A study of naïve inheritance concepts: Phenotypic similarity and difference. *British Journal of Developmental Psychology*, *30*(2), 225–252. https://doi.org/10.1111/j.2044-835X.2011.02031.x

Williams, J. M., & Smith, L. A. (2006). Social and experiential influences on the development of inheritance concepts. *International Journal of Behavioral Development*, *30*(2), 148–157. https://doi.org/10.1177/0165025406063630

Young, A. G., & Shtulman, A. (2020). Children's Cognitive Reflection Predicts Conceptual Understanding in Science and Mathematics. *Psychological Science*, *31*(11), 1396–1408. https://doi.org/10.1177/0956797620954449