Biological robustness and fragility

Biological robustness is the ability of a system to continue carrying out its functions in the face of disturbances from within or outside the system. There are two forms of robustness- the first being homeostasis whereby the system returning to its original steady state to perform its functions, and the second being the system getting driven to a new steady state where it maintains its functions under new conditions (Kitano, 2004). On the other hand, fragility is the vulnerability of a system to internal or external disturbances that causes it to lose functionality. Fragility arises from the lack of robustness against unexpected disturbances, which in turn is due to a trade-off between robustness against some disturbances and fragility against others.

Robustness can arise through four ways- system control, alternative mechanisms, modularity and decoupling. System control consists of positive and negative feedback. Positive feedback amplifies stimuli to activate corresponding pathways and allow for the maintenance of both stimulated and non-stimulated states. Negative feedback diminishes stimuli and is the main type of control that allow for robust response against disturbances. Alternative mechanisms can involve redundancy, whereby similar components take over the function of a failed component, or diversity, whereby the same function can be carried out by multiple components. Modularity is the division of a system's components to independent and individual parts, and can be physical, functional, spatial, or temporal. This helps to limit the effects of disturbances to modules instead of the whole system. Decoupling prevents variation in the basic components of the system from affecting its final functions (Kitano, 2004). One example of robustness that arise from alternative mechanisms would be the diauxic shift in yeast. While yeast prefers to metabolise glucose by glycolysis (and produce ethanol in the process), limiting glucose concentrations will cause yeast to metabolise ethanol aerobically. Thus, ATP is produced through different metabolic pathways depending on the availability of glucose or ethanol (Galdieri *et al.*, 2010).

The Highly Optimised Tolerance theory (Carlson & Doyle, 2002) predicts that systems that are robust against particular disturbances are fragile against unexpected ones. For example, the actions of insulin, glucagon and the associated feedback loops make us robust against the lack of glucose during brief periods of food shortage and high energy demand. However, overconsumption of food combined with a sedentary lifestyle promotes diabetes in a system that does not have strong control measures against excess glucose. In this case, the system controls responsible for robustness against one environment work against us in another.

Robustness is crucial for survival as it ensures the maintenance of vital functions even when the organism experiences disturbances such as trauma, disease, or change in environment. Robustness is also important for the long-term survival of a species. Evolution selects for traits favouring robustness and this, in turn, allows species to evolve to become more robust over time. Through decoupling, robustness also prevents genetic variation from influencing phenotype to a certain extent. Although this interferes with evolution in the short term by preventing phenotype variation, neutral mutations which are not subjected to selective pressure can accumulate within populations. This generates a pool of diverse genotypes which will be subject to selective pressure when robustness mechanisms break down due to intrinsic or extrinsic factors such as mutations and environmental changes respectively (Whitacre, 2012).

Fragility threatens the functioning of a biological system and thus its survival. At the species level, fragility may result in extinction when organisms are unable to adapt to changing environments. Fragility is inevitable as there is a trade-off between robustness, fragility, resource demands and performance, whereby increase in some areas will lead to decrease in others. For example, high performance of an animal in terms of movement speed confers robustness against hunting by predators, but this comes at a cost of increased resource demands, as well as fragility against food availability and presence of competitors (Kitano, 2007). Organisms can also avoid fragility through interactions with the environment. They may perform environmental tracking whereby they move towards environments with less threats and more resources, for example in chemotaxis and migration. Organisms may also perform environment shaping whereby they create favourable environments through processes such as niche construction and cultural inheritance, so as to minimise the types and frequency of disturbances experienced (Whitacre, 2012).

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