

Ending genetic essentialism through genetics education

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Summary

Genetic concepts are regularly used in arguments about racial inequality. This review summarizes research about the relationship between genetics education and a particular form of racial prejudice known as genetic essentialism. Genetic essentialism is a cognitive form of prejudice that is used to rationalize inequality. Studies suggest that belief in genetic essentialism among genetics students can be increased or decreased based on what students learn about human genetics and why they learn it. Research suggests that genetics education does little to prevent the development of genetic essentialism, and it may even exacerbate belief in it. However, some forms of genetics education can avert this problem. In particular, if instructors teach genetics to help students understand the flaws in genetic essentialist arguments, then it is possible to reduce belief in genetic essentialism among biology students. This review outlines our knowledge about how to accomplish this goal and the research that needs to be done to end genetic essentialism through genetics education.

The United States is struggling to address long-standing racial disparities in society^{1–3} that are caused by biases embedded in our institutions and social systems^{4,5} and by prejudiced beliefs that undercut support for ameliorative policy.^{6–8} A cognitive form of prejudice that has been used to justify the social acceptability of racial inequality for 100 years is genetic essentialism.^{5,6,9} Genetic essentialism is the belief that a “race” is a genetically homogeneous grouping of people, and that races differ physically, cognitively, and behaviorally primarily because they differ in a discrete manner at the genetic level.^{10–12} These beliefs make genetic essentialists prone to the naturalistic fallacy—that racial disparities are normal and morally acceptable because they are natural.¹¹ Consequently, belief in genetic essentialism predicts opposition to policies promoting racial equality among white⁸ and non-white⁷ US citizens today. Conversely, correlational research suggests that individuals who believe in genetic essentialism also tend to think that racial stereotypes have a genetic etiology, they view some racial groups as superior to others, they are more supportive of state-sanctioned eugenic policies,^{13,14} and they are less knowledgeable about the complexity of genetic inheritance.^{14–17} Educational, psychological, and sociological studies suggest, at a minimum, 20% of non-Black adults in the United States explicitly agree with genetic essentialism today.^{18–25}

Population geneticists have expressed skepticism toward the essentialist argument that genes are the best explanation for social disparities between races because of the ontological and epistemic weaknesses in this argument.^{6,26–36} Skepticism is warranted because (1) genetic differentiation between human geographic groups is relatively small when compared to variation within groups,²⁹ (2) differences in the social and physical environments of racial groups are relatively large,¹ and (3) you inherit your genes

with your environment.^{35,37} Since no scientist has ever conducted a causal inference study on the genetic basis of racial disparities that conclusively ruled out the confounding effect of the environment,^{30,31,37,38} skepticism is a defensible attitude toward essentialist claims about the genetic etiology of inequality. Such skepticism is also defensible because tests of divergent selection using polygenic scores associated with educational attainment provide no support for the hypothesis that the Black-white achievement gap is due to natural selection.³⁶ Polygenic variation associated with educational attainment is also inconsistent with the bell-curve hypothesis.³⁹

Since humans have control over their social environments, the only ethical response to racial disparities in a democratic society is to try to eliminate the social factors that produce them.^{31,40} This response is not only ethical but also a logical way to explore if racial disparities do, indeed, have a genetic etiology.³¹ Only after the environmental noise induced by systemic and institutional racism is eliminated (i.e., controlled) can we detect a reliable genetic effect on racial disparities. Thus, people who are interested in “proving” that racial inequality is genetic should logically support policy designed to reduce racial inequality.³¹ Paradoxically, however, many of the same scholars who claim that racial inequality is genetic usually also oppose policies designed to reduce such inequality,⁴¹ just like genetic essentialists in non-academic spaces tend to do.⁷

While such opposition might be a biological paradox, it is not a social paradox, as genetic essentialism is a form of motivated cognition that is most often used to justify discriminatory behavior.^{42–45} For example, genetic essentialism became a foundation of Western thinking during the 20th century^{32,46} as genetic ideas were distorted and misused to give scientific credence to white supremacy.⁶

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During and after the eugenics era, genetic essentialist assumptions about the nature of racial difference were inscribed into US laws, policies,^{6,40,47} and cultural artifacts,⁴⁶ including biology curricula.^{48,49} Today, essentialism is known to be a mediator of segregative behavior,⁴⁴ ingroup favoritism,⁴⁴ and interethnic hostility.⁴⁵ It is also a moderator of outgroup derogation and discrimination.⁴³

To grow up in America is to be surrounded by many sociocultural messages suggesting that genetic essentialism is ontologically accurate⁴⁶ and epistemically justified^{6,50,51} and very few messages suggesting otherwise.⁵² Take, for example, genetics education. Students are rarely taught the many ways in which genetic essentialism is ontologically flawed from a population genetics point of view in their genetics courses.⁴ They are rarely taught how biologists and anthropologists discredited essentialism in the mid-20th century by challenging the epistemology of racist science.^{4,6} Instead, when students encounter race during their genetics education, they are usually taught about racial differences in the prevalence of genetic diseases.^{4,5,53} Unfortunately, randomized controlled trials have found that learning about these differences can unintentionally increase belief in genetic essentialism among middle and high school students.^{18,54,55}

This paper argues that belief in genetic essentialism can be promoted or prevented depending on what we teach students about genetics and why we teach it. The paper begins by arguing that school is an important venue for the development of genetic essentialism. Through a review of the literature on genetics literacy,⁵⁶ the paper then advances the argument that a “humane” genetics education has the highest probability of reducing the prevalence of belief in genetic essentialism within schools. Humane genetics education differs from the basic genetics education offered to most students and also most standard views about how to reform genetics education because it has an anti-essentialist purpose¹⁶ derived from anti-racist educational approaches that value humanitarianism.^{57,58} The paper concludes by outlining a discipline-based educational research program to explore the potential of anti-essentialist genetics education.

