Evolution of Intelligence in Cephalopods and Its Genetic Foundation

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Introduction

Octopuses, squids and cuttlefish belong to a sub-class of cephalopods called coleoids. They are soft-bodied molluscs and are more advanced than their invertebrate relatives, in that they have the largest nervous systems and are the most cognitively advanced of all invertebrates. Their behaviour is extremely sophisticated; they can solve complex problems, make use of tools and change their body patterns in order to deceive their predators[1], much like many cognitively-advanced vertebrates. However, many studies show that intelligence in cephalopods and vertebrates evolved independently of each other and that any neural similarities are an example of convergent evolution[2], where unrelated organisms evolve similar features as a result of being exposed to similar environmental pressures.

This paper shall examine the link between the emergence of intelligence in cephalopods and RNA editing. RNA editing is a process through which protein structures in organisms are modified without altering the DNA of the organism itself. In cephalopods, RNA editing allows them to survive in and acclimate quickly to drastically different environments, and is the main strategy used by them to adapt and evolve over time. While vertebrates also possess the enzymes required to carry out RNA editing, it does not occur often in these organisms. In most vertebrates, evolution happens through random mutations in the genome, which get transcribed into the RNA and subsequently translated into a protein(Basic Central Dogma). This protein alters the phenotype of the organism in some way, and natural selection acts on these altered phenotypes over a long period of time to select the best adapted organism[3]. This process will henceforth be referred to as Darwinian or genome evolution.

Similarities and Differences in Neural Systems of Vertebrates and Cephalopods

In many ways, cephalopod brains are similar to that of vertebrates: they are of the same relative size, and both share many features of the nervous system, such as camera-like eyes, long- and short-term memory, types of sleep and methods of learning[4].

When comparing the anatomy of cephalopods and vertebrates, however, it is clear that they do not have any structures in common. Vertebrates have a chordate design, with a brain acting as a centralised processor, coordinating signals that it receives from the rest of the nervous system. In the case of cephalopods, only 10% of their brain is centralised and present as a ring around the oesophagus; 30% is present in the form of paired optic lobes and the remaining 60% as axial nerve cords in the arms[5]. They also possess "thinking skin", that is, chromatophores present on the skin that are controlled by the neural system, used to change their appearance to match their surroundings. They have hundreds of suckers on their tentacles, each of which acts as an independent tactile and sensory organ[6].

Thus, the above observations show that sensory organs of cephalopods and vertebrates are examples of analogous organs(similar function, different origin). It can be assumed that neural structures and hence intelligence itself evolved through different pathways in these two groups.

Evolution of Intelligence in Vertebrates

Predator-Prey interactions indirectly influenced the evolution of intelligence in vertebrates. The presence of predators caused these animals to become more sociable and the need to remember and manage complex social networks led to the evolution of the brain. Since they lived in large groups, they had more protection and could develop other features such as wings and larger bodies to fight off predators, which contributed to the extension of their life span. Thus, smarter vertebrates tended to have longer life spans.

Evolution of Intelligence in Cephalopods

Predator-Prey Interactions directly influenced the evolution of cephalopod brains. Cephalopods evolved from solitary shelled molluscs and are solitary creatures themselves. The loss(octopus) or internalization (squid, cuttlefish) of their shells was thought to have occurred to avoid competition with marine vertebrates and had two major consequences:

- It allowed them to access food in a variety of ecological niches, because they could move faster and extend their tentacles into cracks and crevices. The ability to feed on different types of food meant that they had to use more complex foraging techniques. This forced them to become smarter and led to the development of their brain.
- It also made them more vulnerable to predators. In response to this, they had to develop complex methods to outwit predators, such as changing the colour of their skin to camouflage into their surroundings. The need to develop these techniques also drove the evolution of cephalopods' brains.

Despite all the techniques used by cephalopods, chances of survival to adulthood are rare. Due to the high mortality of these organisms, early reproduction and semelparity, the phenomenon where organisms die after their first reproduction[7], is favoured in these species. Thus, cephalopods have very short life spans[1](at most 2 years).

Cephalopods were able to develop such intricate and multifaceted techniques for feeding and avoiding predation with the help of RNA Editing. The following section will explain how. It will also explain why we observe that vertebrates with longer lifespans favour Darwinian DNA evolution, while cephalopods with shorter lifespans favour RNA editing.

