Current Biology
Magazine

Quick guide

The peppered moth *Biston betularia*

Hannah M. Rowland[1],
Ilik J. Saccheri[2], and John Skelhorn[3,*]

What's a peppered moth? *Biston betularia* is a species of night-flying geometrid moth that is widely distributed across the northern hemisphere. Its colour variation, in both the adult and larval stages, has made it an important model organism in evolutionary biology. Indeed, it is commonly cited as a textbook example of industrial melanism: where animals evolve darker pigmentation in environments affected by industrial pollution. The polyphagous larvae use a wind-assisted dispersal strategy in the first instar stage, and in later instars resemble twigs. They adopt twig-like postures and can change colour to match the branches on which they are located (Figure 1). The adults vary more or less continuously in the proportion of melanised scales covering their wings and body, from lightly 'peppered' to completely black (Figure 1). This variation is genetically determined and, unlike the larvae, the adults cannot change colour.

What have we learned from studying larvae? Larvae can change their appearance to match the colour and luminance of their background even when their ocelli are completely obscured. This is mediated by a suite of visual genes expressed across the integument, allowing extraocular photoreception. Monitoring birds' responses to larvae that match or mismatch the colour of their host plant has also revealed the mechanisms by which camouflage can exploit the sensory and cognitive processes of predators. Colour matching has dual benefits, making larvae more difficult to detect (crypsis), and increasing the chance that predators will mistake larvae for twigs (masquerade). This shows that masquerading animals that resemble inedible objects can gain additional benefits from crypsis, and strongly suggests that masqueraders may be under selection to show phenotypic variability. This variability essentially increases the number of inedible models relative to the number of masqueraders, which is known to enhance the benefit of masquerade. Larvae have also developed behavioral defences that have been shown to increase the protection afforded by their appearance. They use extraocular photoreception to preferentially select colour-matching backgrounds, and they are the first species to have been demonstrated to benefit from postural camouflage. The twig-like postures adopted by the larvae enhance their camouflage but come at an energetic cost, and cannot be maintained when larvae are cold or hungry.

What about the adults? The study of industrial melanism in the British peppered moth population has produced one of the most complete examples of adaptation through natural selection. The melanic *carbonaria* form was first discovered in Britain in the mid-19th century. Over the next 50 years, it rapidly increased in frequency to make up over 90% of the population in some industrial and smoke-blackened regions. This was followed by a decline in melanic frequency in these areas after smoke control was introduced in the mid-1970s. A number of experiments have demonstrated that selective predation by insectivorous birds is the major factor driving these frequency changes. Light morphs are better camouflaged against light backgrounds, such as lichen-covered trees, whereas black morphs are better camouflaged against dark backgrounds, such as tree barks darkened by coal pollution. Crucially, the rapidity of the phenotypic change in populations of the adult moths provided the first evidence that natural selection could be very strong, challenging the prevailing view of early evolutionary biologists that evolutionary change was invariably slow. More recently, the completely black *carbonaria* phenotype in Britain has been shown

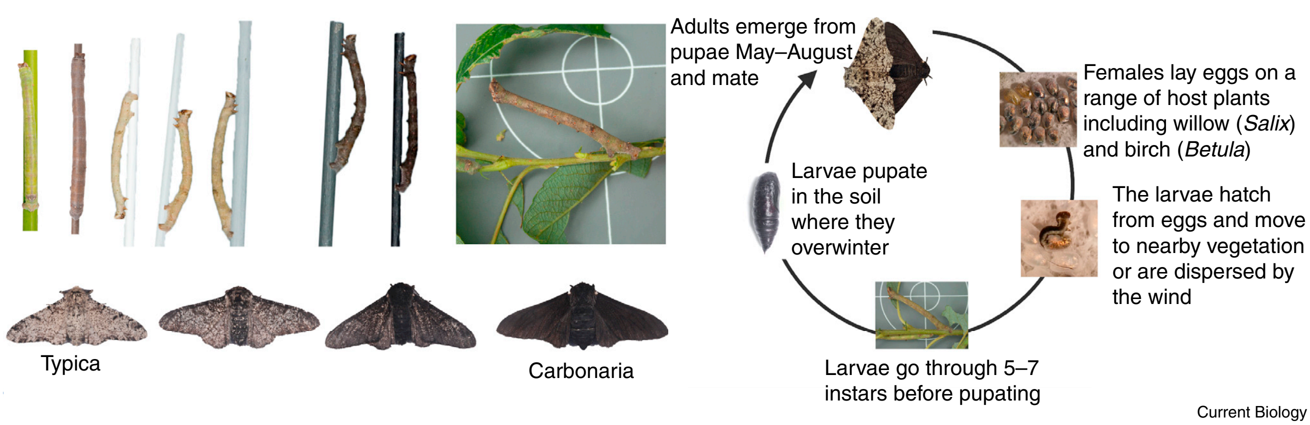

Figure 1. Morphs and life cycle of *Biston betularia*.
(Top left) Peppered moth caterpillars change colour based on background and assume a defence posture. (Bottom left) Adult colour variation. (Right) Life cycle of peppered moths. (Photos of pupa larvae on brown and green dowels by Alfonso Aceves; photos of larvae on white, grey and black dowels by Arjen van't Hof; photos of adults, eggs and hatching larvae by Carl Yung.)

