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Choosing mates: good genes versus genes that are a good fit

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Female choice for male ornamental traits is widely accepted as a mechanism by which females maximize their reproductive success and/or offspring quality. However, there is an increasing empirical literature that shows a fitness benefit of genetic diversity and a tendency for females to use genetic dissimilarity as a criterion for mate choice. This genetic compatibility hypothesis for female mate choice presents a paradox. How can females use both an absolute criterion, such as male ornamentation, and a relative criterion, such as genetic dissimilarity, to choose their mates? Here, we present potential solutions for this dilemma and the empirical evidence supporting them. The interplay between these two contrasting forms of female mate choice presents an exciting empirical and theoretical challenge for evolutionary ecologists.

In recent years, there has been an increasing consensus that ornamental traits are condition-dependent signals of male quality that are used by females to assess potential mates and thereby gain resources or genetic benefits for their offspring [1–4]. This indicator model of sexual selection has been applied successfully to explain traits such as the antlers of deer [5], the exaggerated eye stalks of diopsid flies [6], and the brightly colored plumage of birds [7]. However, indicator (or handicap) models are not the only models for adaptive mate choice. Trivers suggested that selection should favor a choice of a mate that is most compatible in terms of producing adaptive gene combinations in the offspring [8]. Only recently, however, has this genetic compatibility hypothesis gained empirical support and widespread consideration as an explanation for patterns of mate preference [9–14] (Boxes 1,2).

Ornaments and good genes versus dissimilarity and compatibility

Female mate preferences for ornamentation versus choice based on genetic dissimilarity presents an interesting problem that is only beginning to catch the attention of evolutionary biologists. Male ornamentation can signal good genes that would increase offspring fitness. Genetic dissimilarity of potential mates can also result in fitness benefits for offspring in the form of genetic compatibility. Thus, sires with good genes and sires that are optimally genetically dissimilar to their mates can provide fitness benefits to their offspring (Box 1) and, therefore, generate selection for female mate preferences (Box 2). However, for most females, the most-ornamented male is not the most genetically compatible. If females choose mates for good genes, (i.e. genes that are linked to the expression of ornamental traits) they mate randomly with respect to genetic dissimilarity, because the benefits accrued by mating with the most ornamented males are not contingent on the genotype of the female.

Herein lies a paradox. A large body of evidence supports female preferences for ornamental traits [1–4], but theory and an increasing number of empirical studies suggest that females should benefit by choosing genetically dissimilar mates (Boxes 1,2). To date, this apparent conflict between female preferences based on the expression of male ornaments and preferences for genetic

Box 1. Does compatibility matter?

In sexually reproducing organisms, offspring genotypes are the result of combinations of maternal and paternal gametes. Whether females gain more by choosing on the basis of good genes or by matching their genotypes to potential mates depends on the degree to which offspring fitness is affected by specific combinations of maternal and paternal alleles or by particular alleles irrespective of other alleles at a locus. There is considerable evidence for a link between overall heterozygosity and fitness [28,46–50], but exactly how heterozygosity acts on fitness is often unclear [48]. A direct fitness benefit conveyed by particular combinations of maternal and paternal alleles can operate either by masking deleterious alleles (dominance) or through a heterozygote advantage that is independent of deleterious effects in homozygous genotypes (overdominance) [50].

Indeed, there are many examples of particular combinations of alleles contributing to variation in fitness. Perhaps the best example concerns the major histocompatibility complex (MHC) and the function of the vertebrate immune system [31,51–54]. Although it is thought that population-level processes, such as the influence of environments containing multiple pathogens or Red-Queen effects, are primarily responsible for maintaining diversity at MHC loci, there is evidence that individual-level diversity at particular MHC loci conveys a heterozygote advantage [55]. Heterozygote advantage has also been documented for malaria resistance in hemoglobin genotypes in humans [56] and for cholera resistance in mice and humans at the cystic fibrosis trans-membrane conductance regulator gene [57]. In a review of data from humans, mice, and chickens taken from several loci ranging from genes encoding secretor blood groups to myelin protein to neurotransmitters, Comings and MacMurray found evidence for loci-specific heterozygote advantage in ~50% of loci [50]. Thus, there is ample evidence that particular combinations of maternal and paternal alleles affect offspring fitness, but does this affect on offspring fitness lead to female mate preferences for genetically dissimilar males?