RNA Editing

It is the process by which an enzyme(ADAR) acts on mRNA sequences and changes one nitrogen base- Adenosine(A) to Inosine(I) by deamination. This *I* is read a Guanosine(G) during translation and hence, RNA Editing can lead to the production of proteins different from the ones coded for by the original DNA[8]. In a study conducted by Liscovitch-Brauer et. all, it was observed that in mammals, RNA editing sites are mainly present on non-coding regions(introns) and, only a few dozen out of the 20,000 genes in humans possess sites for editing. However, in the case of cephalopods, RNA editing is extremely common. Out of the 20,000 genes that squids possess, nearly 11,000 produce RNA that gets recoded[9]. The study also showed that close(shelled) relatives of cephalopods, such as Nautilus, did not show these levels of RNA editing, suggesting that this feature is unique to shell-less molluscs.

Advantages of RNA Editing

RNA Editing increases the level of complexity of cephalopod DNA. Instead of only 2 alleles producing 2 different effects, this process allows various proteins to be produced by the same gene. Editing happens selectively, in response to certain conditions, and can be partial, full, or even non-existent. Edits are not permanent and can be turned on and off at will as well, allowing cephalopods to modify proteins for many different reasons – temperature, heat stress, starvation and even learning[10] – at will. When more than one editing site is present on the same RNA, different combinations of RNA modifications can occur[8]. This allows for larger intra-species variability and enables individual organisms to adapt in response to extremely specific ecological conditions in their own unique way.

This feature of RNA editing is extremely useful for cephalopods, who live in a variety of complex niches, from tropical shallow seas to the deep-sea hydrothermal vents in Antarctica. Another reason why RNA editing is preferred could be that it is a quicker and easier way for them to adapt and acclimate to their surroundings. Since they have such short lifespans, they can't afford to wait for helpful random mutations to occur. The lack of a shell thus predisposed cephalopods to RNA Editing and, the need to develop complex brains quickly led to this technique being favoured by them over Darwinian evolution. Studies have shown that most of the proteins formed by edited RNA were found in the neural structures of cephalopods. This suggests that RNA editing played a crucial role in the development of complex neural structure in cephalopods[11].

However, it is interesting to note that, due to their short lifespans and resulting rapid rate of reproduction, genome evolution might have happened at a faster rate, with more chances for mutations to occur each time reproduction occurs. Despite this, these organisms favoured individual adaptability over evolution of the species as a whole. This could be due to their solitary nature. Since they lived alone, they had no one to teach them life skills and as such had to adapt to situations however they saw fit. The way they adapted thus varied from one organism to another. They also had a low chance of reproducing due to high mortality rate, and hence might have focussed more on their own survival instead of producing offspring.

Disadvantages of RNA Editing

To be able to maintain flexibility to edit RNA, cephalopods had to give up regular Darwinian DNA evolution. This is because the ADAR enzymes need to bind to 200 base-pair long sequences on either side of RNA to edit it. To minimise changes in these marker sequences, cephalopods evolved DNA that is less likely to mutate. Mutations get suppressed from one generation to the next and hence, these organisms barely evolve[9].

Vertebrates, on the other hand, preferred genome evolution instead of RNA editing. This could be because their longer lifespans meant that they had more chance of producing a higher number of offspring. This, along with higher parental care ensuring that they were focussed on survival of their progeny meant that they favoured transmission of their genes to their offspring over their own survival.