to be the product of an insertion of a large transposable element into the gene *cortex*, which demonstrates a (conditionally) beneficial role for what are considered to be genomic parasites. The timing of this mutation event, estimated by using the molecular footprint left by the selective sweep, also provides direct and independent evidence that the *carbonaria* morph arose in early 19th century Britain. Similar patterns of rise and fall in melanic forms of the peppered moth associated with coal pollution have been detected in eastern North America and continental Europe, and whilst the specific genetic identity and age of these polymorphisms remain to be resolved, *cortex* is likely to be involved. Intriguingly, this gene has also been shown to be involved in camouflage melanism in several species of moth and in the warning signal mimicry of *Heliconius* butterflies.

What is there left to learn from peppered moths? Even though the peppered moth has been and is the focus of much research, the extent to which larvae can change colour has only recently been documented. This raises the possibility that colour change may be more common amongst Lepidoptera larvae than is currently appreciated, and highlights the need for more research in this area. In addition, the larvae's ability to use extraocular photoreception makes the peppered moth a useful species in which to study the molecular, physiological and cognitive mechanisms that contribute to distributed sensing. This could inform the development of technologies that allow mobile objects to change colour to match their background. Moreover, the ability to manipulate larval colour allows us to produce living stimuli that can be used in experiments to address a range of questions about the evolution of many forms of adaptive colouration, and the co-evolution of prey appearance and behaviour. The co-existence of several adult morphs presents an ongoing opportunity for unravelling the interacting genetic and ecological factors involved in the maintenance of colour polymorphisms, and whether adaptation to major environmental change (e.g. pollution) relies more frequently on *de novo* mutations or pre-existing genetic variation. It also provides an excellent system in which to study the regulation and function of *cortex*, which acts as a primary developmental switch for colour pattern diversity in Lepidoptera.

Where can I find out more?

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[1]Max Planck Institute for Chemical Ecology, Hans Knöll Straße 8, Jena 07745, Germany. [2]Department of Evolution, Ecology and Behaviour, University of Liverpool, Liverpool L69 7ZB, UK. [3]Biosciences Institute, Faculty of Medical Sciences, Newcastle University, Henry Wellcome Building, Framlington Place, Newcastle upon Tyne NE2 4HH, UK.
*E-mail: John.Skelhorn@ncl.ac.uk

Primer

Cellular senescence

Marta Varela-Eirín[1,2] and Marco Demaria[1,*]

Cellular senescence defines a state of stable and generally irreversible proliferative arrest associated with various morphological, structural and functional changes (Figure 1), including enhanced expression and secretion of pro-inflammatory and tissue-remodelling mediators. This state is crucial in tissue physiology and pathology and arises as a response to potentially damaging stress signals. Whether the activation of a senescence state provides benefits or detriments for tissue function and homeostasis is strictly dependent on the context. Cell senescence acts as a potent tumour-suppressive mechanism limiting the proliferation of cells at risk of malignant transformation and supports the repair of acute tissue damage, but also represents a key driver of ageing and age-related diseases.

The concept of cell senescence was first described in 1961, in a pioneering study by Leonard Hayflick and Paul Moorhead. While expanding human primary fibroblasts at the Wistar Institute, Hayflick observed that the cells lose the ability to expand after a number of passages, despite remaining alive and metabolically active. This finding was in contrast to the concept that *ex vivo* cultured cells could be expanded indefinitely, initially introduced by Alexis Carris in 1912. Hayflick postulated that this cellular phenomenon of limited proliferative potential could be a reflection of organismal ageing. The observation that cells could only replicate and divide for a limited amount of times (between 40 and 60) was later coined as the Hayflick Limit by Frank Macfarlane Burnet in 1974. After some years of enduring criticisms, other scientists started to support Hayflick's theory and were able to reproduce his findings. Moreover, it became clear that one of the key mechanisms responsible for the limited replicative lifespan of primary cells was the shortening of telomeres. Telomeres are structures at chromosome ends that protect against end–end fusion, discovered by Elizabeth Blackburn and colleagues in 1988. More