The importance of genomics literacy in the development of genetic essentialism

Some adults believe that genetic essentialism is a self-evident, commonsensical, and objective way to view race.⁵ One reason why such adults make this error is because genetic essentialism of race is a form of a more widespread bias called psychological essentialism. Psychological essentialism is the belief that each living category (e.g., species, race, or gender) has an immutable and objective reality that cannot be observed directly (i.e., an essence) because it is internal to category members.⁵⁹ This essence is believed to be responsible for the respective similarities and differences within and between cate-

gories.⁵⁹ Consequently, a belief in essences leads people to infer that categories have an inductive potential, which, in turn, helps them to make predictions about how unknown individuals of a certain category will behave (e.g., stereotypes).⁵⁹

Psychological essentialism emerges early in human development,⁵⁹ and although it has been observed in several cultures,^{60,61} there is no direct genetic evidence that it is an inherited trait^a. Instead, several lines of evidence demonstrate that it is altered through language,⁶² culture,^{61–64} and schooling.^{18,54,65–68} A current working hypothesis is that psychological essentialism is built upon simpler cognitive biases (some of which may be innate) and that culture highly constrains the development of it.⁶⁹ For example, young children (i.e., age 4–5 years) in different cultures are known to essentialize animal and gender categories,^{64,70} but there is cross-cultural variation in the timing of when children begin to essentialize racial or ethnic categories.^{61,63,64,71–74} As far as we know, children (i.e., ages 3–5 years) in the United States tend not to conceptualize race in psychological essentialist terms⁶⁴ like adults do.⁵ Psychological essentialism of race develops at different ages in the United States^{63,64} (and elsewhere^{61,73}) because of differential exposure to cultural content^{5,64} and ethnic outgroups.^{74–76} Altogether, psychological essentialism of race appears to be more dependent on cultural input than essentialism of non-human categories or gender.^{63,64}

During school, US children grow in their tendency to essentialize race and they begin to develop a belief in genetic essentialism of race. For instance, between the ages of 5 and 10 years, evidence suggests that US elementary schoolers stop thinking of racial identity as subjective and flexible and they begin to think of it as natural and stable.^{63,64} Although European American children exhibit these changes later in childhood than African American children do,⁶³ racial essentialism becomes a stronger predictor of racial stereotyping in European American children during the course of elementary school as they realize that race is a salient concept for understanding society.^{65,67} Then, in middle school, when most students are formally introduced to Mendelian genetics during their science classes,⁷⁷ adolescents begin to believe that essences are genetic.⁶⁶ For example, adolescence is when people begin to favor genetic explanations for racially stereotyped traits like intelligence and athleticism rather than the environment or choice.⁶⁶

By the end of high school, US teenagers who attend rural and relatively homogeneous schools are more likely to essentialize race than those who attend schools in diverse

^aFor example, there appear to be no twin studies or genome-wide association studies [GWASs] that have estimated the narrow sense heritability of psychological essentialism. Also, apparently no candidate gene studies have been conducted on psychological essentialism. The claim that humans are born with a biological predisposition for essentialism is debatable, because any research on this claim will be confounded by gene-environment correlation.

cities.⁶⁴ However, the negative relationship between exposure to racial diversity and belief in genetic essentialism in European American high schoolers may be moderated by parental education,⁷⁵ as this negative relationship does not appear to exist among adolescents parented by non-college-educated caretakers.⁷⁵ Such moderation is probably due to the fact that exposure to racial diversity during college is associated with a reduction in belief in genetic essentialism in the European American undergraduate population.⁷⁶ Therefore, K–16 schools may be a cultural context that promotes or prevents the development of psychological essentialism of race in the United States.^{65,67}

Some scholars further argue that genetics education is a factor within schools that gives psychological essentialism a genetic “flavor.”^{4,18,19} Upon first analysis, it seems strange that an education in biology would have this effect. After all, genetic essentialism is a scientifically inaccurate view of intraspecific variation,^{4,6,19,78–80} and several studies have found that belief in species essentialism is positively correlated with misunderstandings of intraspecific variation and natural selection in children,^{81,82} undergraduates,⁷⁹ and adults.^{82,83} A biology educator committed to the scientific literacy of their students should therefore view genetic essentialism as problematic for learning because it is antithetical to evolutionary thinking. Consequently, a scientifically literate biology student should understand why genetic essentialism is genetically flawed. Yet, even though scientific literacy has long been a goal of science education reforms,^{84,85} belief in genetic essentialism persists in US society. Why is this the case?

