

Sex, health and behaviour

Sexual reproduction might have emerged to provide better immunity against pathogens and further evolved to select for behaviour

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Understanding the emergence of sexual reproduction has been one of nature's long-standing mysteries that even now is only partially understood. There is a clear distinction between the reason sex evolved in the first place in early eukaryotes—and even before that in prokaryotes—and why it has been so stubbornly maintained in virtually all higher species. After all, asexual reproduction is superior in a strict Darwinian sense, since it yields more offspring per unit time without having to waste energy on finding mates.

On the question of the origin of sex, there is little progress, with plenty of competing theories but scant evidence. But a clearer picture has emerged of why sex has resisted the pull towards asexual reproduction and what has driven its evolution. According to Manfred Milinski, Director of the Max Planck Institute for Evolutionary Biology in Plön, Germany, the bottom line is that the constant threat from parasites and pathogens has maintained the need for sex. “In a world without infectious diseases, asexual reproduction would prevail,” he explained. “However, with asexual reproduction, there is no evolutionary improvement, only genetic degeneration through fatal mutation accumulation. Infectious diseases are indeed drivers of sexual reproduction and thus evolution. So if we removed all infectious diseases, we would return to asexual reproduction and disappear as a species after about 200 generations because of inevitable mutation accumulation. Infectious diseases help us survive.”

One big advantage of infectious pathogens compared with their larger and longer lived hosts,

including humans, is that they evolve much faster through mutation. The only recourse is a highly diverse immune system capable of quickly adapting to new and mutating pathogens, according to Daniel Davis, Director of Research at the Manchester Collaborative Centre for Inflammation Research in the UK. “The genes that vary the most between individuals are those to do with the immune system,” he said. “It's fundamentally essential that we have that diversity because of the way we handle disease. Genes code for a particular protein molecule that sits on the surface of cells and presents the sample for the immune system to look at. Each of us presents a slightly different shape of protein and as a consequence of that we have different resistances for different diseases.”

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This diversity has to be both maintained and passed on to offspring by sexual selection. The question is whether and how individuals might recognize mates on the basis of key immunity genes, especially those of the major histocompatibility complex (MHC), which controls a major part of the immune response in all vertebrates. MHC molecules come in two classes, with class 1 being the most widespread—found on the surface of all nucleated cells in the body, where they display fragments of non-self-proteins from within the cell to cytotoxic T cells. Humans

have three versions of the class 1 MHC genes and therefore six possible variations, since each individual inherits a copy from either parent.

When it comes to selecting for MHC diversity, there has been increasing evidence that olfactory signals help to identify compatible partners for sexual reproduction, Milinski said: “MHC immunogenes are extremely polymorphic and can be recognized by odour in all vertebrates that have been tested for it so far, including fish, mice, humans and birds.” In 1995, a seminal paper first suggested such a link between odour and selection for MHC genes in humans [1]. Since then, the case for selection by olfactory signals has strengthened according to Milinski, who reported evidence that MHC genes determine people's preferences for body perfumes in 2001. He used functional magnetic resonance imaging (fMRI) to identify a centre in the human brain's right middle front cortex that responds to an individual's own peptides, irrespective of their chemical composition [2]. “Different people have different peptides, which are known as self-peptides,” Milinski said. “This is the personal perfume that we produce to attract mates with complementary MHC (HLA) alleles.”

In parallel with this work on olfactory mechanisms, Milinski has been researching how sexual selection based on olfactory cues maintains MHC diversity in vertebrates. He and his colleagues have already shown that female fish from either a river or lake environment prefer males from the same environment on the basis of odour [3]. Another study provided the first experimental proof of MHC genes adapting to local parasites [4]. The team bred two

groups of fish, one with MHC genes from individuals in a lake and the other from a river, with the rest of the genomes well mixed to avoid any other genetic bias. The idea was to assess whether fish with the lake MHC genes would be better able to resist the more diverse pathogens in that environment and whether the river fish were in turn better able to combat the smaller range of parasites there. Individuals of both types were then put out in cages across both environments and brought back into the laboratory after 10 months to be dissected and screened for macro parasite species. “We found that river MHC worked better than the lake MHC in the river and vice versa in the lake,” Milinski said, highlighting the evolutionary significance of locally adapted MHC genotypes.