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Box 2. Do females use genetic dissimilarity to choose mates?

Given that particular combinations of maternal and paternal genotypes affect offspring fitness, females would benefit by making mate choice decisions based on genetic dissimilarity (for simplicity's sake, we focus here on mate choice in females but we recognize that there are cases where mate choice can also operate in males). Mate choice based on the assessment of male ornamentation and the fitness consequences of those choices are well documented [2], but what about the evidence for female choice for genetic dissimilarity? There is increasing empirical evidence from both field and laboratory studies that genetic compatibility is a consequence of female mate preferences favoring genetically dissimilar males [35,36,44,45,58–64].

Evidence for female choice for genetically dissimilar males has been found in many organisms. A conspicuous example of genetic compatibility as a consequence of mate choice is the selection against self-fertilization in flowering plants [34,65]. There is also increasing evidence for postcopulatory choice for genetically dissimilar males among female animals [14]. Fertilization success in a laboratory population of the marsupial *Antechinus agilis* was negatively associated with allele sharing [35]. Tregenza and Wedell found that female field crickets *Gryllus bimaculatus* reduced the likelihood of hatching failure, suffered from mating with sibs, when mated polyandrously to a sib and non-sib, indicating postcopulatory choice for sperm from unrelated males [36].

There is also evidence for precopulatory choice for genetically dissimilar males. Humans, mice and fish are known to use olfaction to make self-referential decisions of attractiveness based on major histocompatibility complex (MHC) diversity [28,29,42,62]. Female sand lizards *Lacerta agilis* prefer to associate with odor samples that are obtained from males with dissimilar MHC genotypes [64]. Social pairings of females to genetically dissimilar males suggest that free-living female savannah sparrows *Passerculus sandwichensis* are making mate choice decisions that are based on genetic compatibility [44].

Studies of passerine birds hint at a role for genetic compatibility in explaining the prevalence of multiple mating by socially monogamous females. Foerster *et al.* have shown that blue tits *Parus caeruleus* young sired by extra-pair males are more heterozygous than are their within-pair half sibs [23].

Box 3. A paradox: theory and empirical evidence

Colegrave *et al.* proposed an insightful model that deals specifically with the antagonism between female choice for good genes resulting in directional selection on male ornaments and female choice on the basis of genetic compatibility [16]. This model poses two competing female genotypes: females who either mate singly based on precopulatory choice for high quality males or females who mate multiply. Both females in this model are unable to assess the compatibility of male genotypes before mating. Instead, females who mate multiply rely on sperm choice within their reproductive tracts to sort out the most genetically compatible sires. The relative fitness of females that mate monogamously based on male quality versus those who mate polyandrously is a function of the cost of having offspring sired by low-quality males, the cost of having offspring sired by genetically incompatible males, and the degree to which polyandrous females can impose some postcopulatory discrimination between compatible and incompatible sperm.

Colegrave *et al.*'s model is the first theoretical treatment of this paradox, but the authors deal only with the fitness of females who mate singly, presumably owing to choice for good genes, versus that of females who mate multiply, presumably owing to the benefits associated with genetic compatibility, a benefit only realized through postcopulatory choice. This model does not deal directly with the increasing empirical evidence that females can exercise precopulatory choice on the basis of genetic dissimilarity. However, by reducing the cost of polyandry to zero Colegrave *et al.* generated a scenario that is analogous to the case in which females can exercise precopulatory control and mate singly and still avoid genetically incompatible males.

In an elegant experimental design, Roberts and Gosling showed empirical evidence for the antagonism between a choice based on good genes and one based on genetic compatibility [15]. Female mice prefer males who scent mark more frequently, a trait that is correlated with androgen levels and, therefore, male dominance. Females also exhibit a preference for dissimilar MHC haplotypes. Females use both cues during mate choice, via evaluation of the same urinary scent marking signal, but weight scent-marking frequency, and, thus, male dominance, over MHC dissimilarity. MHC dissimilarity predicted female choices only when variation in scent marking rate was small compared with the variation in male dissimilarity. This study indicated that female preferences in mice can incorporate both kinds of male trait simultaneously.

dissimilarity has been recognized in the literature [10], but has received little attention, to our knowledge, being explicitly dealt with by only two studies [15,16] (Box 3). How do we reconcile empirical support for both models of mate preference, sometimes in the same species? Here, we examine some potential solutions to this problem and the evidence that exists to support them.