To answer this question, the concept of scientific literacy and its relationship to genetic essentialism needs to be examined in detail in the context of genetics education. Scientific literacy can be understood in two different senses: the fundamental sense and the derived sense.⁸⁶ Reading and writing about scientific content is the fundamental sense of scientific literacy, and being knowledgeable about science is the derived sense of scientific literacy.⁸⁶ While these two senses are distinctly different cognitive performances, they are intimately related, because knowledge production in science depends heavily on the production and consumption of texts.⁸⁶

Fundamental literacy refers to the linguistic skills that individuals use to comprehend, interpret, analyze, and critique information in a scientific text.⁸⁶ Derived literacy, on the other hand, refers to the scientific knowledge that readers and writers of science use when consuming or producing information in a science text.⁸⁶ Knowledge is called derived literacy, because people can derive scientific knowledge by reading a scientific text.⁸⁶ This means that individuals who possess greater comprehension, interpretation, analysis, and critical reading skills (i.e., fundamental literacy) are more likely to construct an accurate understanding of the concepts and phenomena described by a science text (i.e., derived literacy).⁸⁶ Conversely, the comprehension, interpretation, analysis, and critique of information in a scientific text (i.e., fundamental literacy)

depends heavily on whether a person has the prior knowledge to make sense of the information described by a text (i.e., derived literacy).^{87,88}

From this perspective, fundamental genomics literacy is the ability to comprehend, interpret, analyze, and critique information in a genetics text, and derived genomics literacy is the genetic knowledge that facilitates this ability and ensues from it. This review summarizes research on the relationship between derived genomics literacy and genetic essentialism. It finishes by arguing for a need for more research on fundamental genomics literacy and genetic essentialism, because this body of research is nonexistent, yet critical to preventing the spread of white supremacy in the United States.

Derived genomics literacy can be broken down into the particular kinds of knowledge that students possess about genetics, which includes ontological and epistemic knowledge. Human genetic ontology broadly refers to the kinds of genetic phenomena that exist in humans and how these phenomena relate to, or cause, one another.⁸⁹ Genetic epistemology broadly refers to the many different ways scientists have produced knowledge about human genetic ontology, as well as the strengths and limitations of this knowledge.⁹⁰ Since there are several different ontologies and epistemologies in human genetics research,^{91–94} since scientific concepts are used as tools to solve particular problems,⁹⁵ and since educators have different purposes for teaching science,⁸⁵ different combinations of ontologies, epistemologies, and purposes create different conceptions of derived genomics literacy. These conceptions, in turn, have different relationships with genetic essentialism. The three conceptions that are the focus of this review are basic genetics literacy, standard genomics literacy, and humane genomics literacy.¹⁶ The evidence reviewed below suggests that biology education does more to strengthen belief in genetic essentialism than to weaken it, because it is oriented toward basic genetics literacy and not humane genomics literacy. Table 1 outlines examples of the content that could be learned when developing each of these different conceptions of derived genomics literacy.

Basic genetics literacy refers to Mendelian and molecular genetics, because these fields constitute the basis of genetic knowledge in most genetics curricula and standards.^{19,50,96–98} Having basic genetics literacy means having the ontological knowledge of how meiosis, sexual reproduction, and homologous recombination generate genetic diversity and how the structure of DNA encodes information needed for protein synthesis.⁹⁸ Basic genetics literacy also includes the epistemic knowledge that these concepts were constructed through reductionist epistemologies like breeding studies or pedigree analysis, and molecular methods (e.g., gene knockout studies) (B.M.D., M. Weindling, and D.M. Lee, unpublished data). Altogether, basic genetics literacy is an understanding of the processes that create genetic diversity (i.e., genotypes) within an individual or family and how

Table 1. Contrasting BGL, SGL, and HGL

BGL	All of your DNA is called your genome, and it consists of more than 3 billion nucleotides. Some sequences of nucleotides that are found within your genome are called genes because they encode information to make your body and maintain it. Humans get half of their genome from each parent, because of meiosis, independent assortment, homologous recombination, and sexual reproduction. These processes also ensure that each human has two different versions of each of gene in their genome, which are called alleles. Combinations of alleles are called genotypes. Your unique physical traits are called phenotypes. The cells in your body decipher your genotypes and use them to make your phenotypes through a process called protein synthesis. Scientists know that genotype-phenotype relationships exist because of selective breeding experiments and pedigree analysis. Pedigree analysis shows that certain genotype-phenotype relationships are more common in certain human families or ancestry groups (e.g., diseases like sickle cell anemia in Africans).	
Population thinking		Multifactorial genetics
SGL	Within-group genetic variation is a measurement of the amount of loci in variable DNA that differs, on average, when comparing the genomes of individuals of the same population. ²⁹ Between-group variation refers to the extra amount of loci that differ, on average, when comparing the genomes of individuals in different populations. ²⁹ Patterns of genetic variation in humans result from a variety of interacting factors, including serial founder effects, genetic drift, recent human migrations, admixture, and natural selection.	Most forms of human variation are not discrete, nor are they explained by variation in one gene. ⁹⁷ Rather, complex traits are best explained by multifactorial models of inheritance, where variation in a trait is influenced by a combination of environmental effects, polygenic effects, and gene-by-environment interactions. ¹⁰⁰⁻¹⁰² Some of these factors might be the best explanation for variation within populations, and others might be the best explanation for variation between populations. Figuring out which factors explain intra- and inter-population variance is scientifically difficult.
HGL	Genetic variation within a group is a measurement of the number of nucleotides in variable DNA that differ, on average, when comparing the genomes of individuals of the same population. ²⁹ Between-group variation refers to the extra number of nucleotides that differ, on average, when comparing the genomes of individuals in different populations. ²⁹ When geneticists analyze variable DNA, they have found, repeatedly, that continental populations of humans exhibit low levels of genetic differentiation because there is proportionally more genetic variation within human populations than between them. ²⁹ While these patterns mean that human groups differ genetically, they also mean that genetic essentialism is inaccurate. For example, it is incorrect to assume that stereotypes are “genetically” true, since most genetic variation is found within groups. Likewise, the fact that most alleles are widely distributed and that private alleles are rare within populations means that “races” are genetically alike and not categorically distinct entities.	Studies of multifactorial inheritance make it wrong to claim that racial disparities are genetic, because they show that the impact of genes on human traits is not stable across environments. Rather, this relationship changes from environment to environment. In some environments, genes matter more, and in others they matter less, or not at all. ¹⁰³ Additionally, studies that explore the influence of genes on human traits have limitations that prevent them from explaining racial difference. ^{37,104} One limitation is called gene-environment (g-e) correlation, which refers to the fact that people inherit their genes along with their environments. ³⁷ It is ethically and methodologically impossible to conduct a study in humans that eliminates the problem of g-e correlation. Therefore, if two races have different trait values, different allele proportions, and different environments, it is difficult to know if their trait difference is due to genes, environments, or the interactions between them. ³⁰ Because different races experience different social environments due to structural racism, ¹ genetic studies cannot be used to conclusively support the claim that racial disparities are genetic.