Another study showed that stickleback fish could quickly adapt to new parasites by increasing the frequency of relevant MHC alleles within just one generation [5]. Two parasites were chosen and fish were split into two groups, one exposed to the first parasite and one to the second. Fish were allowed to mate within each group but not with members of the other and it turned out that offspring were more resistant to the parasite their parents had been exposed to than the other.

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The study identified alleles of MHC genes that conferred resistance against each of the parasites and found they increased in frequency in each of the groups. This illustrated how standing genetic variation in key genes allows much faster adaptation and that exposure to a pathogen is sufficient to allow rapid host adaptation within a single reproductive event. As Milinski pointed out, this could have happened because those females carrying the resistance alleles to the given pathogen produced more offspring in that generation than those that did not. Alternatively, females might prefer males that

display higher vigour because they possess those resistance alleles.

As Milinski commented, this study was further evidence in favour of the host-parasite coevolution hypothesis (Red Queen hypothesis), a view that still has to gain wide acceptance among evolutionary biologists. Timothy Barraclough, Professor of Evolutionary Biology at Imperial College in London, UK, argues that other factors might still have a role in the evolution and maintenance of sex. “I think there is good evidence that the need to evolve rapidly in response to evolving parasites is a strong driving force for the evolution of sex,” he commented. “But it probably isn’t the only one and there could be competition with competitors, as well as fluctuating physical environments. There are also hypotheses on efficient removal of deleterious mutations that may also contribute.”

Barraclough also noted that MHC compatibility does not explain the initial evolution of sex because it occurs only in vertebrates, which evolved long after sex. “There will be other systems of resistance in other organisms, however, where shuffling up combinations will also be beneficial in evolving resistance to pathogens.”

Stuart West—an evolutionary biologist at the University of Oxford, UK, who studies social evolution—is another proponent of the idea that other selective factors operate alongside immunity to maintain sexual reproduction. His thesis is that the reasons why sex evolved in the first place are not always the same as those that maintain it and that organisms are subject to a variety of selective forces depending on their ecosystem and environment. Animals and plants as a whole have thus evolved a pluralistic approach to sexual selection with different factors acting in synergy. “This then created a framework for sexual selection on the basis of advantageous behavioural traits, especially among social animals where both parents are involved in upbringing,” West explained. In contrast to bi-parenting animals, males that merely compete for mates may reach almost absurd levels of display that are totally useless for raising offspring, as with the peacock. But, if both parents are involved in raising offspring, there should be strong selection for suitable traits. This raises the question of whether behavioural compatibility can be a selective factor for mating.

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Behavioural compatibility in animals is defined on the basis of traits such as aggression, the tendency to explore novel environments, sociability and response to a mirror image. However it is defined, it must equate with fitness or success as parents. The combinations of traits that make for a good mating fit will vary with species and circumstance, such that it might sometimes be better to have one mate that is more cautious and another that is more aggressive. Behavioural compatibility is only relevant for species where individuals come together for life or long periods, and where males play a significant role in raising offspring.

A recent article by Malika Ihle and colleagues from the Max Planck Institute for Ornithology in Seewiesen, Germany, seems to establish that behavioural factors—rather than genetic or immunological compatibility—determine mate selection in bi-parenting animals [6]. The authors took 160 zebra finches, which form mating pairs for life, with equal numbers of each sex and initially allowed them to form pairs freely. Then, half the females were removed and forced to mate with males they had not chosen. Both groups were then left in cages to bond and breed. The authors found that the survival rate of chicks was 37% higher among pairs that had come together voluntarily compared with the forced pairings. Moreover, three times as many eggs were unfertilized, more eggs were buried or lost, and more chicks died after hatching among the arranged pairs. This correlates with one of the main observable differences in behaviour: that males in the arranged partnerships were less diligent at attending the nests while the chicks were hatching and therefore most vulnerable.

