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Male-to-Female Sex Change in Clownfish

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Abstract. When the social order of a group changes, clownfish can transform from male to female. Usually, the largest fish in the group is the female, and the second largest is the breeding male. If the female disappears, the male will take its place and gradually transform into a new female. This change involves not only behavioral aspects but also the brain, hormones, genes and gonads. However, the rates of their changes are not synchronized. Studies have found that the hormone levels and gonadal tissues of a fish may already be starting to change, but it still maintains male-like aggressive behavior and continues to care for the eggs. Aromatase and estrogen play an important role in ovarian development. Nevertheless, no single gene or hormone can explain the entire process. This paper reviews how social hierarchy initiates sexual transformation, what happens in the male's body during the transformation, and the usefulness of this ability in nature. The paper also discusses questions that scientists have yet to answer, such as how the fish group perceives the disappearance of the female, and which change occurs first in the brain.

Keywords: Clownfish, sex change, social hierarchy, hormones, sexual development

1. Introduction

Most vertebrates remain of the same sex throughout their lives, but some fish can change their gender after reaching adulthood. Clownfish belong to the "protandrous" type, where the young develop into males at the beginning, and then may transform into females. They live in small groups around sea anemones [1]. The reproductive females in the group are usually the largest in size; the second largest is the reproductive male, and the smaller ones do not participate in reproduction. When a female dies or is removed, the male can start to transform into a female, and the largest non-reproductive fish gradually grows into a new male. Thus, the group does not need to wait for new incoming adult fish to re-establish a reproductive pair.

This change does not occur instantaneously. The male fish first ascends to the highest social rank, but the changes in its behavior, hormones, genes and gonads may not be synchronized. A study on the eye-spotted double-scaled fish (Amphiprion ocellaris) found that the fish, while undergoing gender transition, continued to exhibit aggressive behavior similar to males and parental care for a considerable period of time [2]. This implies that merely observing the behavior of the male fish cannot determine whether the fish has completed the sexual transformation. It is also necessary for researchers to examine hormone levels, gene activity, gonadal tissue and spawning ability.

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The defects in current research restrict the in-depth interpretation of clownfish sexual plasticity and its evolutionary ecological significance, and hinder the improvement of relevant theoretical systems. To fill these research gaps, this review first summarizes the existing research deficiencies and further constructs a four-stage progressive analytical framework. On this basis, it systematically sorts out the multi-level regulatory mechanism of clownfish social-dependent sex reversal, analyzes the core defects of current research, and prospects future research directions, aiming to refine the theoretical system of clownfish sex development regulation and provide reliable theoretical references for subsequent basic research and industrial technical optimization.

2. Social hierarchy and reproductive stability

Body size is the primary determinant of social hierarchy within clownfish groups. The female is the largest member of the group, followed by the breeding male, and then the smaller fish. Higher-ranking individuals may chase or threaten lower-ranking ones, while subordinate fish typically retreat or show submission. These daily interactions help maintain a stable size-based hierarchy. Rank also influences access to food, space within the anemone, and growth rate. Thus, a fish learns its position in the group through repeated encounters and interactions with other members [3].

Experiments have shown that clownfish can detect changes in this order. In the case of juvenile clownfish (A. percula), when higher-ranking members are removed, the fish that rise in rank will quickly change certain behaviors [3]. However, moving up one rank does not always lead to sex change. A smaller subordinate fish may simply become a slightly larger subordinate. Reproductive males are different, as their rank is already close to that of the reproductive females, and they can form a new pairing with the largest fish that is smaller than themselves.

It is still unclear exactly how male fish detect that a female has become vacant. They may sense that the female no longer pursues them; visual cues, scent, sound, touch, and the presence of additional space could also play a role. The presence of smaller fish might be equally important, as the transforming male needs a future mate. Thus, the trigger may not be the absence of the female itself, but rather the entire new social context.

3. Transition following the loss of the dominant female

The female fish may suddenly disappear due to some unexpected circumstances, but it takes the male fish several months to transform into a fully functional female. Several parts of the change overlap. The fish gains the top rank, its behavior adjusts, its hormone levels shift, and its gonad begins to develop more ovarian tissue. These signs do not always remain consistent at the same time point. Male-type behaviors can still appear during sex change. One six-month study looked at eye-spotted anemone fish going through sex transformation. Their sex hormone levels were between normal male and female levels during part of the study [2]. Continuing to care for the eggs may be beneficial to the group, as the existing eggs will not be abandoned. It also shows why researchers should not decide the sex-change stage from behavior only.

Male clownfish have "ovotestis", it is a type of gonad that contains both functional testicular tissue and immature ovarian tissue [4]. During sex change, the sperm-producing part becomes less active. Meanwhile, the ovarian tissue keeps growing larger. Instead, it changes the balance between tissues that are already present. A breeding study found that after about three months of pairing, significant changes occurred in the gonadal tissue and the activity of the CYP19 gene. Under those conditions, at least five months were needed for the change to be completed [5].