Heterozygosity versus compatibility

In a discussion of the genetic benefits associated with female mate preferences, it is important to distinguish between mate preferences based on genetic dissimilarity and those based on heterozygosity *per se* [9] (Box 4). For dissimilarity, the female is choosing a mate that enables her to produce offspring with optimally dissimilar alleles across many loci (i.e. genetic compatibility). For heterozygosity, the female is choosing heterozygous mates irrespective of dissimilarity, possibly because heterozygosity is linked to increased vigor and, therefore, more-heterozygous males could more effectively provide direct benefits to females and their offspring. Here, we focus specifically on genetic dissimilarity and not heterozygosity *per se*.

Plastic choice

The criteria underlying female mate preferences might be phenotypically plastic, changing according to changes in the fitness of each strategy across different social, ecological, or genetic contexts [17]. For example, the benefits of genetic compatibility should be across many loci throughout the genome. If the genetic diversity of males in the population was low, then the differences among males in genetic dissimilarity to a female would be small and there would be little variation among potential offspring in terms of genetic compatibility.

Similar to genetic dissimilarity, the fitness benefit of choosing males with condition-dependent good genes should also be sensitive to the genetic diversity among available males. The genic capture model of good genes sexual selection relies on the idea that condition is linked to a large proportion of the genome and, thus, has a high coefficient of genetic variation that covaries with male ornamental traits [3,18]. The more loci there are underlying variation in ornament expression, the greater the relationship between population genetic diversity and the benefits of mating preferences based on good genes will be.

Therefore, both good genes preferences and preferences for genetic dissimilarity should be sensitive to genetic diversity. However, the benefits of preferences based on good genes and preferences resulting from selection for

Box 4. Distinguishing between good genes, heterozygosity and compatibility

Imagine a simplified diploid, single-locus model where females have three male genotypes from which to choose:

Female genotypes	**Male genotypes**
AA	AA
Aa	Aa
aa	aa

Choice for good genes

In this model, particular males have superior alleles or combinations of alleles. Females benefit by mating with males with these good genes because their offspring inherit better than average alleles. According to this model, males with good genes, as signaled by ornamental traits, are universally attractive to females. Assuming that A has a fitness advantage compared to a, and allele expression is additive, all females choose male AA.

Choice for heterozygosity

Males with high mean heterozygosity across many loci are phenotypically superior compared with males with lower mean heterozygosity. According to this model, males with high overall heterozygosity are universally attractive to females, possibly because their increased vigor results in increased direct benefits to females and their offspring, as males cannot pass their heterozygous condition onto offspring. All females choose male Aa.

Choice for compatibility

Heterozygotes have a fitness advantage compared with homozygotes and, therefore, females benefit by choosing sires with whom they are genetically compatible; that is, genetically dissimilar males or those males with whom they share the fewest alleles across loci. By pairing with genetically mismatched males, females produce heterozygous young. In our simplified model, female AA chooses male aa, and female aa chooses male AA. Female Aa does equally well by choosing any male.

The fundamental difference between good genes and compatibility preferences is that, under the good genes model, the fitness benefits of offspring are a function of the haploid contribution of males alone whereas the genetic compatibility model supposes that offspring fitness is a function of the combined diploid contributions of both males and females.

Each case describes different kinds of selection on female mate preferences but different mechanisms of mate choice might often cause confusion between one sort of model and another. For example, there might be some cases where choice for genetic compatibility is indistinguishable from choice for heterozygosity *per se*. Females might be unable to assess accurately their own genotype and make mate choices based on the average male heterozygosity, as heterozygous males will have a greater likelihood of producing genetically compatible offspring [9]. Further confusion could arise in distinguishing one model from another if heterozygosity is correlated with variation in the expression of male ornaments.

genetic compatibility might respond differently to changes in the genetic diversity of available males, depending on the genetic architecture underlying each type of mate choice. This difference would result in selection for females to switch between these two kinds of mate choice depending on the population of available males that they might encounter.