One alternative explanation for the higher survival rate of chicks among the birds allowed to select their own mates would be genetic incompatibility. But the death rate for embryos was the same across the two groups, which suggested the difference in

chick survival resulted from the quality of parenting; if birds were choosing mates on the basis of genetic compatibility, embryo mortality rate should be lower among pairs that select their own mates.

At the same time, the team swapped eggs between nests such that chicks were raised by non-biological parents. “From this large cross-fostering experiment, we know that embryo mortality is determined by the biological parents but not by the incubating parents, and is therefore a sign of genetic incompatibility,” Ihle said. “By contrast, chick mortality is entirely determined by the parents rearing the offspring and not the biological parents. Chick mortality is therefore the result of behavioural incompatibility.”

The study has been much welcomed in the field because it has successfully isolated personality traits from other factors including immunological compatibility. “I think what they’ve done really well is nail down that this behavioural compatibility is what matters and nothing else, while other earlier evidence was more circumstantial,” said Sasha Dall, an ecologist and member of the Behaviour Group at the University of Exeter in the UK. “They’ve demonstrated a really strong effect, with a substantial fitness benefit for behavioural mate selection.”

While the study establishes that zebra finches are choosy about their mates and exhibit clear behavioural or “personality” differences, it also raised the question of how behavioural compatibility is linked to parenting. Ihle has two hypotheses: “Firstly, parents could be better at coordinating activities or synchronizing them, and individuals that have for instance, similar personalities or on the contrary dissimilar personalities, could be better at doing this. This should be investigated further, but in our experiment we do not even have suggestive evidence for this,” she said. “Alternatively, individuals could have specific sensory biases due to random mutations and specific phenotypic traits, also presenting variation due to random mutations. Then a specific male could for instance stimulate the senses of a specific female, which could make her invest more in reproduction. We have evidence that individuals of assigned pairs were less committed to each other, less faithful, less motivated to breed together. For instance, females were less inclined to copulate with their assigned

partner, while males engaged more in extra-pair courtships and attended their nests less on days when chicks hatched, which are crucial days for chick survival.”

“... how much does social evolution depend on behavioural selection through sexual reproduction?”

Another obvious question is whether personality or behavioural differences are underpinned by genetics or emerge as a result of the environment, or are a mixture of both. The answer is the latter, according to Wiebke Schuett, a behavioural biologist at the University of Hamburg in Germany. “Several studies have shown that about 30–50% of behaviour is genetically determined, while for personality it is about 50%,” she said. “The rest is environmentally determined.” Dall reckoned the contribution of the environment on behaviour was actually > 50%. “When we did cross-fostering experiments where we took chicks away from their genetic parents, we found that they more strongly matched their foster parents in personality traits.” Nonetheless, Dall acknowledged that there is still a significant genetic component in personality differences, which suggests that this is maintained by mate selection.

Indeed, Schuett and Dall conducted a study indicating that sexual selection acts to maintain personality differences within a population [7]. “We predicted in our paper that it might be beneficial for a female to choose a male whose behaviour is predictable, so that females could already assess what to expect of their future partner,” Schuett said. “We predict this to be the case in those species in which both parents care for the offspring and to be the case for those male behaviours that are important for the female, such as male provisioning behaviour of offspring.” One corollary of female selection could be that male personality converges towards what appears to be an optimum combination of traits. “Indeed, we found that males were more consistent than females in their offspring provisioning behaviour,” Schuett said. “But these are to date still predictions. Good evidence is still missing, since empirical studies addressing this point are still rare.”