BGL, basic genetics literacy; SGL, standard genomics literacy; HGL, humane genomics literacy.

scientists know that this genetic diversity affects trait variation (i.e., phenotypes) from one ancestor to the next within a family.¹⁶ For these reasons, the purpose of a basic genetics education is to help students understand the relatively simple molecular story undergirding Mendelian inheritance, which, in humans, is usually taught through rare diseases caused by variation in a single gene.¹⁹ For example, the phenotypes that students often learn about in a basic genetics education are the monogenic diseases that occur more frequently in particular groups (i.e., sickle cell anemia in African Americans and cystic fibrosis in European Americans).

Basic genetics education does not help students understand the complex interplay between genes and environments explored in modern genomic science,¹⁹ nor does it help students conceptualize populations as aggregates of genetically varying individuals who differ in a continuous manner (i.e., more or less kind of way) on a variety of quantitative traits.¹⁹ Instead, basic genetics education conceptualizes human variation in terms of types (i.e., phenotypes and genotypes), and it explains such variation through a single causal factor (i.e., the gene). Thus, basic genetics literacy can be used to make a genetic essentialist argument rather easily.^{6,19,50,91} For example, a student

could infer from a basic genetics education that races are types of people who have different phenotypes because they have different genotypes. If such a student later encounters information that intelligence is heritable and that races differ in intelligence, then their basic genetics literacy could lead them to argue (incorrectly) that racial inequality is genetic.

Standard genomics literacy refers to the knowledge that is underemphasized in genetics standards and curricula at the K–12 and undergraduate levels.^{96,97} It is the ontological and epistemic knowledge that many reform-based genetics education researchers would like to add into new standards.¹⁶ It is called standard genomics literacy not only because it is missing from standards but also because it represents the standard concepts and methods that the field of genomics employs to produce knowledge. It includes ontological knowledge about the relationships between genes, environments, and traits within and between populations. It also includes epistemic knowledge about modern statistical methods in genomics, such as GWASs, ancestry inference methods (e.g., Bayesian machine learning algorithms), and cohort studies (i.e., case-control/retrospective/prospective).

Instead of learning that there are types of humans, standard genomics education helps students to understand

that a population is a set of potentially interbreeding individuals who vary in a continuous manner. They also learn that population variation in human traits is influenced by polygenic factors; physical, social, and ecological factors; and the effects of gene-by-environment interactions and epistasis. Thus, standard genomics literacy includes ontological and epistemic knowledge about population thinking and multifactorial causation.¹⁶ Knowing that a human population is a set of continuously varying individuals and that most human traits are influenced by multiple interacting factors makes it difficult to advance genetic essentialist arguments.¹⁶ But it is not impossible. Since standard genomics literacy is not derived for the explicit purpose of refuting genetic essentialism, it could be used by a learner to retrofit their belief in essentialism.¹⁶ For example, a student might justify their belief in genetic essentialism through the concept of polygenic inheritance after a standard genomics education.¹⁶

Humane genomics literacy is founded upon basic genetics literacy, and it is inclusive of the ontological and epistemic knowledge of standard genomics literacy.¹⁶ It differs from standard genomics literacy not in content, but in purpose.¹⁶ It is the story of how population thinking and multifactorial genetics refute genetic essentialist beliefs about race.¹⁶ It is a more humane form of knowledge than standard genomics literacy because it is knowledge that has been structured by the educator so that it can only be used by students to make anti-essentialist arguments about race.¹⁶ It is also anti-racist knowledge because it can be used to critique the argument that racial inequality is unworthy of redress because it is genetic. But even though humane genomics literacy has an anti-essentialist and anti-racist purpose, it is not anti-realist. Rather, it is built upon the assumption that racial phenomena exist, and that the genomic sciences have something to say about them. Genomics says that essentialism is an inaccurate conception of race, but it does not rule out other conceptions of race. For example, several philosophers of race have argued that modern genomic findings are consistent with some forms of biological racial realism and some forms of social racial realism.²⁸ Yet, other philosophers have also argued that the epistemic limitations of scientific methods require us to be skeptical of genetic explanations for social inequalities between races.^{28,37,38,40,99}

Humane genomics literacy is not colorblind or anti-scientific. It is a label for the derived literacy that population geneticists have used for decades in critiques of racist arguments.⁶ It is more than the knowledge that genetic variation is proportionally greater within “races” than between them³³ or that inter-racial trait variance can be explained differently than intra-racial trait variance.³⁵ It is knowledge of how to use findings like these to refute genetic essentialism.