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The same time course may not apply to every fish. Temperature, food, stress, species, and the size of the partner all affect this process [1]. Researchers should report how long the female has been absent and use more than one measurement. Spawning and egg production are the clearest signs that the new female is functional, while earlier hormone and tissue changes help to explain how it reached that stage.

4. Brain, hormones and genes

Scientists have not found one switch that can turn a male clownfish into a female. The most reasonable explanation is a pathway linking the brain, pituitary gland, hormones, and gonads. Kisspeptin may be part of this pathway because it helps control reproduction in many animals. In A. clarkii (Clark's anemone fish), the kiss1 and kiss2 genes show different distribution patterns in male and female brains [6]. This is interesting evidence, but it has a limit: The study only records differences between males and females, rather than explaining what causes these differences to happen.

Another study examined various types of cells in the forebrain of the spotted double-ventral scythe fish. Male and female brains differed in some cell numbers, gene activity, and possible communication between cells. The results included radial glia, estrogen-sensitive pathways, cholecystokinin signaling, and cells in the preoptic area. This study shows that an adult clownfish brain can be reorganized. However, it compared completed male and female states, so it still does not tell us which brain change happened first [7].

Among the mechanisms discussed in this paper, aromatase has some of the clearest evidence connected with gonadal change. Aromatase converts androgens into estrogen, and its production is controlled by the CYP19 gene family. Higher CYP19 activity has been found as captive clownfish move toward the female state [5]. Research on other fish also shows that estrogen helps ovarian tissue develop and remain active [8]. Even so, a single hormone measurement cannot describe the entire state of the fish. Hormones may be locally produced in specific tissues, and the sensitivity of cells to hormones may also increase or decrease.

5. Why sex change is useful

Sex change helps the group recover when it loses its female. The breeding male is already living in the anemone and is the next largest fish, so it is the best member to replace her. At the same time, the largest subordinate can become the new male. The group does not have to wait for a new adult fish to arrive from outside. This is particularly important because clownfish depend on the protection of sea anemones. If a clownfish moves to a new home, it has to leave its anemone shelter and becomes far more open to predator attacks.

The size-advantage idea helps explain why clownfish change from male to female rather than the other way around. A smaller male can produce enough sperm to fertilize many eggs, but a large female can usually produce more eggs than a small female. Therefore, if a fish reproduces as a male when it is smaller and then transforms into a female at the highest level, it will have a higher lifetime reproductive success rate. This explains why the ability may have evolved, although it does not explain the body mechanism.

This knowledge could also help with the artificial breeding of clownfish. Breeders may be able to use differences in body size, group structure, and pairing time to encourage the production of females. Direct hormonal or genetic treatments may have adverse effects on the health, behavior, or

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fertility. Any method should be carefully tested and should produce healthy fish that can breed normally [9].

6. Research limits and future work

The biggest gap in present research is distinguishing between finding connections and proving a cause [10]. Male and female fish have different brain cells, hormones, or gene activity, but these differences may occur before, during, or after the changes in the gonads. Timing makes this harder. The time factor also has a significant impact on the experimental results. If researchers only sample a few times at the beginning of the experiment and after several months, they may miss changes that happen in the first hours or days. A better research design would be to collect more information as soon as the female fish are removed, and then gradually increase the sampling interval as the gonads change slowly, achieving the effect of frequent small samples. Nonlethal hormone tests could help researchers follow the same fish, instead of comparing different fish at every stage.

There is also a problem with comparing species and environments. A. ocellaris, A. clarkii, A. bicinctus, and A. percula do not share exactly the same behavior or habitat. Tank experiments make it easy to control food and group size. However, reefs include predators, competition, and the chances for fish to move between sea anemones. Future research will clearly record the species, body sizes, partner size, group structure, and the time since the female disappeared. Without these records, two studies may appear to produce conflicting results, when they are simply testing different real-world conditions.

The most valuable next step in the experiment is to combine multiple measurement methods on the same fish. Researchers can record behaviors, test hormones, study gene activity, examine gonadal tissue, and finally check whether the fish can produce eggs. They could also change only one possible signal at a time, such as visual contact or the presence of a smaller mate. This will help to answer two basic questions: what tells the male that the social order has changed, and when has the fish truly become a functional female?

7. Conclusion

Male-to-female sex change in clownfish begins when the social order of the group is disturbed. The breeding male moves to the top rank after the female disappears, and the largest subordinate can become the new male. In the changing fish, the brain, hormones, genes, and ovotestis all take part in it. They do not follow one perfectly ordered schedule. Male-like aggression and egg care should continue while ovarian tissue is already growing, and hormone levels may stay between normal male and female levels for part of the transition. Of all the evidence reviewed here, this mismatch between behavior and internal change seems very important. They showed why scientists need more than one sign when studying sex change. Aromatase, estrogen, and sex-related genes provide part of the explanation, but the first social signal and the earliest brain response are still unknown. Clownfish are a useful example of how social life can affect the body of an adult animal. They also show that biological sex is more flexible in some species than it first appears.

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