

Exploring Gloger's ecogeographic rule

Why organisms are darker in wetter & warmer environments



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Critical theory essay

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Gloger's rule is an ecogeographic trend wherein organisms possess darker pigmentation in warmer, more humid environments (Gloger 1833; James 1991; Gaston et al. 2008; Lev-Yadun 2015; Roulin & Randin 2015; Bishop et al. 2016). Gloger (1833) first described this pattern in birds, and consequently the rule is largely treated as applying to endothermic animals (Bishop et al. 2016). However, evidence mounts for the pattern's applicability to ectotherms (e.g. Rapoport 1969; Bishop et al. 2016), and plants (e.g. Lev-Yadun 2007; Koski & Ashman 2015). Though, there may be different processes in different taxa that result in this pattern (and others) of organismal pigmentation across climatic gradients.

Herein, I discuss the treatment of ecogeographic rules in ecological and evolutionary science, and within this context discuss the degree to which Gloger's rule is a genuine pattern in nature. I discuss insights into possible mechanisms that generate the Gloger's rule pattern, and how these vary between taxa, and across levels of biological organisation. I argue that there is sufficient evidence to support Gloger's rule as a useful and true generalisation.

Ecogeographic & biogeographic "rules"

It is important to consider what is meant by the term "rule" in biology. There are many of biogeographic and ecogeographic patterns that are referred to as rules, e.g. Bergmann's rule, Allen's rule, etc. Gloger's rule, the focus here, is also often grouped with these. Like many other other ecogeographic rules, Gloger's rule has gained renewed research interest in the 21st century (Lomolino et al. 2006)

Lomolino et al. (2006) outline the study of observed patterns or trends of organismal traits across geographical space with ecogeographic rules (i.e. observations). They highlight examples of *patterns* at broad ecological scales as consequence of *processes* at a range of scales. Indeed, the patterns themselves are also manifest at a variety of scales and levels of organisation. As such, Lomolino et al. (2006) notes, underlying causal mechanisms behind these patterns are difficult to ascertain. Furthermore, due to the tendency of ecological relationships to be non-linear, studies of these ecogeographic patterns needs to be assisted and informed by theory (Lomolino et al. 2006).

Olalla-Tárraga (2011) discusses approaches to studying rules too, with focus on Bergmann's rule. Olalla-Tárraga (2011) advocates a pluralist approach, wherein the mani-

festations of ecogeographical rules at multiple scales and levels of biological organisation are considered. He also outlines that "laws" and "rules" in ecology, and in science generally, need not *always* contain mechanistic statements, and need not be without exception, as they are "correlative generalisations". Though, mechanistic understandings of the processes that generate patterns is desirable, and indeed often the aim of research, this does not imply that correlative ecogeographic rules are not useful intrinsically. Not least, these rules are often the starting point of research. Thus, these rules represent interesting observed patterns that can motivate research, *and* useful generalisations that can be employed in other work.

Ecogeographic rules operate across various levels of biological organisation. Gaston et al. (2008) differentiate between *intraspecific*, *interspecific*, and *assemblage* patterns in organismal traits across environmental gradients. In the context of Gloger's rule, the pattern would manifest at intraspecific (= "ecotypic" sensu Millien et al. 2006) levels in that pigmentation would generally be darker in populations, of some species, in more humid habitats. The operative question here is whether individuals (or individuals of certain genotypes) are darker in more humid habitats.

At the interspecific level, the organismal pigmentation darkness values measured to vary across a humidity gradient would be derived from populations of *different* species. Here, the question of concern is whether species in humid habitats are generally darker than species in more arid habitats. Similarly, assemblage and community analyses of Gloger's rule are investigating interspecific comparisons of greater quantities. Besides this, communities and assemblages are also meaningfully large units of interspecific comparison. Questions at these scales aim discern Gloger's rule patterns between species, but also between groups of species. Bishop et al. (2016), for example, describe community trait averages in order to describe the extent of Gloger's rule in ants.