Since concepts are cognitive tools that humans have created to solve their problems,⁹⁵ one might wonder how these different genetic literacy tools will affect the problem

of genetic essentialism. The following section reviews research to argue that: (1) basic genetics instruction is probably the wrong tool for helping students to refute genetic essentialism, (2) standard genomics instruction is an imprecise and unreliable tool for this purpose, and (3) humane genomics instruction is a reliable tool that helps novices criticize essentialism. The psychological basis for these claims comes from genetic essentialism theory,¹⁰ which is a social-cognitive theory that explains how genetic information influences the development of genetic essentialism.

Genetic essentialism theory contends that exposure to genetic information that leads learners to believe that there is a specific, proximate, stable, and immutable relationship between genes and traits tends to increase belief in genetic essentialism by influencing causal reasoning in a deterministic manner.¹¹ Also, it contends that genetic information that leads learners to believe that individuals of the same group are genetically uniform and that different groups are genetically discrete tends to increase belief in genetic essentialism by exacerbating social categorization.¹¹ Consequently, curriculum and instruction that help learners to understand the genetic flaws in specificity, proximity, stability, immutability, determination, uniformity, and/or discreteness beliefs should reduce learners’ beliefs in genetic essentialism.¹⁶ From this perspective, basic genetics instruction is ineffective because it can increase the strength of these beliefs, standard genomics instruction is unreliable because it does not help learners understand how genetic concepts refute these beliefs, and humane genomics instruction reliably reduces belief in genetic essentialism because it is learned for the purpose of refuting such beliefs.

The influence of basic genetics instruction on belief in genetic essentialism

Evidence suggests that certain ontological content in the basic genetics curriculum could contribute to the development of genetic essentialism through the causal reasoning and social categorization mechanisms of genetic essentialism theory. Therefore, basic genetics instruction appears to be the wrong tool for reducing belief in genetic essentialism. Experiments have shown that reading basic genetics texts that include the blueprint metaphor for DNA¹⁰⁶ and those that include “gene for” language¹⁰⁷ cause elevated levels of genetic essentialism in adults because of changes in causal reasoning about genes related to specificity, proximity, and stability beliefs.^{11,16} Several other qualitative studies with students also support this hypothesis.^{19,108} Yet, there is also correlational evidence that adults with fewer basic genetics misconceptions are less likely to believe in genetic essentialism,¹⁴ and a study that explored the relationship between relatively high-quality basic genetics instruction and belief in genetic essentialism in adolescents found no relationship between

the two.¹⁶ Therefore, learning about basic genetics concepts may not be the problem. Rather, ineffective basic genetics instruction that fails to redress a student's genetic misconceptions may increase the risk that a student develops a greater belief in genetic essentialism.

A further escalation of this risk could occur when basic genetics instruction includes a discussion of racial difference. Three randomized controlled trials^{18,54,55} have demonstrated that when secondary biology students (i.e., middle and high school) learn from a curriculum describing the prevalence of monogenic disorders in different racial groups—a canonical basic genetics literacy phenomenon—it causes them to believe in genetic essentialism more. For example, Donovan⁵⁴ compared 8th grade students ($n = 43$) who learned about genetic disease prevalence (e.g., sickle cell anemia) in different races to those who learned about it without race. He found that the group who learned with the racialized learning materials was significantly more likely to believe that races differed in their genetic potential for intelligence, science ability, and academic ability.⁵⁴ Students inferred that if each race has its own disease, then each race must be genetically uniform, which makes races differ in many other ways because of their “unique” genotypes (i.e., discreteness beliefs). In two more double-blinded randomized controlled trials, Donovan then replicated these findings with 7th–9th grade students in biology classrooms.^{18,55} These studies show that when basic genetics instruction discusses racial difference, it can unintentionally increase belief in genetic essentialism among adolescent-aged students by interacting with beliefs implicated in social categorization.

Altogether, this literature suggests that belief in genetic essentialism will be increased when genetics educators discuss race in conjunction with ineffective basic genetics instruction that uses inappropriate language (i.e., “gene for”) and metaphors (i.e., DNA as a blueprint rather than a recipe). Educational experts argue that this is the modal approach to secondary and undergraduate genetics education.^{19,97} For example, the sciences of quantitative genetics and population/evolutionary genetics, which add complexity to the simpler stories of basic genetics literacy, tend to be described in a single chapter at the end of undergraduate genetics textbooks,¹⁰⁹ and they tend to be absent from high school texts.¹⁹ Moreover, biology textbooks around the world tend to use gene-determinist concepts and language when describing genes.^{50,110–113} And, the majority of American texts also discuss racial differences in the prevalence of genetic diseases.^{4,49,53}