The genetic diversity of available males might be stable compared with ecological variables. However, pathogens might be much more variable and, therefore, more likely to generate selection for plasticity. If the fitness benefits of good genes are large (e.g. if ornamentation signaled resistance to a widespread and damaging pathogen), then we would predict that selection would favor the choice of mates primarily based on good genes signaled by ornamentation. Fluctuations in the relative abundance of various pathogens might favor different types of female preference. If there were many pathogens in the environment [19] and ornamentation was a poor predictor of overall disease resistance, but heterozygote advantage resulted in enhanced resistance in offspring, then females would do better to choose mates based on genetic dissimilarity.

Rules within rules

Instead of switching between two different rules according to social and ecological context, females could simultaneously assess the ornamentation and genetic dissimilarity of potential mates and use these criteria together as a hierarchical, nested rule for choosing a mate. For example, if females have many males to choose among, they might first limit their choice to those with above-average ornamentation and then, within that pool of males, choose the mate with whom they are most genetically compatible.

Organisms that express multiple cues during mate choice, including ornaments that signal good genes and indicators of genetic dissimilarity, might use nested rule-based mate preferences [20]. Empirical evidence that females simultaneously incorporate good genes and genetic dissimilarity during mate choice comes from a study of mate preferences in mice [15] (Box 3). This study not only supports the idea that female mice are using good genes and genetic dissimilarity simultaneously in the form of a nested rule, but also that females can alter their mate choice strategy in response to changes in the characteristics of available males.

Different criteria for different mates

In species with pair bonds, where variation in offspring fitness results from both direct and indirect benefits, females have a choice of accepting the genotype of their social mate as a sire or choosing from among potential extra-pair sires. In these systems, females might use genetic dissimilarity for one kind of mate and male ornaments for another.

Perhaps the best evidence for females using different criteria for social and extra-pair mates comes from passerine birds. Extra-pair males only contribute genes to their offspring whereas social mates often provide parental care as well as genes. Females might choose social mates largely on the basis of ornaments if those ornaments reflect the ability of a male to provide parental care, and extra-pair mates on the basis of their genetic dissimilarity. Studies of blue tits *Parus caeruleus*, a socially monogamous species with extensive male parental care, suggest that females use the song [21] and plumage coloration [22] in their choice of social mates. However, Foerster *et al.* found that extra-pair young were more heterozygous than were within-pair young and that more-heterozygous young were more likely to survive, suggesting a role of genetic compatibility in offspring fitness [23]. Taken together, these studies suggest that female blue tits use song and coloration as criteria in choice of social mates and use genetic dissimilarity in the choice of extra-pair mates.

However, this explanation is complicated by the fact that female choice is probably also influenced by male behavior, such as forced copulations and mate guarding [24], and by observations in other species demonstrating that extra-pair sires tend to be more ornamented [25]. Also, variation in ornament expression might not be a reliable indicator of the direct benefits females can receive from males [26].

Constraints on genotype assessment

In the real world, choosing genetically dissimilar males is likely to be costly and females are going to have, at best, only approximations of their own genotypes and those of potential mates. Females might be able to avoid inbreeding with first-order relatives through affiliations but be unable to discriminate finely on the basis of genetic dissimilarity. In general, if there is a benefit of compatibility to offspring fitness, we expect an increased reliance on genetic dissimilarity as a criterion in mate choice and an increased ability to assess the genotypes of potential mates [16]. Evidence to date suggests that chemical signals provide a better means of assessing genotypes before mating than do visual signals [27–29]. Therefore, for organisms such as passerine birds, which have acute visual perception but limited olfactory perception compared with other vertebrates [30], genotype matching might be difficult, making choice based on ornamentation preferable to that based on genetic dissimilarity. In taxa such as fish and mammals, with comparatively well developed chemosensory ability, better genotype assessments might be possible and one would expect mate choice based on genetic compatibility to evolve more readily [28,29]. However, the observation that some diurnal, visually oriented birds do exhibit preferences based on male genotypes suggests that visual cues are more reliable than was previously supposed, or that birds are using some unknown mechanism, possibly involving unappreciated olfactory abilities [31], to assess genotypes.