The scale and levels of organisation at which Gloger's rule is an important consideration when discussing case studies and evidence for the rule, as it evidently entails nuances to the questions. Note, Gloger's rule does not appear to concern ontogenetic colour change—that is, colour change within the development and lifespan of an individual organism (Booth 1990). This is because the primary aim of Gloger's rule is to demonstrate trends in the evolutionary and ecological significance of the environment to organismal colour, assuming organismal colour is relatively fixed through out an organism's lifespan.

Gloger's rule—evidence & explanations

How ubiquitous is Gloger's rule? Does the pattern exist? I will now discuss empirical evidence for the rule, or patterns

similar to it, for three major groups of organism: endothermic animals, ectothermic animals, and plants (Table 1). I will then discuss these cases with regard to the level of biological organisation at which they were observed: intraspecific comparisons, interspecific comparisons, and assemblage comparisons (Table 1).

Endotherms

As stated above, Gloger's rule stems from his observations of bird plumage darkness across climatic moisture gradients (and, by the simplest extension, pigmentation in endothermic animals too) Gloger noted bird plumage was darker in warmer, more humid areas (Burt & Ichida 2004; Miksch 2015) than the plumage of conspecific birds in more arid areas (Burt & Ichida 2004). Roulin & Randin (2015) describe the logic of Gloger's rule lucidly:

The rule is based on the assumption that melanin pigments and/or dark coloration confer selective advantages in warm and humid regions.

They investigate animal fitness in warm, humid environments as conferred via alternative phenotypic adaptations (viz. in owls). The implication of *fitness* in a given habitat allows one to see the *evolutionary* aspect to Gloger's *ecogeographic* rule (a sentiment Lomolino et al. (2006) highlights). Colouration is indeed an important aspect to animal evolution. In mammals, predator-prey interactions (e.g. concealment), communication, and ecophysiology drive body and hair colour (Caro 2005, 2013).

There is well studied evidence of Gloger's rule at the intraspecific level in birds. E.g. Song Sparrows (*Melospiza melodia*) in North America (Burt & Ichida 2004), North American Barn Owls (*Tyto alba pratincola*) (Roulin & Randin 2015), Hawaii Elepaio (*Chasiempis sandwichensis*) (VanderWerf 2012), Oahu Elepaio (*C. ibidis*) (in the same study by VanderWerf (2012)), and

Mechanistically, Song Sparrows in humid contexts appear to be under greater pressure from feather-degrading bacteria (Burt & Ichida 2004), as humid environments support a greater abundance of bacteria (Shawkey & Hill 2004). Consequently darker-morphs are more fit there, as melanin increases the resistance of feathers to bacterial degradation (Burt & Ichida 2004; Shawkey & Hill 2004). However, as is discussed by Roulin & Randin (2015) concerning Barn Owls, there are multiple selective pressures that relate to pigmentation, specifically melanin-based darkness. Indeed, Burt & Ichida (2004) describe their findings as "simply another pressure that selects for dark feathers", and outline the myriad other causes (see Table 2 in Burt & Ichida 2004). It is interesting, though, that many of these pressures can align to produce patterns predicted by Gloger's rule—e.g. background matching, thermoregulation, and indeed resistance to bacterial degradation. These mechanisms (Table 2 in Burt & Ichida 2004) are reported to be responsible for interspecific differences in plumage darkness, but are easily extensible to intraspecific differences in evolutionary terms.

VanderWerf (2012) looked at plumage, among other things, within populations of two closely related birds

across environmental gradients in Hawaii. In this regard, Gloger's rule was supported, such that pigmentation was darker for birds of either species in areas of high rainfall, and with "smoothly clinal distributions" [sic] (as a function of the few dispersal barriers and steep environmental gradients). VanderWerf (2012) eliminated thermoregulatory and background-matching mechanisms for the case of Elepaio (because of the observed independence of Elepaio plumage on temperature, and little differential predation upon Elepaio along moisture or temperature gradients, respectively).