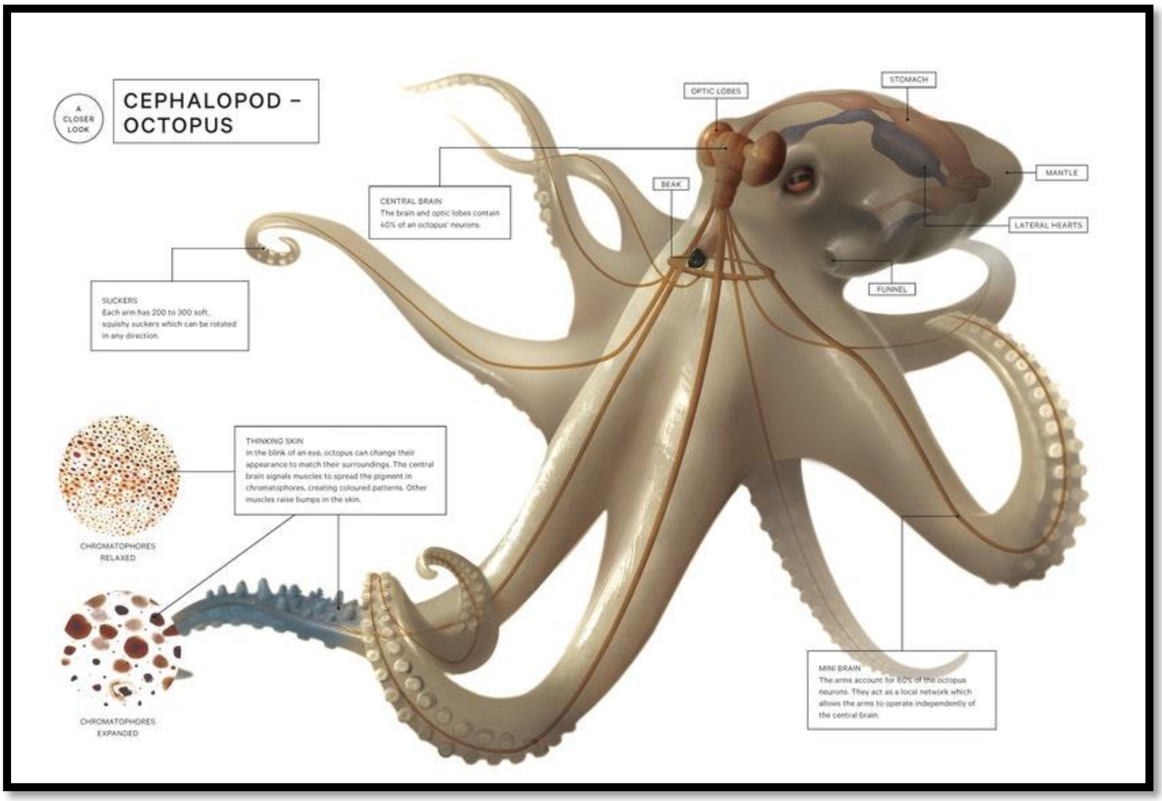
Conclusion

Cephalopods adapt quickly to their environment but evolve extremely slowly as a species. On one hand, this type of evolution might be advantageous, as global warming is causing rapid changes in our environment. On the other hand, their extremely slow rate of evolution means that it will take many millions of years before they show any considerable change in their physiology. Considerably more work is needed to be done to determine exactly how and in which contexts RNA editing occurs, and once we gain a better understanding of this, we could start to use this method to cure genetic diseases like cystic fibrosis, sickle cell anaemia, etc instead of techniques that modify our DNA directly(like CRISPR)[11].

The purpose of this paper was to understand how evolution in cephalopods strongly influenced the way genes behaved. This paper analysed the results of 2 different studies, one which studied how intelligence emerged in cephalopods[1] and the other which analysed the frequency of RNA editing in cephalopods[8]. Taken together, these findings suggest that RNA editing evolved to be of greater importance in cephalopods so that they would be able to respond quickly to environmental cues. This paper discussed the reasons for this and contrasts them with the reasons for why vertebrates prefer genome evolution. Cephalopods faced a trade-off between the ability to adapt quickly and long-term evolution and ultimately chose adaptability in order to quickly evolve to be smarter. Thus, Darwinian evolution may not always be the best course for many organisms.

The fact that cephalopods evolved to be able to perform complex tasks without developing any features of vertebrate brains implies that we – humans are not as unique as we think we are. Thus, through this paper, we also gained new insights into the evolution of intelligence and observed that there are many different evolutionary routes to intelligence.

1. Structure of Brain in Octopus



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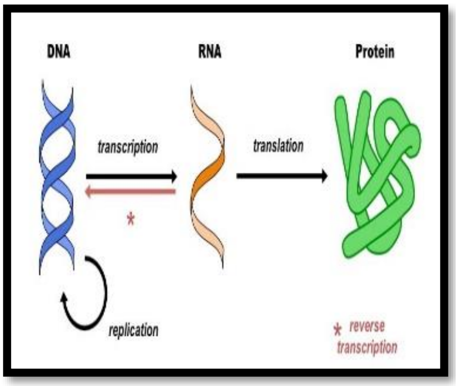
2. Central Dogma



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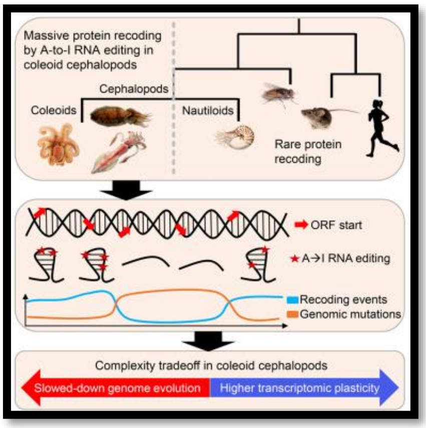
3. RNA Editing in Cephalopods



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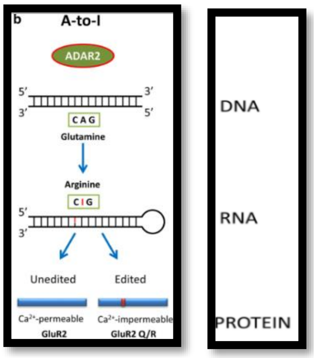
4. RNA Editing



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