Given the constraints on pre-mating genotype assessment, females might be forced to rely on post-mating assessment of the genotypes of potential mates, so-called 'cryptic choice' [16,32,33]. This type of choice is common among plants, where haploid gene expression is more widespread and selection has favored the avoidance of self-fertilization [14,34]. However, cryptic female choice for some sperm over others does occur in some animals and provides a stage for choice based on genetic dissimilarity [32,33,35,36]. Indeed, postcopulatory choice might be the only mechanism by which females of some species can exercise choice based on genetic dissimilarity, as the Colegrave *et al.* model assumes [16] (Box 3).

Instead of being a function of physiological and sensory limitations, constraints might also result from social competition. In highly monogamous species where pair bonds are enforced by female aggression [37], highly ornamented males might be monopolized by dominant females, leaving subordinate females with only poorly ornamented males to choose among. These females might then choose from among the remaining males based on their genetic dissimilarity. Such competition might result in selection for plasticity in female preferences.

Future directions

The increasing empirical support for Trivers' idea that females benefit by optimally matching their genotypes to the genotypes of potential mates [8] is a direct consequence of recent advances in genetic techniques. However, the effects of mate choice based on genetic dissimilarity are likely to be subtle and only evident through studies with large sample sizes and comparison of many hypervariable loci dispersed throughout the genome [38]. Developing ever better genetic tools for studies of genetic compatibility remains a challenge.

Particular organisms might prove to be interesting subjects for studies of the interaction between good genes preferences and genetic compatibility preferences. Taxa where social and genetic mates are not always the same males, as in many passerine birds [24,39], are intriguing subjects for studies of variation in mate choice criteria, because females might be using different rules for different sorts of mates, depending on the kinds of contribution that different males make to their offspring. Species in which females are known to incorporate different kinds of signal during mate choice would also be of interest [15,20]. Humans, mice and fish are known to use olfaction to make self-referential decisions of attractiveness based on major histocompatibility complex (MHC) diversity [15,27–29]. If one class of cues is a signal of good genes whereas another indicates genetic compatibility, experiments manipulating multiple cues might tell us whether these species are following a nested rule and indicate which criterion takes precedence. Male attractiveness in guppies *Poecilia reticulata* based on visual cues for body size [40] and color [41] have been cited as examples of selection for female choice based on good genes, whereas olfactory cues in other fish have been shown to be reliable indicators of genetic dissimilarity [42]. Shohet and Watt demonstrated a negative relationship between visual attractiveness and olfactory attractiveness in guppies [43], which hints at a potential antagonism between good genes selection for mate choice and selection based on genetic dissimilarity. To our knowledge, the study by Roberts and Gosling is the only attempt to examine experimentally both female mate choice based on genetic dissimilarity and male good genes [15] (Box 3).

High variation in male reproductive success and the corresponding extreme sexual dimorphism in male ornamentation in highly polygynous species is likely to be the result of female preferences for universally attractive males rather than of female choice based on genetic dissimilarity. This scenario contrasts to observations of socially monogamous species with comparatively little sexual dimorphism where evidence for mating based on genetic compatibility is strong [44]. Results from Garner and Schmidt also support this conclusion [45]. These authors found evidence for female choice based on genetic dissimilarity rather than body size in *Triturus* new species with reduced male sexual ornamentation compared with other congeners. Comparative studies that examine the relationship between genetic dissimilarity of mated pairs and variation in the strength of sexual selection, as indicated by dimorphism or variance in male reproductive success, would test the hypothesis that directional selection on male ornaments and female preferences favoring genetically compatible offspring are in opposition to one another.

The apparent conflict between female preferences based on expression of ornamental traits and mate choice for genetic dissimilarity present both new challenges and new opportunities to evolutionary ecologists. The idea that females base their mate choice decisions on condition-dependent ornaments to gain direct benefits or good genes for their offspring will have to be reconciled with the increasing evidence that genetic disassortative mating is also a widespread criterion for choice. To date, the evidence that females choose a mate based on genetic dissimilarity is restricted to a few species, so assessing the ubiquity of this behavior is a first priority. Assuming that such choice is a widespread behavioral pattern, then understanding the evolution of ornamental traits and the role that they play in relation to genetic dissimilarity is a major challenge to current concepts of mate choice and sexual selection.

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