When this modal approach to genetics education is combined with the many cognitive demands of learning genetics, it becomes clear that basic genetics instruction is the wrong tool for reducing belief in genetic essentialism. Genetics is difficult to learn because it requires students to reason about the influence of genes across the cellular, organismal, and population levels.⁹⁸ Yet, many studies have found that students enter and leave basic genetics instruction without being able to reason genetically

across these levels.¹⁹ And, they also leave with their deterministic misconceptions intact.¹⁹ Part of the reason for this problem is that basic genetics instruction is often ineffective in helping students to integrate the models of molecular and Mendelian genetics,^{114,115} and it does not help students understand population-level variation in complex traits¹⁶. These failures of basic genetics instruction mean that students have difficulty understanding protein synthesis and the influence of proteins in the bodies of organisms.⁹⁸ It also means that students develop little knowledge about how the environment gets into the body to moderate gene expression by interacting with proteins.¹¹⁶ If basic genetics instruction does not help students to reason across all levels of biological organization (i.e., cellular, organismal, population) to construct a multifactorial explanation of human difference, then why would it help students to disbelieve genetic essentialism?

The influence of standard genomics instruction on belief in genetic essentialism

Correlational and comparative studies on the relationship between standard genomics literacy and genetic essentialism yield inconsistent results. For example, in a sample of 427 Brazilian undergraduates, Gericke et al.¹¹⁷ found that standard genomics literacy was not correlated with belief in genetic determination. Yet, Donovan et al.¹⁷ found that standard genomics literacy had a weak, but statistically significant, and negative, relationship with belief in genetic essentialism in a geographically diverse sample of American high schoolers ($n = 721$, 9th–12th grade). With regard to comparative studies, Jamieson and Radick¹⁰⁸ used a quasi-experimental design to explore if British undergraduates ($n = 56$) learning from a basic genetics curriculum or a standard genomics curriculum differed in gene determinist beliefs about human ability, a key component of the causal reasoning mechanism. Although their study was limited because of selection bias of participants into different treatment conditions, students did not differ in belief in genetic determinism before treatment. Yet afterward the students who learned from the standard genomics curriculum had significantly lower average belief in determinism on the posttest compared to the pretest, whereas those who learned from the basic genetics curriculum exhibited no significant pre-post change. Although the researchers argued that the learning conditions caused these effects, selection bias, measurement problems, and issues with the quality and transparency of their statistical analyses (e.g., insufficient reporting of statistics and conflating a within-subjects change with a between-condition effect) make this conclusion somewhat tenuous.

A reliably negative relationship between standard genomics instruction and belief in genetic essentialism is also tenuous, because at least one randomized trial has found that exposure to standard genomics information can increase belief in genetic essentialism in adults with low biology knowledge.¹¹⁸ For example, Morin-Chassé¹¹⁸ explored if belief in genetic essentialism in

adults ($n = 965$) was affected after reading a text that explained that genes and the environment each influence human behaviors and that genes are a better explanation for intrapopulation variation than interpopulation variation. This is basically the content outlined in Table 1 under the column on multifactorial genetics. Morin-Chassé¹¹⁸ compared this treatment text to a control text that included no genetic information and found that adults with biology bachelor's degrees in the control and treatment conditions did not differ in their post-experimental belief in genetic essentialism. Yet adults without biology bachelor's degrees in the treatment condition had significantly greater belief in genetic essentialism than those without such degrees in the control condition.¹¹⁸ This result is consistent with the claim that the standard genomics text increased belief in genetic essentialism among participants who lacked the appropriate prior knowledge to understand it.

Altogether, these findings suggest that standard genomics instruction has an unreliable relationship with belief in genetic essentialism. In some populations of students it might have a negative effect, and in other populations it might have no effect or even a positive effect. Currently, no research has characterized the clinical sources of variation that might be responsible for such treatment-effect variability, nor has anyone conducted a high-quality causal inference study testing if a well-designed standard genomics education reduces belief in genetic essentialism. What we do know is that standard genomics instruction is uncommon in high schools and in introductory genetics courses at the undergraduate level.^{19,50,96,97,119}

The influence of humane genomics instruction on belief in genetic essentialism

Several studies demonstrate effects consistent with the claim that humane genomics instruction can reliably decrease belief in genetic essentialism through the mechanisms of genetic essentialism theory. For example, through a randomized cross-over trial with 8th and 9th grade students ($n = 166$), Donovan et al.¹²⁰ demonstrated that belief in genetic essentialism could be reduced through five lessons that taught about the population thinking component of humane genomics literacy (see Table 1). These findings were then replicated in two more randomized control trials with adults ($n = 176$) and with biology students ($n = 721$, 9th–12th graders) using a 45-min computer-based intervention about this same idea.¹²⁰ Consistent with the categorization mechanism of genetic essentialism theory, mediation analyses in all three experiments¹²⁰ showed that the humane genomics intervention reduced belief in genetic essentialism by changing how students perceived inter-racial discreteness and intra-racial uniformity. Next, Donovan et al.¹⁶ built out the five-lesson unit on the population thinking component of humane genomics literacy from their first study¹²⁰ into a 6-week unit that informed students about multifactorial genetics from a standard genomics perspective before

informing them about population thinking from a humane genomics perspective.¹⁶ Using a quasi-experimental design ($n = 254$ students in 7th–12th grade), they then compared this intervention to basic genetics instruction.¹⁶ When compared to classrooms learning with basic genetics curriculum, they found that classrooms that learned from the standard/humane genomics intervention grew significantly more in their knowledge of multifactorial genetics ($p < 0.05$) and decreased more on three measures of genetic essentialism (p values < 0.05) during the 6 weeks of instruction. Some evidence suggests that similar effects occur in undergraduates. For example, Hubbard²⁰ found that belief in essentialist misconceptions about race declined significantly after students in her large introductory anthropology course learned about population thinking and biosocial causation from a humane genomics perspective.