Tate et al. (2016) found persistent colour polymorphism within populations of Black Sparrowhawk (*Accipiter melanoleucus*), suggesting equivalent fitness of the morphs in a heterogeneous habitat. They found that darker morphs forage better in darker habitats, as they are better concealed. As mentioned above for mammals (Caro 2005, 2013), predator-prey interactions such as these evidently affect organismal colour. The "light level-detectability hypothesis" (Galeotti et al. 2003) deals explicitly with the relationship between environmental lightness and organismal colour. Since darker habitats are more likely to be wetter and more humid, the findings of Tate et al. (2016) relate to Gloger's rule.

In interspecific comparisons of organismal darkness, Gloger's rule patterns have been observed in birds (...),

Gloger's rule has also been documented within mammal species. House mice (*Mus musculus*) coat colour in Asia follow Gloger's rule, likely due to some combination of background matching, bacterial resistance, and thermoregulatory benefits (Lai et al. 2008). Blind mole rat dorsal colour has been found to follow Gloger's rule as a function of thermoregulatory need and crypsis (Singaravelan et al. 2013). Primate coat colour [Kamilar & Bradley (2011);] and some facial colour patterns (Santana et al. 2012) have also been observed to follow the rule. Kamilar & Bradley (2011) had little mechanistic conclusions in their, and speculate towards the usual plausible set of mechanisms (background matching, bacterial resistance, and possibly thermoregulation). Notably, they conclude that primate coat darkness is unlikely to be for protection from ultraviolet radiation, as the vast majority of primates are arboreal, generally spending the majority of their time shaded in the lower canopy, despite being in the bright tropics. Santana et al. (2012) argue that all these ecological mechanisms, *including* protection from ultraviolet rays, are at play in determining the darkness of primate facial patterns, though more research is needed.

Also consider Dominy & Lucas (2004) food colour and primates—could THIS connect to an environmental pattern in plant colour?

Caro (2013) Primate dorsal colouration follows Gloger's rule, as do carnivores, artiodactyls [all 3 via comparative data], and rodents [via weaker observational data]. Go to the refs for these!!! Cmd-F "gloger"!!

...

These cases exemplify the way in which different, non-mutually exclusive mechanisms and the combinations and

varying strengths thereof can all produce patterns in accordance with Gloger's rule. Each specific case need not display a Gloger's rule pattern as a consequence of all, nor some specific process (Olalla-Tárraga 2011). Thus, the extent of a Gloger's rule pattern seems to be that which arises due to multiple processes.

Ectotherms

intersp. insects examples (e.g. ant assemblages (Bishop et al. 2016)).

Concerning the applicability of Gloger's rule to ectotherms (viz. invertebrates), an "inverse" of Gloger's rule is often reported (Rapoport 1969; Lev-Yadun 2015). Indeed, the major mechanistic explanations for Gloger's rule in endotherms (below) can be reversed in ectotherms—should they deal with temperature—or outweighed by processes more important to ectotherm fitness in a given environment. Collembolates—interspecifically—follow this inverse Gloger's rule pattern (Rapoport 1969), such that the proportion of darker species is greater at higher latitudes. This is likely as they require greater degrees of melanism in order accrue heat from the environment more easily in these typically colder regions (Rapoport 1969).

In the case of ant assemblages (Bishop et al. 2016), a mixture of the class Gloger's rule and its inverse was demonstrated. Ant assemblages tended to be darkest in regions of high and low temperatures, and paler in colour in intermediate regions. At lower temperatures, ant assemblages tended to be darker for thermoregulatory reasons (as found with Collembolates (Rapoport 1969)), while in regions of higher temperature ant assemblages were more melanised also, in order to increase fitness in the high levels of ultraviolet radiation in warmer regions (Bishop et al. 2016). The resulting patterns (see Fig. 2b in Bishop et al. 2016) were also interacting with ant assemblage mean body size, in that assemblages typified by smaller ants were also darker (see Fig. 2a in Bishop et al. 2016). This was concluded to be because smaller ectotherms more strongly require the thermoregulatory benefits of darker colouring, due to their relatively little thermal inertia..