As behavioural selection seems to have augmented immunological selection as a driving force in sexual reproduction, how and to what extent does it guide mate choice in higher primates, in particular humans? In other words, how much does social evolution depend on behavioural selection through sexual reproduction? Most non-human primates are promiscuous and therefore not subject to behavioural selection, behavioural and evolutionary biologist Sonja Koski, from the University of Helsinki, Finland, said that behaviour is a factor for forming stable social groups. Indeed, Koski showed that friendships among chimpanzees are in part determined by whether individuals have similar personalities, especially with regard to sociability and boldness [8].

There is one important aspect of parenting that is particularly relevant for human evolution and which has emerged from studying non-human primates, Koski added. “This is the link between the cooperative breeding system and the evolution of the human brain, social tolerance, and prosocial psychology,” she said. Cooperative breeding involves other members of a larger family or social group beyond the parents in raising offspring. “Essentially, humans evolved as cooperative breeders and this explains many of the thus far under-explained human characteristics,” Koski said. “The essential support for the hypothesis has come from comparative research on cooperatively breeding primates, and from large-scale correlational work on cooperatively compared with individually breeding species in primates, as well as other mammals.”

The argument is that evolution of cooperative breeding leads to psychological changes with an associated increase in sociability. “We propose that these cognitive consequences of cooperative breeding could have become more pervasive in the human lineage because the psychological changes were added to an ape-level cognitive system already capable of understanding simple mental states, albeit mainly in competitive contexts,” Koski said. “Once more prosocial motivations were added, these cognitive abilities could also be used for cooperative purposes, including a willingness to share mental states, thereby enabling the emergence of shared intentionality, which has been identified as the original source of many uniquely human cognitive abilities, including cumulative culture and language.”

[...] In humans, we argue, the two components merged, the cognitive component due to common descent from ape ancestors and the motivational component due to convergent evolution of traits typical of many cooperative breeders.”

If so, then sexual reproduction through the selection of specific behaviours and cognitive abilities evolved to become ever more complex and multifaceted, eventually enabling the evolution of a shared culture and thereby human civilization. Yet, with increasing evidence for some form of the Red Queen hypothesis, it seems that sexual selection is rather hierarchical, with immunity at the top and other factors being subordinate, given that MHC compatibility still seems to be a crucial factor for sexual selection in humans. In any case, it also adds to the explanation of why sexual reproduction

has so doggedly persisted throughout the millennia, despite the costs involved: it allows for faster and more efficient selection of—and thereby evolution of—ever more complex traits from immunology to behaviour to social interactions.

References

1. Wedekind C, Seebeck T, Bettens F, Paepke AJ (1995) MHC-dependent preferences in humans. *Proc R Soc Lond* 260: 245–249
2. Milinski M, Croy I, Hummel T, Boehm T (2013) Major Histocompatibility complex peptide ligands as olfactory cues in human body odour assessment. *Proc Biol Sci* 280: 1775
3. Eizaguirre C, Lenz TL, Sommerfeld RD, Harrod C, Kalbe M, Milinski M (2011) Parasite diversity, patterns of MHC II variation and olfactory based mate choice in diverging three-spined stickleback ecotypes. *Evol Ecol* 25: 605–622
4. Eizaguirre C, Lenz TL, Kalbe M, Milinski M (2012) Divergent selection on locally adapted major histocompatibility complex immune genes experimentally proven in the field. *Ecol Lett* 15: 723–731
5. Eizaguirre C, Lenz TL, Kalbe M, Milinski M (2012) Rapid and adaptive evolution of MHC genes under parasite selection in experimental vertebrate populations. *Nat Commun* 3: 621
6. Ihle M, Kempnaers B, Forstmeier W (2015) Fitness benefits of mate choice for compatibility in a socially monogamous species. *PLoS Biol* 13: e1002248
7. Schuett W, Tregenza T, Dall SRX (2010) Sexual selection and animal personality. *Biol Rev* 85: 217–246
8. Massen JJM, Koski SE (2014) Chimps of a feather sit together: chimpanzee friendships are based on homophily in personality. *Evol Hum Behav* 35: 1–8