Humane genomics literacy also appears to interact with a student's standard genomics literacy to reduce their belief in genetic essentialism. For instance, Donovan et al.¹⁷ found that 11% of the between-student variation in belief in genetic essentialism in their randomized control trial was associated with standard genomics literacy about multifactorial genetics acquired prior to the study, 4% was explained by whether students learned from a humane genomics curriculum on population thinking ($R^2 = 0.04$), and 3% was associated with the interaction between this curriculum and standard genomics literacy ($R^2 = 0.03$). They found that students with more standard genomics literacy were better active readers of the humane genomics curriculum materials, which in turn allowed them to construct more knowledge about how patterns of genetic variation refuted genetic essentialism.¹⁷

They also found a different number needed to treat among students with high and low standard genomics literacy. For every 40 students with low standard genomics literacy treated with a humane genomics intervention, 1 additional student could be prevented from believing in genetic essentialism.¹⁷ Among students with high standard genomics literacy the number needed to treat was 12.¹⁷ At present, no studies have estimated the prevalence of humane genetics curricula in K–16 American genetics education. However, the studies that have explored how race is conceptualized in the genetics curriculum suggest that students rarely receive a humane genomics education.^{4,5,53,121} Therefore, there is little reason to believe that genetics education does much to prevent belief in genetic essentialism through humane genomics instruction.

Implications for genetics education research

Since most genetics instruction emphasizes basic genetics literacy, and many genetics education experts advocate for more standard genomics literacy (and not humane genomics literacy),^{19,50,119,122} it is possible that contemporary genetics education does more to increase belief in

genetic essentialism than to decrease it.⁴ Although no one has directly tested this hypothesis, syntheses of research on genetics education suggest that students bring their genetic essentialist biases into the classroom.¹⁹ Once in the genetics classroom, these biases interact with similar biases in teachers¹²³ and textbooks¹⁹ to further exacerbate student belief in genetic essentialism.¹⁹ When students leave the classroom and make sense of genomic information in the media as adults, research also suggests that their belief in genetic essentialism grows,^{15,107,118,124–126} especially when they do not have the appropriate derived literacy to make sense of such media.^{15,19,118} Therefore, the most current evidence suggests that the system of K–16 genetics education inadequately inoculates students against belief in genetic essentialism.¹⁹ A consequence of this inadequacy is that students probably lack the ability to identify and critique genetic essentialist messages outside of school in the media. This prediction is warranted, because derived and fundamental literacies bidirectionally affect one another⁸⁶ and because genetics education primarily focuses on basic genetics literacy.

Although this hypothesis is untested, it is consistent with studies of adults that explore how the public responds to genetic findings in the media.^{15,118,124–126} Simply put, there is no reason to expect our youth to develop into adults who disbelieve genetic essentialism if formal genetics education does not help youth to understand the flaws in genetic essentialism. Therefore, it should be unsurprising that some journalists continue to misconstrue the findings of population genetic studies to advance the argument that racial inequality is genetic.^{27,127,128} After all, genetics education rarely teaches students why they should be skeptical of this claim. Likewise, it should be unsurprising that American adults grow in their belief in genetic essentialism after reading the results of their own genetic ancestry test or those of others.^{15,124,125} After all, genetics education rarely helps students make sense of patterns of human genetic variation to refute essentialism. Nor should it be surprising that white supremacists continue to cloak their racial animus through genetic arguments about “human biodiversity.”¹²⁹ After all, genetics education rarely helps students understand how Dobzhansky, Lewontin, Feldman, and other modern-day population geneticists have crafted arguments to challenge white supremacy. At best, genetics education does little to prevent genetic essentialism, and at worst it indirectly contributes to it through the kind of instruction it offers to students. While it is defensible to argue that some genetic essentialists will persist in their beliefs regardless of the genetics education that is provided to them, it is indefensible to claim that genetics education is irrelevant to genetic essentialism.

To better understand if and how genetics education influences broader social discourses about race in the United States, more research is needed on the interplay of derived and fundamental genomics literacy. School is not where most American adults learn most of their science.¹³⁰ Many adults learn most of their science in informal set-

tings—the news, the internet, television, movies, and social media.¹³⁰ The ability to identify and dismiss essentialist misinformation in the media is therefore integral to preventing public belief in genetic essentialism. Yet, at the time of this writing (June 18, 2021), a search on google scholar including the terms “fundamental genomic literacy” or “fundamental genetic literacy” and “genetic essentialism” yields no publications matching these terms^b. Thus, we know next to nothing about how students use genetics knowledge derived within school (i.e., derived genomics literacy) to comprehend, interpret, analyze, and critique genetic essentialist messages they encounter outside of school in science journalism or on social media (i.e., fundamental genomics literacy). Research on this relationship is so critical because it will tell us if and how genetics education leads students to believe in the genetic misinformation that is spread through social media by white supremacists as they recruit others to their cause¹²⁹ or whether it helps them to criticize such media.