Plants

Notably, extending the generality of the rule (Koski & Ashman 2015), the plant species *Argentina anserina* has been found to follow the rule in its floral pigmentation (in ultraviolet wavelengths) (Koski & Ashman 2015), having stronger "bullseye" markings when occurring nearer the equator.

Animal vs plant e.g. -> differences in meaning and interpretation

Plants vs endothermic animals vs ectothermic animals (for animals see highlighted § in James (1991)); UV-B protection (Gloger's rule) vs thermal hypothesis vs desiccation hypothesis (Pinkert et al. 2016); Plants foliarly (sensu Lev-Yadun 2007) vs florally (sensu Koski & Ashman 2015)

[Across scales]

Millien et al. (2006) discuss ecotypic (i.e. intraspecific, i.e. between populations) variation in terms of ecogeographic rules, too.

Manifestations of Gloger's rules across various scales and levels of organisation [...] intrasp. Gloger's rule manifestations (= "ecotypic", sensu Millien et al. (2006)) vs intersp./community level manifestations (Lev-Yadun 2015)

(???) seems to say that ecogeographic rules only operate within species. There has been evidence to the contrary (e.g. Bishop et al. 2016). There are more exceptions to these rules at higher levels of organisations (such as assemblages), as the systems become necessarily more complex. That is not to say that there are no exceptions at intraspecific levels (e.g. the inapplicability of Gloger's rule to rare melanistic coyotes in Florida, U.S.A (Caudill & Caudill 2015)), but as (???) suggests:

The fact that "cold climates do not produce a fauna tending towards large-sized globular forms with small protruding parts" (Scholander, 1955) is not in the least in conflict with Bergmann's or Allen's rule.

In other words, ecogeographic rules have been treated as having more predictive power *within* species, not between. But, this should not preclude these ecogeographic patterns from being manifest at higher levels of organisation—even if the original inception of an ecogeographic rule was for intraspecific patterns.

[Evolution-rant]

Studies concerning Gloger's rule, and indeed most patterns in nature, must ideally consider the historical, evolutionary context to organismal form (Lomolino et al. 2006)—not just local deterministic mechanisms. Though, it must be noted, the extent to which historical and deterministic processes govern organismal pigmentation largely depends on the scale of investigation. Ontogenetic changes in pigmentation are a-historical. Intraspecific patterns may represent micro-evolutionary fitness benefits to certain genotypes. Interspecific and assemblage patterns, however, would be indicative of more long-term, persistent selection pressures—e.g. ant species *assemblages* follow Gloger's rule in humid environments, implying that there may be long-standing, consistent strength to Gloger's rule in ants. In other words, enough evolutionary time must pass [...].

Conversely, with respect to interspecific and community ecogeographic patterns, environmental filtering could conceivably produce trait patterns over shorter, ecological time-scales. In this case, if the traits in taxa that follow an ecogeographic rule (e.g. Gloger's rule) *do* confer a fitness benefit as the rule would predict, they would not be adaptations (sensu Baum, Mayr, [...]), having evolved elsewhere.

Distinguishing between whether organismal pigmentation follows the Gloger's rule pattern (if and when it does) is governed by deterministic (i.e. environmental filtering) or historical (i.e. adaptation) processes would be insightful. Research concerning this distinction would further allow one to ascertain the degree to which Gloger's rule is a consequence of multiple processes (at multiple spatio-temporal scales), and the number and relative strength of processes that

partake therein. In such a case that these patterns have, say, historical drivers in one system at one scale, and deterministic drivers in another, this would emphasise the complexity of ecogeographic patterns. It would also mirror the notion Olalla-Tárraga (2011) puts forward, wherein correlative generalisations, such as Gloger's rule, need not encapsulate one, if any, mechanisms. Though, it is unlikely that there is *no* mechanisms behind Gloger's rule patterns. Instead, it is interesting and insightful that multiple mechanisms, combined or in isolation, govern these patterns.

Van Lenning et al. (2004) -> evolutionary, not deterministic, pattern to coccolithophore pigment

Concluding remarks

- ...
- Millien et al. (2006) traits vary with geography, but also with global climate change!

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