Of course, the previous argument implies that a relationship between derived and fundamental genomics literacy will be found if we go looking for it, and that genetics education can influence reasoning outside of school. Neither of these outcomes is guaranteed, because only 4% of high school science teachers report that they teach their students informational reading and writing strategies (i.e., fundamental literacy),¹³¹ and many educational studies have established that people have difficulty transferring their knowledge across reasoning contexts.^{87,132} Given these findings, it would be wise for any research program on scientific literacy, genetics education, and genetic essentialism to move beyond a positive test strategy that affirms the hypotheses laid out in this review. The positive test strategy in science involves designing studies that produce evidence consistent with one’s hypotheses.¹³³ Most of the studies reviewed above used this strategy, because it is commonly used when exploring new hypotheses.¹³³

Moving forward, research on genetics education and genetic essentialism should attempt to produce evidence showing that there is no relationship between genomics literacy and belief in genetic essentialism, as well as studies that explore alternative hypotheses that account for any relationships between the two. Such studies are needed, because they can help us understand the kinds of genetics instruction that reliably increase, decrease, or have no effect on belief in genetic essentialism. Likewise, they can help us understand the teacher characteristics that positively, negatively, or do not affect belief in genetic essentialism among students. Finally, such studies can help us understand how curriculum and teacher variation interact with student-level factors and contextual factors to promote or prevent belief in genetic essentialism outside of school.

^bA more liberal search string using the terms “genetic essentialism” AND “fundamental” AND “literacy” AND “genetic” yielded 196 results on July 12, 2021. None of the publications in this sample explored the relationship between fundamental literacy in genetics and genetic essentialism.

There is much research to do, and one might wonder who is qualified to do this kind of interdisciplinary research. There is a case to be made that one would need training in science education; developmental, social, and cognitive psychology; and genetics to tackle the problem of genetics education and genetic essentialism. In this case, a geneticist might argue that genetic essentialism is not their educational problem, and it is beyond the scope of their training to address. But, of course, this is a relatively weak argument. Public belief in genetic essentialism is a problem created, in part, by the content and focus of genetics research.^{6,124} Geneticists produce the knowledge that is misappropriated in genetic essentialist arguments, and geneticists are aware of their role in this problem and are apparently concerned about it.¹³⁴ If this is not the case, then why did the American Society for Human Genetics denounce attempts to link white supremacy to genomics?¹³⁵ Why have some geneticists spent so many hours reading and critiquing books that advance genetic essentialist arguments (e.g., Coop et al.²⁷)? To an outsider, the obvious answer to these questions is that geneticists must know that genetic essentialism is their problem to address. They must deeply care about this problem. Otherwise, why go through the trouble? Furthermore, geneticists have the relevant expertise and authority to point out the flaws in genetic essentialist arguments. They have a strong intellectual history of tackling this problem,⁶ and every time they teach about race and genetics they probably field questions from students that are unambiguously essentialist.

Given these arguments, a more appropriate question to ask is how do we facilitate interdisciplinary research on the problem of genetic essentialism that leverages the expertise of geneticists, social scientists, and educational researchers? The answer to this question arguably involves discipline-based educational research (DBER). DBER “investigates learning and teaching in a discipline from a perspective that reflects the discipline’s priorities, worldview, knowledge, and practices.”¹³⁶ Singer and Smith¹³⁶ explain that the goals of DBER are to (1) understand how people learn the concepts, practices, and ways of thinking in a science discipline; (2) understand the nature and development of expertise in a discipline; (3) help identify and measure appropriate discipline-specific learning objectives and instructional approaches; (4) translate DBER findings into classroom practice; and (5) identify approaches to make learning in the discipline broad and inclusive. The goals of a DBER program in genetics education could be to: (a) understand how people learn and use genetic concepts to make sense of race; (b) understand the nature and development of belief in genetic essentialism in relation to the nature and development of genetic expertise; (c) identify and measure appropriate learning objectives and instructional approaches to help students understand the flaws in genetic essentialism; (d) study how to translate findings from research programs (a)–(c) into practice in classrooms across K–16 genetics education; (e) study if and how research-based changes in the purpose, practice,

and content of genetics education affect the inclusion, belonging, and participation of students of different races in genetics. If universities provide more institutional support for DBER centers where geneticists, social scientists, and educational researchers work together to train new PhD students in these research areas, then perhaps we will have the knowledge we need to put an end to genetic essentialism. Establishing these research centers might be politically challenging, but the knowledge they produce will be socially valuable.

To evaluate the plausibility of the claim that genetic essentialism can be ended through genetics education, we need answers to many pressing questions. For example, how does epistemic knowledge of genetics influence belief in genetic essentialism? How do basic, standard, and humane genetics literacies interact with one another and with knowledge about race learned in other disciplines (e.g., history or social sciences) to influence the development of belief in genetic essentialism? If the development of humane genomics literacy helps students to disbelieve essentialism, then what kinds of racial conceptions do students construct to fill the void left behind? How do we support teachers in this kind of teaching? What are the boundary conditions that limit the impact of genetics education on belief in genetic essentialism? How do the effects of our interventions vary across different sociodemographic groups of students, such as students of different racial backgrounds? How do the effects vary over time? Until these questions are answered, it is hard to imagine crafting any kind of educational policy that could lead to enduring changes in the prevalence of public belief in genetic essentialism in the United States. But if all genetics educators taught genetics to refute genetic essentialism, then it is hard to imagine how genetic essentialism could live on in our culture. Humans created genetic essentialism, and humane genomics educators can help to end it.

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Declaration of interests

The author declares no competing interests.

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